공학박사학위논문

CHARACTERIZATION OF DUST GENERATION IN LIVESTOCK HOUSES BASED ON FIELD MONITORING AND NUMERICAL APPROACH

현장 모니터링 및 수치해석을 통한 축산시설 내 분진 발생 특성 연구

2016년 8월

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이 논문을 공학박사 학위논문으로 제출함

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CHARACTERIZATION OF DUST GENERATION IN LIVESTOCK HOUSES BASED ON FIELD MONITORING AND NUMERICAL APPROACH

A DISSERTATION

SUBMITTED TO THE DEPARTMENT OF LANDSCAPE ARCHITECTURE AND RURAL SYSTEMS ENGINEERING AND THE COMMITTEE ON GRADUATE STUDIES OF SEOULD NATIONAL UNIVERSITY IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

BY

KYEONG-SEOK KWON

AUGUST 2016

Abstract

The evaluation of airborne dust is of concern because it can result in a deteriorated indoor air quality (IAQ) within livestock houses and compromises the respiratory welfare of both livestock workers and animals. To create adequate aero-environmental conditions inside the livestock houses, an understanding of the mechanisms of dust generation according to a complicated combination of variables is very important. However, investigations based on the single correlation between dust concentration and environmental factors have been mostly carried out up to date; there have been few comprehensive and detailed studies that have statistically investigated various dust generation factors simultaneously. In addition, in spite of the demand of legislation pertaining to the occupational exposure limit for dust level in primary industries, such as agriculture, only few studies are available as the backgrounds related to observation of the dust concentrations within livestock houses in South Korea.

In this thesis, as a first step, comprehensive literature reviews on “source of airborne dust within livestock houses”, “factors leading to generation of airborne dust”, “adverse effects on livestock farmers, animals and neighboring society”, “Computational fluid dynamics (CFD) application in agricultural fields” and “CFD analyses on dust behavior in airspace” were intimately conducted to build the foundation and to suggest the appropriateness of the study.

Intensive and long-term field monitoring of airborne dust defined as ‘total suspended particle (TSP),’ ‘PM10,’ ‘inhalable particulate,’ and ‘respirable particulate’ were carried out to determine the key factors affecting dust generation in different size fractions in commercial nursery pig house, mechanically ventilated broiler house, naturally ventilated broiler house, dairy cattle and Korean native cattle farm which are

typical type of livestock houses in South Korea. From field observations and statistical analyses in nursery pig house, statistical analysis results showed that ventilation was the most influential factor for variation of TSP and PM10. Activity of animals, number of animals, and ventilation were found to be significant factors for the concentration of inhalable particulate, while the ventilation, indoor air temperature, and activity of animals were significant factors for the concentration of respirable particulate. From the statistical models, adjusting the ventilation rate or improving the systematic characteristics of ventilation were identified as effective and practical components of dust reduction strategy in terms of their productivity and economic feasibility. With respect to strategy of ventilation control, CFD technique was used to evaluate the dust reduction efficiencies of conceptual pipe-exhaust systems during feed supply based on Eulerian-Eulerian multiphase model. Boundary and initial conditions for numerical model were constructed from the field measured data and statistically derived equations in this thesis. From the computation of dust concentrations and dust removal efficiencies according to the application of the pipe-exhaust system and their operation methods, the application of the pipe-exhaust system was shown to effectively improve the IAQ, especially for inhalable particulate concentrations in the experimental nursery pig house. Combined use of the pipe-exhaust system and conventional roof-exhaust dust ventilation system produced 31.0% decrease of particulate phase with 20 μm AED (Aerodynamic equivalent diameter) in contrast to single operation of the conventional roof-exhaust duct ventilation system when minimum ventilation rate was adopted.

In case of the field observations and statistical analyses for experimental broiler houses, increase in activity of the broilers, indoor absolute humidity and ventilation were influential factors for variation of the inhalable particulate, while outdoor humidity level, activity of the broilers, ventilation rate and age of broilers were

influential factors for respirable particulate in the mechanically ventilated broiler house. Considering the practical operation and their effectiveness, controlling of humidity level inside the facility was effective manner for dust reduction strategies for mechanically ventilated broiler house. For the naturally ventilated broiler house, ventilation rate and activity of broilers were influential to the inhalable particulate, while, indoor air temperature and outdoor absolute humidity level were statistically significant to the variation of the respirable particulate. From the additional chamber experiment to investigate the effect of water contents of bedding materials on dust generation, approximately 45 and 50% of water content levels was found to be a threshold level for generation of the inhalable and the respirable particulate, respectively. Restrictive and temporal application of the droplets spraying on bedding materials is able to be proper options to reduce the respiratory risk for workers especially during shipment works, considering perils of micro-organisms proliferation.

For the experimental cattle farms, statistical analyses were not carried out due to the limited research periods and outbreak of Foot-and-mouth disease (FMD) during research periods. Relatively low dust concentrations were observed in dairy cattle farm and Korean native cattle farm in contrast to other species. However, substantial quantities of the dust concentrations that exceeded the occupational exposure limit for respiratory health of workers were especially found during hoof actions of the animals and TMR (Total mixed ration) process for feed particulates. Water content of bedding materials were also related to the degree of dispersion of the larger particulates such as inhalable particulate fractions. In case of the TMR processing, size of the feed materials and supply method were strongly related to level of dust concentrations.

Keyword: Animal welfare, Computational Fluid Dynamics, Inhalable particulate, Multiple regression, Livestock house, Respirable particulate

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Abbreviations

AED	Aerodynamic equivalent diameter
AER	Air exchange rate
AI	Avian-Influenza
ANOVA	Analysis of variance
AOZ	Animal occupational zone
AWS	Automatic weather station of KMA
CCS	Carbone capture and storage
CFD	Computational fluid dynamics
CTG	Constant tracer gas
DEM	Discrete element model
DES	Detached eddy simulation
DM	Dry matter
DNS	Direct numerical simulation
DPIs	Dry powder inhalers
DRW	Discrete random walk
EDX	Energy-dispersive X-ray spectroscopy
FEV_1	Forced expiratory volume in the first second of exhalation
FMD	Foot-and-mouth disease
FVC	Forced vital capacity
FVM	Finite volume method
HPAI	Highly pathogenic avian influenza
HVAC	Heating, ventilating and air-conditioning
KMA	Korean Meteorological Administration
KTL	Korea Testing Laboratory

IAQ	Indoor air quality
IBM	Immersed boundary method
ICU	Intensive care unit
KTGF	Kinetic theory of granular flow
KTL	Korea testing laboratory
LES	Large eddy simulation
LPS	Lipopolysaccharide
MERS-CoV	Middle-East respiratory syndrome corona virus
MRF	Multiple reference frame approach
MV	Mechanically ventilated
NIOSH	National institute of occupational safety & health
NV	Naturally ventilated
ODTS	Organic dust syndrome
P.A.	Pig-activity
PCR	Polymerase chain reaction
PED	Porcine epidemic diarrhea
PEM	Personal environmental monitor
PISO	Pressure implicit with splitting of operator
PIV	Particle image velocimetry
PM	Particulate matter
POM	Porous media modelling
PRRSV	Porcine reproductive and respiratory syndrome virus
PTFE	Polytetrafluoroethylene
RANS	Reynolds-averaged Navier-Stokes
SARS	Severe acute respiratory syndrome
SIMPLE	Semi-implicit method for pressure linked equations

SLM	Salted floor modeling
TGD	Tracer gas decay
TMR	Total mixed ration
TSP	Total suspended particle
UDF	User-defined function
URANS	Unsteady Reynolds-averaged Navier-Stokes equation
VIF	Variance inflation factor
VFR	Volume flow rate

Chapter 1. Introduction

1.1. Study Background

The word “wellness” has recently emerged due to an increase in the personal interest in wellbeing, happiness and fitness of humans. The demand for personal physical, mental and social health has gained prominence as a major issue. In this context, the amount of meat consumed in South Korea has been steadily increasing due to improvements in living standards and the adoption of “Epicureanism” trends at the dining table. Livestock yield and its proportion of production to the total agriculture industry in South Korea have been steadily growing (33.5 billion $US and 21.2% in 1990; 68.9 billion US$ and 24.4% in 2000; 149.0 billion US$ and 40.1% in 2010; and 160.2 billion US$ and 39.7% in 2014) (Statistics Korea, 2016). To meet the demand for meat consumption, the scale of production of the livestock industry has been expanded based on “economies of scale.” Consequently, the intensive breeding of a large number of livestock has been promoted to achieve price competitiveness in the market. Figure 1-1 shows total number of breeding heads of main livestock animals in South Korea (Statistics Korea, 2015).

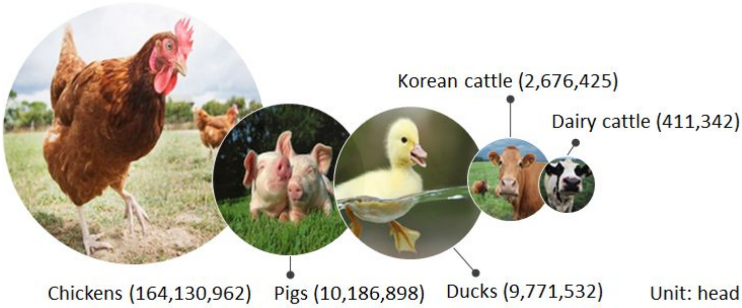


Figure 1-1 Total number of breeding heads of main livestock animals in South Korea (based on the fourth quarter data in 2015, Statistics Korea).

For example, among the main livestock animals in South Korea, the number of breeding pigs has been steadily increasing (4,528,008 in 1990; 9,880,632 in 2010; and 10,332,448 in 2015), and the number of pig farms with over 5,000 heads has also shown an increasing trend; (38 in 1990; 305 in 2010; and 393 and 2015) (Statistics Korea, 2015) (Figure 1-2). However, by the end of 2010, a highly contagious animal epidemic, foot-and-mouth disease (FMD) occurred in South Korea. FMD caused drastic declines of 17.2% of the number of pigs and as a result, 9.9 million heads in 2010 to 8.2 million heads in 2011 after the mass cull as a preventive measure (Statistics Korea, 2015). Subsequently, 360 million USD in economic losses was reported other related industries. However, robust recovery of the livestock industry in South Korea has resulted due to the efforts by the government of South Korea and livestock farmers. The breeding number of pigs in 2012 was reported as 10 million head (Ministry of Agriculture, Food and Rural Affairs in Kora, 2015). Figure 1-2, 1-3, and 1-4 shows breeding scales of pigs, chickens, and cattle (including Korean native cattle and dairy cattle) per household from 1985 to 2015 in South Korea, respectively (Statistics Korea, 2015).

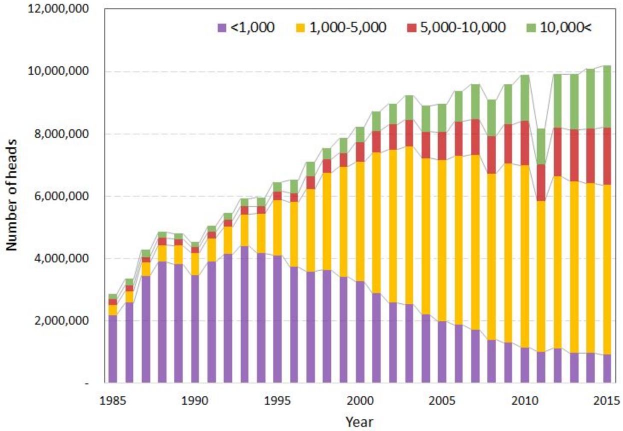


Figure 1-2 Breeding scales of pigs per household from 1985 to 2015 in South Korea
(based on the fourth quarter data of each year, Statistics Korea, 2015).

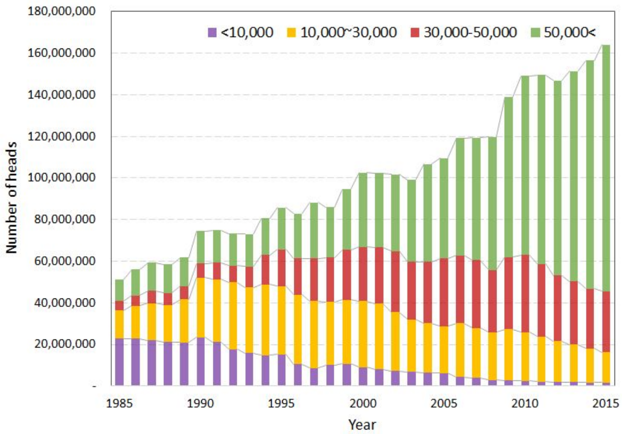


Figure 1-3 Breeding scales of chickens per household from 1985 to 2015 in South Korea
(based on the fourth quarter data of each year, Statistics Korea, 2015).

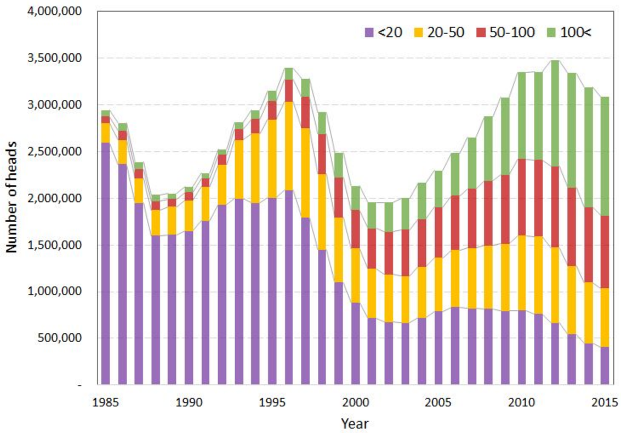


Figure 1-4 Breeding scales of cattle per household from 1985 to 2015 in South Korea (based on the fourth quarter data of each year, Statistics Korea, 2015).

Despite the modernization and automation of livestock facilities, the working environment of livestock farmers is very poor. Livestock farmers are usually exposed to considerably higher levels of pollutants, such as dust, ammonia, hydrogen sulfide and odorous matters, compared to individuals working in other environments. Of the various pollutants present inside a livestock house, many studies have shown that dust is strongly responsible for the largest amount of deterioration in the health and welfare of the farmers (Donham et al., 1986; Popendorf et al., 1986; Takai et al., 1998; Radon et al., 2001; Wathes et al., 2002; Andersen et al., 2004; Banhazi et al., 2008; Cambra-Lopez et al., 2010; Donham, 2010; Sykes et al., 2011) and animals (Donham, 1991; Robertson et al., 1990; Seedorf et al., 1998; Wathes et al., 2002; Al Homidan et al., 2003; Cambra-Lopez et al., 2010). The bulk of the dust is usually generated from feed particles, hair, dander, feces, and bedding materials inside the livestock facilities. Feed particles have been reported as one of the main sources of dust generation based on optical and chemical observations (Honey & McQuitty, 1979; Donham et al., 1986; Heber et al., 1988; Hartung & Saleh, 2007). Fecal materials are also well known contributors to airborne dust (Donham et al., 1986). Fecal airborne dust is usually generated from dried feces due to the activity of the animals (Takai et al., 1998).

A number of studies have indicated that microorganisms, such as endotoxins (i.e., the lipopolysaccharide (LPS) components of the cell wall of gram-negative bacteria (e.g., *Escherichia coli, Salmonella, Shigella, Psuedomonas*) attached to airborne dust) can have negative health impacts on humans following long-term exposure (Clark et al., 1983; Seedorf et al., 1998; Heederik et al., 1991; Donham, 2010). Since a study by Donham et al. (1977), numerous dose-response, epidemiological, and questionnaire-based studies have been conducted to thoroughly investigate the relationship between dust and health impacts on livestock farmers, especially with respect to respiratory disorders (Donham et al., 1986; Rylander et al., 1989; Seedorf et al., 1998; Iversen et al., 2000; Heutelbeck et al., 2009; Basinas et al., 2012). These studies have reported that livestock farmers have a high prevalence of wheezing, coughing, sputum or phlegm, sore throats, runny noses, allergic and non-allergic rhinitis, acute and chronic decline in lung function, organic dust syndrome (ODTS), chronic bronchitis, asthma, and asthma-like syndromes than workers in non-farming occupations. Ultra-fine dust particles are also implicated in cardiovascular diseases (Tucker, 2000). In a recent survey in South Korea, the prevalence rate of respiratory disorders such as asthma (3.6%) and allergic rhinitis (29.2%) of agricultural workers including livestock farmers were higher than people living in urban areas (prevalence rate of asthma of 2.8% and allergic rhinitis of 16.8%) (Center for farmer's safety and health, Hanyang University, 2015).

Dust is also responsible for adverse health effects in livestock animals. Donham (1991) observed increased mortality and reduced live-weights among experimental piglets, and also found elevated mortality and prevalence of pneumonia and pleuritis among fattening pigs exposed to high dust concentrations. Harry (1978) elucidated that airborne dust can increase the susceptibility of birds to respiratory disease by their irritant action or allergic reaction. Dust can also transport gaseous pollutants such as odors, ammonia, and hydrogen sulfide, which can cause aesthetic displeasure and health problems for nearby residents (Takai et al., 1998; Merchant et al., 2005; Radon et al., 2007; Wing et al., 2008). Furthermore, airborne dust is a vector of micro-organisms (Curtis et al., 1975; Martin et al., 1996; Wathes et al., 2002; Andersen et al., 2004; Matkovic et al., 2007; Radon et al., 2007) including various highly pathogenic livestock animal diseases and zoonosis such as FMD (Ryan et al., 2009), highly pathogenic avian influenza (HPAI) (Power, 2005), campylobacteriosis (Berrang et al., 2004), Newcastle disease (Hugh-Jones et al., 1973), colibacillosis (Zucker et al., 2000), and salmonellosis (Gast et al., 2004) both inside and outside livestock houses.

The generation of airborne dust inside the livestock house is influenced and governed by various factors, including animal related factors, such as species, age, and rearing density (Gustafsson, 1997; Hinz & Linke, 1998; Kwon et al., 2013), feeding methods (Pearson & Sharples, 1995; Gustafsson, 1999), breeding management (Seedorf et al., 1998; Takai et al., 1998), ventilation (Pearson & Sharples, 1995; Gustafsson, 1997; Hinz & Linke, 1998; Takai et al., 1998; Gustafsson, 1999; Pedersen et al., 2000; Wang et al., 2000), and micro-climatic features, such as air temperature and humidity (Al Homidan et al., 1996; Seedorf et al., 1998; Ellen et al., 2000; Vučemilo et al., 2008). These studies have usually shown a single correlation between the measured dust concentration and the experimentally studied factor. However, these approaches are limited to fully understand the complexity of characteristics of dust generation within livestock house. There have been few comprehensive and detailed studies that have statistically investigated various dust generation factors simultaneously. Banhazi et al. (2008a) conducted a statistical investigation at the national scale in Australia to determine the key factors for the generation of airborne pollutants inside pig houses using the variables of housing (facility type, rearing stage, and farm size) and management (hygiene, air temperature and humidity) type. However, this study was carried out based on only short-term (single experiment for each experimental building) observations with nominal variables. A long-term and intensive investigation with quantitative variables still remains to be conducted for representing and understanding the characteristics of dust generation. In addition, 90% of the experimental livestock houses investigated in Banhazi et al. (2008a) are naturally ventilated pig houses, of which only 10% are mechanically ventilated, and there were no attempts to determine a quantitative approach toward the ventilation factor.

1.2. Objective of thesis

Deteriorated IAQ in a livestock house can threaten the health and welfare of both livestock farmers and animals. There are several key issues that should be considered with respect to the compromised IAQ in a livestock house. First, it is important to understand the mechanism of, and the key factors leading to, dust generation based on long-term and intensive field observations. Second, an effective dust reduction strategy should be introduced based on a careful investigation.

In this thesis, intensive and long-term field monitoring of airborne dust with different size fractions were conducted at typical commercial livestock houses in South Korea. With the measured dust concentrations and quantitative environmental variables, comprehensive analyses based on statistical approaches were carried out to find key factors of dust generation and possible and effective options for dust reduction.

- The thesis is organized into five chapters. As a first step of compromising the mentioned issues, Chapter 2 is a comprehensive literature review that builds the thesis foundation and suggests the appropriateness of the study. The review included literature on the sources of airborne dust within livestock houses, factors leading to generation of airborne dust, adverse effects on livestock farmers, animals and neighboring areas, computational fluid dynamics (CFD) application in the agricultural sectors and CFD analysis on dust behavior in airspace.

- Chapter 3 discusses the field monitoring of airborne dust in the total suspended particle (TSP), PM10, and inhalable and respirable particulate fractions, which were conducted at commercial nursery pig house. From the measured dust concentrations and environmental factors, statistical approaches were carried out to understand the mechanism of, and the key factors leading to, the airborne dust generation in an experimental nursery pig house. Then, a CFD model was designed to identify effective dust reduction techniques based on the Eulerian-Eulerian multiphase model. For a conceptual case, a pipe-exhaust system was designed and its systematic performance with respect to efficiencies of particulate removal was computed to evaluate the possibility of suggesting a dust control technique.

- Chapter 4 discusses the field monitoring of airborne dust in different size fractions in a commercial mechanically ventilated broiler house and a naturally ventilated broiler house. To overcome the experimental limitations of evaluating the ventilation rate of broiler houses in a quantitative manner, CFD models were designed by considering ventilation characteristics of the experimental broiler houses and outdoor wind conditions. The ventilation rates for each experimental situation were computed using tracer gas decay (TGD) method. From the dust concentrations and experimentally and numerically derived factors, statistical approaches were carried out to understand the mechanism of, and the key factors leading to, the airborne dust generation in the experimental broiler houses. An additional chamber experiment was also conducted to investigate the relationship between dust generation and water content level of the bedding materials.

- Finally Chapter 5 discusses field monitoring of airborne dust in different size fractions in a commercial dairy cattle farm and a Korean native cattle farm. Statistical analyses were not carried out due to the limited research periods and the outbreak of FMD during the research periods. Respiratory risk was evaluated based on the measured dust concentrations according to the working schedule of the farmers, such as cleaning, milking, and TMR processing.

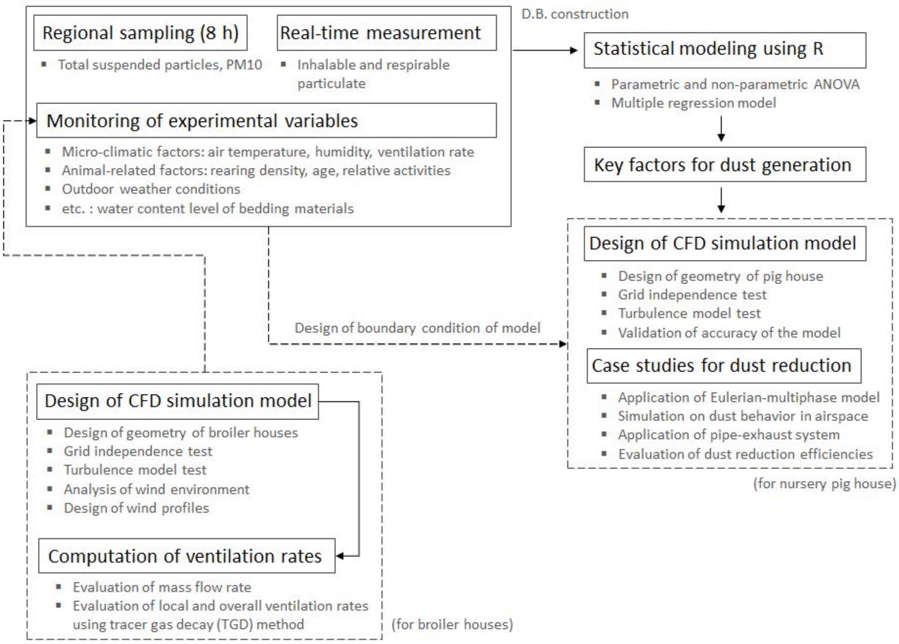


Figure 1-5 Overall research flow to find key factors for dust generation in livestock houses.

Chapter 2. Literature review

2.1. Definition of airborne dust

A particle is defined as a small and discrete object (Cambra-Lopez et al., 2010). Cambra-Lopez et al. (2010) explained that PM (Particulate matter) is often used for air quality applications and refers to fine solid or liquid particulates suspended in a gaseous medium in airspace. This definition is also matched with the term “aerosol”, although this term is more generally used in the atmospheric sciences (Cambra-Lopez et al., 2010). Dust refers to solid particles of the matter formed by the mechanical fracture of the parent materials, which sediment under the force of gravity. TSP and PM10 are the size fractions most commonly used to evaluate the quality of ambient air (US EPA, 2001a). TSP is a measure of the mass concentration of all particulate matter in the air space. The PM10 fraction is defined as the sampling cut-off aerodynamic diameter (AED) of 10 μm of particle separators, through which a mass of TSP passes with a sampling efficiency of 50%. Similarly, the PM 2.5 fraction is also defined as particulate matter that passes through a particle separator with a 50% efficiency cut off at 2.5 μm AED (US EPA, 2001b).

The fractions of size relevant to occupational health are defined by the International Standards Organization (ISO, 1995) based on the behavior of the particles in the human respiratory tract, and are derived from the depth of the entrance into the respiratory system as inhalable (particles that can be inhaled through the upper respiratory tract, such as nose and mouth), thoracic (particles that can penetrate into the larynx), and respirable (particles that can penetrate beyond the larynx and enter the unciliated respiratory system) particulates (Cambra-Lopez et al., 2010). Figure 2-1 shows the parts of the human respiratory tract and possible health issues arising from dust inhalation.

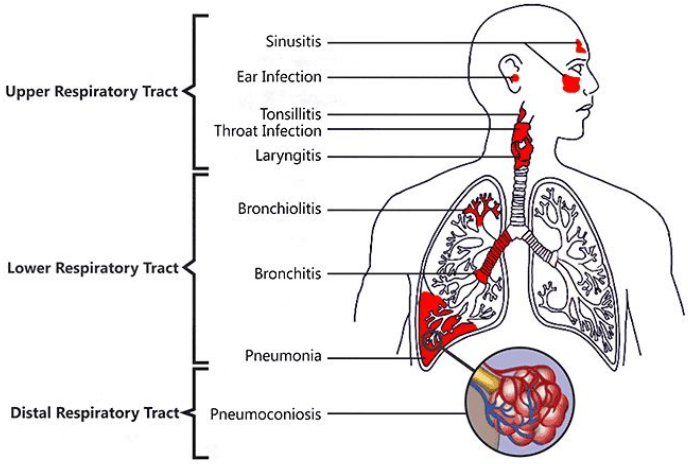


Figure 2-1 Definition of part of human respiratory tract and possible health issues arising from the dust inhalation ("Flow Centric Mining Technology," 2016).

Inhalable particulates are in the size range of 0 to 100 µm AED with 50% deposition efficiency at an AED of 100 µm in the upper respiratory tract, while respirable particulates are in the size range of 0 to 10 µm with an average diameter of 4 µm and 50% deposition efficiency in the alveoli of the lung. Cambra-Lopez et al. (2010) reported that inhalable particulates are considered to be the equivalent of TSP, while the respirable particulates are considered the equivalent of PM4 or PM5 (ISO, 1995).

Despite the scientific evidence indicating adverse health problems among the livestock farmers, the Ministry of Employment and Labor (2015) in South Korea only suggests the occupational exposure limits of 10 mg/m^3 for TSP and 3 mg/m^3 for respirable particulates for workers in the manufacturing industries, which are based on the guidelines of the American Conference of Governmental Industrial Hygienists (ACGIH, 2010). There is still no specific legislation pertaining to the occupational exposure limits in primary industries, such as agriculture, in South Korea. The National Institute of Occupational Safety & Health (NIOSH) of the United States have reported occupational exposure limits of inorganic dust for cotton, grain, and wood dusts in reference to the agriculture industry. However, the direct application of the NIOSH recommendations cannot be extended to the agricultural area, especially in the livestock industry because of the various micro-organisms that can be attached to the surface of dust particles. The components of organic and non-organic dust also behave differently in the human respiratory system.

In this context, Donham & Reynolds (1995) and Reynolds et al. (1996) suggested occupational exposure limits of the inhalable and the respirable organic particulates for pig farmers based on the results of dose-response investigations. Donham & Reynolds (1995) reported that the forced expiratory volume in one second (FEV_1) of pig farmers who worked for two to three hours per day for six years was decreased by more than 10% at an organic inhalable particulate concentration of 2.5 mg/m^3 and organic respirable particulate concentration of 0.23 mg/m^3. Similarly, concentrations associated with significant decrements of the pulmonary function of the poultry farmers were 2.4 mg/m^3 for organic inhalable particulate and 0.16 mg/m^3 for respirable particulate (Donham et al., 2000). CIGR (1994) also suggested the allowable dust exposure limits for animals: 3.7 mg/m^3 for inhalable particulate and 0.23 mg/m^3 for respirable particulate (Table 2-1).

Table 2-1 Occupational exposure limit of inhalable and respirable particulate for pig farmers, poultry farmers and animals.

	Inhalable particulate	Respirable particulate
Pig farmers (Donham & Reynolds, 1995; Reynolds et al., 1996)	2.5 mg/m^3	0.23 mg/m^3
Poultry farmers (Donham et al., 2000)	2.4 mg/m^3	0.16 mg/m^3
Animals (CIGR, 1994)	3.7 mg/m^3	0.23 mg/m^3

2.2. Sources of airborne dust within livestock house

The adverse effects of airborne dust on human and animals within a livestock house and the proper countermeasures for dust reduction are very important to investigate and establish. Some important issues are where the airborne dust comes from, what kinds of components are involved and how airborne dust generates from the source. Many scientists have analogized the sources of airborne dust from qualitative field observations and optical analyses. Recently, various "source apportionment study" for the dust from livestock houses has been conducted with the help of statistics and the technological advances of light- and electron-based microscopes such as EDX (Energy-dispersive X-ray spectroscopy) technique.

Many researchers have reported that dust in the livestock houses is almost entirely organic. The bulk of the dust is composed of feed particles, hair, dander, feces, and bedding materials inside pig house (Donham et al., 1986; Heber et al., 1988; Takai et al., 1998; Wang et al., 2000; Radon et al., 2001; Zhu et al., 2005; Cambra-Lopez et al., 2010). In a poultry house, feed particles, skin, feathers, bedding materials, dried feces and mineral crystals from urine and litter are identified as major sources of airborne dust (Koon, 1963; Harry, 1978; Van Wicklen et al., 1988; Maghirang et al., 1991; Qi et al., 1992; Wathes et al., 1997; Kristensen et al., 2000; Cambra-Lopez et al., 2010). Among them, feed particles and fecal materials are especially well known as important contributors to airborne dust (Clark et al., 1983; Donham et al., 1986; Cambra-Lopez et al., 2010; Wang et al., 2000). Many scientists mentioned that the primary origin of airborne dust in a pig house is feed particles (Honey & McQuitty, 1979; Donham et al., 1986; Heber et al., 1988; Takai et al., 1998). Donham et al. (1986) reported that feed particles are usually more abundant in coarse fraction, which include mechanically generated particles (i.e., crushing). A cut-point diameter between fine and coarse particles is generally defined as 2.5 μm (Cambra-Lopez et al., 2010). Curtis et al. (1975) found higher nitrogen content in airborne dust in a farrowing pig house, indicating a possibly high contribution of feed particles to the generation of the airborne dust. Honey & McQuitty (1979) found from morphological investigation using a microscope that most of the airborne dust larger than 7 μm in a pig house was of feed origin material. They concluded that the airborne dust consisted of 8% skin, 1% hair debris and 91% feed particles. Hartung (1986) reported that dust particles may come from feed (80~90%), litter (55~68%), animals (2~12%), feces (2~8%) and structural elements in the pig house. Heber et al. (1988) also addressed that airborne dust is mainly originated from feed particles and, to a lesser extent from feces. Particles larger than 5.4 μm were identified as 66% grain meal, 14% starch and 0.4% skin, and particles smaller than 1 μm were 65% grain meal, 14% starch and 1.0% skin. Fecal dust is usually observed in a greater extent in the respirable fraction, indicating a potential high risk to the respiratory system such as the alveoli in the lungs (Donham et al., 1986). Fecal dust is generally generated from the dried feces on the ground surface. Takai et al. (1998) reported that feces on a slatted floor in a pig house are normally dry due to the effective drainage and these materials can be easily dispersed by activities of the animals. However, Heber et al. (1988) and Cambra-Lopez et al. (2010) mentioned that discrimination between the feed and fecal materials for evaluating the contribution degree to the airborne dust is very challenging due to the similar morphological and chemical characteristics among them, especially in the case of the existence of undigested feed particles in feces. Choi et al. (2005) reported that dry matter (DM) based protein contents of the airborne dust in the broiler house were in the range of 42.8~65.2%, while those of the feed particles were in the range of 20.5~24.5% from an investigation using SEM-EDX test. These overestimated results could be explained that not only feed particles but also materials such as skin and feathers of the broilers and feces containing undigested feed particles could contribute to the protein composition of the airborne dust. Cambra-Lopez et al. (2010) mentioned that the results in some studies tend to overestimate the contribution of particulate matters from feed because no distinction was made between feed and feces, especially when only light microscopy was used. They concluded that the use of stains might be one of the solution in this case, like in Donham et al. (1986) where iodine was used to stain starch from feed particles, and Nile blue sulfate to stain fecal particles.

Gustafsson (1997) and Hinz & Linke (1998) reported that the major source of airborne dust could be the animals themselves. Hinz & Linke (1998) observed relatively higher dust concentrations in turkey houses with rearing density of 3.5 birds/m^2 than in facilities with 1.5 birds/m^2. Hinz et al. (1999) concluded that the animals and their excrements were the main sources of dust in the poultry houses. Gustafsson (1999) indicated that a considerable part of the dust could be generated from the animals themselves by the fact that the measured dust concentration was proportional to the number of animals and their weights. The generation of airborne dust also showed increasing trends according to the age of the animals in the broiler house. However, the mentioned animal related factors seemed ambiguous to be defined as the exact “sources” of the airborne dust. These can be concluded as an aspect of the “effects” of the animals such as breeding numbers, weights and ages of the animals on the generation of airborne dust.

However, different results have been suggested up to date due to the complexity of the PM and experimental conditions even though various optical and chemical analyses have been conducted to investigate the source of airborne dust inside the livestock houses. A follow-up study should investigate the exact origin of airborne dust in order to establish the proper countermeasures for dust reduction.

2.3. Factors leading to generation of airborne dust within livestock houses

The components and concentration of airborne dust inside livestock houses are governed by numerous factors, including animal related factors (i.e., species, age, weight, activity, and breeding density), ventilation, micro-climatic factors (i.e., air temperature and humidity), management practices, feeding methods, and waste handling method (Table 2-2).

Table 2-2 Main factors affecting dust concentration inside livestock houses.

Factors	Authors
Seasonal changes and ventilation	Pearson & Sharples (1995), Gustafsson (1997), Gustafsson (1999), Hinz & Linke (1998), Seedorf et al. (1998), Takai et al. (1998), Golbabaei & Islami (2000), Pedersen et al. (2000), Wang et al. (2000), Banhazi et al. (2008a), Banhazi et al. (2008b), and Kwon et al. (2013)
Animal species, ages, weights, activity, and breeding density	Bundy & Hazen (1975), Mc Daniel et al. (1977), Yoder & Van Wicklen (1988), Qi et al. (1992), Pedersen (1993), van't Klooster et al. (1993), Gustafsson (1997), Wathes et al. (1997), Hinz & Linke (1998), Ellen et al. (2000), Seedorf & Hartung (2000), Redwine et al. (2002), and Hessel & Van den Weghe (2007)
Air temperature and humidity	Butera et al. (1991), Noll et al. (1991), Qi et al. (1992), Al Homidan et al. (1996), Seedorf et al. (1998), Takai et al. (1998), Guarino et al. (1999), Ellen et al. (2000), Iversen et al. (2000), Pedersen et al. (2000), Zucker et al. (2000), Banhazi et al. (2008a), and Vučemilo et al. (2008),

2.3.1. Seasonal changes and ventilation

A number of studies (Hinz & Linke, 1998; Seedorf et al., 1998; Takai et al., 1998; Golbabaei & Islami, 2000; Kwon et al., 2013) have shown that a relatively higher dust concentration is usually observed in the winter season than in the summer season in livestock houses. These phenomena are strongly related with the ventilation effect. Ventilation is one of the significant factors for creating favorable breeding conditions for animals inside the facility. In the summer season, heat stress of the animal occupational zone (AOZ) is very fatal to the productivity and the welfare of the animals. Therefore, relatively high values of the ventilation rate are usually adopted to effectively remove surplus heat by full opening of the winch curtains for a naturally ventilated livestock facility or application of tunnel ventilation for a mechanically ventilated facility. In these cases, various pollutants such as airborne dust, odorous matter, ammonia and hydrogen sulfide as well as surplus heat can be eliminated to the outdoor environment. However, a relatively low ventilation rate is generally applied in the cold season in order to consider internal heat conservation and expense of heating costs. That is, elimination of the internal pollutants is relatively unfavorable than in the summer season. it brings about deteriorated IAQ for both livestock farmers and animals.

A number of studies measured the level of airborne pollutants in a livestock house. These studies were usually conducted in naturally ventilated facilities and simply reported the differences of the airborne dust according to the seasonal change in a qualitative manner. Many of these studies did not explain the relationship between the level of airborne dust and the ventilation in a quantitative manner. Quantification of the ventilation was very restricted due to the experimental limitations of measuring invisible and unstable airflow patterns. The energy balance model (Sase et al., 1980; Fernandez & Bailey, 1992; Boulard & Draoui, 1995), pressure difference model (Boulad et al., 1996; Papadakis et al., 1996), and tracer gas technique (Bot, 1983; Nederhoff et al., 1985; De Jong, 1990) have been widely adopted to quantify the ventilation rate in a livestock facility based on the mass conservation law. However, these methods still have weakness. For examples experimental and theoretical assumptions cannot embrace the realities in the facility.

These techniques cannot guarantee the actual local and overall ventilation effect inside the facility; and experimental situations are always restricted due to the existence of live animals in terms of experimental convenience and animal welfare problems. Consequently, the mentioned studies indirectly analogized that ventilation might be an important factor of causing the difference of airborne dust according to the seasonal change. For example, Takai et al. (1998) conducted extensive field research and statistical investigation on airborne dust in the livestock houses (e.g., pigs, chickens and cattle in the Netherlands, Germany and Belgium). Various factors such as country, housing type, seasonal difference and sampling periods were used to carry out the multifactorial analysis of variance on the dust concentration and its emission. In spite of the comprehensive work which is receiving textbook attention in the area of airborne pollutants in livestock houses, ventilation was not included in a qualitative manner.

In a piggery building, ventilation rates in the winter season are generally lower than those in the summer, thus leading to higher inhalable particulate concentration within the facility (Pearson & Sharples, 1995). They reported that ventilation airflow is more capable of removing the inhalable particles than the respirable particles, because the air turbulence induced by ventilated air agitates and dissipates the smaller particles in the airspace. In a broiler house, Hinz & Linke (1998) observed low dust concentrations when the inside air temperature exceeded the outside air temperature by less than 10°C (usually in the summer season), than when the difference was more than 10°C (winter season). Hinz & Linke (1998) concluded that smaller differences between inside and outside air temperature are normally associated with higher ventilation rates, thus showing again a high influence of the ventilation rates on the internal environmental factors. Golbabaei & Islami (2000) also showed a high level of dust concentration during the winter season relative to the summer season in a target experimental facility.

Despite the well-known ideas that explain the dilution effect of the ventilation on airborne dust, some researchers have suggested different views. Pedersen et al. (2000) and Wang et al. (2000) observed that there was a high variation in the spatial dust distribution in a mechanically ventilated pig building according to the operation of the ventilation system. They suggested that the ventilation system has direct effects on the spatial dust concentration whereas the increase in ventilation rate will not necessarily reduce the overall dust concentration effectively because the dust generation rate will be increased according to the increasing of the ventilation rate. Gustafsson (1997) also experimentally observed that the ventilation rate had a limited diluting effect on the total mass of airborne dust. They concluded that the settling of the airborne dust on a different surface was a more important mechanism for removing larger particulates from the airspace than the ventilation rate. Measurement of the number of different sized particles in a pig house have indicated that increased ventilation rates mainly reduce the particles larger than 1.0 μm and had only limited effects on the particles smaller than 1.0 μm. Turbulence associated with the increased ventilation rates can influence the re-suspension of pre-settled particles (Banhazi et al., 2008). Guarino et al. (1999) suggested that the ability of the ventilation system on the re-suspended particles can be influenced greatly by the effectiveness of the systematic and general cleaning of the poultry units.

Effects of ventilation on airborne dust are very complex. Increase in the ventilation rates does not always mean an apodictic decrease of the dust concentration; because the ventilation can also influence the increase of turbulence and re-suspension of the pre-settled dust. In addition, ventilation also increases the heating requirement of AOZ in the winter season. Livestock operators scarcely ever increase the ventilation rate in these periods considering the heating costs and thermal stability.

In summary, the effects of ventilation on the generation of airborne dust should be evaluated in a qualitative manner and the complexity of its influence on micro-climatic conditions should also be carefully investigated.

2.3.2. Animal related factors

The generation of airborne dust inside a livestock house is influenced by numerous animal related factors such as species, breeding number, stocking density, age and their activities. The continual development of an intensive livestock production system has been associated with increased stocking density and herd size (Kwon et al., 2015). The concentration of airborne pollutants in the livestock house such as airborne dust, ammonia, hydrogen-sulfide and various micro-organisms normally are increased as the stocking density. Thus, this has changed the working patterns of livestock farmers, leading to a long exposure to pollutants. Various researchers have examined the relationship between animal related factors and the generation of airborne pollutants. Gustafsson (1997) found that the amount of airborne dust is proportional to the number and their weights of the animals in the pig house. In the case of chickens, age and weights have a positive relationship with dust concentration (Mc Daniel et al., 1977; Hinz & Linke, 1998; Redwine et al., 2002). Wathes et al. (1997) indicated that bird age affects dust generation from broilers probably because of the changes in litter moisture and composition. An increased amount of dried manure with bird age, as well as increased bird activities and ventilation rates may also contribute to increased dust generation. Yoder & Van Wicklen (1988) found a logarithmical correlation between the concentration of respirable particulate and total bird weights.

Animal activity is another influential animal related factor affecting the generation of airborne dust inside the livestock houses. A number of studies have focused on the relationship between dust concentration and application of a light program or diurnal changes, especially in the chicken house (Van Wicklen et al., 1988; Yoder & Van Wicklen, 1988; Qi et al., 1992; Takai et al., 1998; Ellen et al., 2000; Mitchell et al., 2002; Hessel & Van den Weghe, 2007). For examples, Takai et al. (1998) mentioned that there were clear differences between day and night in perchery and caged layer building for airborne dust. The average inhalable particulate concentrations for layers in perchery and cage were 7.33 and 1.51 mg/m^3 for day time, and 2.82 and 0.82 mg/m^3 for night time, respectively. Hinz & Linke (1998) observed that dust concentration in a mechanically ventilated turkey house were up to five times higher during day time (light on) than night time (light off). In the study conducted by Hessel & Van den Weghe (2007), measured dust concentration were twice as high during the light period (5.54 mg/m^3) in comparison to the dark period (2.60 mg/m^3) in a commercial broiler house. Seedorf & Hartung (2000) also reported that the length of the photoperiod is considered a key factor in the dust generation in poultry farming.

In pig houses, a high level of inhalable particulate was usually observed during day time especially at feeding than during night time (Hinz & Linke, 1998). Gustafsson (1997) observed a variation in the number of different sized particles during day time with the constant ventilation rate condition in a growing-finishing pig house. In their study, the increase of dust concentration was found when the activity of animals was relatively higher. Cambra-Lopez et al. (2010) and Kwon et al. (2013) explained that the amount pollutants originating from feces and feed residuals deposited in a dry state on the floor could be considerably dispersed into the airspace due to a frequent movement of the pigs during day time. Livestock animals are generally more vigorous during day time because feeding and activities of farmers are mainly restricted to the day time. Animal movement can cause air turbulent motion around them and disperse settled particulates from building surfaces, causing an increase in dust concentration (Takai et al., 1998).

From the mentioned results, diurnal changes and use of lighting programs affect the generation of the airborne dust concentration according to the increase in animal activities. The activity of animals can be also influenced by the farm's operations such as weighing, feeding and cleaning. However, different viewpoints on the activities of animals have been suggested. Pearson & Sharples (1995) mentioned that concentration of the respirable particulate might not be affected by the animal activity to the same extent as the inhalable particulate concentration, because there are different aerodynamic behaviors in the airspace. Respirable particulate would be suspended in the airspace for longer times after the movement of the animals, and thus reduced animals' activity would have less impact on their concentration. However, the settling rate of relatively larger particles is greater Thus, a decrease in animal activity would have a more immediate effect on the concentration of the inhalable particulate (Pearson & Sharples, 1995; Pedersen et al., 2000). Meanwhile, in contrast to the mentioned positive trends with dust concentration and age and weights of the animals (birds), some researchers observed decreasing trends of airborne dust with the age and weight of animals, especially in pig houses. Hinz & Linke (1998) reported that the increase in live weights of fattening pigs make animals tardigrade. That is, reduced animal activity as pigs grow can cause A relatively low dust concentration. However, increased ventilation rate with the live weights of pigs may also have an influence on the dust concentration as pigs grow.

2.3.3. Micro-climatic factors

A number of studies have shown the effects of micro-climatic factors such as air temperature and relative humidity on the dust concentration in livestock houses (Noll et al., 1991; Qi et al., 1992; Al Homidan et al., 1996; Seedorf et al., 1998; Takai et al., 1998; Guarino et al., 1999; Ellen et al., 2000; Pedersen et al., 2000; Banhazi et al., 2008a; Vučemilo et al., 2008). Generally, increase of inside air temperature effects on the excitement of animals and the buoyancy force of various pollutants can lead to an increase in airborne pollutants. When the air temperature increases inside the livestock houses, it can accelerate the dry conditions of the feces and feed particles on the ground (van't Klooster et al., 1993; Seedorf et al., 1998; Takai et al., 1998; Gustafsson, 1999). Therefore, opportunities of the dispersion of these dried matters can be easily increased according to the air flow pattern and behavior of the animals. Temperature is usually positively correlated with pollutants such as dust, ammonia and various micro-organisms (Noll et al., 1991; Al Homidan et al., 1996; Guarino et al., 1999; Pedersen et al., 2000), whereas relative humidity generally shows the negative trends towards pollutants (Qi et al., 1992; Al Homidan et al., 1996; Takai et al., 1998; Ellen et al., 2000; Iversen et al., 2000; Vučemilo et al., 2008). Many studies focused on the relationship between relative humidity and water content of bedding materials. For example, Seedorf (1997) observed that cattle buildings and fattening pig buildings with litter were wetter than other building types, which was reflected in the high relative humidity and low dust concentration. Takai et al. (1998) explained that a relative humidity of 70% or higher may contribute low airborne dust concentration due to high equilibrium moisture contents. Thus, particles on the surface of the bedding materials may contain bound and condensed water, which may cause particles to aggregate together. Recently, Banhazi et al. (2008b) found a reduction effect of humidity on the concentration of respirable particulate in a deep-bedding pig house. They explained that these tendencies were caused by the increased “stickiness” of the bedding materials under high moisture conditions. Takai et al. (1998) also elucidated these phenomena using the characteristics of grain materials, which is a constituent of the bedding materials. For example, an equilibrium moisture content of feed grain such as barely or wheat was about 16% at a relative humidity of 70%. Above this moisture content, the grain particle contained condensed water on its surface, which prevented particles from becoming airborne. The mentioned relationship between relative humidity and the water content of the bedding materials seems as am effective measure to reduce the concentration of airborne dust. However, many studies pointed out the perils of the proliferation of micro-organisms in these humid conditions. Banhazi et al. (2008b) observed a higher concentration of endotoxin, which is a lipopolysaccharide (LPS) component of cell walls of gram-negative bacteria in the fattening pig house with high humidity conditions. Endotoxin is strongly responsible for decrement in lung function of livestock farmers (Rylander et al., 1989; Heederik et al., 1991; Vogelzang et al., 1998). Butera et al. (1991) and Zucker et al. (2000) indicated that higher endotoxin levels with increased humidity conditions were due to prolonged bacterial survival times in the airspace. They explained that the natural half-life of airborne micro-organisms such as gram-negative and gram-positive bacteria generally range between a few minutes and an hour. After this time, bacteria become deactivated and release amounts of endotoxins into the airspace. Chang et al. (2001) also noted similar opinions that water remaining on the pen floors provides an ideal environment for the multiplication of microbes in piggery buildings.

2.3.4. Other factors

Banhazi et al. (2008a, 2008b) investigated the correlation between aerial pollutants and environmental variables of pig house such as building classification, level of pen hygiene and animal management method. They observed that airborne bacteria and respirable endotoxin concentrations were affected by building classification according to pig breeding stage such as weaner, grower/finisher and farrowing. Concentrations of airborne bacteria and ammonia showed increasing trends as the level of pen hygiene decreased. In their statistical investigations, concentrations of the respirable particulate were primarily affected by building classification, pen hygiene, pig flow management and pre-mentioned main factors such as seasonal changes, ventilation rate, air temperature and relative humidity.

Feeding techniques have been also reported as an influential factor on the dust generation in a pig house (Gore et al., 1985; Chiba et al., 1987; Heber & Martin, 1988; Gustafsson, 1999; Paik & Kim, 2013). For example, with a dry feeder, feeding twice a day showed lower dust concentration than free access to feed by pigs (Bundy & Hazen, 1975). Takai et al. (1986) observed a dust concentration of 1.8 mg/m^3 at a dry feeding management and 1.4 mg/m^3 for a wet feeding management in an experimental pig house. Robertson (1992) also presented results that showed significantly lower dust concentration at restrictive feeding in comparison to the ad libitum feeding method. Gore et al. (1985), Heber & Martin (1988), Pearson & Sharples (1995), Takai et al. (1998) and Banhazi et al. (2008b) suggested that the addition of oil or fat to the feed stuff may decrease the generation of dust in the pig house.

In a broiler house, the type of litter is also an influential factor for dust generation (Ellen et al., 2000; Kaliste et al., 2004; Nimmermark & Gustafsson, 2005; Banhazi et al., 2008b). As mentioned above, bedding materials can hold dust particles when water moisture contents are relatively high. Thus parts of dust particles deposited on the bedding materials may be retained with the layer of straw. Takai et al. (1998) mentioned that fine chopped straw may contain a number of relatively small particles, which were produced during chopping. Consequently, there was a high possibility of becoming airborne. Banhazi et al. (2008) described the influence of litter materials on the generation of airborne dust through a literature review. In these sections, the litter can be regarded as a major source of airborne dust in poultry houses and their physical and chemical characteristics can affect the concentration and composition of the airborne dust. They mentioned that 60% of airborne dust in a layer house with deep bedding management was composed of some components from bedding materials, whereas 80% of airborne dust in a layer house with cage was composed of feed materials. Similarly, Aarnink & Ellen (2007) showed the influences of the use of litter and the type of breeding system such as aviary and cage on the concentration of airborne dust in a poultry house. They observed relatively higher dust concentration and emission rates in the aviary system than those of the cage system. They mentioned that the reason for these differences were the large exposed surface of the manure and the litter in the aviary system. Furthermore, the cage system could restrict the activity of the layers. In this context, Ellen et al. (2000) and Banhazi et al. (2008) suggested that impregnating the bedding materials with a mixture of oil and water could significantly reduce dust generation in a poultry house.

2.4. Adverse effects on livestock farmers and animals

Airborne dust inside livestock houses may deteriorate the health condition and welfare of farmers (Donham et al., 1977; 1986; Iversen & Pedersen, 1990; Tielen et al., 1995; Iversen et al., 2000; Radon et al., 2001; Andersen et al., 2004; Cambra-Lopez et al., 2010) as well as the health and productivity of animals (Donham & Leininger, 1984; Robertson et al., 1990; Robertson, 1992; Al Homidan et al., 2003; Banhazi et al., 2008a; Cambra-Lopez et al., 2010). Furthermore, emitted particulates to the outside of the livestock house can have an influence on neighboring areas and environment (Takai et al., 1998; Sigurdarson et al., 2004; Merchant et al., 2005; Radon et al., 2007; Banhazi et al., 2008a).

2.4.1. Livestock farmers

Respiratory disease is one of the primary health problems of livestock farmers (Andersen et al., 2004). Since the first report of pulmonary disorders of pig farmers by Donham et al. (1977), a number of studies in the fields of medicine, and health and veterinary sciences have exampled the relationship between airborne pollutants and respiratory symptoms of livestock farmers (Donham et al., 1986; Bruce & Sommer, 1987; Rylander et al., 1989; Iversen & Pedersen, 1990; Crook et al., 1991; Olson & Bark, 1996; Seedorf et al., 1998; Iversen et al., 2000; Whyte, 2002; Basinas et al., 2012). The influences of airborne dust on the human respiratory system are generally governed by the size of the particulates and their behaviors in the respiratory tract. Particles larger than 10 μm usually settle out rapidly of the airspace due to the force of gravity. If these particles are inhaled through the human breathing process, they are trapped by moist tissue in the nose and throat, called the upper respiratory tract. The particles can cause irritation of the nose and throat. However, particles less than 5 μm in size may reach the bronchiole and alveoli in the human breathing process. Cambra-Lopez et al. (2010) elucidated that there are three ways in which airborne dust may affect the health of livestock farmers: by irritation of the respiratory tract and reduction of immune resistance to respiratory disease by dust inhalation; by irritation of the respiratory tract by certain biological compounds present in the particulate; and by inhalation of pathogenic and non-pathogenic micro-organisms carried by airborne dust. As mentioned earlier, since the first report by Donham et al. (1977), epidemiological investigation and questionnaires in numerous dose-response studies have shown a high prevalence of respiratory related disorders from livestock farmers such as wheezing, coughing, sputum of phlegm, sore throats, runny noses, allergic and non-allergic rhinitis, acute and chronic decline in human lung function, asthma, asthma-like syndrome, ODTS and chronic bronchitis. The following examples are representative cases showing a high prevalence of the respiratory disorders of livestock farmers than for non-farming occupations:

- Bar-Sela (1984) found that "wheal-and-flare" reaction to poultry antigen could be diagnosed in poultry workers displaying respiratory symptoms. That is, a causal relationship between exposure to airborne pollutants in the poultry house and development of respiratory disease is demonstrated.
- 60% of pig farmers who have worked for six or more years have one or more respiratory symptoms (Donham et al., 1989). The prevalence rate of respiratory symptoms among livestock farmers working in a confined pig house was 25% in comparison with 12% of livestock farmers working in a naturally ventilated pig house (Donham et al., 1990).
- About 80% of studied livestock farmers experienced work-related respiratory symptoms such as chest tightness, and nasal and eye irritation (Crook et al., 1991).
- Larsson et al. (1994), Zhiping et al. (1996), Larsson et al. (1997) showed that relatively short exposure to airborne dust in a pig house can cause an intense inflammatory reaction of the airway and fever to the pig farmers.
- In the UK, an epidemiological survey reported that 8% of the stockman working with laying hens showed the prevalence of respiratory impairment (Whyte et al., 1998).
- Donham (2000) reported that 25% of piggery workers in the US are potentially affected by non-allergic occupational asthma, and 33% have shown episodes related

with ODTS.

- Palmberg et al. (2002), Von Essen & Romberger (2003) and Kim et al. (2013) found that exposure to airborne dust alters lung function and cytokine production in the blood of livestock farmers.
- 24.3% of livestock farmers working in a broiler house showed lower FEV_1 (Forced expiratory volume in the first second of exhalation) and FVC (Forced vital capacity), and 2.7% showed severe obstruction. Alencar et al. (2004) explained that livestock farmers had higher pulmonary health risks when working more than four years within more than poultry house, and exceeding five hours per day of work.
- From an epidemiological study, Rosentrater (2004) reported that over 700,000 people (including livestock farmers, their family members and veterinarians) in the US are exposed to hazardous levels of dust, and over 60% suffered from respiratory disorders such as ODTS, chronic bronchitis, hypersensitivity pneumonitis and occupational asthma.
- In South Korea, the Center for Farmer's Safety and Health at Hanyang University conducted a survey to investigate the prevalence rate of respiratory disorder of agriculture farmers including livestock and horticulture farmers. The prevalence rate of asthma (3.6%) and allergic rhinitis (29.2%) were higher for farmers than that of asthma (2.8%) and allergic rhinitis (16.8%) for people living in urban areas in South Korea (National Health Insurance Corporation, 2015).

A number of studies reported that a high level of endotoxin inside the livestock house is strongly responsible for various respiratory symptoms of livestock farmers (Donham et al., 1989; Heederik et al., 1991; Donham & Reynolds, 1995; Vogelzang et al., 1998; Zucker et al., 2000; Sykes et al., 2011). In a recent study, Donham (2010) explained that the risk of acute and chronic respiratory health effects in livestock farmers are related to the genetic susceptibility to endotoxin or allergens of the individual, the length of working time, whether the person smokes, and whether they have other respiratory conditions. Endotoxin is a lipopolysaccharide component of cell walls of gram-negative bacteria (e.g., of *Escherichia coli, Salmonella, Shigella, Pseudomonas, Neisseria, Haemophilius,* etc.) and is released after the death of the gram-negative bacteria. Although gram-negative bacteria are found in a relatively low percentage in livestock houses (≤10%) in comparison with gram-positive bacteria (Zucker et al., 2000), Seedorf (1997) reported that endotoxin is a significant toxin compound because this compound still represents a high amount in the airspace due to the extremely high concentration of total bacteria. These kinds of bacteria are usually adhered to the surface of dust particulates and are often referred to as a viable dust. Dust less than 5 μm usually functions as a carrier of these kinds of viable particles. Consequently, the viable particles can cause various respiratory disorders for livestock farmers. Kim et al. (2013) found that exposure to a high concentration of dust and endotoxin of pig farmers can cause deflective activation of the T lymphocytes. That is, a high concentration of dust and endotoxin systematically demonstrated the higher prevalence of allergic diseases such as asthma, allergic rhinitis and bronchitis among the livestock farmers.

Moreover, dust particles can also adsorb irritant gaseous matter such as ammonia and hydrogen-sulfide, which play a role in inflicting toxic effects on farm workers and livestock animals (Coleman et al., 1991; Takai et al., 1992; Razote et al., 2004). Ammonia is usually produced as a result of chemical and biological breakdown of urea contents in the urine. Dietary nitrogen in the fecal materials (Groot Koerkamp et al., 1998) and hydrogen sulfide is also produced when liquid manure is agitated (Osbern & Crapo, 1981). Gaseous matter can be very hazardous in itself (e.g., causing severe eye irritation, coughing and frothing at mouth, reduced appetite, convulsions and irregular breathing). However, if gaseous matter is adhered to the surface of dust particles, the possibility of deeper inhalation in the human respiratory tract can be increased, and thus a potential health hazard can be increased.

2.4.2. Livestock animals

Airborne dust inside a livestock house can also bring on adverse health effects of livestock animals. Seedorf & Hartung (2000) reported that the effects of airborne dust on the health status of animals are governed by the compounds of the particles carrying micro-organisms and the physical properties of the particles such as size and shape. Dust particles smaller than 5 μm can penetrate deep into the lungs and a high concentration of the dust can irritate the mucous membranes and overload the lung clearance mechanisms. Similar to humans, micro-organisms adhered to the surface of the dust particles can be also transported into the deeper respiratory system of animals. A number of studies investigated the relationship between health status and productivity of the animals and the level of airborne pollutants inside the livestock houses (Kovacs et al., 1967; Hayter & Besch, 1974; Drummond et al., 1980; Donham, 1991; Hamilton et al., 1993; Urbain et al., 1994; Al Homidan et al., 1998; Urbain et al., 1999; Kristensen et al., 2000; Al Homidan et al., 2003; Wathes et al., 2004). The following representative studies show adverse health effects and decrease of productivity of livestock animals.

For pigs:

- Kovacs et al. (1967) observed that 87% of the studied pigs were affected by severe pneumonia during conditions of high dust concentration.
- Doig & Willoughby (1971) investigated the effect of pollutants such as ammonia

and dust on the health status of piglets in experimental chambers. All experimental cases showed no effect on growth rates of the piglet. However, exposure to a combination of ammonia and dust caused damage to nasal and tracheal epithelium tissues of the piglets.

- Donham (1991) observed increased mortality and reduced weight gain among experimental piglets exposed to a dust concentration higher than 5.2 mg/m^3. An elevated mortality and high prevalence of pneumonia and pleuritis among fattening pigs exposed to a dust concentration higher than 3.7 mg/m^3 were also found in their investigation.
- Robertson (1992) suggested that the IAQ inside the pig house is strongly associated with various adverse health effect such as atrophic rhinitis and enzootic pneumonia of the animals.
- Banhazi & Cargill (1998) observed 8% of the growth rate improvement of pigs in conditions with a 17% decrease of viable bacteria, 42% decrease of inhalable particulate and 76% decrease of ammonia concentration.
- Pigs exposed to 4.4 mg/m^3 of inhalable particulate in an experimental chamber over six days showed increased macrophage counts and airway inflammation (Urbain et al., 1999).
- Wathes et al. (2004) observed a decrease of food intake and live weight gain for weaner pigs that were exposed to a dust concentration in the range of 5.1~9.9 mg/m^3 than pigs that were raised in an environment with a dust concentration below 5 mg/m^3.
- Lee et al. (2005) investigated the growth rates and immune response of male weaner pigs in a “clean” and “dirty” environment. The weaner pigs grew significantly faster and consumed more feed under “clean” conditions where daily cleaning was conducted.

For chickens:

- Airborne dust in a poultry house can carry *Escherichia coli* (Harry, 1964), Newcastle disease (Hugh-Jones et al., 1973), and Marek's disease (Beasley et al, 1970; Jurajda & Klimes, 1970), causing an immunological challenge and increased mortality of broilers.
- Harry (1978) elucidated that airborne pollutants such as dust can increase the susceptibility of birds to respiratory disease by irritant action or allergic reaction.
- Oyetunde et al. (1978) examined exposure effects of dust, ammonia and *E.coli* separately and in combination on chickens for four weeks. They found that *E. coli* alone had no ill effects on the experimental chickens. However, pathogenic effect on the respiratory system was observed when combined with either dust or ammonia or both.
- Klasing & Barnes (1988) conducted experiments to determine the influence of immunologic stress on methionine and lysine requirements of growing chickens. *Escherichia coli* lipopolysaccharide or heat-killed *Staphylococcus* aureus was injected to introduce the immunologic stress of animals. They found that immunogen injection decreased methionine and lysine requirements, probably because of a decreased need of amino acids for growth and tissue accretion. Compared with saline-injected chickens, immunogen-injected chickens had significantly higher serum interleukin-1 activity by 53% when fed the methionine-sufficient diet. However, they did not have significantly greater interleukin-1 levels when fed the methionine-deficient diet.

The mentioned observations and studies indicated that the immunologically challenged livestock animals from airborne pollutants, including dust, gaseous matters and various micro-organisms, have shown a decline of feed intake and productivity, scars on the internal organs, respiratory disorders and increased mortality. Therefore, controlling airborne pollutants and increasing the IAQ inside livestock houses are very important to enhance animal welfare and economics when considering productivity.

2.4.3. Neighboring societies

The harmful effects of airborne dust outside and inside livestock houses have been reported (Schiffman et al., 1995; Groot Koerkamp et al., 1998; Takai et al., 1998; Pope et al., 2002; Radon et al., 2004; Merchant et al., 2005; Zhu et al., 2005; Gloster et al., 2007; Radon et al., 2007; Wing et al., 2008; Cambra-Lopez et al., 2010). Various pollutants can be released to the outside through ventilated air from the livestock house (Phillips et al., 1998). The transport of odors (Hammond et al., 1979; Hammond et al., 1981; Hartung, 1986; Williams, 1989; Schiffman et al., 1995; Liao & Singh, 1998; Takai et al., 1998; Bottcher, 2001; Oehrl et al., 2001; Radon et al., 2004; Nimmermark & Gustafsson, 2005; Wing et al., 2008; Cambra-Lopez et al., 2010) and pathogenic micro-organisms (Hugh-Jones et al., 1973; Donaldson, 1978; Seedorf et al., 1998; Baykov & Stoyanov, 1999; Berrang et al., 2004; Gast et al., 2004; Mitchell et al., 2004; Rosentrater, 2004; Power, 2005; Zhu et al., 2005; Gloster et al., 2007; Ryan et al., 2009; Cambra-Lopez et al., 2010; Zucker et al., 2000) to the neighboring areas are regarded as the main harmful effects of exhausted pollutants from the livestock houses.

In the case of odor-related problems, Takai et al. (1998) mentioned that airborne dust can transport and amplify odor to neighboring areas. Ammonia and odorant matters can be absorbed on the surface of dust particles. Reynolds et al. (1998) showed that a significant proportion (15~23%) of airborne ammonia in a livestock house is related with dust particles. Cai et al. (2006) revealed more than fifty compounds bound to airborne dust from a pig house, belonging to a different chemical characteristics including alkanes, alcohols, aldehydes, ketones, acids, amines and nitrogen heterocycles, sulfides and thiols, aromatics and furans. It is obvious that dust particles can be a vector of odorant matters inside and outside the livestock houses. There are a number of evidences showing adverse health, emotional and social effects on people living in neighboring areas due to the particulates, gases and odor from livestock houses (Schiffman et al., 1995; Radon et al., 2004; Wing et al., 2008). Schiffman et al. (1995) demonstrated that odorant matters can cause nausea, vomiting, headache, shallow breathing, coughing, sleep disorders, upset stomach, appetite depression, eye, nose, and throat irritation and mood disturbances such as agitation, annoyance and depression. They also conducted a study to investigate the mood profiles of forty-four people living near livestock houses. From this investigation, the studied group was angrier, tense, confused, depressed and fatigued than the control group. Moreover, odors from the livestock house can cause social and legal conflicts between livestock operators and those living in the vicinity of the farms. The dispersion of odors can be varied according to the environmental conditions such as wind speed, wind direction, atmospheric stability, and odor emission rate. Therefore, evaluation and control of odor are one of the emerging concerns in the livestock industry.

Airborne dust emitted from a livestock house is also associated with airborne transmission of pathogenic micro-organisms. Homes et al. (1996) and Seedorf et al. (1998) indicated that the possibilities of survival of micro-organisms in the outside air can be increased when they are attached to the surface of a dust particle. Dust particulates carrying micro-organisms, so called viable dust or bio-aerosol show biological actions, which are indicated by viability, infectivity, allergenicity, toxicity or pharmacological activity (Cox & Wathes, 1995). The identification of various bacteria and viruses from airborne dust at the outside of a livestock house has been carried out (e.g., *Salmonella, Staphylococcus, Streptococcus, Campylobacter, Escherichia coli, Micrococcus*, endotoxin and rotavirus), implying that airborne dust can be a vector for various contagious livestock disease among the livestock houses (Curtis et al., 1975; Martin et al., 1996; Zucker et al., 2000; Berrang et al., 2004; Gast et al., 2004; Mitchell et al., 2004; Rosentrater, 2004; Matkovic et al., 2007). Pathogenic particulates can be also dispersed long distances to the vicinity of the livestock houses. For example, Baykov & Stoyanov (1999) observed that the amount of micro-organisms can be transmitted up to 3,000 m by the ventilated air from a poultry house. Dee et al. (2009) experimentally proved diagnostic evidence that porcine reproductive and respiratory syndrome virus (PRRSV) and *Mycoplasma hyopneumoniae* could be transported up to 4.7 km in the airspace from an experimental source farm. Otake et al. (2010) also examined airborne transport distance of PRRSV and *Mycoplasma hyopneumoniae* and they found the maximum transmission distance of 9.2 km through dust sampling and qualitative polymerase chain reaction (PCR) assays. FMD virus which is one of the severe and highly infectious livestock diseases can be also dispersed for some kilometers away from the sources, and infect livestock animals in other farms or wild animals (Donaldson et al., 1970; Hugh-Jones & Wright, 1970; Gloster et al., 2007).

The outbreak of these kinds of contagious livestock diseases can cause a decrease of feed and water intake, decline of productivity and increase in mortality rate of the animals. When there is an outbreak of highly-pathogenic diseases such as FMD and HPAI, a number of livestock animals within some kilometers from the source must be slaughtered as preventive measures. Consequently, vast economic loss to the livestock industry can be incurred. Furthermore, some bio-aerosols are also responsible for many infections in human (Gunn & Davis, 1988; Degener et al., 1994; Razonable et al., 2001; Bakutis et al., 2004; Seedorf, 2004; Cai et al., 2006). A number of studies have reported the prevalence of respiratory symptoms from people living in the vicinity of a livestock farm, including symptoms of bronchitis, asthma, and asthma-like diseases (Merchant et al., 2005; Sigurdarson & Kline, 2006; Radon et al., 2007). Aben et al. (2002) reported that the inhalation of a high concentration of airborne pollutants can cause early deaths due to heart and lung health issues, especially in the elderly, children and ill persons who live in the vicinity of livestock houses. Moreover, the perils of zoonosis have been in the forefront due to recent outbreak of SARS (Severe Acute Respiratory Syndrome), Brucellosis, MERS-CoV (Middle-East Respiratory Syndrome Corona Virus), Anthrax and AI (Avian-Influenza) which caused severe casualties and economic loss. Scientific evidence revealing the possibilities of the airborne dispersion of zoonosis have been experimentally demonstrated. Table 2-3 shows the examples of the airborne transmittable zoonosis (Cambra-Lopez et al., 2010).

The emitted airborne dust from livestock houses have also elucidated other harmful effects such as reduced visibility, vegetation stress, ecosystem alteration (Grantz et al., 2003), eutrophication and acidification of both soils and surface water (Harssema & Klarenbeek, 1981; Buijsman & Erisman, 1988; Groot Koerkamp et al., 1998; Hooda et al., 2000) and change in soil pH (Misselbrook et al., 2000; Arogo et al., 2003).

Table 2-3 Potential airborne transmittable zoonosis (Cambra-Lopez et al., 2010).

Zoonosis	Micro-organisms	Authors
Campylobacteriosis	*Campylobacter spp.*	Berrang et al. (2004) Wilson (2004)
Influenza	Avian-Influenza virus	Power (2005)

Newcastle disease	Newcastle disease virus	Hugh-Jones et al. (1973)
Colibacillosis	*Escherichia coli*	Sauter et al. (1981) Zucker et al. (2000)
Salmonellosis	*Salmonella spp.*	Mitchell et al. (2002) Gast et al. (2004)
Foot-and-mouth disease	Foot-and-mouth disease virus	Hugh-Jones & Wright (1970) Gloster et al. (2007) Ryan et al. (2009)

2.5. Application of Computational fluid dynamics technique to agricultural fields

Computational fluid dynamics (CFD) is a numerical analysis method for computing behavior of fluid by solving a nonlinear partial differential equation, such as the Navier-Stokes equation, based on the principles of mass conservation, Newton's second law, and the first law of thermodynamics (Norton et al., 2007; Kwon et al., 2015). Convective heat and mass transfers dominate the exchange process of the energy, and materials in ventilated structures. As a consequence, indoor environmental parameters such as air temperature, humidity and pollutants are governed by the airflow patterns. These airflow patterns can be also an essential link between the outdoor environment and indoor micro-climate (Norton et al., 2007). Therefore, successful operation of agricultural facilities is strongly connected with the proper design of ventilation systems. In this context, CFD has been widely used as a powerful tool in the field of agriculture to overcome the filed-experimental limitations and give resilience of the design evaluation for microclimatic analyses of greenhouses (Bournet et al., 2007; Teitel et al., 2008; Boulard et al., 2010) and livestock houses (Norton et al., 2009; Seo et al., 2009; Seo et al., 2012; Wu et al., 2012; Kwon et al., 2015), as well as studies of the dispersion of livestock odors (Li & Guo, 2008; Hong et al., 2011) and aerosols in the airspace (Bitog et al., 2012; Hong et al., 2014).

In this section, recent state-of-the art studies especially on for livestock houses using CFD techniques will be briefly introduced. Comprehensive reviews on related studies using the CFD technique for the animals production system and the greenhouse can be also found in Norton et al. (2007) and for the external atmospheric environment, and land and water management in agricultural fields in Lee et al. (2013).

2.5.1. Recent CFD studies related to pig houses

The present application of CFD techniques on the internal and external environment analyses in livestock houses has shown different approaches and objectives according to the livestock species. Recently, major interests of CFD studies related to pig houses were mostly the evaluation of modeling techniques for porous media of perforated ceilings, partitions, and slatted floors, realization of the animal geometries in the computational domain, evaluation of HVAC (Heating, ventilating, and air-conditioning) systems with respect to the thermal comfort and gas dispersion, and external dispersion analyses of the pollutants from pig houses. Bjerg et al. (2008) and Bjarne et al. (2011) investigated the efficiency of the partial pit ventilation system to reduce ammonia emissions from a pig production unit. In their studies, the porous media assumption was used to avoid a detailed geometrical modeling and complicated subdivision of the space around animals. The perforated ceiling, slatted floors and AOZ were designed as foam of the porous media in the computational domain. However, Adrion et al. (2013) assumed the perforated ceiling as the foam in a small number of openings instead of applying the porous media modeling technique. However, the accuracy of the modeling technique was not validated. Rong et al. (2015) compared the effects of the porous media modeling (POM) for slatted floors and direct geometrical modeling for those (SLM; salted floor modeling) using air speed, concentration and emissions in a scaled pig barn (1:12.5) with isothermal conditions. These studies showed that SLM generally provided better predictions of air speed than POM. POM could predict air speed below the slatted floor appropriately, but failed to predict the air speed above the slatted floors. Rong et al. (2015) concluded that POM may lead to uncertainties in the prediction of emissions in a full scale pig house where gas emissions are released from the slatted floor. These discrepancies in the CFD-computed results between SLM and POM could be explained by the application of incorrect resistance coefficients of the porous media according to the three-dimensional (3D) directions. The exact values of the aerodynamic resistance coefficients for all directions should be well evaluated through field measurements and wind tunnel tests. Studies on the suggestion of appropriate resistance coefficients for the slatted floors, the perforated ceilings and the AOZ, and exact modeling techniques for porous media should be followed.

The presence of the animals in a livestock house can also significantly influence the airflow pattern and micro-climatic conditions. In this context, recent studies tried to realize the presence of pigs in computational domain using the modeling technique of the porous media (Bjerg et al., 2008; 2011; Shen et al., 2009) and direct modeling technique of solid objects for animals (Seo et al., 2012; Adrion et al., 2013). Seo et al. (2012) and Adrion et al. (2013) simulated airflow pattern and thermal distribution in a pig house according to various ventilation configurations. The aim of these studies was to suggest optimum ventilation configurations in order to achieve uniformity and stability of the environmental conditions for the occupants. In contrast to studies using the porous media technique to realize the existence of the animals in the AOZ, they tried to design animals as solid objects in the computational domain. Adrion et al. (2013) designed geometries of the pig as a cylindrical solid body, while Seo et al. (2012) directly designed the real shape of pigs to accurately simulate the turbulence dissipation and heat transfer in the AOZ.

Analyses of internal dispersion of gaseous matters including ammonia in pig houses have been studied recently. As mentioned, Bjerg et al. (2011) and Rong et al. (2015) evaluated the potential of reducing indoor ammonia emissions and concentrations from slurry using the partial pit ventilation system. Rong et al. (2010) also investigated ammonia emission from a pig house, which include the effects of airflow and aqueous ammonium solution temperature on ammonia mass transfer.

Recent study trends for external dispersion from pig houses were mainly restricted to odor analyses, and disease dispersion and design of wind breaks (Li & Guo, 2006; 2008; Lin et al., 2007; 2009; Hong et al., 2011a; 2011b; Seo et al., 2015). Cruz et al. (2010) evaluated the effect of a porous windbreak installed in front of the exhaust fans to reduce the emission potential of the pollutants from the pig house. Kafle et al. (2015) studied aerodynamic resistance of bio-filters using the CFD technique to treat emitted odorous matter, ammonia and hydrogen-sulfide. Lin et al. (2007; 2009a; 2009b) used the CFD technique to simulate windbreak effects on odor dispersion from the livestock house. Effects of the physical characteristics of the windbreak such as tree porosity, type and height, and installation distance from sources were studied. Hong et al. (2011a; 2011b) simulated the dispersion of livestock odor over a complex terrain considering physical phenomena such as wind shear, insolation flux from the ground and atmospheric stability. Seo et al. (2015) developed a web-based forecasting system for the airborne spread of livestock infections disease using the CFD model. The developed model could predict the dispersion area and possible route of livestock infectious diseases for the next forty-eight hours using real-time weather forecasting data through computation of scalar transport equations with pre-calculated airflow fields.

2.5.2. Recent CFD studies related to poultry houses

In the case of poultry houses, the main issues have been the investigation of thermal distribution related to heat stress of broilers in summer season and heating efficiencies in the winter season, and design optimization of the ventilation system to increase the productivity of the animals. Bartzanas et al. (2007), Lee et al. (2007), Blanes-Vidal et al. (2008), Pawar et al. (2010), Bustamante et al. (2013; 2015) and Guerra-Caldo et al. (2015) used CFD techniques to evaluate the air velocity distribution and the ventilation rate in poultry buildings. Bustamante et al. (2015) computed air velocity distribution in a tunnel ventilated broiler house located in Mediterranean climate areas in order to investigate the effects of a hot climate on broilers. Excessive heat stress of the broilers can cause an increase in mortality, decrease in meat quality and welfare, and changes in the metabolism of the broilers including losses in feed and water intake, and body weight. Therefore, thermoregulation to reduce the heat stress of animals is very important in the studied areas. CFD techniques were used to compute air velocity distribution of the AOZ in order to evaluate the applicability of the chilling effect of the airflow on the broiler's bodies. For the analyses of the thermal comfort of the AOZ during the winter season, Seo et al. (2009) and Mostafa et al. (2012) simulated the air temperature distribution of the AOZ according to a modified ventilation system to improve the rearing conditions. Kwon et al. (2015) computed thermal distribution of the AOZ using the CFD technique to predict thermal instability and inhomogeneity by incoming cold air based on the jet-drop distance theory. Damasceno et al. (2014) and Mogharbel et al. (2014) investigated the performance of a conventional and newly modified heating system in a poultry house using numerical models. Mogharbel et al. (2014) evaluated the performance of an alternative heating system such as the localized solar-assisted pen heating system for young broilers. They reported that the systems of the solar concentrators can cater for 87% of the peak heating load and a designed system could save 87% of the energy consumption when compared with the full-mixed fuel-based convective heating system. Saraz et al. (2013) also simulated thermal distribution of AOZ in broiler houses with negative and positive tunnel ventilation. In this study, they tried to simulate the heat transfer effects of evaporative water from a misting system on the AOZ.

One of the latest issues on studies with poultry houses was the evaluation of contaminants such as ammonia inside the facility. Pawar et al. (2010) studied the ammonia distribution in an egg-laying hen house according to the wind conditions and ventilation types. Saraz et al. (2015) conducted CFD-based approaches for the evaluation of ammonia concentration profiles and flux from poultry houses, with natural ventilation typically found in subtropical and tropical countries.

2.5.3. Recent CFD studies related to beef and dairy cattle farms

In the cases of beef and dairy cattle, studies have recently investigated the design of conductive cooling pads to reduce heat stress of the animals using CFD techniques (Liang et al., 2013; Mondaca et al., 2013; Harper et al., 2014; Mondaca & Choi, 2015). Heat stress in dairy cattle during the summer season can significantly affect milk production, decrease feed intake and have adverse effects in reproduction rate and health status. Feasibilities of the conductive cooling pads according to the application of a heat exchanger, combination of the pad materials, physiological reaction of the animals, and wind conditions were studied with numerical models. Mondaca et al. (2013) tried to simulate physiological reactions such as the sweating of dairy cows based on empirical relationships from previous observations. They assumed the cow body as a cylindrical shape instead of the real shape of the animals.

However, they tried to design the layers of the core body, skin and hair to intensively simulate the conductive cooling effects. However, this study just dealt with one object of the dairy cow with a cooling effect. A study on a full-scale animal farm is still needed to evaluate the total cooling loads and their effectiveness.

Naturally ventilated dairy cattle buildings are major sources of ammonia and greenhouse gas emissions. The greatest uncertainty in the emission estimation from a naturally ventilated building is the determination of air exchange rate. The wind environment in nature is usually irregular and multidirectional and the large opening may act as an inlet and outlet simultaneously during specific periods (Wu et al., 2012). In this context, CFD evaluations of the ventilation effects according to the ventilation type of the cattle farm have been widely carried out (Norton et al., 2009; 2010; Wu et al., 2012a; 2012b; Rong et al., 2015). Among them, Wu et al. (2012) simulated the air exchange rate in a naturally ventilated dairy cattle building with large openings using three evaluation methodologies including volume flow rate (VFR), tracer gas decay method (TGD), and constant tracer gas method (CTG). AOZ was treated as porous media and the resistance coefficient of that was derived by pressure drop across the AOZ using a sub-CFD model. Norton et al. (2010) used the response surface methodology and CFD technique to develop predictive models that described the homogeneity of the indoor environment of a naturally ventilated livestock house as a function of its geometry and ventilation configurations such as three different eave opening conditions. Norton et al. (2010) reported that modifying the building geometry has the greatest effect on the environmental heterogeneity when the most restrictive eave opening condition was employed. Rong et al. (2015) studied performance of the hybrid ventilation system by combining a natural and partial pit mechanical ventilation system in a dairy cattle building in Denmark to overcome the drawback of the natural ventilation. In their study, for plants located outside the buildings, AOZ and slatted floors were simplified by using porous media modeling. The development of a modeling technique for a partial pit ventilation system and an evaluation of their performance in the dairy cattle buildings airspace have been intensively conducted recently in the same way as the CFD study trends in pig houses (Wu et al., 2012; 2013; Rong et al., 2015). Among them, Wu et al. (2013) compared two numerical approaches for simulating the effect of slatted floor using Large eddy simulation (LES) in order to understand ammonia transportation from the pit to the airspace: They used direct modeling slatted floors with geometrical details and treated the slatted floors as a porous media. They also showed the weakness of the porous modeling method for realizing the air flow and turbulent kinetic energy in the space next to the upwind wall. Wu et al. (2013) reported that more investigations and comparisons using both the LES and RANS (Reynolds-Averaged Navier-stokes) models to check the feasibility of the porous modeling method would be needed.

2.6. CFD technique on realization of dust behavior in air space

Analyses of dust behavior in the livestock houses using CFD technique were rarely conducted in the fields of agricultural area, in the teeth of widespread awareness of adverse health effect of the dust on both human and livestock animals. However, studies aiming to realize and understand the behavior of the airborne dust using the CFD techniques have been widely conducted in the mining industry, medical sciences, epidemiology, pharmacology, plants, and indoor building environments. In this section, CFD studies implementing dust behavior in airspace were reviewed. The methodology on how to treat the particle phase in a computational domain were also compared to introduce a proper methodology for realizing dust behavior in livestock houses.

2.6.1. Realization of dust behavior with CFD in the fields of indoor environment

CFD studies to investigate particle distribution and its behavior in airspace have been mostly and intensively carried out in indoor environments including hospitals, living spaces in general buildings, and aircraft. From the outbreak histories of influenza in aircraft (Moser et al., 1979), measles in offices (Bloch et al., 1985), tuberculosis in hospitals (Menzies et al., 2000) and SARS (Severe acute respiratory syndrome) in aircraft and hospital (Olsen et al., 2003; Li et al., 2005; 2007; Nielsen et al., 2010), these outbreaks have been proven to be strongly connected with airflow and the direct contact among infected people in an enclosed environment (Li et al., 2007; Chen et al., 2014). Chen et al. (2014) reported that exhalation activities such as breathing, coughing, talking, and sneezing by an infected person can generate particles carrying pathogens and can cause the transmission of infectious diseases (Nicas et al., 2005; Morawska, 2006). With the difficulties in aerosolizing micro-organisms in most experiments and the perils of additional secondary infections of the disease, CFD has been widely adopted to analyze and predict the dispersion of bio-aerosols and particulates in the airspace (Hathway et al., 2011).

In this context, Lai & Cheng (2007), Zhang & Chen (2007), Gupta et al. (2012), Li et al. (2012), Seepana & Lai (2012) and Chen et al. (2014; 2015) investigated potentials of the infection risks related to “person-to-person” and “person-to-space” particle transport in hospital rooms, experimental chambers and aircraft cabins according to various ventilation configurations and operating conditions using the Eulerian-drift flux, model, Eulerian-Eulerian multiphase model and Lagrangian model. Chen et al. (2010) evaluated the particle removal effectiveness of an air cleaner to control the dispersion of aerosol particulates emitted from the mouth of patients during treatment at a dental clinic according to the device installation position. Gilkeson et al. (2011) computed the transport of pathogenic aerosols within a six-bed partitioned Nightingale style hospital ward in order to evaluate the infection risk to both patients and healthcare workers based on the Eulerian approach for the particulate phase. King et al. (2013) investigated dispersion trends of bio-aerosols in hospital rooms according to the placement of single or double beds in the space and the ventilation status using the Lagrangian particle tracking method with a stochastic discrete random walk (DRW) model. Ogasawara et al. (2011) tried to simulate the biological properties of the influenza virus including the half-life, survival rate in humid conditions, and the active/inactive status in a typical four bed hospital room, using the Lagrangian particle tracking method. Despite of the many incomplete assumptions implementing biological properties of the virus, these studies showed applicability of computing more realistic dispersion trends of bio-aerosols using CFD. Lavoie et al. (2015) experimentally measured the concentration of pathogenic micro-organisms and also simulated their behaviors in a hospital room during bronchoscopy examinations when bio-aerosols were emitted from the patient's coughing event. Similarly, Balocco (2011) computed dispersion trends of the bacteria-carrying droplet from the patient's cough event using a simplified CFD model.

Wang & Chow (2015) reported that human movement can cause a strong secondary airflow and consequently influence the distribution of airborne particulates in the airspace. Hathway et al. (2011), Chow & Wang (2012) and Wang & Chow (2015) analyzed the impact of human activities on the distribution of pathogenic particulates using the Eulerian-drift flux model and dynamic mesh techniques. However, movement of the human bodies and their interactions with the behavior of the particulates were very simplified with many physical assumptions in the numerical model. Further studies are needed to realize the effects of human body movement with the CFD model.

As mentioned above, dispersion analyses of droplets, bio-aerosols and particulates using the CFD technique have been widely conducted in order to investigate the IAQ in contrast with CFD study trends in the agricultural sectors. However, various factors including geometries of the computational domain, physical and biological properties of the particulate matter and boundary conditions for the model were simplified in the studies. Further innovative and comprehensive studies are needed to more accurately realize the behavior of the particulates in the airspace. To realize the behavior of the particulate phase in the CFD model, various multiphase modeling techniques such as the Euelrian-drift flux model, Euelrian-Euelrian multiphase model, and Lagrangian model were recently adopted. The characteristic of each model will be introduced in following Section 2.6.4.

2.6.2. Realization of dust behavior with CFD in the fields mine industry

In the mining industry, mining operations including excavating, crushing, grinding, separation, smelting, refining and tailing management tasks can generate plenty of dust to the airspace. The high temperature processes can also produce fume and very fine particulates potentially laden with metals and metalloids that are present in the ore (Csavina et al., 2012). Csavina et al. (2012) reported that dust and aerosols emitted from mining operations may mobilize high levels of metals and metalloids including the neurotoxic element to human health such as Pb and As. The generation and subsequent dispersion of coal dust in a mining operation can be a health risk and potentially contribute to coal mine gas explosion hazards (Soukup et al., 2000, Ghio & Devlin, 2001, Csavina et al., 2012; Ren, 2013; Ren et al., 2014). Csavina et al. (2012) pointed out various possible adverse health effects in mining operations in a their comprehensive review paper. The inhalation of particulates emitted from a mining operation can reduce mental and nervous system functions, cause lower energy levels, and damage vital organs (ATSDR, 2011), and cause DNA damage (Yanez et al., 2003). The long-term exposure to these contaminants may also mimic degenerative diseases such as Alzheimer's, Parkinson's, muscular dystrophy and multiple sclerosis (IOSHIC, 1999). Due to the awareness of related adverse health effects of workers in the mining industry, measurements of contaminants and development of dust control strategies have been intensively investigated (Kissell, 2003; Gillies & Wu, 2006; Xie et al., 2007; Torano et al., 2009; Ren et al., 2011; Zhang et al., 2011; Ren & Wang, 2013; Ren et al., 2014). Proper operation of the ventilation inside mining operations is very important for diluting hazardous gases including methane and dust contaminations in addition to providing fresh air to the mine workers (Ren, 2013). However, practical management of respirable particulates and gaseous pollutants in underground coal mines remains to be a challenging issue for mine operators because of experimental limitations in the reality and difficulties in quantitative and qualitative evaluation of the dispersed phases.

Accordingly, CFD has come to the forefront as a powerful tool to assist mining engineers and to find solutions to the mentioned problems due to its potential evaluation of the invisible airflow patterns in coal mining places without any restriction in the experimental design process. In this context, Hargreaves & Lowndes (2007) and Torano et al. (2009) simulated transport of a ventilated airflow during the drivage process and methane behavior in auxiliary ventilation in underground coal mining, respectively. Silvester et al. (2009) computed dispersion and deposition of fugitive dust generated during the process of a surface quarry excavation from an open pit quarry under neutral atmospheric condition. Influence of dust source location, wind direction and application of the alternative ventilation system such as in-pit ventilation were investigated. However, accuracies of the designed CFD model were not validated with the experimental data. Torano et al. (2011) designed a CFD model for realizing the behavior of dust at the working face of the mine workers with auxiliary ventilation in mining roadways driven with road-headers. The Lagrangian particle tracking method was implemented to analyze each trajectory of the dispersed particulates with one-way phase coupling on the assumptions that airflow could affect the particles only while the particles did not affect the airflow pattern. Kurnia et al. (2014) evaluated the effects of various auxiliary ventilation strategies in order to dilute hazardous gases from diesel emissions in a coal mining process. The concept of the "age of air" was also adopted with the CFD technique in the mine industry by Parra et al. (2006) in order to evaluate the local ventilation effect. The authors suggested that local analyses using the "age of air" concept were favorable to examine the performance of the ventilation system in the mine industry and to secure the respiratory safety of mine workers. Similarly, Zhang et al. (2011) used concepts of the "dead zone" and "age of air" in order to investigate the effectiveness of the push-pull auxiliary ventilation system using the CFD technique. Ren & Wang (2013) analyzed gas dispersion from the coal cutting process by a long-wall shearer and respirable particulate behavior in the long-wall face with the Lagrangian particle tracking method. To induce the strategy of dust control, impact of Venturi air sprayers was also simulated to find an optimum solution. Similarly, Ren et al. (2014) designed a CFD model to analyze ventilation effectiveness and behavior of the respirable particulate above an underground bin based on the Lagrangian approach. To mitigate the dust problems in the mine intake roadway, two possible solutions were evaluated and proposed: modifying performance of the conventional ventilation system; and application of the water mist droppers to suppress and capture the majority of the airborne dust. Another dust control strategy using physical barriers was also studied by Torno et al. (2010). Dust dispersion during the blasting process in limestone quarries were computed while taking into account the blasting characteristics, meteorological conditions and ground morphologies with the Lagrangian particle tracking method. The authors tried to design optimum barriers for minimizing dust pollution during the tasks and for evaluating a reduction of the dust emission rate.

2.6.3. Realization of dust behavior with CFD in the fields of other industries

Numerical investigations of airborne dust and various particulates using the CFD technique were widely carried out in other industries, including medical sciences, pharmacology and plants. In this section, representative and recent CFD studies implementing the behavior of airborne dust and various particulates in the medical sciences and pharmacology, plant and other industries will be briefly introduced.

Medical sciences and pharmacology:

- Performances of two commercial dry powder inhalers (DPIs) were compared using the CFD technique and Lagrangian particle tracking method according to the geometrical differences, which could influence the aerodynamic characteristics of the inhalers and physical properties of the particulates such as size fractions (Donovan et al., 2012). The carrier particles were modeled as a spherical mono-disperse particulates with small (32 μm), medium (108 μm) and large (275 μm) aerodynamic diameters.
- Tong et al. (2013) used CFD/DEM (discrete element model) coupling technique to investigate dispersion mechanisms of particulates in a commercial DPI. From numerical investigations, the authors found that multiple major impactions occurred between agglomerates and the chamber wall, which fragmented the agglomerates

into large pieces without generating many fine particulates. Performance of the dry powder inhaler was also investigated according to the experimental airflow rate conditions.

- A 3D pulmonary airway CFD model was designed by importing images of a high resolution CT-scan. Then, transport and deposition of the particulates were investigated with the Lagrangian particle tracking method by Taherian et al. (2011). Particle depositions, variation of the wall shear stress and air velocities in the pulmonary airway were computed during the breathing process cycle.
- Anthony et al. (2005), Li et al. (2007), King et al. (2010) and Inthavong et al. (2013) used the CFD technique to study the inhalability characteristics of airborne particulates near the human face. Among them, Inthavong et al. (2013) investigated the trajectories of inhaled particulates and their deposition in the internal respiratory airway of humans. Computational domains of the human occupant and the internal nasal-pharynx-larynx-trachea respiratory airway were designed in detail based on a 3D scanned image. Particle trajectories surrounding the human and their inhalation and deposition in the respiratory airway were simulated according to the particle release location and various surrounding velocities. Critical areas in each respiratory airway were also investigated according to the deposition characteristics of the studied particulate with different fractions.
- Nguyen et al. (2014) used the Eulerian-Eulerian multiphase model to simulate particulate flow and mixing behavior in the blending of dry powder for inhalation. The kinetic theory of granular flow (KTGF) and the friction stress model were also employed to close the transport equations of the dense particulate flow in a high shear mixer. The designed CFD model was compared with experimental data obtained from a particle image velocimetry test.

Plant industries:

- Alobaid et al. (2013) designed a sophisticated CFD/DEM model in order to realize particle motions and pressure gradients of a circulating fluidized bed. A new procedure allowing the variation of the grid resolution for the particle size was introduced and validated with the observations. The authors reported that the proposed design process was suitable for simulating the high complex hydrodynamic behavior of dense gas-solid flow in a fluidized bed.
- Liu et al. (2015) investigated the fluidization behavior of high-density particulates in a spouted bed using the CFD/DEM coupling method. Trajectories of the particulates according to the spouting process were simulated and the effect of particle density on spout dominant frequency and gas-solid contact efficiency were also studied.
- Black et al. (2013) used the CFD technique to evaluate the effect of firing coal and biomass under oxy-fuel conditions in a power plant boiler which was the most promising technologies for carbon capture and storage (CCS). The combustion process and chemical reactions were simulated and compared with experimental data and empirical models. The motion of coal and biomass particulates during the combustion process at the power plant boiler was tracked within a Lagrangian frame.
- Tamburini et al. (2013) designed a CFD simulation model to compute dense solid-liquid suspensions in baffled stirred industrial tanks with the Eulerian-Eulerian multiphase model. To realize the behavior of the suspended particulates by rotation of the Rushton turbine in the tanks, the MRF (multiple reference frame approach) technique was also adopted.
- Chen & Wheeler (2015) used the CFD model to evaluate dust emission potentials from bulk material transfer chutes. Eulerian-Eulerian multiphase model incorporating the KTGF was adopted to simulate the behavior of fugitive dust from transfer chutes. To accurately compute the dust distribution, various physical

modeling parameters, including the viscosity model, drag model, and turbulence model were tested. The conceptual case study was carried out to compare the effectiveness of dust control strategies according to the design parameters of the transfer chute.

- Guo et al. (2013) developed an immersed boundary method (IBM) and incorporated the IBM into the coupled CFD/DEM model to simulate particulate systems consisting of a compressible gas and solid particles. Based on the developed methodology, behavior of the powder bed during the vibration and collision process according to the direction were simulated and evaluated.

Other industries:

- Coetzee & Els (2009), Boac et al. (2010), Iroba et al. (2011) and Parafiniuk et al. (2013) adopted the CFD/DEM technique to investigate the motion and distribution of discrete grain kernels in grain handling processes such as separators and silos.
- Hosseini & Tafreshi (2012) computed efficiencies of the particle loaded single fiber, pressure drop, collection efficiency of the filter medium and fiber drag based on the Lagrangian particle tracking method. The authors developed and linked UDF (user-defined function) subroutine to the main-solver to simulate a particle collection effect from interception and Brownian diffusion as well as dendrite formation on a fiber.
- Guo & Maghirang (2012) evaluated airflow and particle collection effectiveness by vegetative barriers which was designed as a foam of porous tree to mitigate airborne dust from open dust sources using a two dimensional (2D) numerical model. The Eulerian-Eulerian multiphase model was adopted to simulate the behavior of particulates. Predicted particle collection efficiencies ranged from less than 1% for 0.875 µm diameter to approximately 32% for 15 µm diameter.

2.6.4. Methodology on how to treat particle phase in CFD

As noted in the literature review with regard to the realization of dust behavior with the CFD model in various fields, the Eulerian-drift flux model, Eulerian-Eulerian multiphase model, Lagrangian model and the CFD/DEM coupling techniques have been widely adopted according to the purpose of each study.

2.6.4.1. Eulerian−drift flux model

The Eulerian-drift flux model (mixture model) is a simplified multiphase model that can be used to simulate multiphase flows where the phases move at different velocities, but assume local equilibrium over short spatial length scales. The Eulerian-drift flux model can be generally used to model homogeneous multiphase flows with very strong coupling and phases moving at the same velocity. The mixture model is used to calculate non-Newtonian viscosity (ANSYS Inc., theory guide). The phases in the mixture model are treated as interpenetrating continua. The mixture model can model a number of phases by solving the momentum, continuity, and energy equations for a single mixture, the volume fraction equations for the secondary phases, and algebraic expressions for the relative velocities, which describe the coupling with dispersed phases, based on the "single-fluid approach." Basically, the mixture model solves a single set of conservation equation for mixture properties. Then, the movement of the particulate phase can be indirectly calculated using the concept of drift velocity and slip velocity between the phases and mixture. The full multiphase modeling may not be feasible due to the wide distribution of particulate phases or unknown information with regard to interphase laws. Thus the mixture model can be an alternative solution. Considering the constraint condition of the Eulerian-drift flux model, this technique is generally applicable only to particulates having low particle relaxation times, which means that effects of the secondary phase toward the continuum phase is negligible. Therefore, realization of the larger particulates, which are greatly affected by gravity and inertia forces can be very limited with this technique. The governing equations for the Eulerian-drift flux model are given below.

Continuity equation:

$$\frac{\partial}{\partial t}(\rho_m) + \nabla \cdot (\rho_m \overrightarrow{v_m}) = 0$$

$$\overrightarrow{v_m} = \frac{\sum_{k=1}^{n} \alpha_k \rho_k \overrightarrow{v_k}}{\rho_m}, \qquad \rho_m = \sum_{k=1}^{n} \alpha_k \rho_k$$

Momentum equation:

$$\frac{\partial}{\partial t}(\rho_m \overrightarrow{v_m}) + \nabla \cdot (\rho_m \overrightarrow{v_m} \overrightarrow{v_m}) = -\nabla \mathrm{p} + \nabla \cdot \left[\mu_m \left(\nabla \overrightarrow{v_m} + \nabla \overrightarrow{v_m}^{T}\right)\right] + \rho_m \vec{g} + \vec{F} + \nabla \cdot \left(\sum_{k=1}^{n} \alpha_k \rho_k \vec{v}_{dr,k} \vec{v}_{dr,k}\right)$$

$$\mu_m = \sum_{k=1}^{n} \alpha_k \mu_k, \qquad \vec{v}_{dr,k} = \vec{v}_k - \vec{v}_m$$

Volume fraction equation:

$$\frac{\partial}{\partial t}(\alpha_p \rho_p) + \nabla \cdot (\alpha_p \rho_p \overrightarrow{v_m}) = -\nabla \cdot (\alpha_p \rho_p \vec{v}_{dr,p}) + \sum_{q=1}^{n} (\dot{m}_{qp} - \dot{m}_{pq})$$

Where, $\vec{F}$ is the body force, n is the number of phases, $\dot{m}_{pq}$, $\dot{m}_{qp}$ is the mass transfer from the pth to qth phase and from the qth to pth phase, respectively, $\vec{v}_{dr,k}$ is the drift velocity for secondary phase k, $\overrightarrow{v_m}$ is the mass-averaged velocity, α_k is the volume fraction of phase k, ρ_m is the mixture density, μ_m is the viscosity of the mixture.

Table 2-4 shows the recent representative application examples of adopting Eulerian-drift flux model with CFD technique.

Table 2-4 Application examples of Eulerian-drift flux model with CFD technique.

Authors	Application
Chen et al. (2006)	Particle dispersion in indoor building
Gao & Nui (2007)	Particle dispersion in experimental chamber
He et al. (2011)	Droplet transmission between occupants
Li et al. (2011)	Droplet dispersion under different ventilation methods
Seepana & Lai (2012)	Droplet dispersion after sneezing in full-scale chamber
Chow & Wang (2012)	Bio-aerosol transportation in operating theatre
Chen et al. (2014)	Droplet dispersion from a couth with mouth covered

2.6.4.2. Eulerian–Eulerian multiphase model

In contrast to the Eulerian-drift flux model, the Eulerian-Eulerian multiphase model solves the continuity and momentum equations for each phase. This multiphase model considers each phase separately, and can be used to model both dispersed flow regimes and separated flow regimes. The coupling between the phases is modeled via interfacial exchange forces which account for momentum, mass and energy transfer (ANSYS Inc., theory guide). The governing conservation equations for the Eulerian-Eulerian multiphase model are given below.

Continuity equation (for q^{th} phase):

$$\frac{\partial}{\partial t}(\alpha_q \rho_q) + \nabla \cdot (\alpha_q \rho_q \vec{v_q}) = \sum_{p=1}^{n} (\dot{m}_{qp} - \dot{m}_{pq}) + S_q$$

Momentum equation (for q^{th} phase):

$$\frac{\partial}{\partial t}(\alpha_q \rho_q \vec{v_q}) + \nabla \cdot (\alpha_q \rho_q \vec{v_q}\vec{v_q})$$

$$= -\alpha_q \nabla \mathrm{p} + \nabla \cdot \overline{\tau_q} + \alpha_q \rho_q \vec{g} + \sum_{p=1}^{n} (\overrightarrow{R_{pq}} + \dot{m}_{pq}\overrightarrow{v_{pq}} - \dot{m}_{qp}\overrightarrow{v_{qp}})$$

$$+ (\overrightarrow{F_q} + \overrightarrow{F_{lift,q}} + \overrightarrow{F_{wl,q}} + \overrightarrow{F_{vm,q}} + \overrightarrow{F_{td,q}})$$

Where, $\overrightarrow{F_q}$ is the external body force, $\overrightarrow{F_{lift,q}}$ is the lift force, $\overrightarrow{F_{wl,q}}$ is the wall lubrication force, $\overrightarrow{F_{vm,q}}$ is a virtual mass force, and $\overrightarrow{F_{td,q}}$ is a turbulent dispersion force, $\overrightarrow{R_{pq}}$ is an interaction force between phases, S_q is the source term, $\overrightarrow{v_q}$ is the velocity, and $\overline{\tau_q}$ is the q^{th} phase stress-strain tensor.

Table 2-5 shows the representative application examples of adopting Eulerian-Eulerian multiphase model with CFD technique.

Table 2-5 Application examples of Eulerian-Eulerian multiphase model with CFD technique.

Authors	Application
Zhang & Chen (2007)	Particle dispersion in aircraft cabin
Lai & Cheng (2007)	Droplet dispersion in experimental chamber
Gilkeson et al. (2011)	Pathogen transport within a naturally ventilated hospital ward
Memarzadeh & Xu (2012)	Bio-aerosol transmission according to the air exchange rate
Guo & Maghirang (2012)	Particle collection by vegetative barriers
Tamburini et al. (2013)	Particulate suspension in baffled stirred tanks
Hang et al. (2014)	Bio-aerosol transmission according to the human movement in a six-bed isolation room
Zhu et al. (2014)	Investigation of optimal use of ceiling fans for disinfection efficacy of the particulate
Nguyen et al. (2014)	Particulate mixing in a high shear mixer
Lavoie et al. (2015)	Bio-aerosol transmission during hospital bronchoscopy examinations
Chen & Wheeler (2015)	Particle dispersion in the transfer chutes

2.6.4.3. Lagrangian model

In the case of the Lagrangian model, the fluid phase is treated as a continuum by solving the Navier-Stokes equations, while the dispersed phase is solved by tracking a large number of particles, bubbles, or droplets through calculated flow fields. The dispersed phase can exchange momentum, mass, and energy with the fluid phase. The trajectories of the particulates or droplets are computed individually in a Lagrangian reference frame at specified intervals during the fluid phase calculation. The continuum phase is modeled by the Eulerian method (ANSYS Inc., theory guide). The discrete and continuous phases are coupled through sources terms in the governing equations. Therefore, the Lagrangian model can directly accommodate the physical phenomena of particulates, including forces, heat transfer, mass transfer, chemical reactions, coagulation, and deposition (Wang et al., 2012). The equation of force-balance for each particulate is given below.

$$\frac{d\overrightarrow{u_p}}{dt} = F_D\left(\vec{u} - \overrightarrow{u_p}\right) + \frac{\vec{g}(\rho_p - \rho)}{\rho_p} + \vec{F}$$

$$F_D = \frac{18\mu}{\rho_p d_p^2}\frac{C_D Re}{24}$$

Where, d_p is the particle diameter, $\vec{F}$ is the additional acceleration (force/unit particle mass) term such as Saffman lift force and Brownian force, F_D is drag force, Re is the relative Reynolds number, and μ is the molecular viscosity of the fluid.

In above equation, the term $\vec{u}$ is usually defined as summation of mean air velocity and the fluctuating velocity component. The values of the fluctuating velocity component can be solved by the Discrete Random Walk (DRW) model.

$$\acute{u_\imath} = \xi_i\sqrt{\frac{2k}{3}}$$

Where, k is the turbulent kinetic energy $\acute{u}_i$ is the fluctuating component of air velocity and ξ_i is a normally distributed random number.

Table 2-6 shows the recent representative application examples of adopting Lagrangian model with CFD technique.

Table 2-6 Application examples of Lagrangian model with CFD technique.

Authors	Application
Zhang & Chen (2007)	Particle dispersion in aircraft cabin
Chen et al (2010)	Droplet dispersion emitted from patient's mouth during dental clinic
Gupta et al. (2012)	Particle dispersion in aircraft cabin
Torano et al. (2011)	Particle dispersion according to the application of auxiliary ventilation in mining roadway
Ogasawara et al. (2011)	Bio-aerosol dispersion in hospital room
Zhang & Li (2012)	Droplet dispersion in a fully-occupied high-speed rail cabin
King et al. (2013)	Bio-aerosol dispersion in single and two bed hospital room
Ren & Wang (2013)	Respirable particulate dispersion in coal mining
Ardkapan et al. (2014)	Dust dispersion in a building room with a heat source
Ren et al. (2014)	Respirable particulate dispersion in coal mining
Wang & Chow (2015)	Bio-aerosol dispersion according to human movement in a hospital

2.6.4.4. Other models

Realization of the motion and distribution of the finite and discrete materials including grain kernels and powder have been usually modeled with the CFD/DEM technique (Chung & Ooi, 2008; Coetzee & Els, 2009; Boac et al., 2010; 2014; Iroba et al., 2011; Gonzalez-Montellano et al., 2011; 2012; Guo et al., 2013; Parafiniuk et al., 2013). Boac et al. (2014) reported that granular materials such as cereal grains that exhibit discontinuous behavior cannot be simulated solely using a conventional continuum-based modeling technique. The DEM technique has been widely used to model the mentioned discrete and finite particulate motions. DEM can analyze multiple, interacting, deformable, discontinuous, or fractured bodies undergoing rotations and large displacement (Boac et al., 2014). DEM technique can be defined as a numerical model capable of describing the mechanical behavior of assemblies of discs and spheres. This model is based on an explicitly numerical scheme in which the particle interaction is monitored at each contact and the particle motions is modeled particle by particle (Boac et al., 2014). The contact forces and displacements of a stressed particle assembly are obtained by tracking the motion of individual particles. Thus, the DEM technique is more favorable for studying particle mechanics in solids handling and processing applications.

Another alternative technique using the Markov chain model to analyze dust dispersion with the CFD technique was conducted by Chen et al. (2014) and Chen et al. (2015). The Markov chain model is based on random process and probability theory that undergoes transitions from one state to another on a state space. This model must possess a property that is usually characterized as “memorylessness.” The probability distribution of the next state depends only on the current state and not on the sequence of events that preceded it. This theory has been widely adopted in the fields of statistical physics when specific information of the total system is not well known. The system is not depended on the transient variation over time and current state can be explained without the information of a precedent record. Chen et al. (2015) first calculated a transition probability matrix using the Lagrangian model with CFD simulation. Then, the Markov chain model was used to quickly calculate the transient distribution of particulates according to the location of the particle source. However, only the pulse source was available in this technique. The following experimental situations were limited to realize the phenomena of the dispersed particulates based on the Markov chain model. The continuous source and specific sources could change the airflow patterns such as a powerful cough or sneeze. The authors especially pointed out other limitations of the current state of the techniques employing the Markov chain model. For example, various mechanisms related to particulate such as gravitational settling, thermophoresis, particle fluctuation due to turbulence effect and particle acceleration were not reflected in the mode. Gravitation settling can significantly affect the distribution and concentration of the particles with a diameter larger than 5 μm.

2.6.4.5. Conclusions

From the introduced methodology on the realization of particulate behavior in the airspace, it could be concluded that the Eulerian-Eulerian multiphase model and the Lagrangian model are practically available for modeling the particulates in livestock houses. The Eulerian-drift flux model is not applicable for simulating particulates with larger AED governed by the force of gravity. The selection of a proper model for computing particulate behavior highly depends on the objective and characteristics of the study. As noted earlier, the Eulerian-Eulerian multiphase model has been used to study distribution of the particle concentration indoors while, the Lagrangian model is mainly used to predict the overall particle dispersion pattern and temporal development of the mean concentration (Zhang and Chen, 2007). Zhang and Chen (2007) especially compared the accuracies of the solutions using the Eulerian-Eulerian multiphase model and the Lagrangian model under steady-state conditions. They commented that both methods were able to predict the distribution of the particle concentration well and the results agreed reasonably with the experimental data. The Lagrangian method needs more computation time than Eulerian-Eulerian multiphase model because the former model needs to track the development of each particle and the particle number needs to be sufficiently large to ensure statistical stability of the model (Zhang and Chen, 2007). In contrast to the Eulerian-Eulerian multiphase model, application of the Lagrangian model is a more complex problem. Accuracies of the model are strongly governed by a mesh design and the number of tracking particulates. An additional independence test for the number of tracking particulates on accuracy of the model should be needed to ensure reliability of the model. In contrast to the view of Zhang and Chen (2007), Wang et al. (2012) recently commented that the particle distribution pattern for the Lagrangian model was primarily determined by the accuracy and richness of the flow structure resolved by the airflow model. Therefore, the general Reynolds-Averaged Navier Stokes equation (RANS) and unsteady Reynolds-Averaged Navier Stokes equation (URANS) models cannot guarantee the reliability of the models based on the Lagrangian approach. The authors recommended use of the LES (Large eddy simulation) or the DES (Detached eddy simulation) turbulence model which provide well-resolved eddy structure for particle tracing. However, application of the LES and DES turbulence model with a number of computational meshes are very time-consuming problems.

Chapter 3. Identification of key factors for dust generation in nursery pig house

3.1. Introduction

Intensive and long-term field measurement of airborne dust in TSP, PM10, inhalable and respirable particulate fractions was conducted in a commercial nursery pig house for 21 months. For the comprehensive analyses, various environmental factors such as indoor micro-climatic factors, ventilation rate, animal related factors, and outdoor weather conditions were simultaneously investigated. Then, statistical analyses were carried out to understand the mechanism of, and the key factors leading to the dust generation in the nursery pig house. A CFD simulation model was also designed to identify the applicability of the dust reduction technique such as pipe-exhaust system. The behavior of the inhalable and the respirable particulate were simulated especially during feed supply periods based on the Eulerian-Eulerian multiphase model, with minimum ventilation rate in the cold season, when a severe deterioration in IAQ is likely inside the facility. Figure 3-1 shows the overall research flow of this chapter.

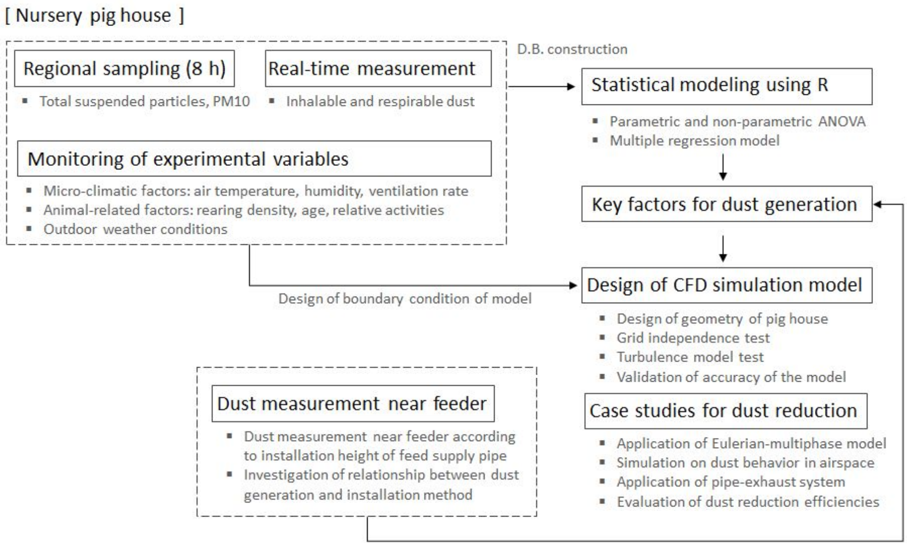


Figure 3-1 Overall research flow to find key factors for dust generation in experimental nursery pig house.

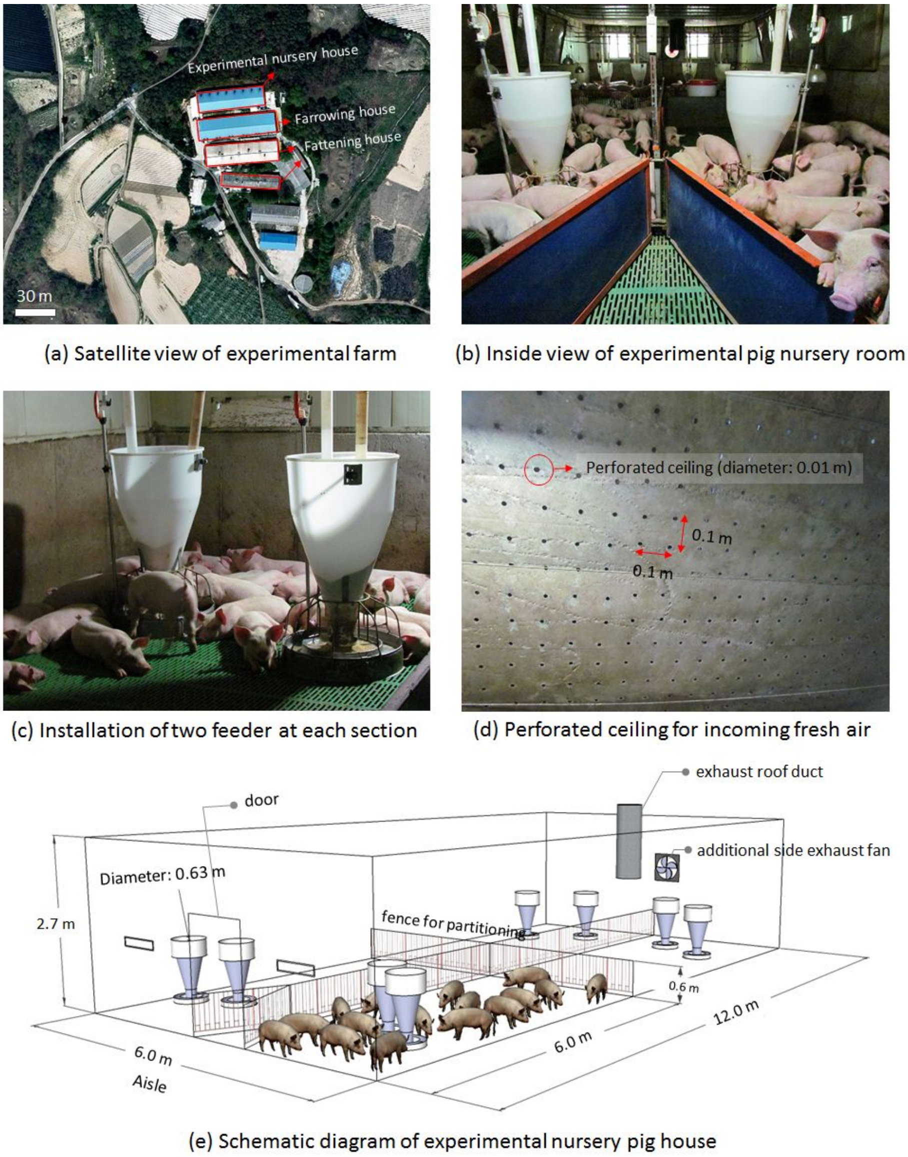
3.2. Materials and methods

3.2.1. Experimental nursery pig house

In South Korea, almost nursery pig houses are mechanically ventilated, while a number of fattening pig houses are mostly naturally ventilated using winch curtain openings. The concentration of airborne dust inside a mechanically ventilated nursery pig house is generally higher than the concentration inside a fattening pig house because of the limited ventilation rate, considering the need to foster thermal comfort of the young piglets. In this context, experimental monitoring of the airborne dust was conducted in a commercial mechanically ventilated nursery pig house, which is a common type of facility in South Korea. Dust measurement in a naturally ventilated fattening pig house was also carried out during experimental periods, however details and results are not included in this thesis (Kwon et al., 2013).

The target facility was located in Yeo-ju City, Gyeonggi-do Province, South

Korea (Figure 3-2). One nursery pig stall was chosen as the experimental room to intensively investigate the relationship between environmental variables and airborne dust concentrations, with consideration of the prevention of epidemics during experimental periods. The size of the experimental nursery pig room was 6.0 m wide, 12.0 m long, and 2.7 m high, as shown in Figure 3-2 (e). The disposal method for livestock manure was of a slurry type and the floor was covered with a fully slotted plastic pit, which is typically used in commercial nursery pig houses in South Korea. The experimental pig house was mechanically ventilated using a roof-exhaust duct with a diameter of 0.52 m, and side-exhaust fan with a diameter of 0.6 m. Fresh air could enter the AOZ through the perforated ceiling; the diameter of each aeration hole was 0.01 m. The adjustable roof-exhaust duct was the main exhaust and its operating systematic output was governed by a programed temperature controller. In summer, the side-exhaust fan was additionally used to discharge the surplus heat inside the facility. About 150~160 heads of piglet were raised in the experimental room, resulting in a density of 2.1~2.2 heads/m^2, while the actual number of piglets varied according to the operation policies of the farm manager and the market situation. When the weight of the piglets reached about 25~30 kg (74~81 days), the animals were transferred to a fattening pig house. The experimental room was divided into four sections by steel fences (Figure 3-2 (e)), and two feeders with a height of 1.10 m and diameter (bottom part) of 0.64 m of were installed in each section (Figure 3-2 (c)).



(a) Satellite view of experimental farm
(b) Inside view of experimental pig nursery room
(c) Installation of two feeder at each section
(d) Perforated ceiling for incoming fresh air
(e) Schematic diagram of experimental nursery pig house

Figure 3-2 The experimental nursery pig house located in Yeo-ju city, Gyonggi-do province, South Korea.

In the experimental farm, three pig farmers were working during the experimental periods however, only one-woman farmer worked for the experimental nursery pig house; rest of them worked in the fattening and farrowing pig houses. Daily routine was usually begun at 6:00 am, and finished at 8:00 pm. The farmer usually spent about 4 hours in the nursery pig house. Checking of the health status of the animals (1 hour), cleaning of the slotted floors (once a week, 2 hours) and feeding animals (2 hours) were main tasks. Feeding was automatically controlled twice each day (7:00 am and 3:00 pm).

3.2.2. Experimental instruments

3.2.2.1. Experimental instruments for dust monitoring

A polytetrafluoroethylene (PTFE) membrane filter (SKC Inc., Eighty Four, PA, USA, 2.0 μm pore size, 37 mm diameter) was used for the sampling of airborne TSP and PM10 (Figure 3-3 (a)). PTFE membrane filters were inserted into a 3-stage polystyrene cassette (SKC Inc.) for TSP, while a Personal Environmental Monitor (PEM) (SKC Inc.) sampler was used for PM10 fraction. Airborne dust was collected using an air-sampler (AirChek XR5000; SKC Inc.), which was connected to the 3-stage polystyrene cassette and PEM sampler (Figure 3-3 (a)). Table 3-1 shows the systematic description of air-sampler used in this study. The sampling cut-off diameter of the PEM sampler was 10 μm. Particles with a larger diameter than the cut-off size were attached to the surface of an oil coated "single-stage impactor" by their inertia, while particles smaller than the cut-off diameter were deposited into a PTFE membrane filter by following the air flow inside the PEM sampler. To determine the level of the personal exposure, the collected dust should be analyzed gravimetrically for particle mass. Gravimetric measurement of the filters with sampled particulates were carried out using the device of electronic balance (Ohaus Discovery balance DVG214C; Ohaus Co.) with sensitivity of 0.01 mg.

An Aerosol spectrometer (Model 1.109; GRIMM Aerosol Technik GmbH & Co.) was used to measure the concentration and particle numbers of inhalable, thoracic, and respirable particulate (Figure 3-3 (b)). Dust particulates were collected through a built-in pump with a flow rate of 1.2 l/min and passed to the optical chamber inside the device for measurement of the concentration and number of each particle size fraction, based on a laser light scattering method. Dust was measured in the range of 0.001~100 mg/m^3, with a detection sensitivity of 0.001 mg in real time (Table 3-2). Measured values of the dust concentration and the particle numbers were saved on the data storage card every 6 seconds.

Table 3-1 Systematic description of air-sampler kit (AirChek XR5000; SKC Inc.).

System	Patented isothermal closed loop flow sensor (U.S. Patent No. 5,892,160)	
Accuracies	Timing	1 min/mo at 25 ℃
	Flow rate	±5% of set-point after calibration
Operating humidity	0 to 95% non-condensing	
Typical run time	2 l/min	40 hours (High-power Li-Ion battery)
	5 l/min	22 hours (High-power Li-Ion battery)
Flow range	1000 to 5000 ml/min (5 to 500 ml/min requires optional low flow adapter kit)	
Size	14 cm × 7.6 cm × 5.8 cm	
Weight	0.6 kg	

Table 3-2 Systematic description of an Aerosol spectrometer (Model 1.109; GRIMM Aerosol Technik GmbH&Co.).

Measuring principle	Laser light scattering and filter collection	
Measuring range	Sizes	31 channel sizes
	Concentration	0.001~100 mg/m^3
Sampling flow rate	1.2 l/min ±5% stability	
Sensitivity	1 particle/l, 0.001 mg	
Operating temperature	5 to 45 ℃	
Size	24 cm × 12 cm × 6 cm	
Weight	2.5 kg (with battery)	

(a) 3-stage polystyrene cassette, PEM sampler (cut-off diameter: 10 μm) and AirChek air-sampler (SKC Inc., USA)

(b) Aerosol spectrometer (Model 1.109, GRIMM Technik GmbH & Co., Germany)

Figure 3-3 Experimental instruments for airborne dust sampling for TSP and PM10 (a) and for inhalable and respirable particulates (b).

3.2.2.2. Experimental instruments for environmental variables monitoring

For comprehensive analyses related to the dust generation inside the facility, various experimental instruments for monitoring of the environmental factors were also used (Figure 3-4). T-type thermocouples (Omega Engineering Inc., Stamford, CT, USA) and a data-logger (GL-820; Graphtec Inc., Jessup, MD, USA) were used to record the internal thermal distributions of the experimental nursery pig house. HOBO sensors (UX100-003; Onset Computer Co., Bourne, MA, USA) were also used to measure indoor air temperature and relative humidity in the experimental space. A portable weather station (WatchDog 2700; Spectrum Tech, Inc., Aurora, IL, USA) was used to monitor outdoor environmental conditions such as wind speed, wind direction, solar radiation, rainfall, air temperature, and humidity near the experimental livestock house (Table 3-3). Ventilation rates of the experimental nursery pig house were measured using an airflow meter (A3EL own manufactured device) and a manometer (TSI-5815; TSI, Dallas, TX, USA). Diameter of the airflow meter was 0.5 m and flow rate of the target ventilation system could be measured using pitot probes following the Bernoulli's principle. A portable camera (HD-3000; Microsoft, Redmond, WA, USA) was also used to capture the status of the animals and humans including farmers and research members in real-time during the experiment periods.

Table 3-3 Systematic description of a portable weather station (WatchDog 2700; Spectrum Tech, Inc., Aurora, IL, USA).

Sensors	Specifications	Measurement accuracy
Wind speed	0, 1 to 322 km/h	±3 km/h (±5%)
Wind direction	1°	±3°
Air temperature	-32 to 100℃	±0.6℃
Relative humidity	10 to 100% (5 to 50℃)	±3%
Dew point	-73 to 60℃	±2℃
Rainfall	0.25 mm	±5% at 5 cm/hr
Solar radiation	0 to 1,500 W/m^2	±5%

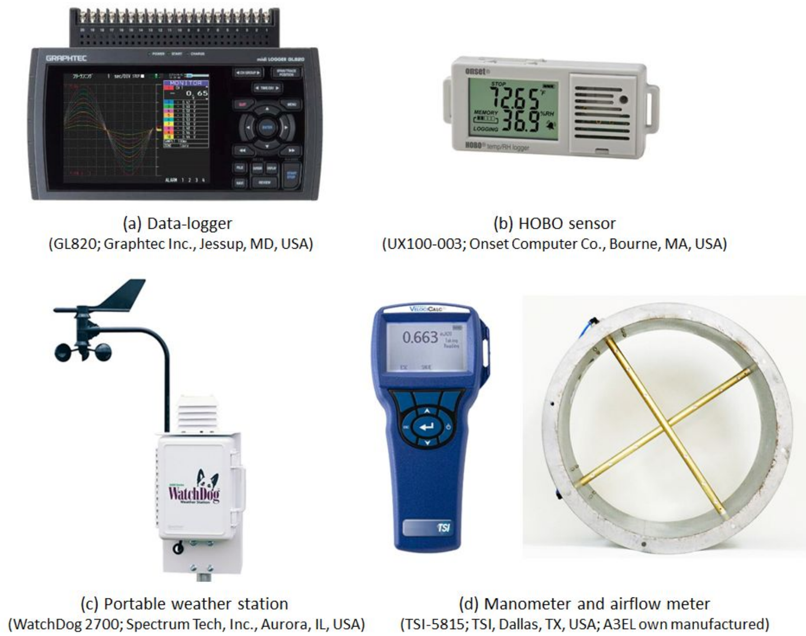


Figure 3-4 Experimental instruments for monitoring of environmental variables.

3.2.3. Computational fluid dynamics

Numerical modeling technique such as CFD have been widely and actively used to supplement and overcome the experimental limitations in the fields and wind tunnel. Due to potential and strength of the CFD technique in academic fields, CFD has proven its effectiveness in system design and optimization within the chemical, aerospace, HVAC, and hydrodynamics industries (Norton et al., 2007). However, to successfully analyze the system and its performance using the CFD, the accuracies of the numerical model should be well guaranteed with the experimental observations. CFD is a numerical analysis method for computing behavior of fluid by solving a nonlinear partial differential equation, such as the Navier-Stokes equation, based on the principles of mass conservation, Newton's second law, and the first law of thermodynamics using an algorithm of numerical analysis, such as the finite volume method (FVM) (Norton et al., 2007; Kwon et al., 2015). In this thesis, for a pre-processing of CFD simulation, a Design Modeler and an ANSYS Meshing (ANSYS Inc., Canonsburg, PA USA) software was used to construct the frame of the computational domain and design meshes for numerical computation, respectively. ANSYS FLUENT (ver 15.0., ANSYS Inc.) was used to solve a set of discretized governing equation. FLUENT solves the continuity, momentum and energy conservation equation in the computational domain based on the iterative calculation process.

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_j) = 0$$

Conservation of momentum equation:

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_i u_j) = \frac{\partial}{\partial x_j}\left[-p\delta_{ij} + \mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] + \rho g_i$$

Conservation of energy equation:

$$\frac{\partial}{\partial t}(\rho C_a T) + \frac{\partial}{\partial x_j}(\rho u_j C_a T) - \frac{\partial}{\partial x_j}(\lambda\frac{\partial T}{\partial x_j}) = s_T$$

Where, C_a is a specific heat capacity (W/kg·K), g is a gravity acceleration (m/s^2), s_T is a sink or source term (W/m^3), T is a temperature (K), t is a time (s), u is a velocity components (m/s), ρ is a density (kg/m^3), δ is a Kronecker delta, λ is a thermal conductivity (W/m·K), i, j and k are Cartesian coordinated indices.

The existing computational capability cannot solve the whole fluid motion in the Kolmogorov microscales associated with turbulent flow regimes (Friedrich et al., 2001; Norton et al., 2007). To solve the turbulent behavior of the target fluid, RANS equations can be used to calculate the averaged turbulence effects in time and space; LES and DNS (Direct numerical simulation) turbulence models were not used in this thesis considering the computational applicability. From the Reynolds-averaging technique, transport equations for mean flow quantities can be solved and all scales of turbulence can be modeled. The following equations are the general form of the RANS equations, which have the same general form as the instantaneous Navier-Stokes equations, with the velocities and other solution variables representing ensemble-averaged values. RANS turbulence models can be categorized based on how to solve additional terms, such as Reynolds stress ($-\rho\overline{\acute{u}_i\acute{u}_j}$).

RANS (Reynolds-averaged Navier-Stokes) equations:

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x_j}(\rho u_i)=0$$

$$\frac{\partial}{\partial t}(\rho u_i)+\frac{\partial}{\partial x_j}(\rho u_i u_j)=-\frac{\partial p}{\partial x_i}+\frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}-\frac{2}{3}\delta_{ij}\frac{\partial u_l}{x_l}\right)\right]+\frac{\partial}{\partial x_j}(-\rho\overline{\acute{u}_i\acute{u}_j})$$

where p is static pressure (Pa), $\acute{u}_i$ is a fluctuating velocity component (m/s), x is a Cartesian coordinate (m), and μ is dynamic viscosity (k·g/m·s).

Figure 3-5 shows the overall systematic and numerical process of CFD.

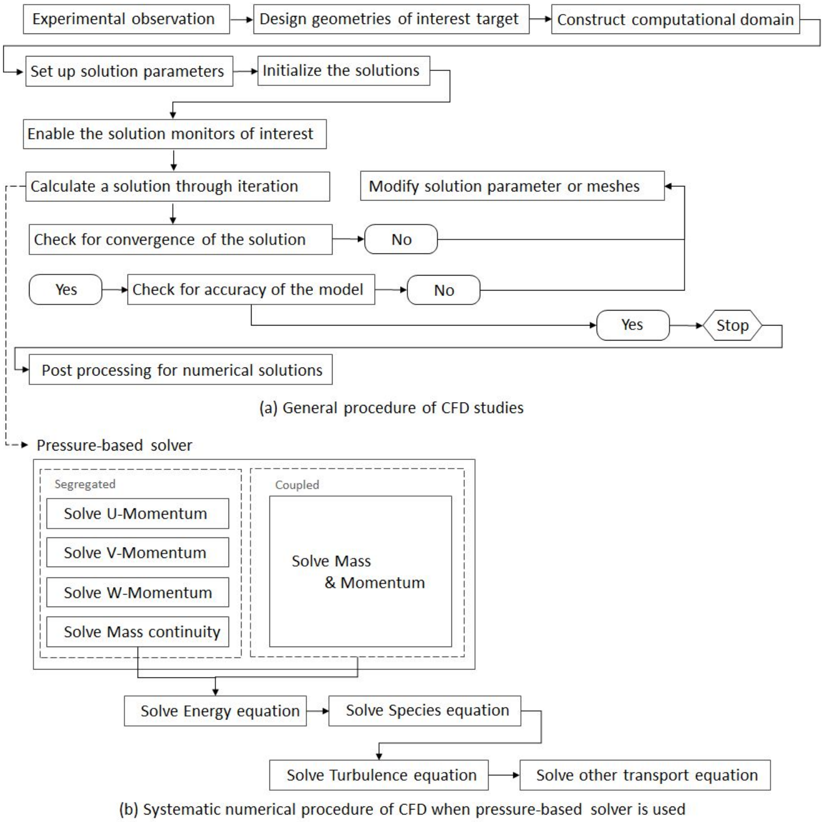


Figure 3-5 Numerical procedure of Computational fluid dynamics.

3.2.4. Monitoring of airborne dust

Long-term and intensive airborne dust monitoring in the experimental nursery pig house was conducted regularly from August 2012 to May 2014 (1~2 experiments for each month). Measurement of the concentration of TSP and PM10 was conducted until April 2013 according to an arrangement between the research team and farm manager to prevent the possibility of epidemics. The measurement of inhalable and respirable particulate, which was a relatively casual experiment compared to area sampling, was conducted throughout the whole experimental period, while the experiments were temporarily stopped from December 2013 to April 2014 due to an outbreak of porcine epidemic diarrhea (PED) in South Korea. The researchers and experimental instruments were thoroughly disinfected before visiting the experimental pig house to prevent the dispersion of the disease vector to the livestock.

To determine the TSP and PM10 concentration through the area sampling, the PTFE membrane filters were fully desiccated for 24 hours and pre-weighed using the instrument of the electronic balance in the laboratory. Each filter was then housed in a 3-stage polystyrene cassette for TSP, while sampling PM10 in the PEM. The flow rates for the sampling of TSP and PM10 were 2 and 4 l/min for 8 hours, respectively. Dust sampling instruments were installed at a height of 1.5 m above the floor in consideration of the average height of a pig farmer's respiratory intake. In total, 10 locations were used for area sampling: 1 on the outside of the experimental nursery pig room, 1 in the entrance of the experimental room, 3 in the vicinity of feeders, 3 in the middle sections of the experimental room, 1 in the vicinity of the roof exhaust duct, and 1 in the vicinity of the side exhaust fan. Figure 3-6 shows the measurement locations for TSP and PM10 samples (red colored circles in Figure 3-6).

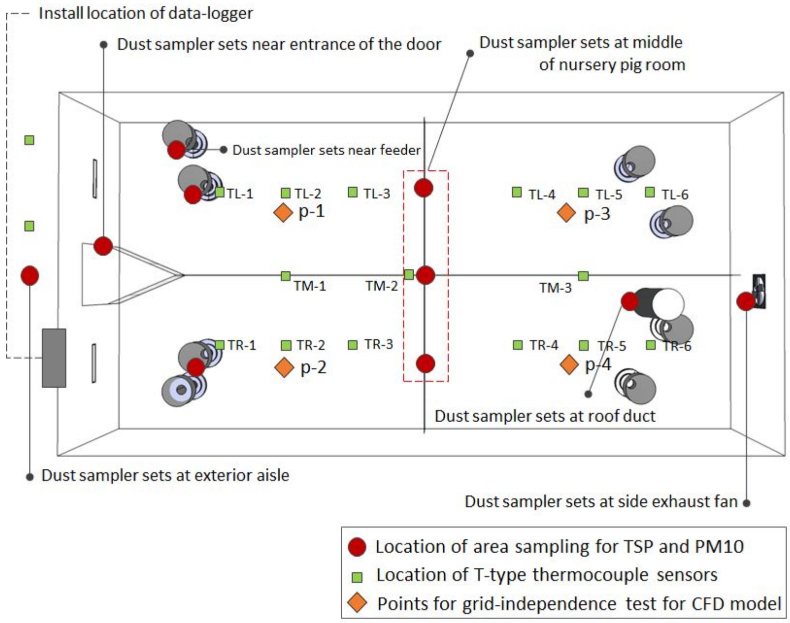


Figure 3-6 Location of area sampling for TSP and PM10, location of t-type thermocouple sensors for thermal monitoring and investigated points for grid independence test for CFD simulation model.

Area sampling of TSP and PM10 usually began at 9:00 AM. When the sampling was finished, the used filters were inserted into a cleaned polystyrene storage cassette and completely sealed using paraffin film. Filters were completely desiccated again for 24 hours in the laboratory and then weighed to determine the particle mass based on the gravimetric method. To minimize the measurement error, more than six blank samples were used for each experiment, and the calibration of the flow rate of the air-sampler pump was also conducted before and after each experiment. Concentration of the sampled TSP and PM10 could be measured by gravimetric method; mean weight of the blank samples was considered in the following equation to minimize the measurement error during the experiment.

$$\mathrm{C} = \frac{[(WS_p - WS_i) - (WB_p - WB_i)]}{Flow\ rate \times Sampling\ time} \times 10^3$$

Where, C is dust concentration (mg/m^3), WS_p is the weight of the filter after dust sampling (mg), WS_i is the weight of the filter before dust sampling (mg), WB_p is the weight of the blank filter after dust sampling (mg) and WB_i is the weight of the blank filter before dust sampling (mg).

The concentration of inhalable and respirable particulate was measured using the Aerosol spectrometer at a height of 1.5 m according to the experimental situation, such as the feed supply, work activity of the pig farmer, and any increase in the activity of the animals. Data was continuously recorded for 5~10 minutes and saved onto a memory card at intervals of 6 seconds, which was the minimum time-step of the device. However, there was a mechanical failure of the device during the early stage of the experiment (August-November, 2012); thus, some experimental data was lost. The experiment using the Aerosol spectrometer resumed after examining the calibration of the device. Figure 3-7 shows photographs of the dust monitoring in the experimental nursery pig house.

Figure 3-7 Scenes of dust monitoring in experimental nursery pig house

3.2.5. Monitoring of experimental variables

Information regarding the number of piglets and their ages was provided regularly by the farm manager through interviews conducted during the dust monitoring. Various experimental instruments were also installed to collect raw data inside and outside the experimental nursery pig house. A data-logger and 20 T-type thermocouples were installed to gather thermal raw data throughout the experimental period. Thermocouples were installed at a height of 1.5 m at regular intervals inside the experimental room, in consideration of the average height of a worker's respiratory intake, with two of them located in the outside aisle. Air temperature data was recorded by the data-logger every minute. The air temperature data were also used to validate the accuracy of the CFD model. A HOBO sensor was used to measure the air temperature and humidity inside the experimental room. Unfortunately, the sensor experienced a mechanical failure in the middle of the experimental period. Given the failure of the device, the measured humidity data were considered unreliable and were not used as independent variables in the statistical analyses. After replacing sensors, the measured humidity was in the range from 81 to 87%, with relatively little variation (83.82±2.36%). Research team concluded that the moisture level in the airspace of the experimental building, which was a modernized facility based on a design that is popular in South Korea, was uniformly well controlled (coefficient of variation = 0.03); therefore, the humidity in the experimental facility might have had less impact on the generation of airborne dust than would have been the case in other livestock houses. However, humidity is clearly an important factor contributing to the generation of airborne dust, and therefore consideration of humidity in a comprehensive statistical approach is required in future studies. A portable weather station was also installed in near open terrain to record outside weather conditions, such as wind speed, wind direction, solar radiation, rainfall, air temperature, and humidity (Figure 3-8 (a)). A portable camera was installed at the entrance door to record the status and movement of the piglets and farmers. From the scene analysis, the relative level of P.A. (pig-activity) was categorized to enable the statistical analysis to indicate the effect of the animal's movement on the generation of airborne dust (Figure 3-8 (b)). The ventilation rate of the experimental nursery pig room was also measured by an airflow meter and a manometer (Figure 3-8 (c) and (d)). The ventilation rate of the roof-exhaust duct and side-exhaust fan was determined by the arithmetical mean value of 3 minutes' worth of measured data. The ventilation rate was measured over the whole range of the controlled systematic output (10~100%) of the ventilation system.

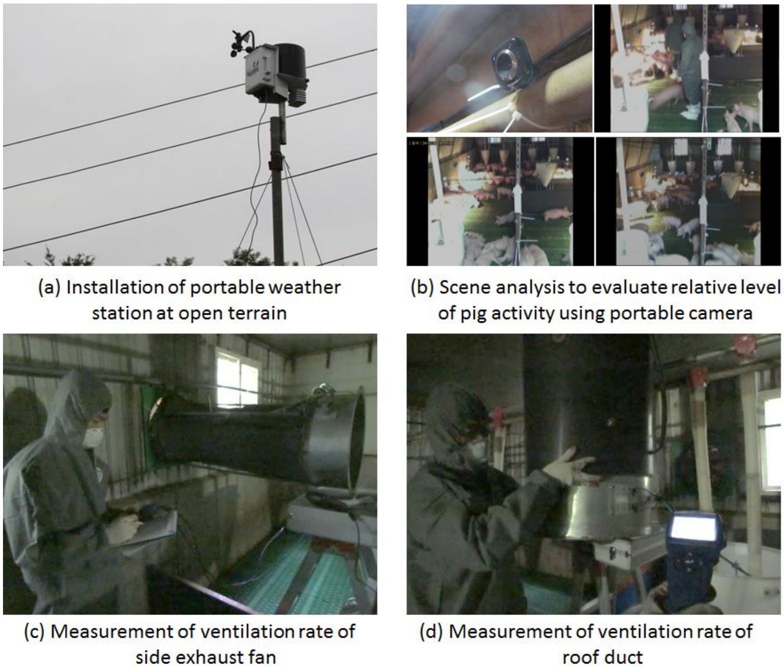


Figure 3-8 Measurement of environmental variables in nursery pig house.

3.2.6. Statistical analyses to determine key factors in dust generation

From the sampled dust concentrations and various experimental variables, such as ventilation rate, age of the animals, number of animals, P.A. level, and indoor and outdoor air temperature, various statistical analyses were conducted to determine the key factors contributing to airborne dust generation in the different size fractions. Statistical analyses were conducted using the language-based R program (ver 3.2.4., R Development Core Team, 2016). Shapiro-Wilk normality test for each step was conducted to validate the normality of the residuals from the statistically derived models. From the results of normality test, parametric ANOVA and non-parametric Kruskall Wallis test were carried out to identify the effect of increase in animal's activity on dust concentrations. Multiple regression analyses were also conducted to find key factors affecting variations of the dust generation inside the experimental nursery pig house. Before regression analyses, multi-collinearity tests were also conducted to improve the reliability of the model and to select proper independent variables through verification of the variance inflation factor (VIF) and correlation test.

3.2.7. CFD analysis to evaluate potentials of dust control strategy

Based on the measured information of the experimental nursery pig house and the statistically derived equations in this chapter, a CFD simulation model was designed to simulate the dispersion of the airborne dust and evaluate their removal efficiencies in a conceptual case study, which adopted a pipe-exhaust system as the dust control strategy during the feed supply in cold season. The designed CFD model was validated with the experimentally measured indoor air temperature distributions.

3.2.7.1. Design of CFD simulation model

The computational domain of the experimental nursery pig house and meshes were designed using Design Modeler and ANSYS Meshing software. The ventilation system, including the roof-exhaust duct and side-exhaust fan, feeders, feed supply pipes, and steel fences were thoroughly designed based on the field-measured dimensions and information regarding the facility. A total of 160 pigs were randomly located in the computational domain to generate turbulent dissipation effects due to the distribution of the animals in AOZ, following the three-dimensional pig object model designed by Seo et al. (2012), as shown in Figure 3-9. Animal objects were scaled based on the assumption that the age of the piglets in the computational domain was 50 days.

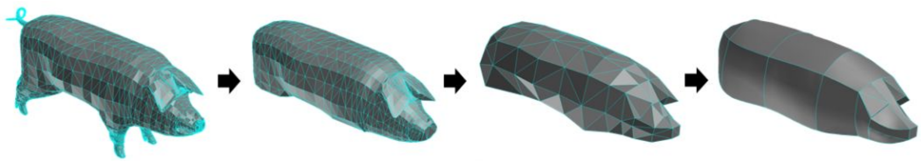


Figure 3-9 Simplified three-dimensional pig object model by Seo et al. (2012).

Computational meshes were designed with tetrahedron cells. Considering the mesh qualities, such as orthogonal quality and skewness in the AOZ where the pig object models were included, the mesh size in the AOZ volume was fixed at 0.05 m through a process of trial and error. Dense anisotropic meshes, with a size of 0.005~0.03 m, were also used in the vicinal area of the ventilation system, feeders and feed supply pipes where could significantly influence the convergence of the numerical solutions. For the remainder of the computational domain, total 10 different mesh sizes were evaluated as a grid-independence test. The tested sizes based on one side of the cell were 0.05, 0.075, 0.1, 0.125, 0.15, 0.175, 0.2, 0.3, 0.5, and 1 m. Designed meshes were converted to the polyhedral meshes in FLUENT to increase economic feasibility in computational time. Table 3-4 lists the total number of designed meshes according to the tested cell sizes. Comparative analyses were conducted based on the CFD results when the cell size was at a minimum, e.g., 0.05 m. Four representative points with five different heights (0.5, 1, 1.5, 2 and 2.5 m) were selected to compare the errors between the CFD results. Each point was located at the center of each pen in the experimental nursery pig house (Figure 3-6). Figure 3-10 shows example of computational domain and meshing results of the experimental nursery pig house.

To accurately predict the airflow patterns and dispersion of airborne dust within the computational domain, the CFD simulation model was validated with experimentally measured variations of the indoor air temperature according to the cyclical (on/off) operation of the ventilation system. Simulations for the validation tests were conducted based on four selected experimental periods: 1) December 2012, 2) February 2013, 3) April 2013, and 4) November 2013. The boundary and initial conditions for the simulation model were designed based on the field-measured data in each experimental period. Comparative analyses were conducted based on the CFD results and the experimentally measured indoor air temperature using 20 thermocouples. The measurement points for CFD model validation are shown in Figure 3-6. A total of five RANS models (standard k-ε, RNG k-ε, realizable k-ε, standard k-ω and SST k-ω) were also evaluated to choose the proper turbulence model.

Table 3-4 Tested size of computational meshes and designed number of meshes for a grid-independence test.

	Tested size of one side of each cell (m)				
	0.050	0.075	0.100	0.125	0.150
Number of meshes (million)	9.68	6.26	5.22	4.83	4.61
	0.175	0.200	0.300	0.500	1.000
Number of meshes (million)	3.86	3.67	3.59	3.46	3.29

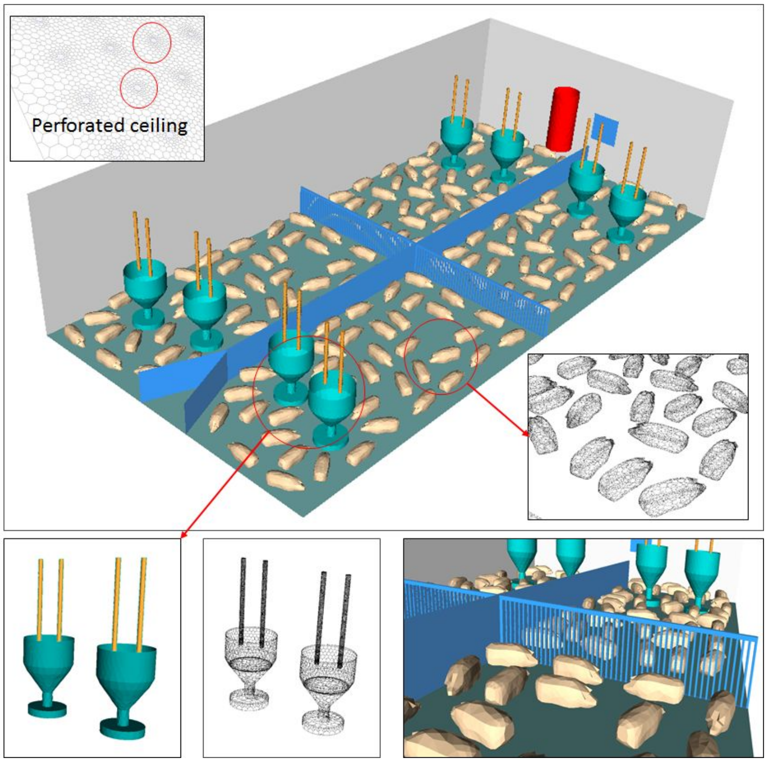


Figure 3-10 Designed computational domain and meshes for experimental nursery pig house.

3.2.7.2. CFD-based case study for evaluating dust reduction potentials

A pipe-exhaust system was proposed and a conceptual case study of its use was carried out based on the validated CFD model in order to introduce effective measures for dust reduction in a nursery pig house. In the experimental nursery pig house, two feed supply pipes were installed at each feeder. However, only one pipe was actually used for the feed supply. The pipe-exhaust system using the unused feed supply pipe as an alternative ventilation system was designed to immediately eliminate airborne dust, especially during feeding periods. Boundary conditions for the ventilation rate were designed based on practical operating conditions during the winter when minimum ventilation was usually adopted to ensure the thermal comfort of the AOZ. Thus, deterioration of IAQ might be expected inside the facility at this time.

The experimental cases were simulated to investigate the dust reduction efficiencies according to the ventilation type and the combinations of ventilation systems (Table 3-5). Experimental boundary conditions, including the surface temperature of each side wall, fence, feeder, duct, pig, and door, were designed based on winter conditions and field-measured values in January, 2013. Two main scenarios were adopted and simulated: a minimum ventilation rate (20% of the systematic ventilation output of the roof-exhaust duct, 0.085 AER/min) and an average winter ventilation rate (40% of the systematic ventilation output of the roof-exhaust duct, 0.164 AER/min). The experimental cases were designed based on a combination of ventilation systems, with a set proportion of ventilation rate provided by conventional roof-exhaust duct and pipe-exhaust ventilation systems.

Table 3-5 Experimental cases for the CFD simulation of dust reduction efficiencies according to the ventilation type and operation methods.

Minimum ventilation rate (20%, 0.085 AER/min)			Average ventilation rate (40%, 0.164 AER/min)		
Case	Roof exhaust duct ventilation	Pipe-exhaust ventilation	Case	Roof exhaust duct ventilation	Pipe-exhaust ventilation
Original case	20%	-	Original case	40%	-

Case 1	10%	10%	Case 1	20%	20%
Case 2	-	20%	Case 2	30%	10%
Case 3	10%	20%	Case 3	-	40%
Case 4	20%	10%	Case 4	30%	20%
Case 5	30%	-	Case 5	40%	10%
			Case 6	50%	-

% refers to the systematic output value of the ventilation system, which was experimentally measured using an airflow meter and manometer in an experimental nursery pig house; 10% was equivalent to 0.043 AER/min and this value increased linearly.

The Eulerian-Eulerian multiphase model, which treats the particle phase as a continuum, was used to simulate the distribution of airborne dust inside the facility. This Eulerian-based model considers each phase separately and can be used to model both dispersed and separated flow regimes. Navier-Stokes equations are solved separately for each phase. The coupling between each phase is modeled via interfacial exchange forces, which account for continuity, momentum, and energy transfer (ANSYS theory Guide, 2016). Based on the assumption that large amounts of airborne dust within a pig house are generated from feed particulates, physical properties of the feed materials (e.g., bulk densities) were evaluated from the Korea Testing Laboratory (KTL) using a gas pycnometer (Humipyc M2-50-1-100-240; InstruQuest Inc., Boca Raton, FL, USA). The measured bulk density of feed particulates was 1.395 kg/m^3. The average AED of 4 μm was applied as a definition of the particle phase for the respirable particulate fraction. Meanwhile, an AED of 20, 40 and 100 μm were separately applied to define the mean diameter of the particle phase for inhalable particulates in order to analyze the dust distribution according to the each defined AED. The mean AED of the inhalable particulates have not yet been documented in contrast to that of the respirable particulates in the related academic fields.

The initial boundary conditions of all cell zones for the airborne concentration of inhalable and respirable particulates were calculated from the statistically derived equations for each size fraction. The equations will be introduced in the results and discussion Section 3.3.6. The concentration of airborne dust in each size fraction was calculated based on the assumption that 160 heads of piglets with an age of 50 days were stocked in an indoor air temperature of 25°C and a relative pig activity of level 2. The concept of relative pig activity level will be explained in the results and discussion Section 3.3.1. The concentrations of airborne dust generated from the feeder during periods of feed supply were also calculated from the linear equations derived in this thesis. The installation depth of the feed supply pipe was assumed to be 0.05 m from the upper surface of the feeder. The phase-coupled Semi-Implicit Method for Pressure Linked Equations (SIMPLE) algorithm was used for pressure-velocity coupling and a second-order upwind scheme was used for the spatial discretization of momentum, the volume fraction, turbulent kinetic energy, and turbulence dissipation rate. Table 3-6 and 3-7 shows the numerical schemes and input values for the CFD simulation in this thesis, respectively.

The transient variations in concentration of particulate phases were simulated on the assumption that the feed was supplied for an initial period of 30 s and then stopped. The ventilation system was continuously operated for an additional 30 s. Reduction efficiencies of the airborne dust, including the inhalable and respirable size fractions, were evaluated according to the ventilation system and its method of operation.

Table 3-6 Numerical schemes of the CFD simulation model.

Numerical schemes of the CFD model	Turbulence model	Selected from the validation test (standard k-ε, RNG k-ε, realizable k-ε, standard k-ω, and SST k-ω)
	Multiphase model	Eulerian-Eulerian multiphase model
	Pressure-velocity coupling	Phase Coupled SIMPLE algorithm
	Spatial discretization of	Second-order upwind

	momentum, volume fraction, turbulent kinetic energy, and turbulence dissipation rate	
	Spatial discretization of gradient	Least squares cell-based
	Transient formulation	First order implicit

Table 3-7 Input values for the boundary conditions of the CFD simulation model.

Contents	Value
Density of air	1.255 kg/m^3
Density of airborne dust	1395.900 kg/m^3
Average AED of airborne dust	Inhalable particulate: 100, 40 and 20 µm Respirable particulate: 4 µm
Surface temperature (side walls, door, fences, feeder, duct, and pigs)	Experimentally measured values on January, 2013
Initial conditions of dust concentration	Calculated from statistically derived regression equations of inhalable and respirable particulates (160 heads of piglets, 50 days of age, 25°C, and P.A. level-2)
Concentration of airborne dust generated from feeder	Calculated from the derived equations explaining the relationship between dust concentrations and installation depth of feed supply pipe (0.05 m installation depth)
Maximum cell size	Selected from the grid-independence test (0.050, 0.075, 0.100, 0.125, and 0.150 m for one side of each cell)

3.3. Results and discussions

3.3.1. Evaluation of relative pig-activity level from scene monitoring

Every movement of animals, workers, and research team members was recorded in real time using a portable camera and the concentration of occupational dust including inhalable, thoracic, and respirable particulate was simultaneously measured at a height of 1.5 m above the ground. As presented in Figure 3-11, when almost all piglets were lying on the ground, the dust concentration was lower than during other experimental conditions for all size fractions, with relatively small variations. When some piglets were moving to receive feed and the others remained lying on the ground, the concentration of dust in all size fractions had a tendency to slightly increase compared to when they were all lying on the ground. When pig farmers or research team members entered the facility, all piglets began to move, with some being very active. In this case, the concentration of the inhalable particulate was dramatically increased, with unstable and fluctuating trends over the time compared to the other experimental situations. Similar trends in dust concentration were also observed during the feeding periods. From the scene monitoring and dust measurements, it was concluded that the activity of occupants including animals and humans and the feed supply event significantly contributed toward dust generation. Therefore, when the pig farmers enter the nursery pig house to check the status of the animals especially during feeding periods, they can be exposed to adverse respiratory health conditions.

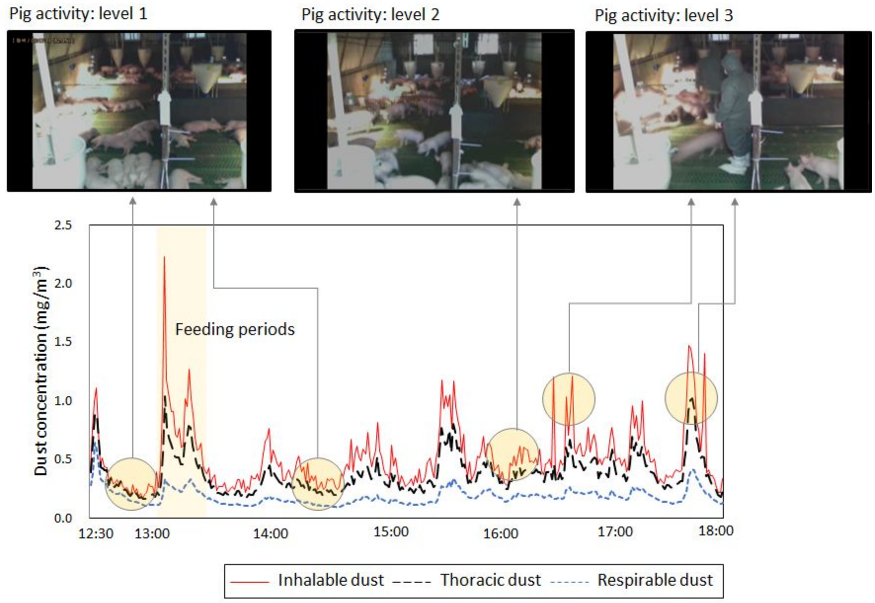


Figure 3-11 Example of evaluation of relative pig-activity (P.A.) levels from scene analysis and simultaneous measurement of dust concentrations.

In this thesis, the relative P.A. (pig-activity) level was defined to derive experimental variables for a statistical approach based on the piglet's movement and measured trends of dust concentration. The relative P.A. levels were defined as follows; 1) level-1: almost piglets were lying on the ground; 2) level-2: some piglets were eating feed and moving around slowly; and 3) level-3: piglets were very active and vigorous when pig farmers entered the facility. These relative P.A. levels recorded alongside the measurement of the dust concentrations during whole experimental periods.

3.3.2. Periodic monitoring of TSP and PM10

Table 3-8 shows the overall monitoring results of TSP and PM10 measured at middle of pig room and near the feeder in the experimental nursery pig house.

Table 3-8 Overall monitoring results of TSP and PM10 in the experimental nursery pig house (Unit: mg/m^3).

Date	Dust concentrations measured at middle of pig room						b/a (%)	
	TSP (a)			PM10 (b)			AM	GM
	n	AM±SD	GM(GSD)	n	AM±SD	GM(GSD)		
Aug. 1. 2012	3	0.42±0.24	0.38(1.57)	3	0.16±0.19	0.10(2.71)	38	26
Aug.22. 2012	3	0.74±0.45	0.66(1.57)	3	0.37±0.17	0.34(1.46)	50	52
Sep.19. 2012	3	0.87±0.07	0.87(1.07)	3	0.36±0.06	0.35(1.15)	41	40
Oct.18. 2012	3	1.96±0.37	1.93(1.16)	3	1.06±0.06	1.06(1.04)	54	55
Nov.21. 2012	3	1.36±0.20	1.35(1.12)	3	0.71±0.05	0.71(1.06)	52	53
Dec.12. 2012	3	1.59±0.17	1.58(1.09)	3	1.06±0.04	1.06(1.03)	67	67
Jan.29. 2013	3	1.43±0.21	1.42(1.12)	3	0.63±0.01	0.63(1.01)	44	44
Jan.30. 2013	3	1.11±0.03	1.11(1.02)	3	0.39±0.02	0.39(1.04)	35	35
Feb.27. 2013	3	0.63±0.32	0.58(1.51)	3	0.59±0.29	0.54(1.50)	94	93
Apr. 2. 2013	3	1.41±0.14	1.40(1.08)	3	0.99±0.12	0.98(1.10)	70	70
Date	Dust concentrations measured at near feeder						b/a (%)	
	TSP (a)			PM10 (b)			AM	GM
	n	AM±SD	GM(GSD)	n	AM±SD	GM(GSD)		
Aug. 1. 2012	3	0.43±0.24	0.43(1.16)	3	0.13±0.08	0.11(2.12)	30	26
Aug.22. 2012	3	0.94±0.40	0.87(1.53)	3	0.46±0.07	0.46(1.13)	49	53
Sep.19. 2012	3	0.75±0.16	0.74(1.21)	3	0.27±0.05	0.27(1.17)	36	36
Oct.18. 2012	2	2.32±0.36	2.31(1.12)	3	1.52±0.11	1.51(1.06)	66	65
Nov.21. 2012	3	1.09±0.15	1.08(1.12)	3	0.63±0.06	0.63(1.08)	58	58
Dec.12. 2012	2	1.47±0.50	1.43(1.28)	3	1.01±0.08	1.01(1.07)	69	71
Jan.29. 2013	3	1.19±0.24	1.17(1.20)	3	0.56±0.04	0.56(1.06)	47	48
Jan.30. 2013	3	0.68±0.03	0.68(1.03)	3	0.40±0.04	0.40(1.08)	59	59
Feb.27. 2013	3	0.99±0.25	0.98(1.23)	1	0.98	0.98	99	100
Apr. 2. 2013	3	1.52±0.49	1.47(1.28)	3	1.15±0.38	1.11(1.29)	76	76

n refers to number of subject.

Figure 3-12, 3-13 and 3-14 show the example results of measured TSP and PM10 concentrations inside the nursery pig house. Figure 3-12 shows the results for October 2012, where 83 heads of piglet whose age was 55 days were being raised, the mean outdoor air temperature during experiment was 15.95°C, and the ventilation rate was 992.17 m^3/h (0.085 AER/min). Figure 3-13 shows the results for 186 heads of piglet at 54 days of age, with a mean outdoor air temperature of -3.05°C, and ventilation rate of 531.87 m^3/h (0.046 AER/min) in December 2012, and Figure 3-14 depicts the results for 169 heads of piglet at 39 days of age, with a mean outdoor air temperature of -1.99°C, and ventilation rate of 992.17 m^3/h (0.085 AER/min) in January 2013. Occupational exposure limit of inhalable particulate with respect to the respiratory health of pig farmers (Donham & Reynolds, 1995) is also shown in mentioned figures. As shown in Figure 3-12, the TSP concentrations at the feeder and side exhaust fan exceeded 2.5 mg/m^3, whereas the other measurements did not exceed the recommended level. Although various other factors, including hygiene status, indoor air temperature, and humidity could influence the generation of the airborne dust, it was concluded that relatively high dust concentrations of TSP and PM10 were generally observed at the feeder and in the middle of the room. This experimental evidence indirectly implied that the presence of animals and the feed supply could contribute to the high concentration of the airborne dust. Although relatively high dust concentrations were found near the feeder, the measured concentrations differed according to the experimental situations. The measured TSP and PM10 concentrations at the feeder were 2.32 and 1.52 mg/m^3, respectively in October 2012 (Figure 3-12), but were lower in December 2012 (Figure 3-13) and January 2013 (Figure 3-14), with values of 1.47 (63%) and 1.01 (66%) mg/m^3, 0.68 (29%) and 0.40 (26%) mg/m^3, respectively. The differences in dust concentration near the feeder were strongly related to the installation depth of the feed supply pipe. Details are provided in 3.3.4. Section. The feed supply pipe was usually inserted into the upper surface of the feeders, but in October 2012, it was installed 15 cm above the top surface of the feeder. These facts meant that substantial amounts of the dust from the supplied feed particles could be spread and dispersed more easily than in other experimental situations.

A number of previous studies have reported that dust concentrations within mechanically ventilated pig house are usually high in cold season because of the application of limited ventilation rate. However, the data collected in January 2013 showed relatively lower values compared to other experimental periods. This implied that other experimental factors, such as the number of animals, age of animals, hygiene status, ventilation rate and indoor micro-climatic factors could influence the generation of the airborne dust. Therefore, a comprehensive statistical approach considering various factors is needed to explain the dust generation mechanisms. Similarly, the differences in the observed tendencies in dust concentration near the roof-exhaust duct and side fan according to the experimental date could be explained with the help of a qualitative and quantitative numerical analysis, such as CFD.

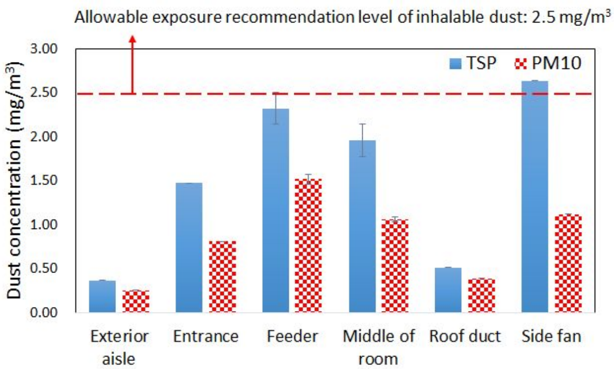


Figure 3-12 Measured TSP and PM10 concentrations in experimental nursery pig house at October 2012.

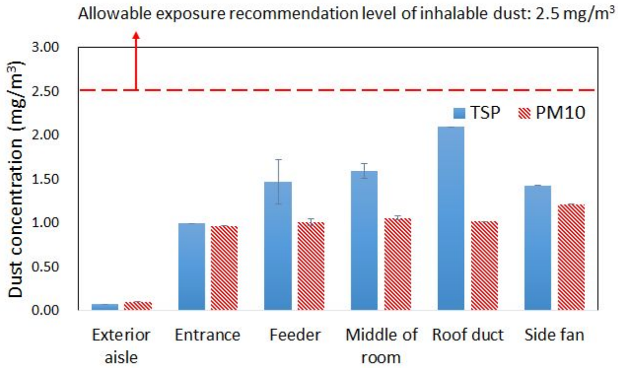


Figure 3-13 Measured TSP and PM10 concentration in experimental nursery pig house at December 2012.

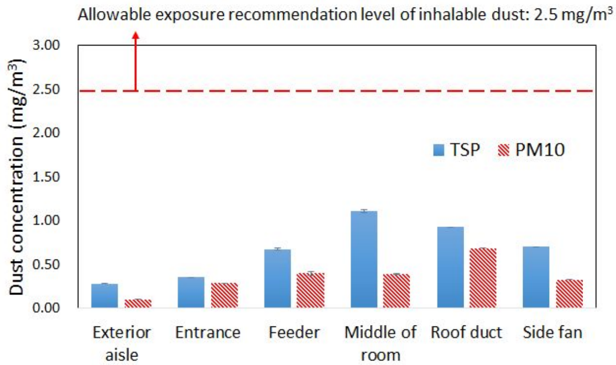


Figure 3-14 Measured TSP and PM10 concentrations in experimental nursery pig house at January 2013.

Figure 3-15 shows the average TSP and PM10 concentration in different seasons. Although previous studies observed higher dust concentrations during the cold season, the highest concentrations of TSP (1.40±0.10 mg/m^3) and PM10 (0.78±0.0.04 mg/m^3) were observed during the change of seasons relative to the cold and warm seasons. Average TSP and PM10 concentrations were lowest in summer and accounted for about 41.4% and 33.3% of the respective concentrations during the change of seasons. However, the differences of the averaged TSP and PM10 dust concentration were not statistically significant (p=0.137 for TSP and 0.176 for PM10) from the ANOVA test. Notwithstanding mentioned results of ANOVA test, based on observed ventilation rate data, it was obvious that a higher ventilation rate would effectively remove the pollutants to the outside, and therefore IAQ would be improved. However, our observations in winter did not agree with the results of previous studies. As mentioned earlier, there is a complexity with respect to the contribution of various sources to the generation of airborne dust within the space.

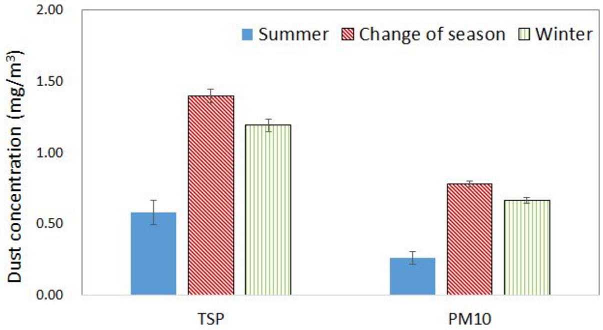


Figure 3-15 Average TSP and PM10 concentrations at locations in the middle of the experimental room in different seasons.

3.3.3. Periodic monitoring of inhalable and respirable particulate

The concentrations of occupational dust, including the inhalable and respirable size fractions were observed under various experimental conditions, such as an increase in the P.A. level and feed supply event. Table 3-9, 3-10 and 3-11 especially shows the parts of monitoring results of inhalable and respirable in the experimental nursery pig house according to P.A. levels.

Table 3-9 Parts of real-time monitoring results of inhalable and respirable particulates in the experimental nursery pig house (P.A. level-1) (Unit: mg/m^3).

Date	Inhalable particulate (a)		Respirable particulate (b)		b/a (%)	
	AM±SD	GM(GSD)	AM±SD	GM(GSD)	AM	GM
Data was destroyed due to mechanical failure (Aug.-Nov. 2012)						
Dec.12. 2012	2.23±0.04	2.23(1.02)	0.64±0.00	0.64(1.01)	29	29
Jan.29. 2013	2.10±0.36	2.07(1.20)	0.20±0.02	0.20(1.09)	9	9
Jan.30. 2013	0.74±0.17	0.72(1.26)	0.12±0.01	0.12(1.05)	16	16
Feb.27. 2013	1.24±0.10	1.23(1.08)	0.14±0.00	0.14(1.02)	11	11
Apr. 2. 2013	2.12±0.18	2.11(1.09)	0.21±0.02	0.21(1.09)	10	10
May.21.2013	2.05±0.11	2.04(1.06)	0.18±0.00	0.18(1.03)	9	9
Jul.10. 2013	0.15±0.06	0.14(1.44)	0.04±0.00	0.04(1.06)	28	30
Aug. 7. 2013	0.12±0.02	0.12(1.18)	0.07±0.00	0.07(1.03)	56	57
Oct. 7. 2013	0.47±0.23	0.40(1.83)	0.02±0.01	0.02(1.30)	5	6
Nov.26. 2013	0.84±0.15	0.83(1.18)	0.11±0.01	0.11(1.11)	13	13
May.26.2014	1.23±0.26	1.21(1.23)	0.09±0.02	0.09(1.28)	8	7
May.27.2014	1.13±0.19	1.11(1.20)	0.08±0.01	0.08(1.07)	7	7

Table 3-10 Parts of real-time monitoring results of inhalable and respirable particulates in the experimental nursery pig house (P.A. level-2) (Unit: mg/m^3).

Date	Inhalable particulate (a)		Respirable particulate (b)		b/a (%)	
	AM±SD	GM(GSD)	AM±SD	GM(GSD)	AM	GM
Data was destroyed due to mechanical failure (Aug.-Nov. 2012)						
Dec.12. 2012	3.34±0.21	3.33(1.06)	0.86±0.04	0.86(1.04)	26	26
Jan.29. 2013	2.64±0.67	2.56(1.30)	0.26±0.08	0.24(1.39)	10	9
Jan.30. 2013	0.81±0.33	0.75(1.49)	0.14±0.01	0.14(1.06)	17	19
Feb.27. 2013	2.37±0.62	2.30(1.27)	0.18±0.01	0.17(1.04)	7	8
Apr. 2. 2013	2.38±0.42	2.34(1.21)	0.24±0.02	0.24(1.11)	10	10
May.21.2013	3.70±1.46	3.44(1.46)	0.27±0.06	0.26(1.25)	7	8
Jul.10. 2013	0.13±0.03	0.12(1.23)	0.05±0.00	0.05(1.04)	38	39
Aug. 7. 2013	0.39±0.11	0.37(1.35)	0.03±0.00	0.03(1.07)	9	9
Oct. 7. 2013	1.00±0.29	0.96(1.34)	0.04±0.00	0.04(1.10)	4	4
Nov.26. 2013	1.59±0.18	1.58(1.12)	0.17±0.02	0.17(1.15)	11	11
May.26.2014	1.64±0.45	1.58(1.30)	0.12±0.03	0.12(1.22)	8	8

May.27.2014	1.55±0.64	1.42(1.50)	0.12±0.03	0.12(1.24)	8	8

Table 3-11 Parts of real-time monitoring results of inhalable and respirable particulates in the experimental nursery pig house (P.A. level-3) (Unit: mg/m^3).

Date	Inhalable particulate (a)		Respirable particulate (b)		b/a (%)	
	AM±SD	GM(GSD)	AM±SD	GM(GSD)	AM	GM
Data was destroyed due to mechanical failure (Aug.-Nov. 2012)						
Dec.12. 2012	6.22±0.64	6.19(1.11)	1.51±0.09	1.51(1.06)	24	24
Jan.29. 2013	4.44±0.54	4.40(1.15)	0.48±0.03	0.48(1.06)	11	11
Jan.30. 2013	2.51±0.44	2.47(1.20)	0.15±0.02	0.15(1.11)	6	6
Feb.27. 2013	4.49±0.49	4.47(1.11)	0.21±0.01	0.21(1.07)	5	5
Apr. 2. 2013	6.58±2.15	6.16(1.48)	0.35±0.10	0.34(1.36)	5	6
May.21.2013	9.36±1.44	9.23(1.20)	0.40±0.04	0.39(1.12)	4	4
Jul.10. 2013	0.24±0.06	0.24(1.25)	0.05±0.00	0.05(1.06)	20	20
Aug. 7. 2013	1.63±0.24	1.62(1.15)	0.06±0.00	0.06(1.04)	4	4
Oct. 7. 2013	4.61±1.21	4.46(1.29)	0.16±0.01	0.16(1.09)	3	3
Nov.26. 2013	3.29±0.70	3.21(1.27)	0.20±0.03	0.20(1.13)	6	6
May.26.2014	4.74±0.55	4.71(1.13)	0.27±0.07	0.26(1.35)	6	6
May.27.2014	4.47±1.16	4.31(1.34)	0.30±0.07	0.29(1.30)	7	7

Figure 3-16 shows the example results of the observed inhalable and respirable particulate concentrations measured in February 2013 and May 2014. As mentioned in Section 3.3.1., the concentration of the airborne dust was higher when the level of P.A. increased. For example, a 31% increase in the inhalable particulate concentration was observed at P.A. level-2 compared to P.A. level-1 (1.18 mg/m^3), while a 278% increase was found for P.A. level-3 when the experiment was conducted in May 2014 (Figure 3-16 (c)). Similarly, for the same month, increases of 40 and 261% in the concentration of the respirable particulate were also observed at P.A. level-2 and P.A. level-3, respectively, based on the observed respirable particulate concentration of 0.08 mg/m^3 at P.A. level -1 (Figure 3-16 (d)). It was obvious that an increase in animal movement contributed to the generation of the airborne dust inside the pig house. Active movement of excited animals can generate turbulent air motions in the vicinity of the animals; thus, substantial amounts of dust particulates could be easily dispersed from the dry slatted floor and the skin of the animals. In comparison with the occupational exposure limit of inhalable particulate with respect to the respiratory health of pig farmers (Donham & Reynolds (1995)), it was noted that the measured inhalable particulate exceeded 2.5 mg/m^3 at P.A. level-3, and during the feeding periods (February 2013) (Figure 3-16 (a)). In observations from May 2014 (Figure 3-16 (c)), only the result at P.A. lelvel-3 exceeded the recommended level. For respirable particulate, the observed concentrations exceeded the recommended level when feed particles were supplied in February 2013 and P.A. level-3 in May 2014. There were relatively large differences between both experimental situations in terms of ventilation rate (0.204 vs 0.367 AER/min) and number of animals (167 vs 194 heads), whereas there were relatively small differences in the ages of animals (69 and 68 days) and indoor air temperature (25.46 vs 27.03℃). Even though the experiment conducted in May 2014 included a larger number of animals with a similar age (116%), the overall dust concentration tended to be lower than in the experiment conducted in February 2013. The higher ventilation rate (180%) may have contributed to the lower dust concentration; thus, the overall IAQ could be improved due to the increased removal rate of the airborne particulate matter. However, an increase in the ventilation rate is always not recommended in terms of providing a comfortable and favorable thermal environment in the AOZ.

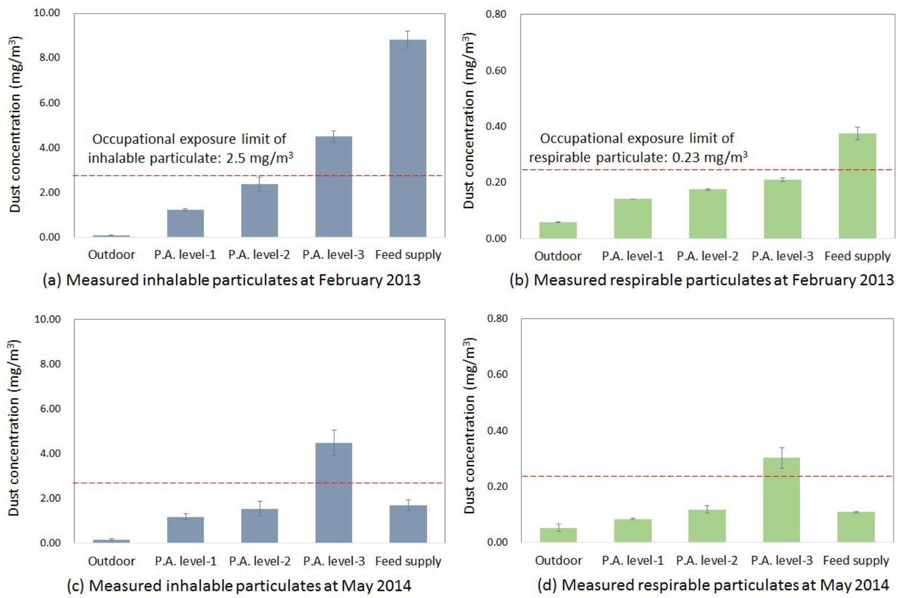


Figure 3-16 Measured concentration of inhalable and respirable particulates in experimental nursery pig house in February 2013 ((a) and (b)) and May 2014 ((a) and (b)).

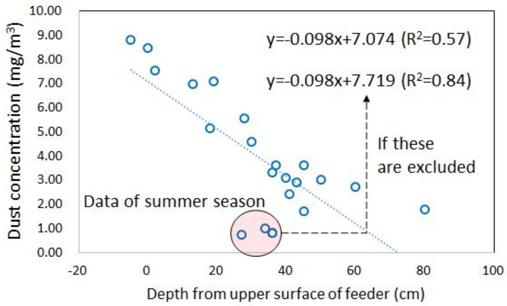
Parametric one-way ANOVA test was also conducted for measured occupational dust during whole experimental periods according to the P.A. level. Contribution of the animal's activities were clearly evident in the generation of the inhalable particulate (p-value=4.905e-05). P.A. level-3 explaining extremely active status of the animals were statistically influential to the generation of the inhalable particulate (p=value=2.45e-05) in contrast to the P.A. level-2 (p-value=0.37). In case of respirable particulate, activity of the piglets was not relatively significant to the suspension of the particulates (p-value=0.232); P.A. level-3 was not also influential (p-value=0.10). These observations can be supported by reports of Pearson & Sharples (1995). Authors mentioned that dust fractions which have smaller AED such as respirable particulate might not be affected by the animal activity to the same extent as the inhalable particulate concentration. Respirable particulate would be suspended in the air for longer times after the movement of the animals, thus reduced animals' activity would have less impact on their concentration. Whereas, the settling rate of relatively larger particles is greater, so a decrease in animal activity would have a more immediate effect on the concentration of the inhalable particulate. In other words, an increase in animal activity could contribute to the immediate suspension of the inhalable particulate in the airspace.

The measured dust concentration near the feeder did not correspond with the overall trends. The reason for the discrepancies in dust concentration near the feeder was strongly connected to the installation depth of the feed supply pipe. Details are provided in later Section 3.3.4.

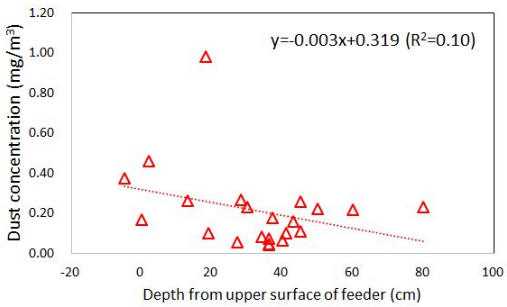
From the observations, the possibilities of being exposed to a harmful environment, in terms of human respiratory health, was increased when pig farmers entered the pig house during feeding periods. Instantaneous health problems in the upper respiratory system could occur due to the increase in the inhalable particulate concentration. Short- and long- term exposure to the inhalable and respirable particulates could lead to a deterioration in the respiratory welfare of both pig farmers and animas. Therefore, it was concluded that pig farmers should limit their visits to the pig house or wear personal protective equipment during certain activities.

3.3.4. Dust concentration near the feeder according to the installation depth of the feed-supply pipe

Feed particulates were automatically supplied twice each day through a mechanical control. The plastic cover of the feeder was not usually in place for practical reasons, for example in terms of the convenience of making visual observations of feed residues and moisture control insider the feeder. This is the case in the majority of commercial pig houses in South Korea. The installation heights (depth) of the feed supply pipes were randomly controlled by the pig farmers, and were dependent on the required feed rate and residues. Two plastic pipes were installed within each feeder, and were designed to penetrate the top surface of the feeder; only one feed-supply pipe was practically used. The status of each feed supply pipe was checked every visit, and the concentration of inhalable and respirable particulates, was simultaneously measured near the feeder (1.5 m above the ground). Figure 3-17 is a scatter diagram showing the measured inhalable and respirable particulate concentration versus the installation depth of the feed supply pipe in the experimental nursery pig house. The concentration of inhalable particulate generally displayed an inverse linearity with the installation depth of the feed supply pipe (R^2=0.57). Therefore, as the depth of the feed supply pipe increased, the concentration of the inhalable particulate was decreased. It can be seen that three data points deviated from the linear trends, and thus limited the predictive capability of the derived linear equation. These points could be explained by the seasonal situation. The three data points were all obtained in summer season when a relatively higher ventilation rate was adopted (1.44~1.57 AER/min). An additional side-exhaust fan was also operated to eliminate surplus heat inside the facility. Considering the locations (near the feeder) of dust concentration measurements and the ventilation systems, it was estimated that the operation of the ventilation systems could influence the turbulence of the surrounding air and the levels of airborne dust after feeding events. A higher ventilation rate could immediately eliminate the dispersed dust particles near the feeder. If mentioned three data points were excluded as outliers, the R^2 of the regression could be increased from 0.57 to 0.84. From the corrected linear regression equation, if the installation depth was set to be 0 cm below the top surface of the feeder, the predicted concentration of inhalable particulate was 7.07 mg/m^3, while it was 4.13 mg/m^3 when the installation depth was 30 cm below the surface (i.e., a 41.6% decrease), and 1.19 mg/m^3 when the installation depth was 60 cm depth below the surface (i.e., an 83.2% decrease). In comparison to the inhalable particulate, the respirable particulate concentrations did not show any specific trends with the installation depth of the feed supply pipe (R^2=0.10). This suggested that there was no large influence on relatively small particles, with a mean aerodynamic diameter smaller than 4 µm. Respirable particulate would be suspended in the air for longer than inhalable particulate after feeding; thus, control of the feed supply pipe would have less impact on their generation. From these results, it was clear that a simple control of the feed supply pipe could be an effective way to reduce the generation of airborne dust during the feeding periods, especially for particulates with a relatively large AED.



(a) Scatter diagram of concentration of inhalable dust



(b) Scatter diagram of concentration of respirable dust

Figure 3-17 Measured inhalable (a) and respirable (b) particulate concentrations versus the installation depth of the feed supply pipe.

3.3.5. Multiple regression analysis of measured TSP and PM10

Multiple regression analyses were conducted on the basis of the measured dust concentration of TSP and PM10 at the measurement locations in the middle of the experimental nursery pig house. To identify the independence among the experimental variables, correlation test and multi-collinearity test using VIF (verification of the variance inflation factor) as a post hoc test were carried out before selecting independent variables for regression analyses. Table 3-12 shows the results of correlation coefficients among TSP and PM10 and environmental variables. The TSP and PM10 showed relatively strong reverse linear trends to the ventilation rate, respectively (R=-0.85, -0.76). This implied that operation of ventilation system could dilute the airborne concentration of the TSP and PM10 as noted in previous studies. Among the variables, outdoor air temperature was strongly related to the ventilation rate (R=0.83). This could be explained that operation of the ventilation system was automatically controlled based on the indoor air temperature; outdoor weather conditions determined the variation of the indoor air temperature due to the incoming air from outside and heat loss according to conduction effect. However, used value of mean indoor air temperature at each experimental date was considered as a kind of steady-state thermal condition due to the systematic operation of the ventilation system to keep proper temperature for AOZ and thermal equilibrium status between heat gain from animals and heat loss from ventilation and conduction; therefore, correlation between indoor air temperature and ventilation rate was not strongly distinguished from the given conditions.

Table 3-12 Computed correlation coefficients among TSP and PM10 concentrations and environmental variables.

	Ventilation rate	Age of animals	Number of animals	Outdoor air temperature	Indoor air temperature	TSP	PM10
Ventilation rate	1.00						
Age of animals	-0.12	1.00					
Number of animals	0.00	-0.44	1.00				
Outdoor air temperature	0.83	0.04	-0.25	1.00			
Indoor air temperature	0.15	-0.02	0.15	0.10	1.00		
TSP	-0.85	-0.04	-0.27	-0.60	-0.08	1.00	
PM10	-0.76	0.08	-0.09	-0.63	0.29	0.86	1.00

From the correlation analysis and multi-collinearity test, outdoor air temperature seemed to strongly correlated with the ventilation rate. Thus, the variable of the outdoor air temperature was excluded from the multi-regression analyses for TSP and PM10; the selected independent variables were ventilation rate, age and number of animals and indoor air temperature.

Table 3-13 and 3-14 shows the results of the multiple-regression analyses of TSP and PM10, respectively. From the results of the multiple regression analysis of the TSP concentrations, ventilation rate was the most significant variable among the experimental variables with a p-value of 0.002 ($p<0.01$). As mentioned earlier, the TSP concentration displayed a decreasing trend as the ventilation rate increased ($R=-0.85$). As noted in Table 3-13, the variables could be ranked in terms of the significance of their contribution toward the generation of TSP as follows: ventilation rate, number of animals (p-value≅0.05), age of animals, and indoor air temperature. A decrease of number of animals can definitely contribute to an increase in the IAQ of the AOZ in such facilities. However, stocking density is strongly connected with both the productivity and total yield of pig farms. In European countries, to comply with the "1994 Welfare of Livestock Regulations and EU91/630", the recommended minimum space for one piglet with a live weight under 30 kg in a partial or fully slatted house is 0.30 m^2 (Carr, 1998). The calculated space for one piglet in the experimental nursery pig house in this thesis were in a range between 0.28 and 0.61 m^2. The average space for one piglet was calculated to be 0.44 m^2, which was 46.7% higher than the recommended level in European standard. Considering that the rearing piglet density is generally calculated and taken into consideration in commercial nursery pig houses in South Korea, the control of the rearing density of piglets is required to improve animal welfare and the IAQ in the facility. Nevertheless, this may be practically restricted in the near future due to economic issues. Therefore, controlling the ventilation could be the most effective practice in a dust reduction strategy, based on the evaluation of the degree of contribution of ventilation toward the generation of TSP. However, care should be taken when controlling the ventilation rate because of the need to maintain the thermal comfort of the AOZ and to control heating costs. The linear regression equation derived for TSP is given below, and the R^2 and adjusted R^2 value was 0.89 and 0.80, respectively.

$$\mathrm{TSP} = 1.913 - 1.179 \cdot \text{ventilation rate} - 0.010 \cdot \text{age of animals} - 0.005 \cdot \text{number of animals} + 0.050 \cdot \text{indoor air temperature}$$

Table 3-13 Computed regression coefficients, standard errors, t-values, and p-values from the multiple regression analysis of TSP with selected variables.

TSP	Multiple R^2	0.89	Adjusted R^2	0.80
	F-statistic	9.75	p-value	0.01
	Coefficient	Standard error	t-value	Pr (>$\lvert t \rvert$)
(intercept)	1.91	1.54	1.25	0.268
Ventilation rate (m^3/s)	-1.18	0.20	-5.86	0.002**
Age of animals (days)	-0.01	0.01	-2.00	0.102
Number of animals (heads)	-0.01	0.00	-2.55	0.051
Indoor air temperature (°C)	0.05	0.06	0.79	0.465
Significance: 0 “***” 0.001 “**” 0.01 “*” 0.05 “.” 0.1 “ ” 1				

From the results of the multiple regression analysis of the PM10 concentrations, it was apparent that ventilation rate was also most significant variable, with a p-value of 0.012 ($p<0.05$). The PM10 concentration displayed an inverse linear trend with the increase in the ventilation rate (R=-0.76). The correlation coefficient was slightly lower than that for the TSP. Other variables were not statistically significant at a confidence level of 95%. From the computed t-values and p-values, the ranking of variables in terms of their contribution toward the generation of PM10 was as follows: ventilation rate, indoor air temperature, number of animals, and age of animals. As noted earlier, adjusting the ventilation was determined to be the key factor in the generation of PM10. The linear regression equation derived for PM10 is given below, and the R^2 and adjusted R^2 value was 0.77 and 0.59, respectively.

$$\mathrm{PM10} = -1.575 - 0.729 \cdot \text{ventilation rate} - 0.002 \cdot \text{age of animals} - 0.002 \cdot \text{number of animals} + 0.121 \cdot \text{indoor air temperature}$$

Table 3-14 Computed regression coefficients, standard errors, t-values, and p-values from the multiple regression analysis of PM10 with selected variables.

PM10	Multiple R^2	0.77	Adjusted R^2	0.59
	F-statistic	4.29	p-value	0.07
	Coefficient	Standard error	t-value	Pr(>$\lvert t \rvert$)
(intercept)	-1.58	1.44	-1.09	0.324
Ventilation rate (m^3/s)	-0.73	0.19	-3.86	0.012*
Age of animals (days)	-0.00	0.01	-0.42	0.691
Number of animals (heads)	-0.00	0.00	-0.81	0.457
Indoor air temperature (°C)	0.12	0.06	2.04	0.096.
Significance: 0 “***” 0.001 “**” 0.01 “*” 0.05 “.” 0.1 “ ” 1				

3.3.6. Multiple regression analysis of measured inhalable and respirable particulate

Multiple regression analyses were also conducted on the basis of the measured inhalable and respirable particulates in the experimental nursery pig house. To identify the independence among the experimental variables, correlation and multi-collinearity test were carried out test before selecting independent variables for regression analysis. Table 3-15 shows the results of computed correlation coefficients among concentrations of the inhalable and respirable particulates and environmental variables.

Table 3-15 Computed correlation coefficients among inhalable and respirable particulate and environmental variables.

	Ventilation rate	Age of animals	Number of animals	P.A. level	Outdoor air temperature	Indoor air temperature	Inhalable particulate	Respirable particulate
Ventilation rate	1.00							
Age of animals	0.48	1.00						
Number of animals	-0.54	-0.15	1.00					
P.A. level	0.00	0.00	0.00	1.00				
Outdoor air temperature	0.96	0.45	-0.33	0.00	1.00			
Indoor air temperature	0.77	0.52	-0.41	0.00	0.82	1.00		
Inhalable particulate	-0.45	-0.05	0.56	0.63	-0.34	-0.31	1.00	
Respirable particulate	-0.57	-0.16	0.33	0.28	-0.59	-0.27	0.58	1.00

The measured concentration of inhalable and respirable particulate showed relatively lower reverse linear trends to the ventilation rate, respectively (R=-0.45, -0.57) in contrast to the results of TSP and PM10. In contrast to results of correlation analysis for TSP and PM10, indoor air temperature showed correlation with outdoor air temperature (R=0.77). This could be explained that the experimental periods for monitoring of occupational dust were longer than experimental periods for TSP and PM10, thus relatively large amount of collected data could elucidate the relationship between indoor and outdoor conditions. From the correlation analysis and multi-collinearity test, outdoor air temperature seemed to strongly be correlated with the ventilation rate and indoor air temperature. Thus, the variable of the outdoor air temperature was excluded from the multi-regression analyses for occupational dust like the analysis cases for TSP and PM10; the selected independent variables were ventilation rate, age and number of animals, P.A. level and indoor air temperature. The P.A. level was a nominal factor, which had a discrete distribution; therefore, dummy variables were adopted to reflect the effects of the P.A. level. Here, dummy variable (a) was used to evaluate the statistical difference of the effects between P.A. level-1 and level-2 while, dummy variable (b) was used to evaluate the effects between P.A. level-1 and level-3. Table 3-16 shows the results of the regression analysis for inhalable particulate. The degree of contribution of the indoor air temperature toward the generation of inhalable particulate was very small (p-value=0.715). Therefore, the indoor air temperature was excluded from the independent variables and the regression model was re-analyzed in a backward elimination process. From the results of the multiple regression analysis of the inhalable particulate, dummy variable (b) was found to be the most significant variable among the designed experimental variables with a p-value of 8.51×10^{-9} ($p<0.001$). This indicated that vigorous movement of excited animals due to the activity of pig farmers could contribute substantially and positively to the generation of inhalable particulate compared to the situation when almost all piglets were lying on the ground. The number of animals was also determined to be a statistically significant factor, with a p-value of 1.33×10^{-4} ($p<0.001$). An increase in the number of piglets reared in an enclosed space may naturally lead to a rise in the inhalable particulate concentration because of the accumulation of feces and feed residues on the slatted floor, and hair and dander emitted from the bodied of the livestock. Inhalable particulate concentrations displayed a decreasing tendency with ventilation rate ($R=-0.45$, $p<0.05$). The reason for the relatively small correlation coefficients between the inhalable particulate concentration and ventilation rate was that the effect of the P.A. level and the number of animals was more dominant than in the results for TSP and PM10 in given conditions.

From the corrected model, the ranking of the degree of contribution of each variable to the inhalable particulate concentration was as follows: P.A. level-3; number of animals; ventilation; age of animals; and P.A. level-2. This indicated that working inside a pig house where a large number of animals are being raised could be obviously harmful to the respiratory health of pig farmers, especially during the cold season. Even though the degree of contribution of animal's age to the generation of inhalable particulate was relatively small (p-value=0.144), the age of animals could have a positive influence on dust generation. Hinz & Linke (1998) observed a decreasing trend of dust generation with increasing age and live weight of the animals in a fattening pig house. They reported that the increase in the live weights of fattening pigs reduced their activity, resulting in relatively low dust concentrations. However, younger piglets are more active and vigorous than the fattening pigs and there may be a deterioration in hygiene status when piglets grow, with urine and feces accumulating on the slatted floor.

As mentioned earlier, when establishing a dust reduction strategy, controlling the rearing number of animals is difficult because of considerations regarding economic feasibility. Movement of animals is also an uncontrollable variable. Consequently, the control of ventilation is a practical way to improve the IAQ of the AOZ in a pig house, according to derived model. Based on the corrected model, the linear regression equation derived for the inhalable particulate concentration according to the level of P.A. is given below. The R^2 and adjusted R^2 value was 0.81 and 0.78, respectively. Here, dummy variables (a) and (b) are 0 and 0 for P.A. level-1, 1 and 0 for P.A. level-2, and 0 and 1 for P.A. level-3.

$$\begin{aligned}\text{Inhalable particulate} \\ &= -3.314 - 1.273 \cdot \text{ventilation rate} + 0.026 \cdot \text{age of animals} + 0.024 \\ &\cdot \text{number of animals} + 0.591 \cdot \text{dummy variable (a)} + 3.178 \\ &\cdot \text{dummy variable (b)}\end{aligned}$$

The linear regression equation derived for the inhalable particulate concentration when pig farmers are working inside the facility is as follows:

$$\begin{aligned}\text{Inhalable particulate} \\ &= -0.163 - 1.273 \cdot \text{ventilation rate} + 0.026 \cdot \text{age of animals} + 0.024 \\ &\cdot \text{number of animals}\end{aligned}$$

For example, from the derived linear equation and experimental condition for April 2013, where 188 heads of piglet whose age was 54 days being raised, and the ventilation rate was 1452.47 m^3/h (0.403 AER/min), 3.1% of decrease in inhalable particulate could be estimated when additional 10% of systematic out of the ventilation was temporarily increased when pig farmers entered the room while, 8.7%

of decrease for the case when 10% of rearing number was decreased with given conditions.

Figure 3-18, 3-19 and 3-20 depict the estimated inhalable particulate concentration from derived equation in this thesis according to the P.A. level and age of animals in the experimental nursery pig house; (a) 40 days, (b) 50 days, (c) 60 days and (d) 70 days in each figure. From the given figures, concentration of the airborne inhalable particulate could be predicted according to variation of each environmental condition.

Table 3-16 Computed regression coefficients, standard errors, t-values, and p-values from the multiple regression analysis of inhalable particulate with selected variables.

Inhalable particulate	Multiple R^2	0.81	Adjusted R^2	0.78
	F-statistic	25.11	p-value	6.94e-10
	Coefficient	Standard error	t-value	Pr(>|t|)
(intercept)	-3.34	1.30	-2.58	0.015*
Ventilation rate (m^3/s)	-1.27	0.48	-2.64	0.013*
Age of animals (days)	0.03	0.02	1.67	0.106
Number of animals (heads)	0.02	0.01	4.38	1.33e-04***
Dummy variable (a)	0.59	0.40	1.47	0.153
Dummy variable (b)	3.18	0.40	7.88	8.51e-09***

Significance: 0 “***” 0.001 “**” 0.01 “*” 0.05 “.” 0.1 “ ” 1

Dummy variable (a) was used to evaluate statistical differences between P.A. level-1 and P.A. level-2.

Dummy variable (b) was used to evaluate statistical differences between P.A. level-1 and P.A. level-3.

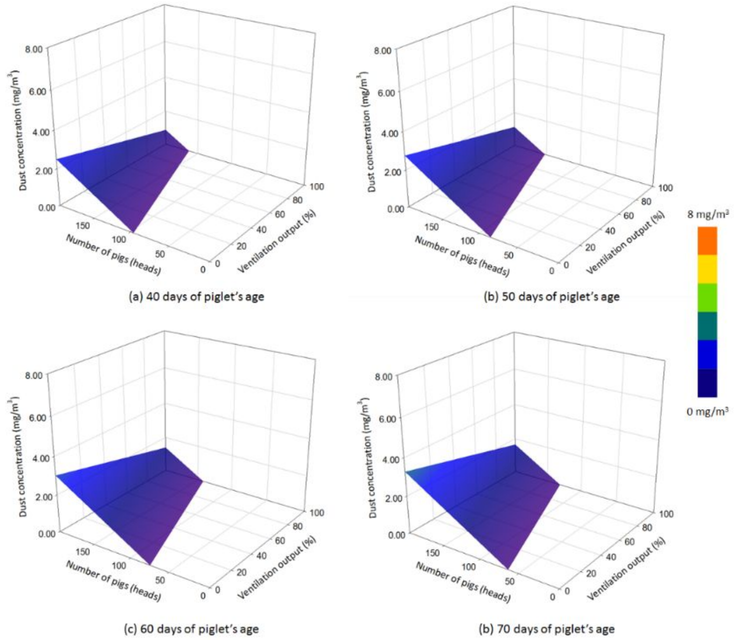


Figure 3-18 Estimated concentration of inhalable particulate according to environmental conditions with P.A. level was 1.

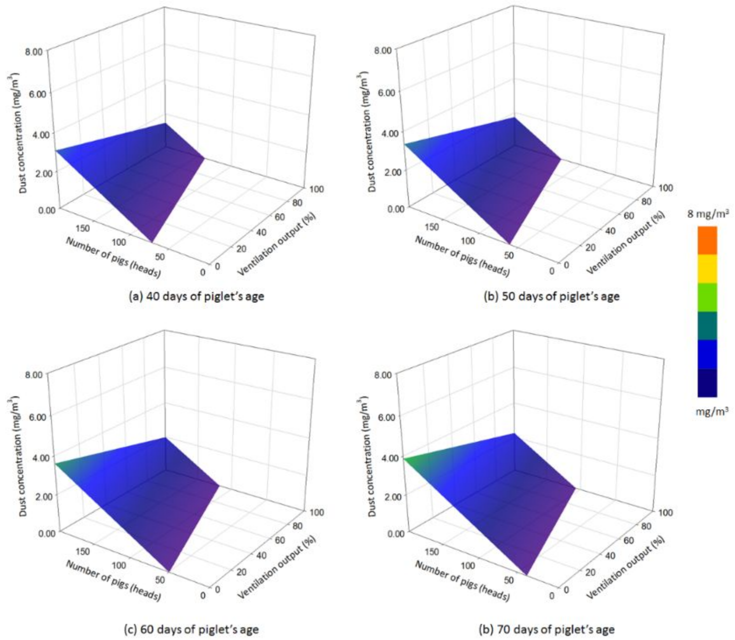


Figure 3-19 Estimated concentration of inhalable particulate according to environmental conditions when P.A. level was 2.

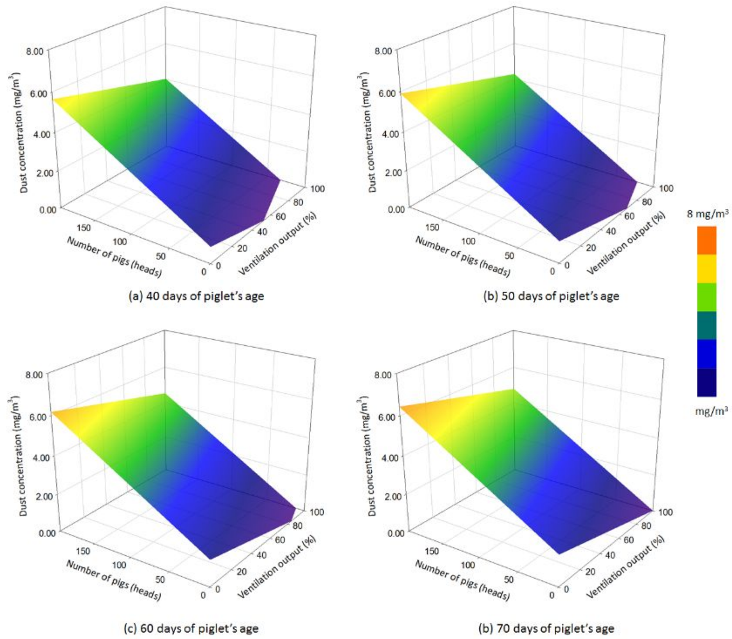


Figure 3-20 Estimated concentration of inhalable particulate according to environmental conditions when P.A. level was 3.

From the computed statistics for respirable particulates, it was concluded that the age of animals (p-value=0.742) and the number of animals (p-value=0.995) were less significant variables in derived model. Therefore, these variables were excluded in the backward elimination process. To statistically evaluated the appropriateness of the elimination of these two variables, an additional F-test between the original and corrected model was conducted. The computed p-value for the excluded variables was 0.946, which indicated that the influence of two excluded variables was relatively slight.

From the multiple regression analysis of the respirable particulate, the ventilation rate was also found to be the most significant variable, with a p-value of 2.55×10^{-5} ($p<0.001$) as shown in Table 3-17. The concentration of respirable particulate decreased due to the increase in the ventilation rate (R=-0.57). From the statistical results, the ranking of the degree of contribution toward the generation of respirable particulate was as follows based on t-value and p-value: ventilation; indoor air temperature; P.A. level-3; and P.A. level-2. Unlike the results for inhalable particulate, P.A. level-3 was not the most influential factor for respirable particulate. Pearson & Sharples (1995) reported that the concentration of respirable particulate might not be affected by animal activity to the same extent as the inhalable particulate concentration, due to the different aerodynamic behavior of the two size fractions. Respirable particulate would be suspended in the air for a longer period after the movement of the animals; thus, reducing animal activity would have less impact on the concentration of this size fraction. Indoor air temperature may also have an effect on the buoyancy of small particles, which could consequently influence the sedimentation rate of particles. Thus, it could be estimated that high concentration of the respirable particulate can be observed in the airspace during the winter season when additional heating system was generally adopted for young piglets. Based on the corrected model, the linear regression equation derived for respirable particulate is given below. The R^2 and adjusted R^2 value was 0.53 and 0.47, respectively. Here, dummy variables (a) and (b) are 0 and 0 for P.A. level-1, 1 and 0 for P.A. level-2, and 0 and 1 for P.A. level-3.

$$\begin{aligned}\text{Respirable particulate} \\ &= -1.040 - 0.624 \cdot \text{ventilation rate} + 0.053 \cdot \text{dummy variable (a)} \\ &+ 0.190 \cdot \text{dummay variable (b)} + 0.064 \cdot \text{indoor air temperature}\end{aligned}$$

The linear regression equation derived for respirable particulate when animals are actively moving in the facility is as follows:

$$\text{Respirable particulate} = -0.85 - 0.624 \cdot \text{ventilation rate} + 0.064 \cdot \text{indoor air temperature}$$

Table 3-17 Computed regression coefficients, standard errors, t-values, and p-values from the multiple regression analysis of respirable particulate with selected variables.

Respirable particulate	Multiple R^2	0.53	Adjusted R^2	0.47
	F-statistic	8.65	p-value	8.22e-05

	Coefficient	Standard error	t-value	Pr(>|t|)
(intercept)	-1.04	0.53	-1.95	0.061.
Ventilation rate (m^3/s)	-0.62	0.13	-4.94	2.55e-05***
Dummy variable (1)	0.05	0.08	0.64	0.526
Dummy variable (2)	0.19	0.08	2.29	0.029*
Indoor air temperature (℃)	0.06	0.02	2.77	9.50e-03**

Significance: 0 "***" 0.001 "**" 0.01 "*" 0.05 "." 0.1 " " 1

Dummy variable (a) was used to evaluate statistical differences between P.A. level-1 and P.A. level-2.

Dummy variable (b) was used to evaluate statistical differences between P.A. level-1 and P.A. level-3.

However, notwithstanding the mentioned results above, variations in environmental factors such as ventilation rate and indoor air temperature were very slight within actual rearing situations of nursery pig house. Considering these actual situations and coefficients of dummy variable (b), it could be concluded that increase in animal's activity was still practically significant toward the generation of the respirable particulates. For example, from the derived linear equation and experimental condition for April 2013, where 188 heads of piglet whose age was 54 days being raised, the ventilation rate was 1452.47 m^3/h (0.403 AER/min) and indoor air temperature was 24.9°C, about 26.7% of decrease in respirable particulate could be estimated when additional 10% of systematic out of the ventilation (basic unit for ventilation operation of experimental nursery pig house) was temporarily increased when P.A. level-1 while, 21.1% of increase for the case when indoor air temperature of 1℃ was increased with given conditions (P.A. level-1). However, 62.5% increase in respirable particulates could be estimated when pig farmers entered the room (P.A. level-3) with identical environmental conditions for April 2013. Figure 3-21 shows the estimated respirable particulate concentration from derived equation in this thesis according to the P.A. level.

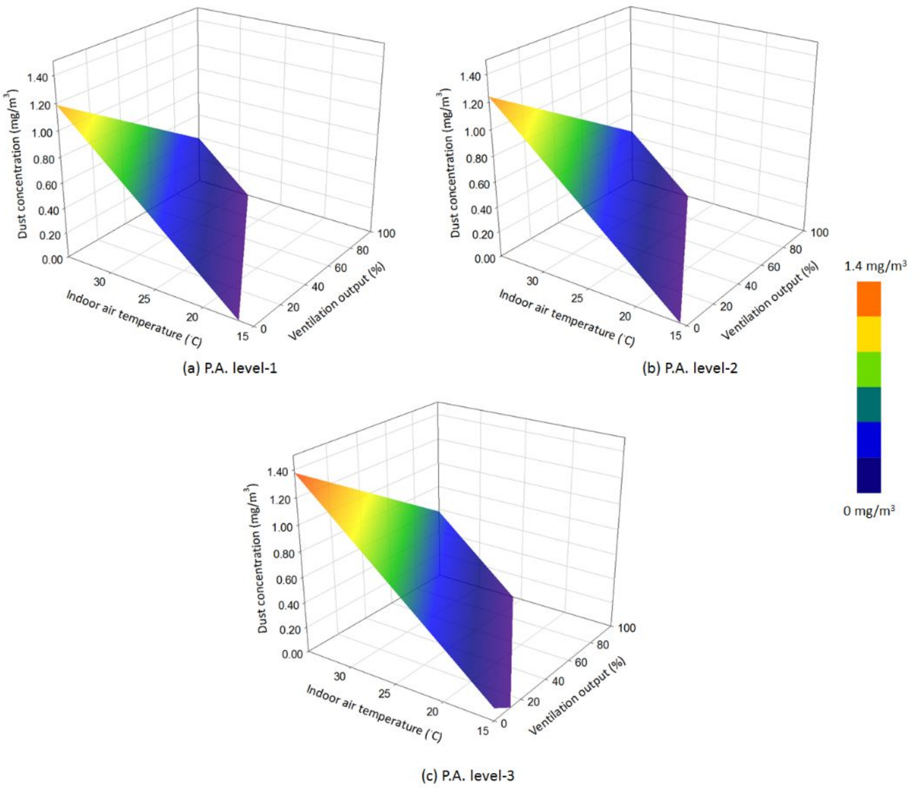


Figure 3-21 Estimated concentration of respirable particulate according to environmental conditions and P.A. level.

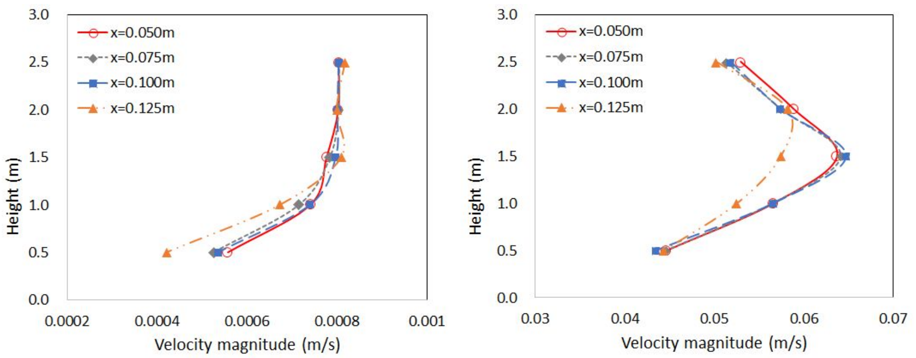
3.3.7. Validation results of the CFD simulation model

A grid independence test was conducted for different maximum cell sizes.

Velocity magnitude distributions in a total of 20 sections (4 points [p-1, p-2, p-3, and p-4 in Figure 22]×5 heights [0.5, 1, 1.5, 2 and 2.5 m from ground]) were compared based on the CFD-computed values when the maximum cell size had a minimum value of 0.05 m among the variables. The computed CFD results showed that the velocity magnitude at p-1 and p-2 were relatively small, in the range of 0.0006 to 0.001 m/s, while the velocity magnitude of p-3 and p-4 were in the range of 0.018 to 0.0637 m/s according to the application of the minimum ventilation rate in the winter and the location of the ventilation system. The two pens where p-3 and p-4 were located were close to the roof exhaust duct as shown in Figure 3-6. Table 3-18 shows the absolute values of the calculated errors at p-1 and p-4, according to the height of each point and the cell sizes. The CFD-computed errors were dramatically increased with an increase in the maximum cell size, especially after 0.15 m. A qualitative comparison of the CFD-computed errors for cell sizes from 0.005 m to 0.125 m is shown in Figure 3-22. The vertical distributions of the velocity magnitude at p-1 and p-4 when the maximum cell size was 0.125 m were slightly different from those of other cell sizes. To accurately evaluate the errors according to the cell size, the average R^2 values of p-1 and p-2 and p-3 and p-4 according to the cell size, was calculated when considering the range of the velocity magnitude at each point (Table 3-19). Considering the R^2 values according to the scale of the velocity magnitude and computational cost, a cell size of 0.1 m was selected as a proper mesh size for the CFD simulation model of the experimental nursery pig house.

Table 3-18 CFD-computed errors according to the location of points, their heights, and maximum cell size based on results for a 0.050 m cell size as a grid independence test (Unit: %).

Location	Height (m)	Maximum cell size (m)								
		0.075	0.100	0.125	0.150	0.175	0.200	0.300	0.500	1.000
p-1	2.5	0.00	0.08	1.78	248.91	607.63	152.68	4.71	23.68	318.91
	2.0	0.00	0.36	0.38	258.67	560.80	257.78	0.32	11.99	379.13
	1.5	0.84	2.54	4.20	296.84	557.35	550.14	1.24	4.08	291.14
	1.0	3.46	0.13	9.04	169.19	585.02	96.47	1.85	10.33	74.06
	0.5	5.63	3.85	24.34	405.67	478.84	197.69	2.33	56.92	448.98
Average error (%)		1.98	1.39	7.95	275.86	557.93	254.55	2.09	21.40	302.24
Location	Height (m)	Maximum cell size (m)								
		0.075	0.100	0.125	0.150	0.175	0.200	0.300	0.500	1.000
p-4	2.5	3.02	2.05	5.15	7.03	25.93	2.92	4.03	0.82	9.52
	2.0	2.37	2.46	1.12	1.36	22.95	5.16	0.03	4.21	2.50
	1.5	0.63	1.53	9.86	10.90	5.88	4.46	1.74	5.78	0.53
	1.0	0.17	0.07	7.21	9.71	129.97	3.84	10.84	1.64	4.83
	0.5	0.08	2.67	0.69	12.69	112.39	3.40	4.99	1.56	9.55
Average error (%)		1.26	1.76	4.81	8.34	59.43	3.96	4.33	2.80	5.38



(a) Vertical distribution of velocity magnitude at p-1

(b) Vertical distribution of velocity magnitude at p-4

Figure 3-22 Vertical distribution of the velocity magnitude at p-1 (a) and p-4 (b) according to the maximum cell size of the computational domain.

Table 3-19 Computed R^2 values based on the CFD-computed results when the cell size was at a minimum (0.050 m) as a grid independence test.

	Maximum cell size (m)			
	0.050	0.075	0.100	0.125
p-1 and p-2	-	0.99	0.98	0.93
p-3 and p-4	-	1.00	1.00	0.99

Velocity magnitude ranges of p-1 and p-2: 0.0006~0.0010 m/s

Velocity magnitude ranges of p-3 and p-4: 0.0180~0.0637 m/s

From the comparative analyses performed using the turbulence model, the differences in the CFD-computed values of the standard error based on the experimentally measured air temperature value were relatively small. The comparative analyses were carried out in identical ways for validating the accuracies of the model when boundary conditions of the CFD model were designed based on the experiments of December 2012. Details of how to validate the CFD-computed results with experimentally measured data are given in the next paragraph. The RNG k-ε turbulence model was selected as a more suitable turbulence closure model when considering the low standard error value of 2.57% (Table 3-20) and the qualitative variation in the air temperature according to the ventilation progress time. Figure 3-23 shows air temperature variation at specific points in the computational domain according to the one cycle ventilation operation in the winter season, which is one example of a comparative analysis for turbulence models.

Table 3-20 Results of comparative analyses of standard errors according to application of turbulence models.

	Turbulence closure models				
	Standard k-ε	RNG k-ε	Realizable k-ε	Standard k-ω	SST k-ω
Standard error	3.08%	2.57%	2.82%	2.96%	2.77%

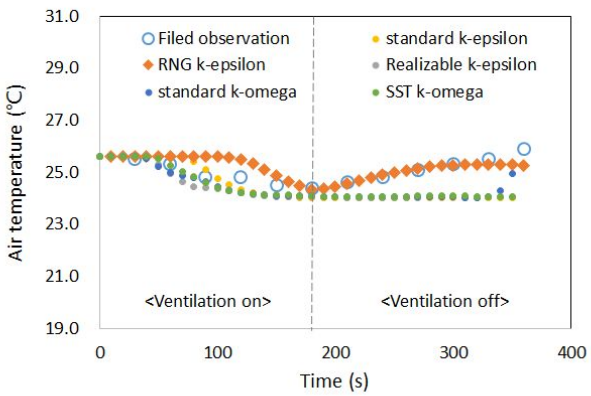
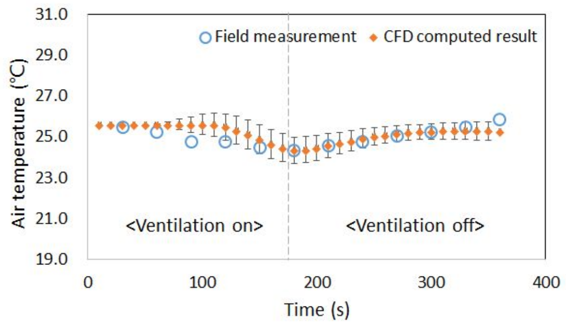


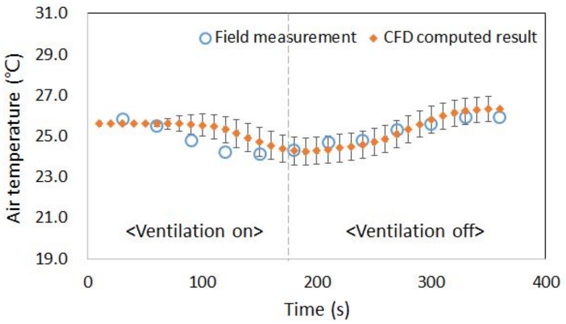
Figure 3-23 Qualitative variations of air temperature at specific point in computational domain according to turbulence models.

To validate the accuracies of the CFD simulation model for an experimental nursery pig house, a total of four experimental periods were simulated according to the cyclical (on/off) operation of the ventilation system. In the field-measured data, when the ventilation system was operated, air temperature inside the experimental nursery pig house decreased over time, but then increased after the ventilation system was shut down. Figure 3-24 shows one of the example results of a comparison between field-measured air temperature data and CFD-computed data when the boundary and initial conditions were set based on the observation for February 2013.

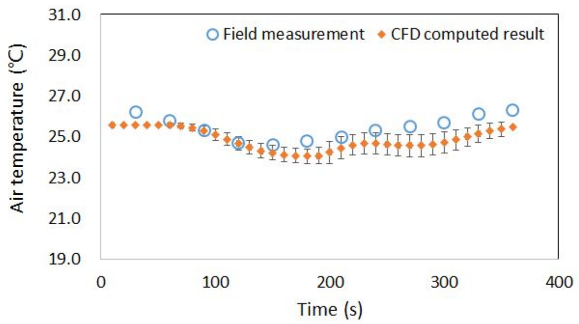
During the field experiment, the installation height of the thermocouples was slightly changed to allow frequent access for the pig farmers and effective cleaning activities. The original installation height of the thermocouples was 1.5 m. However, the height of each sensor randomly varied within a range of 1.3~1.7 m during the experimental periods. The error bars plotted in Figure 3-24 were calculated from the CFD-computed air temperature distribution at heights of 1.3, 1.5 and 1.7 m above the slatted floors. Figure 3-24 shows that the air temperature distribution of CFD-computed results was very close to the experimentally measured data, especially at TL-1 and TM-2 according to the time progress. The average error at TL-1, TM-2, and TM-3 was 0.28, 0.38 and 0.57℃, respectively. The CFD-computed standard error of each measurement point was 1.12, 1.52 and 2.24%, respectively. The air temperature distributions in the field-measured data at TM-3 were slightly higher than the CFD-computed results, especially after shutting down the ventilation system. There were various reasons for the relatively large error at the TM-3 point, including the location of the measurement point and roof-exhaust duct, and the presence of animals inside the experimental nursery pig house. In the computational domain of the CFD simulation model, animals were randomly and uniformly distributed in each pen. However, a group of piglets occasionally congregated at specific locations to find warm places. Table 3-21 shows the calculated standard errors for all simulated cases in the validation test. The average standard errors were about 2.10%, which implied that the CFD simulation model for the experimental nursery pig house was reasonably well-designed and predicted accurate solutions. The forms of the governing equations of the Eulerian-Eulerian multiphase equations for each phase including primary airflow phase and secondary particulate phases were very similar to the general form of the Navier-Stokes equation. Therefore, it was concluded that the CFD model could also reasonably predict the airborne dust distribution in the computational domain.



(a) Temperature variations according to operation cycle of ventilation at TL-1



(b) Temperature variations according to operation cycle of ventilation at TM-2



(c) Temperature variations according to operation cycle of ventilation at TM-3

Figure 3-24 Comparison of air temperature variations according to the operating cycle of the ventilation system between field-measured and CFD-computed data at the measurement points of TL-1 (a), TM-2 (b) and TM-3 (c).

Table 3-21 Calculated standard errors between field measurements and CFD-computed data when different experimental dates were sued to set initial and boundary conditions.

Experimental date for boundary and initial conditions for CFD model			
November 2012	February 2013	April 2013	November 2013
2.02%	2.27%	2.53%	1.59%

3.3.8. CFD-computed dust reduction efficiency according to application of alternative pipe-exhaust systems

The CFD simulation model was designed to estimate and evaluate dust reduction efficiencies for different ventilation method scenarios in the experimental nursery pig house based on the Eulerian-Eulerian multiphase model. In this thesis, based on the validated CFD model, conceptual experimental cases using a pipe-exhaust system were designed with the initial and boundary conditions from the experimentally measured data and derived equation for dust concentrations in earlier sections. Figure 3-25 shows one of the examples of CFD-computed streamline when feed was supplied to each feeder for two different ventilation systems: (a) a conventional roof-exhaust duct system (Original case); and (b) a combination of pipe-exhaust ventilation system and conventional roof-exhaust duct system (Case 1) when a minimum ventilation rate (20%, 0.085 AER/min) was used. The color maps refer to feed particle residence time after being released from each feed supply pipe. As shown in Figure 3-25 (a), when feed particulates were dropped from the feed supply pipe into the feeder, airborne dust generated from the feed particulates was transported in the airflow in the direction of the roof-exhaust duct. However, particulates released from four feeders located close to the entrance could not reach the roof-exhaust duct for initial the 30 s after starting the feeding process. When the pipe-exhaust system was additionally used with the minimum ventilation rate of 0.085 AER/min during the cold season (Figure 3-25 (b)), substantial quantities of dust particulates were rapidly and directly eliminated by the exhaust systems, while unremoved airborne dust remained in the air space or transported in the airflow in the direction of the roof exhaust duct.

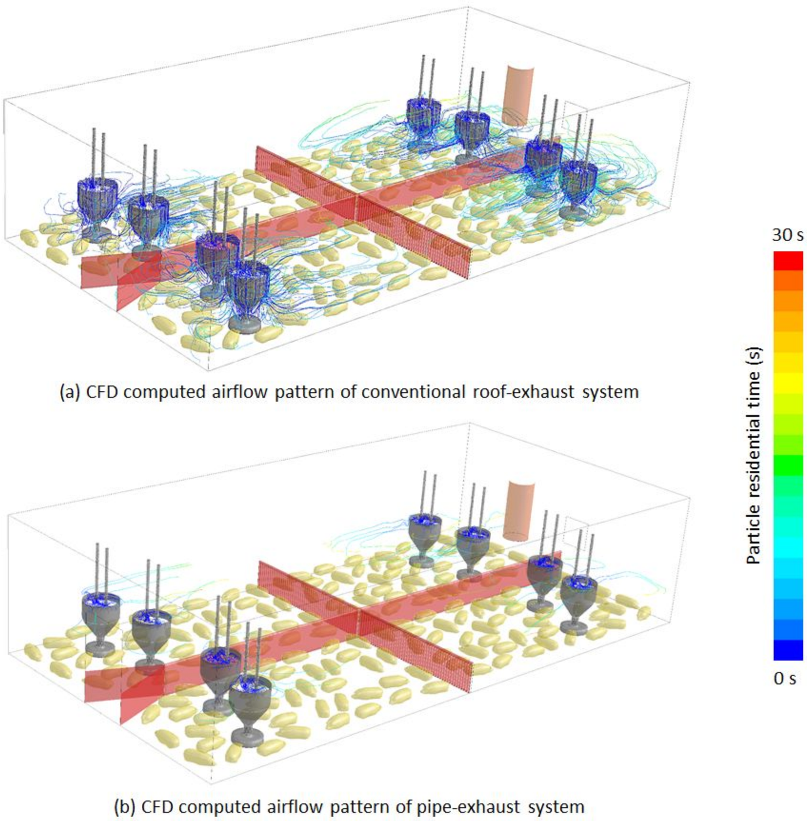


Figure 3-25 CFD-computed airflow pattern when feed was supplied at each feeder for two different ventilation systems; (a) conventional roof-exhaust system and (b) pipe-exhaust system when minimum ventilation rate was adopted for cold season.

Figures 3-26 and 3-27 show consecutive scenes of concentrations of inhalable particulates where the pre-defined mean AED was 20 μm for the different ventilation system at an average respiratory intake height of the workers (1.5 m above the ground), which is the original case and Case 2 when the minimum ventilation rate was adopted. Feed particles were supplied for an initial 30 s, and then the feed supply was stopped. Each ventilation system was steadily operating until the end of the simulation. In the case of the conventional roof-exhaust duct system (i.e., original case), a relatively high concentration of inhalable particulate (≥2 mg/m^3) was distributed near the feeder despite the feed supply being stopped after 60 s of computational time. In contrast to the application of the conventional roof-exhaust ventilation system, substantial quantities of the airborne dust near the feeder were rapidly eliminated by the pipe-exhaust system. Consequently, a relatively low concentration of inhalable particulates was observed in the airspace.

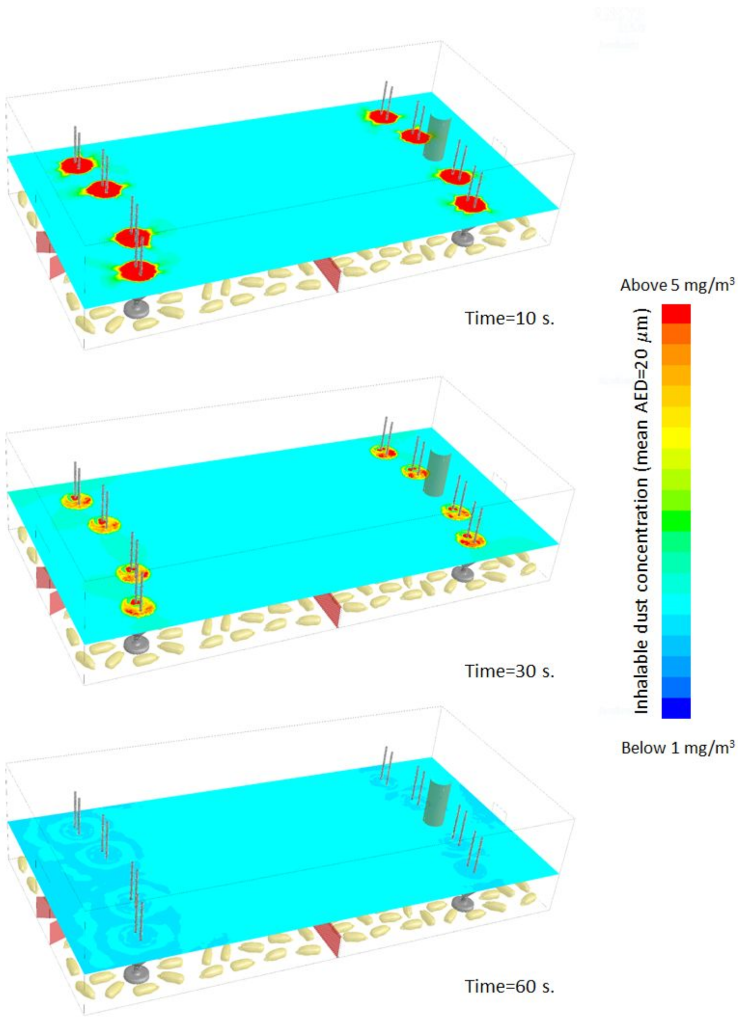


Figure 3-26 CFD-computed concentration of inhalable particulate (mean AED= 20 µm) according to flow-time when conventional roof-exhaust system was used with minimum ventilation rate (Original-case).

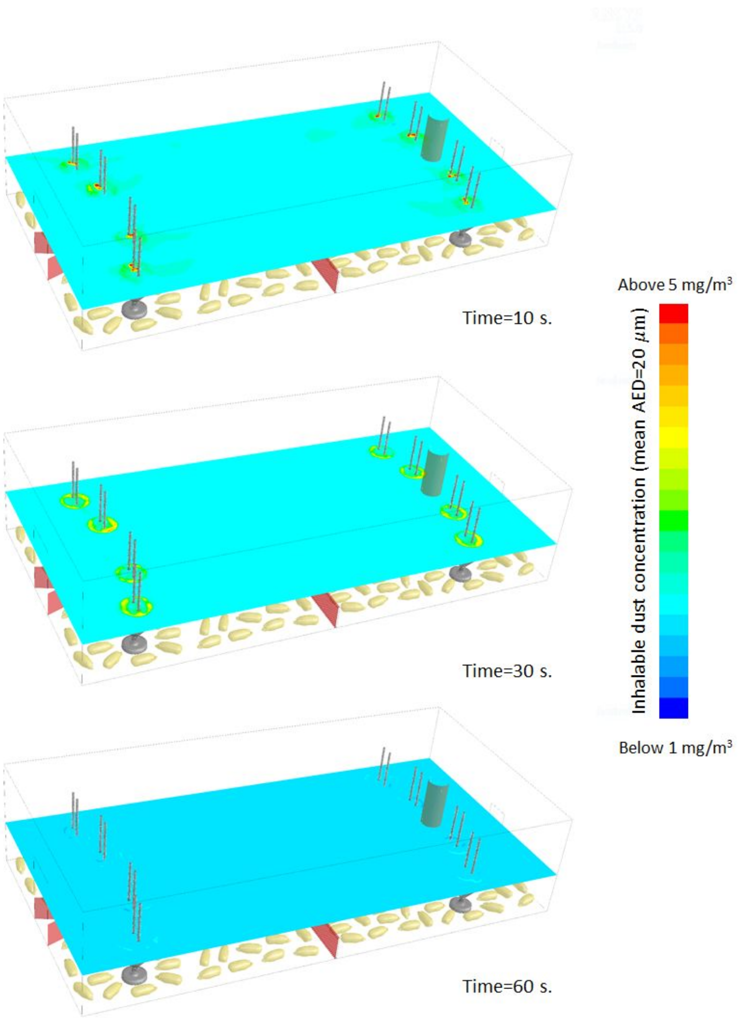


Figure 3-27 CFD-computed concentration of inhalable particulate (maenad=20 µm) according to flow-time when pipe-exhaust system was used with minimum ventilation rate (Case-2).

Although the application of the pipe-exhaust system was a conceptual case, it was concluded that the dust removal efficiency of the system was remarkably better than that of a conventional roof-exhaust ventilation system in an experimental nursery pig house. From the quantitative results, application of the pipe-exhaust system especially during periods of feeding supply might be helpful to improve the IAQ inside the facility with respect to the respiratory health of workers and animals.

The average AED of 4 µm was applied as a definition of the particulate phase for the respirable particulates in the simulation model. However, AEDs of 20, 40 and 100 μm were separately applied to define the mean AED of the inhalable particulate for analyzing the dust distribution according to the diameter of the studied dust. Tables 3-22, 3-23 and 3-24 show the CFD-computed occupational dust concentration and dust reduction efficiencies according to the measurement height when the minimum ventilation rate was used in the winter in an experimental nursery pig house. The reported values of the dust concentrations and dust reduction efficiencies were based on the results at the end of CFD calculation time (t=60 s.). The dust reduction rate was calculated based on the dust concentrations of the original case, which used the conventional roof-exhaust duct ventilation system. In comparison with the dust concentrations according to the measurement height, the larger AED particulates had the higher dust concentrations and were distributed at a lower position. For example, the average concentration of inhalable particulates which had an AED of 100 μm at a height of 0.9 m, was 23.64 mg/m^3. However, the values below 0.001 mg/m^3 were found at 1.2 and 1.5 m heights for the original case when the minimum ventilation rate was adopted in the winter. These are also found in other experimental cases. Basically, the mass of the particulates is proportional to the cube of the length of diameter, and consequently, larger particulates are more affected by gravity forces when the density of the particulates is in an identical condition. These mentioned tendencies are also coincidental with the previous observations in which particulates of 100 μm AED tend to rapidly settle out of the airspace than smaller particulates. Considering that the distribution of very low air velocities was developed in the nursery pig house AOZ due to the prevention of the chilling effect on piglets, it could be concluded that the re-suspension of particulates with 100 μm AED was practically and stochastically impossible. The moist or damp status of the slatted floor by the feces and urine might also influence the re-suspension rate of the larger particulates deposited on the ground. For the defined inhalable particulates of 40 μm AED, values of dust concentrations above 10 mg/m^3 were generally found at 0.9 m height for most experimental cases. However, very small values were found at 1.2 and 1.5 m heights. These might be caused by the discrepancies of the settlement velocities of the particulates according to the diameter sizes. With respect to the height of the average respiratory intake of the workers (1.5 m), the CFD-computed dust concentrations with defined inhalable particulates of 20 μm AED showed similar values as the field measured values. These observations indirectly implied that particulates larger than 20 μm were settled out of the airspace due to the force of gravity and settlement velocities, and the mean diameter of the dispersed inhalable particulates might be close to the defined values. The dispersed particulates might have a specific distribution such as log normal distribution or Rosin-Rammler's distribution. However, exact observations for mean diameter of the dispersed particulates in a pig house are still in question and related field observations should take precedence. From the exact observations for dust distributions according to the particulates size fractions, it will be possible to simulate more realistic dust behavior in the airspace.

In Scenario 1, the minimum ventilation rate was adopted in Case 4, which operated based on a 20% output of the roof-exhaust duct ventilation system and a 10% output of the pipe exhaust ventilation system, had superior dust reduction efficiencies (31.0% for defined inhalable particulate with 20 μm AED) at a 1.5 m height. However, Case 3, which was operated based on a 10% output of the roof-exhaust duct ventilation system and a 20% output of the pipe exhaust ventilation system, showed the highest dust reduction efficiencies of 7.3% at a 1.2 m height and 15.7% at a 0.9 m height. In contrast to the distribution of the defined inhalable particulates of 20 μm AED, increases in dust concentrations for the defined inhalable particulates of 100 μm AED were found for all experimental cases at a 0.9 m height. These inhalable particulates could be harmful to the respiratory health of animals. However, re-suspension of the deposited particulates of 100 μm AED might be practically impossible when considering the air velocity distribution and humid conditions on the slatted floors. Case 2 which only used the pipe-exhaust ventilation system with 20% output, had limited dust reduction efficiencies of 3.6% for defined inhalable particulate of 20 μm AED at a 1.5 m height, while 2.9% and 14.6% for the height of 1.2 and 0.9 m, respectively. This indicated that exclusive use of a pipe-exhaust system would have limited dust reduction efficiency, whereas the combined use of the pipe-exhaust system and the conventional roof-exhaust duct ventilation system produced a better performance. Generally, the application of a pipe-exhaust ventilation system resulted in an excellent inhalable particulate removal performance after feeding activities in terms of the concept of local ventilation.

In contrast to the reduction effect of inhalable particulates, especially for particulates with 20 μm AED conditions, there were no significant variations of the respirable particulate concentrations according to the experimental cases. Gustafsson (1997) reported similar tendencies on dust concentrations in a pig house. They mentioned that ventilation had limited effects on the number of particulates smaller than 1.0 μm. Other studies also commented that respirable particulates would be suspended in the air for longer times due to the small scale of settlement velocity. Therefore, ventilation or activities of animals have less impact on the concentration than larger particles. These correspond with the results derived from a field observation and statistical analyses in this thesis.

Table 3-22 CFD-computed occupational dust concentrations and dust reduction efficiency at 0.9 m height when the minimum ventilation rate was adopted in winter season.

Mean concentration and dust reduction effectiveness				
Height: 0.9 m	Inhalable particulate (100 μm)	Inhalable particulate (40 μm)	Inhalable particulate (20 μm)	Respirable particulate (4 μm)
Original case	- (23.81 mg/m^3)	- (16.04 mg/m^3)	- (4.62 mg/m^3)	(0.51 mg/m^3)
Case-1	-19.3% (28.40 mg/m^3)	27.4% (11.80 mg/m^3)	13.7% (3.99 mg/m^3)	-3.5% (0.52 mg/m^3)
Case-2	-24.5% (29.65 mg/m^3)	37.6% (10.00 mg/m^3)	14.6% (3.95 mg/m^3)	-5.1% (0.53 mg/m^3)
Case-3	-24.9% (29.74 mg/m^3)	37.7% (10.00 mg/m^3)	15.7% (3.90 mg/m^3)	-4.9% (0.53 mg/m^3)
Case-4	-18.4% (28.20 mg/m^3)	26.3% (11.82 mg/m^3)	12.6% (4.04 mg/m^3)	-3.6% (0.53 mg/m^3)
Case-5	0.7% (23.65 mg/m^3)	-0.8% (16.17 mg/m^3)	0.1% (4.62 mg/m^3)	0.2% (0.51 mg/m^3)

Table 3-23 CFD-computed occupational dust concentrations and dust reduction efficiency at 1.2 m height when the minimum ventilation rate was adopted in winter season.

Mean concentration and dust reduction effectiveness				
Height: 1.2 m	Inhalable particulate (100 μm)	Inhalable particulate (40 μm)	Inhalable particulate (20 μm)	Respirable particulate (4 μm)
Original case	- (0.001 mg/m^3)	- (0.001 mg/m^3)	- (2.03 mg/m^3)	- (0.51 mg/m^3)
Case-1	3.3% (0.001 mg/m^3)	-84.6% (0.003 mg/m^3)	1.7% (2.00 mg/m^3)	-0.8% (0.51 mg/m^3)
Case-2	2.5% (0.001 mg/m^3)	-103.2% (0.003 mg/m^3)	2.9% (1.97 mg/m^3)	-1.2% (0.52 mg/m^3)
Case-3	3.4% (0.001 mg/m^3)	-28.0% (0.002 mg/m^3)	7.3% (1.88 mg/m^3)	-1.3% (0.52 mg/m^3)
Case-4	4.0% (0.001 mg/m^3)	-23.4% (0.002 mg/m^3)	6.8% (1.89 mg/m^3)	-0.7% (0.51 mg/m^3)
Case-5	0.4% (0.001 mg/m^3)	30.4% (0.001 mg/m^3)	4.3% (1.94 mg/m^3)	0.1% (0.51 mg/m^3)

Table 3-24 CFD-computed occupational dust concentrations and dust reduction efficiency at 1.5 m height when the minimum ventilation rate was adopted in winter season.

Mean concentration and dust reduction effectiveness				
Height: 1.5 m	Inhalable particulate (100 μm)	Inhalable particulate (40 μm)	Inhalable particulate (20 μm)	Respirable particulate (4 μm)
Original case	- (0.001 mg/m^3)	- (0.000 mg/m^3)	- (1.41 mg/m^3)	- (0.52 mg/m^3)
Case-1	3.2% (0.001 mg/m^3)	0.5% (0.000 mg/m^3)	6.2% (1.32 mg/m^3)	-0.2% (0.52 mg/m^3)
Case-2	3.2% (0.001 mg/m^3)	3.8% (0.000 mg/m^3)	3.6% (1.36 mg/m^3)	-0.1% (0.52 mg/m^3)
Case-3	2.8% (0.001 mg/m^3)	5.9% (0.000 mg/m^3)	29.6% (0.99 mg/m^3)	-0.4% (0.52 mg/m^3)
Case-4	2.7% (0.001 mg/m^3)	-1.7% (0.000 mg/m^3)	31.0% (0.97 mg/m^3)	-0.4% (0.52 mg/m^3)
Case-5	-0.6% (0.001 mg/m^3)	-3.4% (0.000 mg/m^3)	24.8% (1.06 mg/m^3)	-0.4% (0.52 mg/m^3)

In Scenario 2 (Tables 3-25, 3-26 and 3-27), Case 4, which was operated based on a 30% output of the conventional roof-exhaust ventilation system and a 20% output of the pipe-exhaust ventilation system, produced the best dust removal efficiencies (46.2% for defined inhalable particulates of 20 μm AED at 1.5 m height, and 21.5% at 1.2 m height) than original case. In comparison to Case 6, which was operated based on the identical value of the total ventilation rate with Case 4 using the conventional roof-exhaust ventilation system, Case 4 showed more superior dust reduction efficiencies for the defined inhalable particulates of 20 μm AED at 1.2 and 1.5 m heights. As mentioned earlier with the results of Scenario 1, combined use of the pipe-exhaust system and conventional roof-exhaust duct ventilation system produced a better performance for eliminating dispersed particulates of 20 μm AED during the feeding process. Case 5 also showed superior dust removal efficiencies of 42.8% for defined inhalable particulate of 20 μm AED at a 1.5 m height, and 18.6

and 15.4% at 1.2 and 0.9 m heights, respectively. Various combinations of the ventilation system also showed limited variations in respirable particulate concentrations.

Table 3-25 CFD-computed occupational dust concentrations and dust reduction efficiency at 0.9 m height when the average ventilation rate was adopted in winter season.

Mean concentration and dust reduction effectiveness				
Height: 0.9 m	Inhalable particulate (100 μm)	Inhalable particulate (40 μm)	Inhalable particulate (20 μm)	Respirable particulate (4 μm)
Original case	- (23.64 mg/m^3)	- (16.36 mg/m^3)	- (4.01 mg/m^3)	- (0.28 mg/m^3)
Case-1	-24.4% (29.41 mg/m^3)	37% (10.31 mg/m^3)	16.9% (3.33 mg/m^3)	-3.5% (0.29 mg/m^3)
Case-2	-18.6% (28.04 mg/m^3)	26.1% (12.09 mg/m^3)	14.4% (3.43 mg/m^3)	-2.4% (0.29 mg/m^3)
Case-3	-29.6% (30.64 mg/m^3)	47.7% (8.56 mg/m^3)	20.6% (3.18 mg/m^3)	-4.5% (0.29 mg/m^3)
Case-4	-24.6% (29.46 mg/m^3)	36.7% (10.36 mg/m^3)	18.1% (3.28 mg/m^3)	-3.5% (0.29 mg/m^3)
Case-5	-19.0% (28.14 mg/m^3)	26.2% (12.07 mg/m^3)	15.4% (3.39 mg/m^3)	-2.3% (0.29 mg/m^3)
Case-6	-0.8% (23.83 mg/m^3)	1.4% (16.13 mg/m^3)	-0.1% (4.01 mg/m^3)	-0.2% (0.28 mg/m^3)

Table 3-26 CFD-computed occupational dust concentrations and dust reduction efficiency at 1.2 m height when the average ventilation rate was adopted in winter season.

Mean concentration and dust reduction effectiveness				
Height: 1.2 m	Inhalable particulate (100 μm)	Inhalable particulate (40 μm)	Inhalable particulate (20 μm)	Respirable particulate (4 μm)
Original case	- (0.001 mg/m^3)	- (0.001 mg/m^3)	(1.40 mg/m^3)	(0.28 mg/m^3)
Case-1	2.1% (0.001 mg/m^3)	-17.9% (0.001 mg/m^3)	6.4% (1.31 mg/m^3)	0.05% (0.28 mg/m^3)
Case-2	1.7% (0.001 mg/m^3)	-13.2% (0.001 mg/m^3)	4.2% (1.34 mg/m^3)	0.02% (0.28 mg/m^3)
Case-3	1.7% (0.001 mg/m^3)	0.6% (0.001 mg/m^3)	9.6% (1.26 mg/m^3)	0.06% (0.28 mg/m^3)
Case-4	2.2% (0.001 mg/m^3)	9.2% (0.001 mg/m^3)	21.5% (1.10 mg/m^3)	0.01% (0.28 mg/m^3)
Case-5	1.1% (0.001 mg/m^3)	8.6% (0.001 mg/m^3)	18.6% (1.14 mg/m^3)	0.01% (0.28 mg/m^3)
Case-6	0.1% (0.001 mg/m^3)	6.4% (0.001 mg/m^3)	13.2% (1.21 mg/m^3)	0.01% (0.28 mg/m^3)

Table 3-27 CFD-computed occupational dust concentrations and dust reduction efficiency at 1.5 m height when the average ventilation rate was adopted in winter season.

Mean concentration and dust reduction effectiveness				
Height: 1.5 m	Inhalable particulate (100 μm)	Inhalable particulate (40 μm)	Inhalable particulate (20 μm)	Respirable particulate (4 μm)
Original case	- (0.001 mg/m^3)	- (0.000 mg/m^3)	(0.57 mg/m^3)	(0.28 mg/m^3)
Case-1	6.5% (0.001 mg/m^3)	6.7% (0.000 mg/m^3)	13.8% (0.49 mg/m^3)	-0.01% (0.28 mg/m^3)
Case-2	5.1% (0.001 mg/m^3)	1.6% (0.000 mg/m^3)	10.5% (0.51 mg/m^3)	-0.01% (0.28 mg/m^3)
Case-3	4.3% (0.001 mg/m^3)	6.7% (0.000 mg/m^3)	12.2% (0.50 mg/m^3)	0.03% (0.28 mg/m^3)
Case-4	5.8% (0.001 mg/m^3)	1.4% (0.000 mg/m^3)	46.2% (0.31 mg/m^3)	-0.01% (0.28 mg/m^3)
Case-5	4.4% (0.001 mg/m^3)	0.1% (0.000 mg/m^3)	42.8% (0.33 mg/m^3)	-0.01% (0.28 mg/m^3)
Case-6	-0.3% (0.001 mg/m^3)	-3.7% (0.000 mg/m^3)	34.4% (0.37 mg/m^3)	-0.01% (0.28 mg/m^3)

3.4. Conclusions

In this chapter, long-term and intensive field observations were conducted in a commercial, mechanically ventilated nursery pig house, which are common type of facilities in South Korea. From field observations and statistical analyses for experimental nursery pig house, high dust concentrations, which exceeded the recommended occupational exposure limit of inhalable and respirable particulates with regard to the respiratory health of pig farmers, were observed during periods when feed was supplied and the animals were actively moving. These observations emphasize that pig farmers should wear personal protective equipment (e.g., a respiratory mask) when working in the facility, especially during the supply of feed.

The controlling of ventilation rate was determined to be the most significant factor for the generation of TSP and PM10. For inhalable particulates, the activity of animals, the number of animals, and the ventilation rate were influential factors, while the ventilation rate, the indoor air temperature, and activity of animals were influential factors for the variation of the respirable particulates. From the derived regression equations, a 3.1% of decrease in inhalable particulate could be estimated when additional 10% of systematic out of the ventilation was temporarily increased when pig farmers entered the room while, 8.7% of decrease for the case when 10% of rearing number was decreased. About 26.7% of decrease in respirable particulates could be estimated when additional 10% of systematic out of the ventilation was temporarily increased when P.A. level-1 while, 21.1% of increase for the case when indoor air temperature of 1 ℃ was increased. When considering the economic feasibility and thermal comfort of AOZ, controlling the number of animals and the thermal environment are not practical solutions for the reduction of dust generation. Therefore, ventilation could be the key factor for improving the IAQ of an experimental nursery pig house.

From the CFD-computed results, it was concluded that the application of the combination use of the pipe-exhaust ventilation system and conventional roof-exhaust duct system was favorable for airborne dust removal especially for defined inhalable particulate of 20 μm AED (31.0% for Scenario 1 and 46.2% for Scenario 2 in maximum), because airborne dust can be eliminated immediately after finishing the feeding activity near each feeder. Larger particulates than 20 μm AED were rapidly settled out of the airspace and deposited on the ground surfaces. However, dust control strategy for respirable particulate fraction is still in question.

Chapter 4. Identification of key factors for dust generation in boiler houses

4.1. Introduction

Intensive and long-term field measurements of airborne dust in TSP, PM10, inhalable and respirable particulate fractions were conducted in two types of commercial broiler houses for thirteen months: a mechanically ventilated broiler house and a naturally ventilated broiler house. For the comprehensive analyses, various environmental factors such as the indoor micro-climatic factors, ventilation rate, animal related factors, outdoor weather conditions and water content level of bedding materials were simultaneously investigated. The CFD technique was adopted to evaluate the ventilation rate of two broiler houses according to the ventilation operation procedure and outdoor wind conditions based on the TGD (Tracer gas decay) method. Then, the occupational exposure levels of airborne dust for farmers and animals were evaluated according to seasonal changes, rearing stages and working activities of the farmers. Statistical analyses were also carried out to understand the mechanism of, and the key factors leading to dust generation in the experimental broiler houses. A chamber experiment was also conducted to investigate the relationship between dust generation and water content levels of bedding materials. Figure 4-1 shows the overall research flow of this chapter.

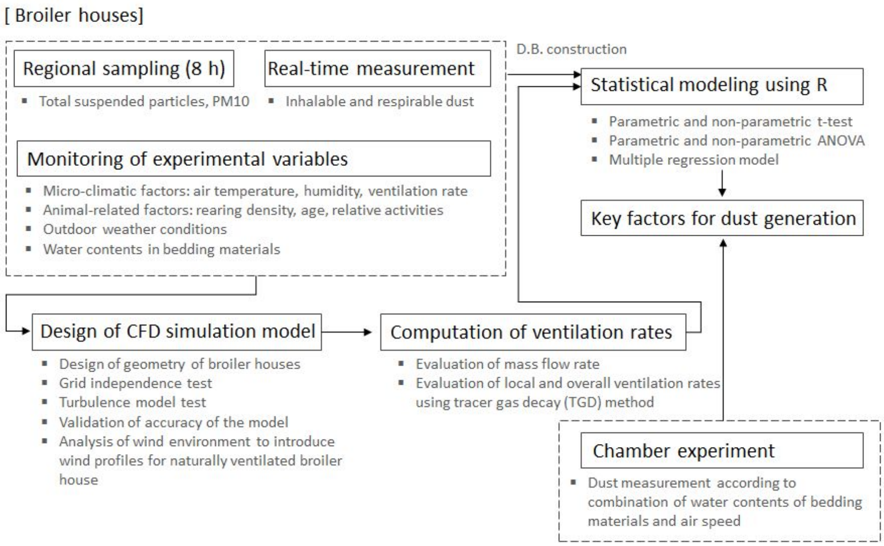


Figure 4-1 Overall research flow to find key factors for dust generation in experimental broiler houses.

4.2. Materials and methods

4.2.1. Experimental broiler houses

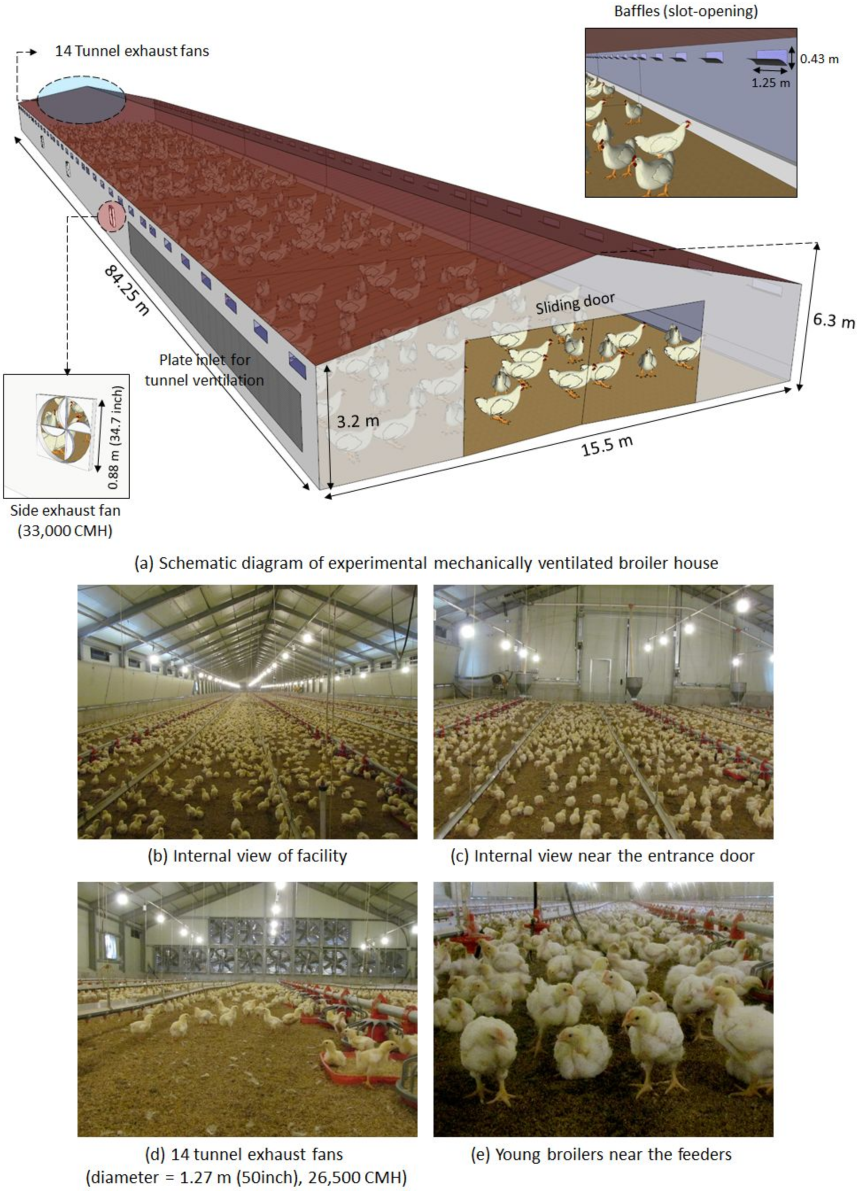
Despite the national modernizing project of the broiler facilities in South Korea, a considerable portion of the present facilities still consist of the naturally ventilated broiler house type. In this context, experimental farms located in Jeongeup City, Jeonllabuk-do Province, South Korea were selected to simultaneously investigate the dust concentrations in both mechanically and naturally ventilated broiler houses, which were popular and commercially used in South Korea (Figure 4-2). In the experimental farm, owners operated two mechanically ventilated broiler houses and one naturally ventilated broiler house.

(a) Satellite view of experimental farm

(b) View of naturally and mechanically ventilated broiler house

Figure 4-2 The experimental broiler houses located in Jeongeup city, Jeonllabuk-do province, South Korea.

The size of the mechanically ventilated broiler house (hereinafter, MV broiler house) was 15.0 m wide, 85.0 m long, 3.2 m high for the eaves and 6.3 m high for the ridge (Figure 4-3 (a)). 14 tunnel exhaust fans with a diameter of 1.27 m (26,500 CMH) and plate openings with a length of 24.45 m and a height of 1.58 m were located at both side walls near the main entrance door and were used for tunnel ventilation to effectively discharge the surplus heat inside the facility in the summer season. Meanwhile, 3 side exhaust fans with a diameter of 0.88 m (33,000 CMH) and a number of battles (slot-openings) with a length of 1.25 m and a height of 0.43 m were used for cross ventilation in the winter season. The baffles were located 2.3 m above the ground and installed at regular 2.9 m intervals along the side walls. The guide plates of the baffles for incoming outside air were automatically controlled according to the pressure difference between the outside and inside facility. 30,000 heads of broilers were raised in the facility, resulting in a 23.53 heads/m^2 rearing density. However, the actual numbers varied according to the early death of the broilers in the initial rearing stages. When the age of the broilers reached 28~29 days, the broilers were shipped to the market. In the winter season, unused tunnel fans were completely sealed off to prevent leakage of cold air into the facility. All walls consisted of sandwich panels with polyurethane treatment for insulation.



(a) Schematic diagram of experimental mechanically ventilated broiler house

(b) Internal view of facility

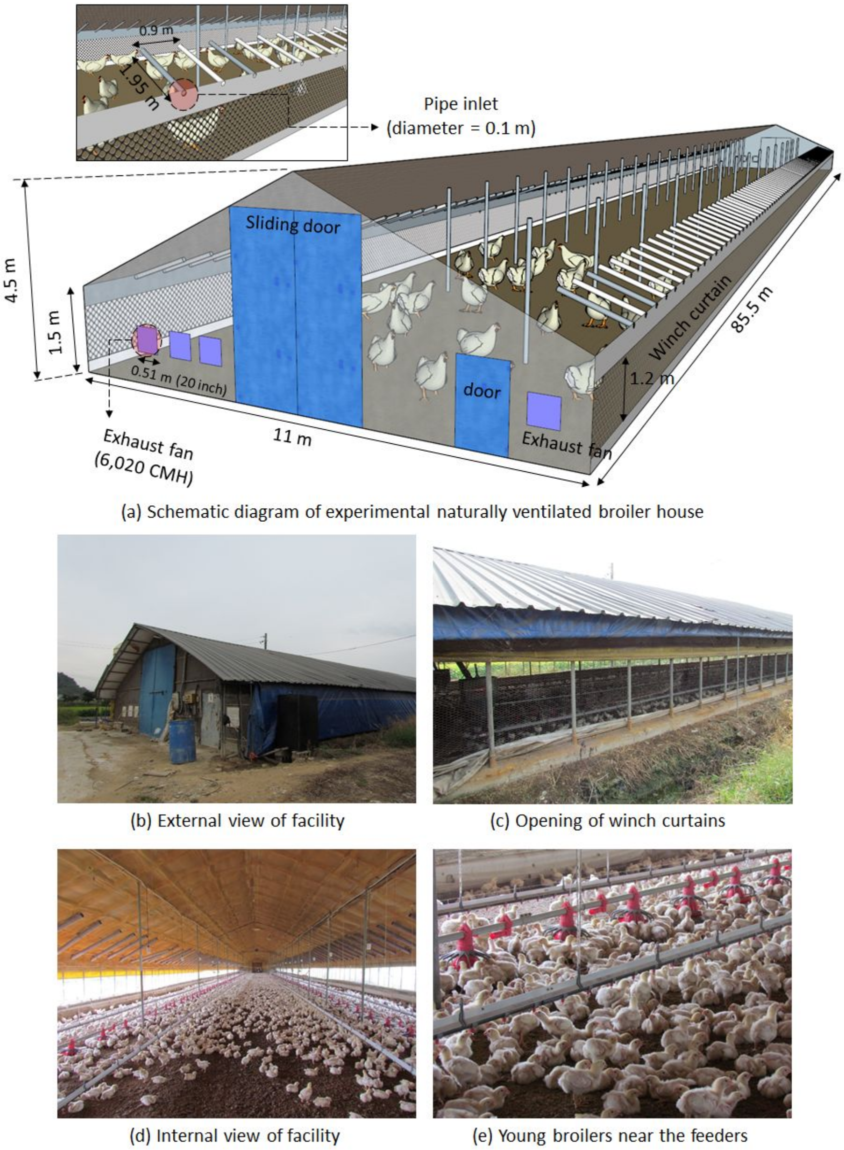
(c) Internal view near the entrance door

(d) 14 tunnel exhaust fans (diameter = 1.27 m (50inch), 26,500 CMH)

(e) Young broilers near the feeders

Figure 4-3 Schematic diagram and internal views of the experimental mechanically ventilated broiler house.

In the case of the naturally ventilated broiler house (hereinafter, NV broiler house), the facility used a combination of natural ventilation with winch curtain openings and mechanical ventilation with 8 exhaust fans during the summer season. However, mechanical ventilation using 8 exhaust fans and a number of pipe inlets, which were installed along the roof slope was adopted during the winter season and early rearing stages of the broilers (under the age of 1 week). The opening area of the winch curtains were manually adjusted by farmers according to the rearing stage of the broilers and the outdoor weather conditions. The size of the experimental NV broiler house was 11.0 m wide, 85.5 m long, 1.5 m high for the eaves and 4.5 m high for the ridge (Figure 4-4 (a)). The winch curtain openings with a length of 85.5 m and a height of 1.2 m (full-opening) were installed at both side walls for natural ventilation. The air exchange could be carried out according to the outside wind environmental conditions. 4 exhaust fans with a diameter of 0.51 m (6,020 CMH) were installed at both front and back side walls to achieve additional ventilation operation. These exhaust fans were operated by programmed on/off cycles according to the rearing stages of the broilers and outdoor weather conditions. For ventilation operation during the winter season, 90 PVC pipe inlets with a diameter of 0.1 m and a length of 1.95 m were installed along the slope beneath the roof. Fresh air could be introduced through the opening of the pipe inlet according to the negative pressure generated by the 8 exhaust fans in the winter season. 25,000 heads of broilers were raised in this facility, resulting in a 26.58 heads/m^2 rearing density, which is 1.13 times larger than those of the MV broiler house. In the winter season, winch curtain areas were fully closed and completely sealed off to prevent additional leakage of cold air into the AOZ while the openings of the pipe inlets were fully sealed off during the summer season.



(a) Schematic diagram of experimental naturally ventilated broiler house

(b) External view of facility

(c) Opening of winch curtains

(d) Internal view of facility

(e) Young broilers near the feeders

Figure 4-4 Schematic diagram and external and internal views of the experimental naturally ventilated broiler house.

Two broiler farmers were working during the experimental periods and daily foreign laborers were included when the shipment activities were carried out for mature broilers with an age of 28 days. The daily routine usually began at 6:00 am ~ 7:00 am, and finished at 8:00 pm. The main tasks of the two farmers were mainly to check the health status of the broilers (2 hours), ventilation system including exhaust fans, baffles and leakage status (30 minutes), manual controlling of the winch curtains for NV broiler house (15 minutes), and feeding management (1 hour).

4.2.2. Experimental instruments

4.2.2.1. Experimental instruments for dust monitoring

The area sampling for TSP and PM10 fractions, and real-time measurement of inhalable and respirable particulates were carried out using the same instruments that were used in dust monitoring for the nursery pig house (see Chapter 3). Details of the instruments can be found in Section 3.2.2.1.

4.2.2.2. Experimental instruments for environmental variables monitoring

Comprehensive analyses related to dust generation was conducted. Various experimental instruments for monitoring of the environmental factors were used inside the MV and NV broiler houses. T-type thermocouples and a data-logger were used to measure the internal thermal distributions of the MV and NV broiler houses. HOBO sensors were also used to measure indoor air temperature and relative humidity in the experimental space. A portable weather station was installed to monitor outdoor environmental conditions such as wind speed, wind direction, solar radiation, rainfall, air temperature, and humidity. Ventilation rates of the broiler houses were measured using an airflow meter and a manometer based on Bernoulli’s principle. A portable camera was also used to capture the status of the broilers and humans including farmers and research members in real-time during the experiment periods. Details of the instruments for monitoring environmental variables can be found in Section 3.2.2.2. A multi-channel hot-wire anemometer (Model 1560;

KANOMAX Inc., USA) was also used to measure the air velocity for an additional chamber experiment and to evaluate dust generation potentials according to the water content of the bedding materials and surrounding air velocities.

4.2.3. Computational fluid dynamics

Details in backgrounds of CFD can be found in Section 3.2.3.

4.2.4. Monitoring of airborne dust

Long-term and intensive airborne dust monitoring in the experimental broiler houses was conducted from September 2013 to September 2014 for 13 months. The experiment was regularly conducted according to the rearing stage of broilers (e.g., age of 1, 2, and 4 weeks). The mean ages of the broilers at the experiments were 8, 13.3 and 26 days (Figure 4-5). The experiments were temporarily stopped from January 2014 to May 2014 due to a nationwide outbreak of a highly pathogenic avian influenza (HPAI) in South Korea. After lifting the curfew for livestock vehicles in the country, the experiments were resumed until September 2014. The researchers and experimental instruments were thoroughly disinfected before visiting the experimental broiler houses to prevent the dispersion of the disease vector to the livestock.

(a) 1 week old (b) 2 weeks old (c) 4 weeks old

Figure 4-5 Status of broilers according to rearing stages.

The preparation of the PTFE membrane filters for area sampling of TSP and PM10 were carried out under identical experiment conditions for the nursery pig house. The filters were fully desiccated for 24 hours and pre-weighed using an electronic balance. The measured filter was then housed in a 3-stage polystyrene cassette for TSP, while sampling PM10 in a PEM. The flow rates for the sampling of TSP and PM10 were 2 and 4 l/min for 8 hours, respectively. Dust sampling instruments were installed at a height of 1.5 m above the broiler zone in consideration of the average height of the farmer's respiratory intake. 3 experimental area sampling locations were selected for each experimental broiler house (Figure 4-6). Area sampling of TSP and PM10 usually began at 9:00 am. When the sampling was finished, the used filters were inserted into a cleaned polystyrene storage cassette and completely sealed using paraffin film. Filters were completely desiccated again for 24 hours in the laboratory and then weighed to determine the particle mass based on the gravimetric method. Six blank samples were used to minimize the measurement error. Gravimetric measurement of the sampled TSP and PM10 dust concentrations were conducted in the same way as the experiments were conducted in the nursery pig house (see Section 3.2.4.).

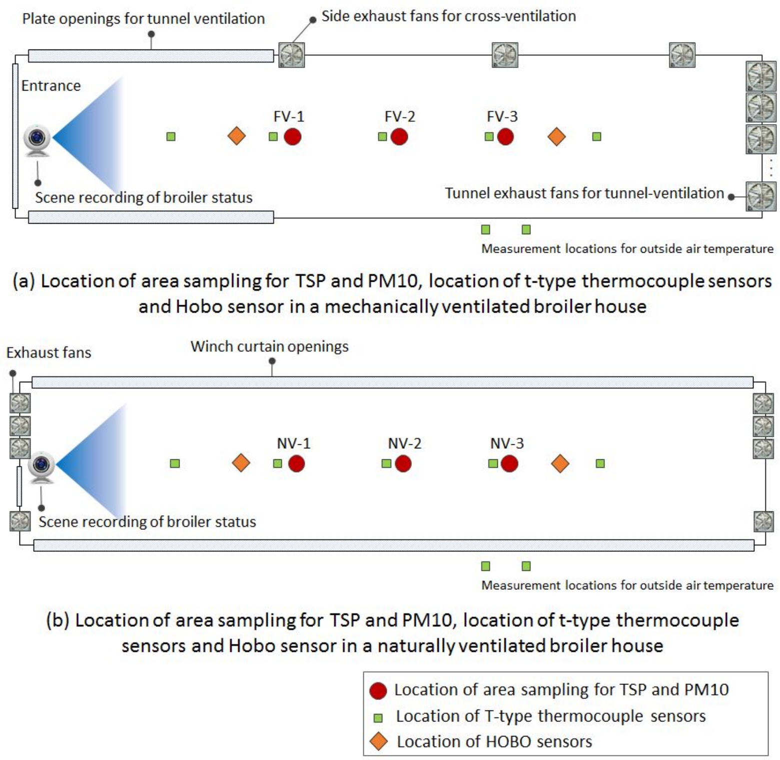
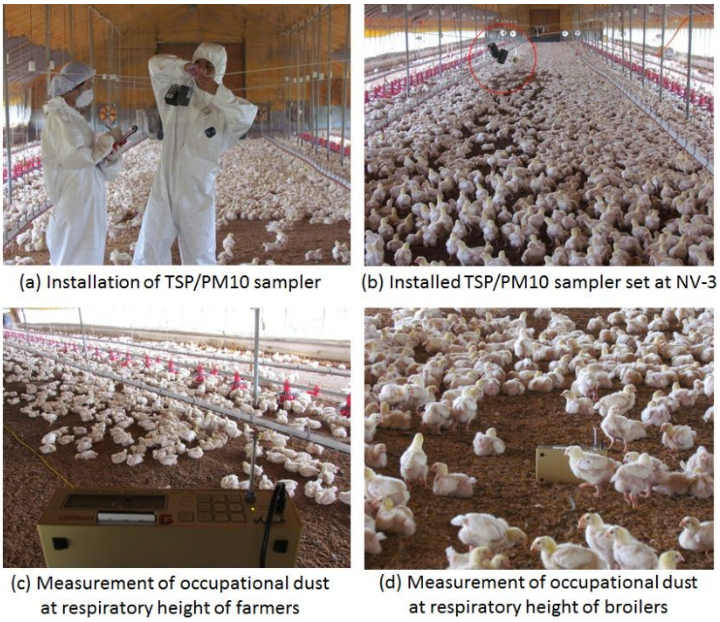


Figure 4-6 Location of area sampling for TSP and PM10, location of t-type thermocouple sensors and HOBO sensors for monitoring of micro-climatic factors.

The concentration of inhalable and respirable particulates was measured using an Aerosol spectrometer at a height of 0.2 and 1.5 m in consideration of the average respiratory height of the broilers and farmers, respectively. Measurements were conducted at the locations near the entrance and at the middle of the facility. The concentration of occupational dust was measured according to two experimental situations: when status of the broilers was very calm, which is defined as “stable” status; and when the broilers showed active and vigorous movement due to the work activity of the farmers and research team members, which is defined as “active” status. Data was continuously recorded for 5~10 minutes and saved onto a memory card at intervals of 6 seconds. Additionally, the concentrations of inhalable and the respirable particulates were also measured when shipment activities were carried out at the end of the rearing cycles for broilers.

(a) Installation of TSP/PM10 sampler
(b) Installed TSP/PM10 sampler set at FV-3
(c) Measurement of occupational dust at respiratory height of farmers
(d) Measurement of occupational dust at respiratory height of broilers

Figure 4-7 Scenes of dust monitoring in mechanically ventilated broiler house.



(a) Installation of TSP/PM10 sampler
(b) Installed TSP/PM10 sampler set at NV-3
(c) Measurement of occupational dust at respiratory height of farmers
(d) Measurement of occupational dust at respiratory height of broilers

Figure 4-8 Scenes of dust monitoring in naturally ventilated broiler house.

4.2.5. Monitoring of experimental variables

Information regarding the number of broilers and their ages was provided regularly by the farm manager through interviews during the experimental periods. 30,000 and 25,000 heads of broilers were raised in the MV and NV broiler houses, respectively, while the actual numbers varied according to the early death of the broilers in the initial rearing stages. An average of 3-5 heads of broilers died per day. However, the exact count of the dead broilers per day could not be reported by the farm manager. The variation of the rearing number of the broilers was not dramatic. Therefore, it could be concluded that the rearing number of the broilers might have had less impact on the generation of airborne dust.

Various experimental instruments were also installed inside and outside the broiler houses in order to statistically analyze the correlation between airborne dust and environmental factors. 1 data-logger and 7 T-type thermocouples were installed to gather indoor air temperature in each broiler house. Thermocouples were installed at a height of 1.5 m at regular intervals inside the experimental building, in consideration of the average height of a worker's face. Two thermocouples were located outside the building. Two HOBO sensors were also used to measure the air temperature and humidity inside each broiler house. Data was recorded and stored every 30 seconds (Figure 4-6).

A portable weather station was also installed at the roof of the broiler farmer's house to in order to record outside weather conditions, such as wind speed, wind direction, solar radiation, rainfall, air temperature, and humidity (Figure 4-9 (a)). Measured wind speed and wind direction data were also used to construct boundary conditions for the CFD simulation model in order to evaluate the ventilation rate of the target facility. The flow rate of the exhaust fans of the MV and NV broiler house was also measured by an airflow meter and a manometer. The flow rates of the exhaust fans were determined by the arithmetical mean value of 3 minutes' worth of measured data. A pressure drop according to an increase of the operating fans was also measured. A portable camera was installed near the entrance door to record the status and movement of the broilers and farmers in each broiler house. From the scene analysis, two binominal level broiler activities (i.e., stable and active) were categorized to enable specific definition of the experimental situation (Figure 4-9 (b)).

(a) Installation of portable weather station at roof of farmer's house

(b) Scene analysis to evaluate broiler activity using portable camera

Figure 4-9 Measurement of outdoor weather conditions (a) and broiler's activities according to farmer's entrance (b).

The water contents of the bedding materials were also investigated through KS F2306 test methods. The top soils of the bedding materials were collected in the pre-weighted aluminum foil bag (12 cm × 12 cm) and the sampled foil bags were weighted in the laboratory using an electronic balance. The weighted foil bags were oven-dried for 24 hours with a constant temperature of 110℃. Then, the weighing processes were repeated to measure the weight of the fully-dried samples with foil bags. Figure 4-10 shows the process of investigation of the water content of the bedding materials. The equation for calculating water contents of bedding materials based on the KS F2306 test method is discussed in the following paragraph.

$$W = \frac{m_a - m_b}{m_b - m_c} \times 100$$

Where, m_a is the mass of bedding material and aluminum foil bag (g), m_b is the mass of oven-dried bedding material and aluminum foil bag (g), m_c is the mass of aluminum foil bag (g), and W refers to water content of sampled bedding material (%).

(a) Sampling of bedding materials (b) Drying process of sampled bedding materials with foil bag (b) Gravimetric weighing process

Figure 4-10 Experimental scenes of measuring water content levels of bedding materials in both experimental broiler houses.

4.2.6. CFD analysis to evaluate ventilation rates of broiler houses

The CFD simulation models were designed to evaluate the ventilation rate of the MV and NV broiler houses in order to overcome the experimental limitations. The computational domain of the experimental broiler houses was designed using Design Modeler and ANSYS Meshing software. Physical geometries of each broiler house including exhaust fans, baffles and winch curtain openings were designed based on the field measured dimensions and information regarding the facilities. For the MV broiler house, tunnel exhaust fans, side exhaust fans, plate openings for tunnel ventilation and a number of baffles were designed in detail as shown in Figure 4-11.

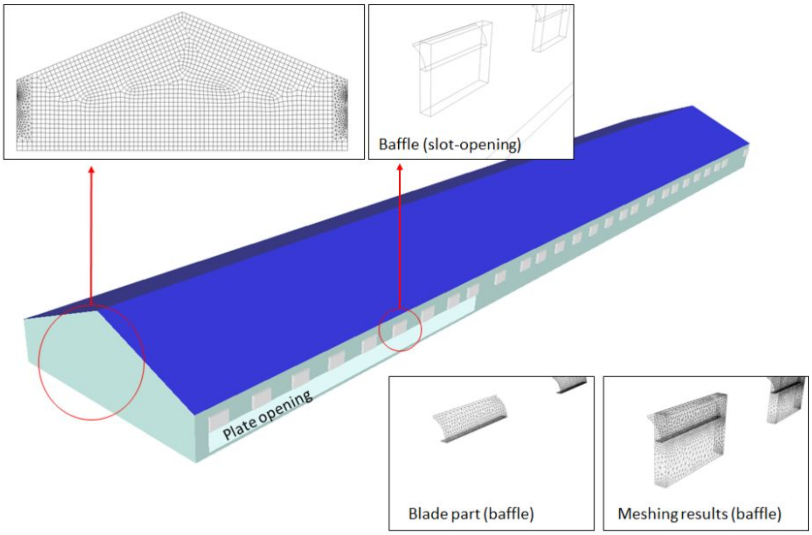


Figure 4-11 Computational domain of mechanically ventilated broiler house.

In contrast to the CFD model for the MV broiler house, design of the exterior regions is very important to accurately realize the air exchange effects according to the incoming wind profiles through the winch curtain openings of the NV broiler house. Despite the importance of a proper design of the exterior domain for the computing effects of natural ventilation, optimum design criteria for the computational domain have not yet been well established. Trials to find the proper criteria have been conducted by various researchers. However, they have suggested slightly different opinions (Bournet et al., 2007; Hefny & Ooka, 2008; Tominaga et al. 2008; Bournet & Boulard, 2010; Kim et al., in review). Kim et al. (in review) suggested the design criteria of exterior computational domain for the CFD model in order to evaluate wind pressure coefficients of multi-span greenhouse facilities. The authors investigated the effects of various conditions of domain size of upstream, downstream, and side and upper parts on the accuracies of the CFD computed solutions based on the results of wind tunnel tests. Kim et al. (in review) suggested that size of the computational domain should be bigger than 3H (H refers to height of the building) for the upstream section, 15H for the downstream section, 5H for the side and upper section of the buildings. In this context, size of the exterior computational domain of the NV broiler house was designed with the following conditions when considering the number of computational meshes, calculating time, and convergence of the numerical solution: 5H for the upstream section, 25H for the downstream section, 5H for the side section and 15H for the upper section. Figure 4-12 shows the computational domain of the NV broiler house.

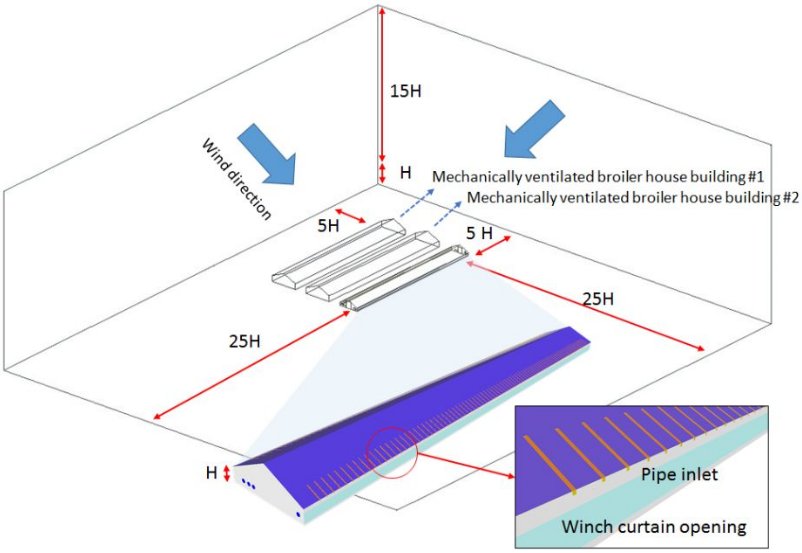


Figure 4-12 Computational domain of naturally ventilated broiler house.

Wind profiles, including profiles of vertical wind velocity, turbulent kinetic energy and turbulent energy dissipation were designed as boundary conditions of the CFD model for the NV broiler house in order to realize experimental atmospheric conditions. To design the proper wind profiles, frequency analyses of the wind environment were carried out to induce prevailing wind speed and direction of each experimental situation using the observed wind data from the portable weather station.

Each profile was designed using the following equation and applied to the boundary condition of the numerical model.

$$\mathrm{u(y)} = \frac{u_*}{\kappa}\ln\left(\frac{y+y_0}{y_0}\right), \qquad \mathrm{k(y)} = \frac{u_*^2}{\sqrt{C_\mu}}, \qquad \epsilon(\mathrm{y}) = \frac{u_*^3}{\kappa(y+y_0)}$$

Where, C_μ is dimensionless constant (0.09), $\mathrm{u(y)}$ is wind velocity profile (m/s), $\mathrm{k(y)}$ is turbulent kinetic energy (m^2/s^2), u_* is friction velocity (m/s), y is height (m), y_0 is roughness height (m), $\epsilon(\mathrm{y})$ is turbulent energy dissipation (m^2/s^3).

Computational meshes were designed with tetrahedron and hexahedron cells. For the MV broiler house when considering the mesh qualities near the geometries of the baffles, the mesh size of the vicinal area of the baffles was fixed at 0.01 m through a process of trial and error. For the remainder of the computational domain for both broiler houses, 6 different mesh sizes were tested as a grid-independence test. The tested sizes based on one side of the cell were 0.1, 0.15, 0.2, 0.3, 0.5 and 1 m. From the grid-independence test for both broiler house models, 0.2 m was chosen as the proper cell size when considering the accuracies and convergence of the numerical solutions. Details in the process of design of the CFD simulation model can be found in Park et al. (in review).

A PISO (Pressure implicit with splitting of operator) algorithm was used for pressure-velocity coupling. The RNG k-ε turbulence model was applied based on the results of Lee et al. (2007), who studied the accuracies of various turbulence models in CFD simulation for a broiler house based on the results from wind tunnel tests and particle image velocimetry (PIV) investigations. The RNG k-ε turbulence model was developed to address the deficiencies in a standard k-ε turbulence model. The RNG k-ε turbulence model shows improved performance for predicting flows with streamline curvature, such as where there are separation and recirculation airflow phenomena (Kwon et al., 2015). Time-step size was chosen to be 1 s when considering the accuracies of predicting the thermal environment and computation time following the pre-test results in the CFD model with a broiler house conducted by Kwon et al. (2015).

The concept of tracer gas decay (TGD) method was adopted to evaluate the ventilation rate of both broiler houses under actual wind environment conditions and ventilation operation strategies. The TGD method has been widely used to evaluate the overall and local ventilation rate of agricultural facilities (Kittas et al., 1995; 1996; Hong et al., 2008; Seo et al., 2009). The ventilation rate was computed through monitoring the concentration decay curve of the tracer gas in the numerical process. Based on the fundamental assumption of TGD, the inside of each broiler house was uniformly filled with tracer gas. Then, transient variation of the tracer gas concentration at each specific location was simultaneously monitored as the ventilation progressed. Evaluation of the ventilation rate by TGD could be computed by the following equation in order to solve the value of the ventilation rate at each local region inside the broiler house. An additional UDF (user-defined function) subroutine was designed and linked to the main module.

$$\mathrm{TGD} = \frac{\ln(\frac{C_0}{C_t})}{t - t_0}$$

Where, TGD is air exchange rate (number of air exchange/m), C_0 is initial concentration of tracer gas (dimensionless), C_t is concentration of tracer gas at t seconds (dimensionless), t and t_0 is a ventilation time (s).

Information of experimentally measured airflow rates of exhaust fans for MV and NV broiler houses were used as input values in order to define boundary conditions of the CFD models. The opening ratio of the winch curtains also reflected the CFD model. It was assumed that the ground was fully filled with broilers, and they emitted a heat flux according to their weights using the following equation (CIGR, 2002):

$$\Phi_{tot} = 10.62m^{0.75}$$

Where, m is body mass of broiler (kg) and Φ_{tot} is total animal heat dissipation in animal houses (W).

The initial conditions for indoor air temperature were assumed to be identical values of averaged air temperature during each experiment. The density of air was defined as incompressible ideal gas. The density of gas could be calculated as a function of surrounding pressure and air temperature. Table 4-1 shows the basic information of the CFD simulation model in order to evaluate the ventilation rate of the experimental broiler houses.

Table 4-1 Boundary conditions and numerical schemes for CFD models to evaluate ventilation rates using TGD method.

	Contents	Value
Boundary conditions of CFD model	Density of air	Incompressible ideal gas 1.255 kg/m^3 at 20℃
	Surface temperature of broiler zone	Heat flux equation in CIGR (2002)
	Surface temperature of walls (side walls, door)	Experimentally observed outdoor air temperature
	Initial air temperature inside broiler houses	Experimentally observed indoor air temperature
	Maximum cell size	0.2 m (Park et al., In review)
Numerical schemes of CFD model	Turbulence model	RNG k-ε (Lee et al., 2007)
	Pressure-velocity coupling	PISO
	Spatial discretization of momentum, volume fraction, turbulent kinetic energy, and turbulence dissipation rate	Second-order upwind
	Spatial discretization of gradient	Least squares cell-based
	Transient formulation	First order implicit

4.2.7. Statistical analyses to determine key factors in dust generation

Various statistical analyses were conducted to determine the key factors contributing to dust generation in different size fractions using the R program. Dust concentrations and experimental variables such as age of the broilers, indoor micro-climatic factors, outdoor weather conditions, activity of broilers, water content of bedding materials and CFD computed ventilation rate were simultaneously analyzed. The Shapiro-Wilk normality test was conducted to validate the normality of the residuals from the statistically derived models. Parametric ANOVA and the non-parametric Kruskall Wallis test were carried out to identify the effect of an increase in broiler's activity, seasonal change, and the rearing stages of the broilers on dust concentrations. Multiple regression analyses were also conducted to find key factors affecting variations of dust generation inside the broiler houses. Before the regression analyses, multi-collinearity tests were conducted to select proper independent variables through verification of the VIF and the correlation test.

4.2.8. Chamber experiment to investigate relationship between water contents of bedding materials and dust generation

Many studies have mentioned that bedding materials are one of the major sources of airborne dust in broiler houses. Banhazi et al. (2008) found that physical and chemical characteristics of the bedding materials could affect the concentration of airborne dust. They mentioned that 60% of the airborne dust in a layer house with deep bedding management was composed of some bedding material components. Takai et al. (1998) elucidated this phenomenon based on the characteristics of grain materials. For example, an equilibrium moisture content of feed grain was about 16% at a relative humidity of 70%. Above this moisture content, the grain particle contained condensed water on its surface, which prevented particles from becoming airborne. The relationship between relative humidity and the water content of the bedding materials seems as an effective measure for reducing the potentials of dust generation. However, there are a few present experimental investigations that aim to elucidate a relationship between the water content of the bedding materials and dust generation. Systematic experimental observations are still required. In this section, a chamber experiment was conducted to investigate the mechanisms of dust generation from the bedding materials according to the water content and surrounding air velocity conditions. The size of the experimental chamber was a diameter of 0.6 m and a height of 0.7 m, and the chamber was made with anti-static electricity treated acrylic materials. A power-controllable dust generator, which was manually designed using a small electric fan, was located in the middle of the experimental chamber. Three-levels of output could be controlled through a variable resistor. Six holes were perforated along the circumference of the cylindrical chamber at regular intervals. The holes were drilled at 0.1 m above the ground. Hot-wire anemometers were inserted into the perforated holes to measure the arithmetical mean value of surrounding air velocity inside the chamber. Bedding materials consisting of grain materials such as rice husks were collected from the experimental broiler houses. The collected materials were fully oven-dried for 24 hours in the laboratory, and then uniformly spread on the bottom of the chamber. The dispersed dust concentration inside the chamber due to the operation of the dust generator was measured using an Aerosol spectrometer at 0.5 m above the ground in real time. The experiments were repeated after uniformly increasing the water content of the bedding materials by water spray. The water content of the experimental bedding materials was evaluated through the KS F2306 test method. Figure 4-13 shows a schematic view of the chamber experiment. This chamber experiment was carried out according to the combination of four water content conditions and three air velocity conditions. Each experiment was repeated two times with identical experimental conditions.

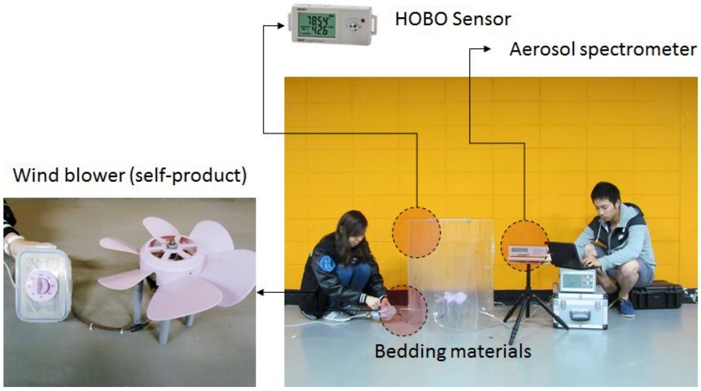


Figure 4-13 Schematic diagram of chamber experiment for measuring dust generation from bedding materials.

4.3. Results and discussions

4.3.1. Analyses of wind environment near the experiment site

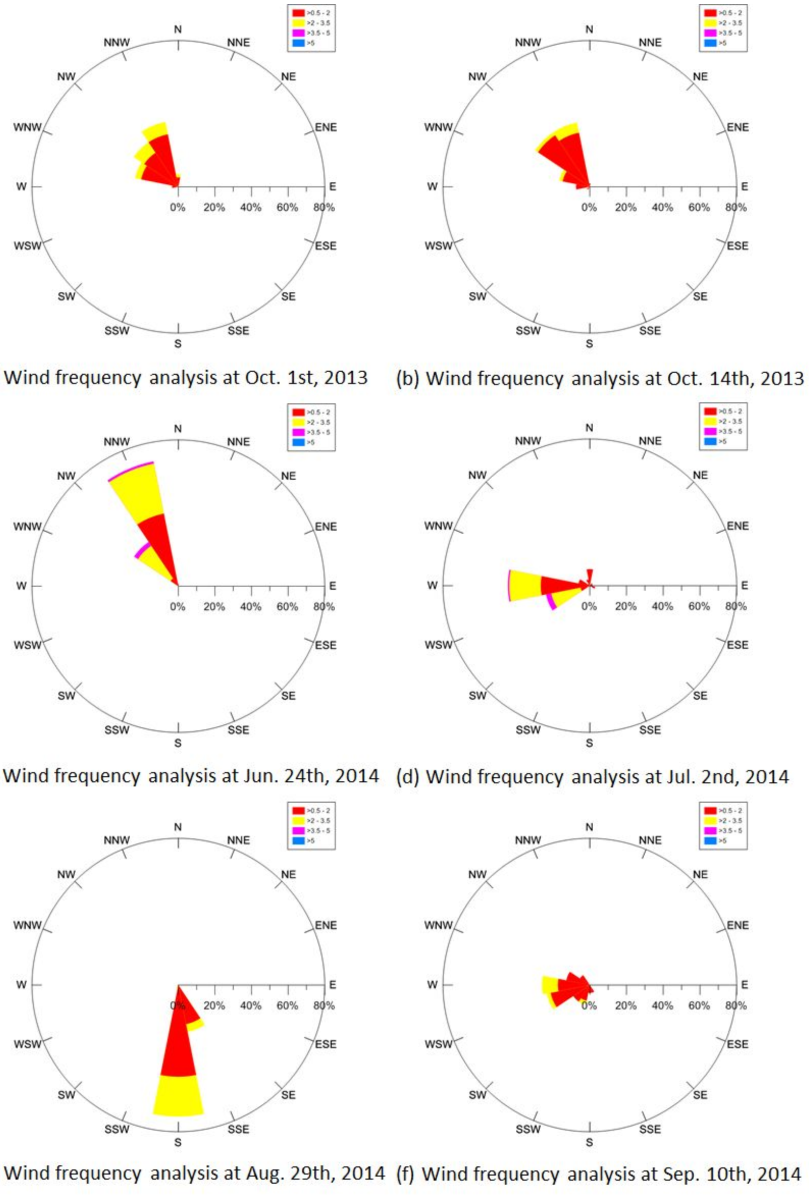
Table 4-2 and Figure 4-14 show the results of prevailing wind directions and their frequencies near the experimental broiler houses. The results were given for the experimental date when the winch curtain opening was used for natural ventilation. The winch curtain was generally opened when the broiler was at the ages of 2 and 4 weeks, except during the cold season.

Table 4-2 Prevailing wind direction from wind frequency analyses of experimental site.

Experimental date	1st prevailing wind	2nd prevailing wind	3rd prevailing wind
Oct. 1st, 2013	NNW 19.3%	NW 15.60%	WNW 12.84%
Oct. 14th, 2013	NNW 17.43%	NW 17.43%	WNW 8.26%
Jun. 24th, 2014	NNW 50.46%	NW 21.10%	N 0.917%

Jul. 2nd, 2014*	W 44.65%	WSW 24.35%	N 9.04%
Aug. 29th, 2014	S 30.28%	SSE 11.00%	SSW 0.92%
Sep. 10th, 2014	W 11.00%	WSW 10.09%	WNW 5.51%

* Data was destroyed due to spider web around portable weather station.
AWS (Automatic weather station of KMA) data of Jeongeup city was used.



(a) Wind frequency analysis at Oct. 1st, 2013 (b) Wind frequency analysis at Oct. 14th, 2013

(c) Wind frequency analysis at Jun. 24th, 2014 (d) Wind frequency analysis at Jul. 2nd, 2014

(e) Wind frequency analysis at Aug. 29th, 2014 (f) Wind frequency analysis at Sep. 10th, 2014

Figure 4-14 Results of wind frequency analysis when winch curtain opening was used for ventilation of naturally ventilated broiler house.

From the results, north-northwesterly winds were mostly prevalent during the change of seasons (i.e., autumn) (Figure 4-14 (a) and (b)) and on July 2, 2014 (Figure 4-14 (c)). The second prevailing wind direction during the mentioned experimental periods was of the north-west series. As shown in Figure 4-2, two MV broiler house buildings were the located at north-northwest area of the NV broiler house. Therefore, two buildings could be a sort of obstacle and could disturb the effective air exchange through the winch curtain openings of the NV broiler house. The deteriorated IAQ inside the broiler house could be expected due to the unfavorable supply of fresh air and removal of noxious gaseous matter such as ammonia and hydrogen sulfide from the bedding materials. Results of the prevailing wind directions for other experimental periods in Figure 4-14 also indicated that direct and indirect disturbance of effective air exchange could be expected due to the effects of turbulence dissipation and generation of the backflow around the winch curtain openings. Details of the effects of prevailing wind directions on the actual ventilation rate of the NV broiler house can be found in Park et al (in review). From the mentioned results of prevailing wind directions and wind velocities at each specific experimental date, profiles of wind velocity, turbulence kinetic energy and turbulence dissipation for the CFD simulation model were designed to calculate the ventilation rate of the target facilities.

4.3.2. Periodic monitoring of TSP and PM10

Tables 4-3 and 4-4 show the overall monitoring results of TSP and PM10 (area sampling) in the MV and NV broiler houses, respectively. Arithmetic and geometric mean values of measured dust concentrations and the proportions of PM10 to TSP are given in each table. Partial results of area sampling for PM10 were destroyed due to the condensation problems during the winter season.

Table 4-3 Overall monitoring results of TSP and PM10 in experimental mechanically ventilated broiler house (Unit: mg/m^3).

Date	Dust concentrations measured in MV broiler house						b/a (%)	
	TSP (a)			PM10 (b)			AM	GM
	n	AM±SD	GM(GSD)	n	AM±SD	GM(GSD)		
Sep.24. 2013	3	0.78±0.13	0.77(1.18)	3	0.65±0.02	0.65(1.03)	84	84
Oct. 1. 2013	3	0.60±0.08	0.60(1.14)	3	0.52±0.06	0.52(1.12)	86	87
Oct.14. 2013	3	1.94±0.06	1.94(1.03)	1	1.70	1.70	88	88
Dec. 3. 2013	3	2.19±0.23	2.18(1.11)	1	1.58	1.58	72	72
Dec.10. 2013	3	2.16±0.26	2.14(1.13)	1	1.97	1.97	91	92
Dec.20. 2013	3	3.79±0.47	3.77(1.13)	3	2.70±0.20	2.70(1.07)	71	71
Jun.17. 2014	3	0.90±0.20	0.89(1.26)	3	0.47±0.21	0.43(1.71)	52	49
Jun.24. 2014	2	0.48±0.08	0.48(1.19)	2	0.43±0.02	0.43(1.05)	89	89
Jul. 2. 2014	3	0.63±0.05	0.63(1.07)	3	0.54±0.02	0.54(1.05)	86	86
Aug.22. 2014	3	0.81±0.01	0.81(1.01)	3	0.58±0.12	0.57(1.22)	72	71
Aug.29. 2014	3	0.43±0.06	0.43(1.16)	3	0.33±0.05	0.33(1.15)	77	77
Sep.11. 2014	3	0.75±0.04	0.75(1.06)	3	0.56±0.06	0.55(1.11)	74	74

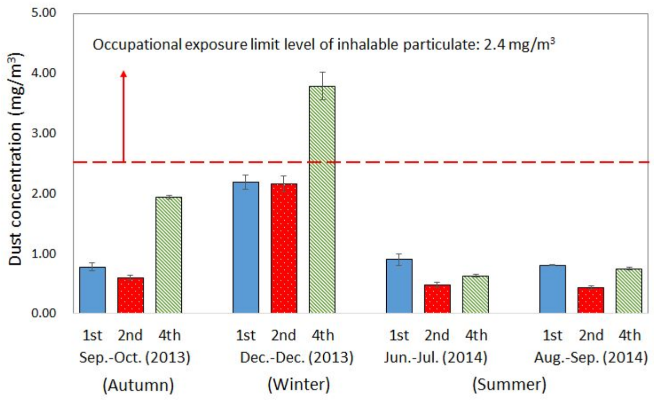
n refers to number of subjects

Table 4-4 Overall monitoring results of TSP and PM10 in experimental naturally ventilated broiler house (Unit: mg/m^3).

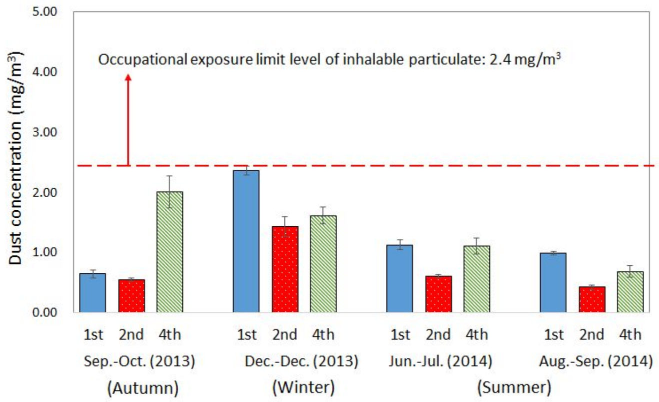
Date	Dust concentrations measured in NV broiler house						b/a (%)	
	TSP (a)			PM10 (b)			AM	GM
	n	AM±SD	GM(GSD)	n	AM±SD	GM(GSD)		
Sep.24. 2013	3	0.65±0.13	0.64(1.24)	3	0.490.03	0.49(1.05)	75	76
Oct. 1. 2013	3	0.55±0.06	0.55(1.12)	2	0.500.02	0.50(1.05)	91	91
Oct.14. 2013	3	2.01±0.54	1.97(1.30)	1	2.54	2.54	126	129
Dec. 3. 2013	3	2.37±0.15	2.37(1.07)	0	-	-	-	-
Dec.10. 2013	3	1.44±0.32	1.42(1.27)	2	0.850.04	0.85(1.05)	59	60
Dec.20. 2013	3	1.63±0.27	1.61(1.19)	0	-	-	-	-
Jun.17. 2014	3	1.08±0.08	1.08(1.08)	3	0.560.29	0.51(1.72)	51	47
Jun.24. 2014	3	0.61±0.07	0.60(1.13)	3	0.560.03	0.56(1.06)	93	93
Jul. 2. 2014	3	1.11±0.27	1.09(1.28)	3	0.770.26	0.74(1.37)	69	68
Aug.22. 2014	3	1.00±0.06	0.99(1.06)	3	0.550.08	0.55(1.15)	55	55
Aug.29. 2014	3	0.43±0.07	0.43(1.18)	3	0.340.02	0.34(1.06)	78	79
Sep.11. 2014	3	0.69±0.20	0.67(1.31)	3	0.630.16	0.62(1.26)	92	92

n refers to number of subjects

Figure 4-15 shows the results of TSP concentrations inside the MV and NV broiler houses, according to the age of the broilers (by week) and seasonal change. Table 4-5 also shows the arithmetic mean TSP concentration, their variations and proportion of TSP concentrations in the MV broiler house to those in the NV broiler house according to the seasonal changes and rearing stages. Measured mean TSP from each broiler house showed similar concentrations and tendencies except for experimental situations when the broilers were at the ages of 2 and 4 weeks in the cold season. For example, TSP concentrations from the NV broiler house with the experimental condition of age of the 4 weeks in the cold season had a considerably lower value (1.62 ± 0.27 mg/m^3) than that (3.79 ± 0.47 mg/m^3) of the MV broiler house (43%) despite the application of relatively higher rearing density. Unfortunately, there were possibilities of reliability problems for TSP and PM10 dust in the cold season due to the condensation problems on the surface of the sampling devices. Details will be presented in conclusion Section 5.4. On the other hand, mean TSP concentrations measured from the NV broiler house during the summer season generally showed higher values than those of the MV broiler house (92~176%). These differences in the dust concentrations could be elucidated by the following three reasons: unfavorable air exchange through the winch curtain openings due to the relationship between wind direction and building arrangement; increase in broiler's activities where a brighter light environment could be created due to the broad winch curtain openings and incoming sunlight; and dehumidification effects of incoming sunlight on the bedding materials in the NV broiler house. When the winch curtain openings were used, a relatively lower level of water content (62~99%) were found on the bedding materials.



(a) Measured TSP concentrations in mechanically ventilated broiler house



(b) Measured TSP concentrations in naturally ventilated broiler house

Figure 4-15 TSP concentrations according to broiler age and seasons in the mechanically ventilated broiler house (a) and naturally ventilated broiler house (b).

A number of previous studies reported that the dust concentrations of livestock houses including chicken production facilities in the cold season, were generally higher than the summer season due to the different ventilation rate applications (Gustafsson, 1997; Hinz & Linke, 1998; Takai et al., 1998). A parametric one-way ANOVA test was carried out to investigate the effects of seasonal changes on TSP concentrations. From the test, clear differences in TSP concentrations according to the seasonal change were observed (i.e., Winter>Autumn>Summer): broilers at the age of 1 week (p-value=2.06e-06), 2 weeks (p-value=5.23e-07) and 4 weeks (p-value=5.57e-08), respectively, in the MV broiler house. However, TSP concentrations according to the seasonal change in the NV broiler house were more complicated. From a parametric one-way ANOVA test, it could be concluded that the seasonal change affected the TSP dust concentrations within the NV broiler house. However, the ranks in terms of dust concentration showed different tendencies. For example, the ranks of Winter>Summer>Autumn were observed for the experimental situation with the age of 1 week (p-value=2.91e-08), Winter>Autumn ≥ Summer for 2 weeks (p-value=6.41e-09) and Autumn>Winter>Summer for 4 weeks (p-value=5.06e-03), respectively. As mentioned above, the acquired results from the experimental conditions at the age of 4 weeks in the cold season were questionable due to the observation of condensation on the surface of the devices.

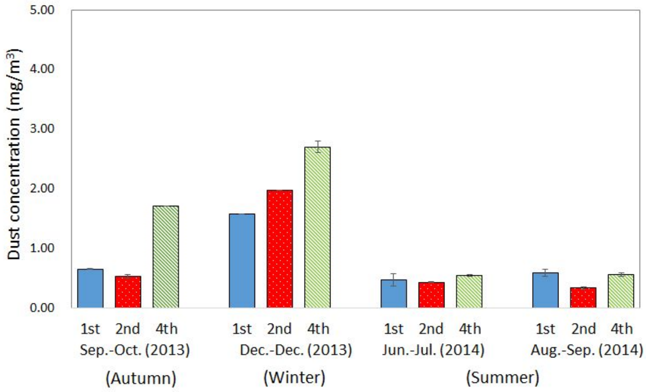
Table 4-5 Mean value of measured TSP concentrations according to age of broiler (week) and seasons in mechanically and naturally ventilated broiler house.

Season	Autumn			Winter		
Experimental date	Sep.-Oct. 2013			Dec. 2013		
Broiler age	1 week	2 weeks	4 weeks	1 week	2 weeks	4 weeks
MV*	0.78±0.13 mg/m^3	0.60±0.08 mg/m^3	1.94±0.06 mg/m^3	2.19±0.23 mg/m^3	2.16±0.26 mg/m^3	3.79±0.47 mg/m^3
NV**	0.65±0.13 mg/m^3	0.55±0.06 mg/m^3	2.01±0.54 mg/m^3	2.37±0.13 mg/m^3	1.44±0.32 mg/m^3	1.62±0.27 mg/m^3
NV/MV ratio	83.3%	91.7%	103.6%	108.2%	66.7%	42.7%
Season	Summer					
Experimental date	Jun.-Jul. 2014			Aug.-Sep. 2014		
Broiler age	1 week	2 weeks	4 weeks	1 week	2 weeks	4 weeks
MV*	0.90±0.20 mg/m^3	0.48±0.08 mg/m^3	0.63±0.05 mg/m^3	0.81±0.01 mg/m^3	0.43±0.06 mg/m^3	0.75±0.04 mg/m^3
NV**	1.13±0.16 mg/m^3	0.61±0.07 mg/m^3	1.11±0.27 mg/m^3	1.00±0.06 mg/m^3	0.43±0.07 mg/m^3	0.69±0.20 mg/m^3
NV/MV ratio	125.6%	127.1%	176.2%	123.5%	100.0%	92.0%

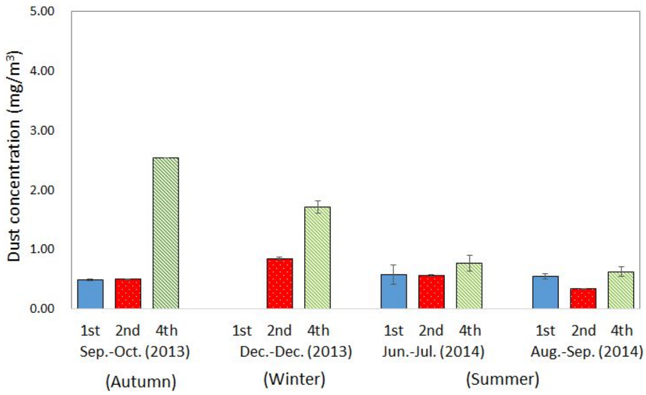
*MV refers to mechanically ventilated broiler house

**NV refers to naturally ventilated broiler house

Figure 4-16 shows the results of measured PM10 concentrations inside the MV and NV broiler houses, according to the age of the broilers (by week) and seasonal change. Mean PM10 concentrations measured from the NV broiler house during the summer season generally showed higher values than those of the MV broiler house (95~143%) (Table 4-6). These tendencies were also explained by unfavorable air exchange problems due to the wind environment, building arrangement and increase in activities of the broilers due to incoming sunlight through the broad winch curtain openings as mentioned earlier. To statistically investigate the effect of seasonal changes on the concentration of PM10, a parametric one-way ANOVA test was carried out. Clear differences in PM10 concentrations according to the seasonal change were found in the MV broiler house for all ages as presented in a number of previous studies (Winter>Autumn>Summer): 1 week (p-value=9.63e-06), 2 weeks (p-value=1.06e-06) and 4 weeks (p-value=7.77e-08). However, PM10 concentrations according to the seasonal change in the NV broiler house also displayed more complicated tendencies. In the case of the results measured from the experimental conditions with the age of 1 week broilers, the mean value of PM10 concentrations measured during the summer season was higher than that of autumn. However, the difference was not statistically clear (p-value=0.59). PM10 dust concentrations measured during the winter season were destroyed due to reliability problems. Condensation phenomena were found at surface of the PEM device and the incoming droplets through perforated holes might affect the sampling efficiency of the airborne dust. For the rest of the experimental conditions for the seasons, Winter >Autumn≥Summer were observed at the age of 2 weeks (p-value=7.09e-03) and Autumn>Winter>Summer for 4 weeks (p-value=2.78e-04), respectively.



(a) Measured PM10 concentrations in mechanically ventilated broiler house



(b) Measured PM10 concentrations in naturally ventilated broiler house

Figure 4-16 PM10 concentrations according to broiler age and seasons in the mechanically ventilated broiler house (a) and naturally ventilated broiler house (b).

Table 4-6 Mean value of measured PM10 concentrations according to age of broilers (week) and seasons in mechanically and naturally ventilated broiler house.

Season	Autumn			Winter		
Experimental date	Sep.-Oct. 2013			Dec. 2013		
Broiler age	1 week	2 weeks	4 weeks	1st week	2 weeks	4 weeks
MV*	0.65±0.02 mg/m^3	0.52±0.06 mg/m^3	1.70±0.00 mg/m^3	1.58±0.00 mg/m^3	1.97±0.00 mg/m^3	2.70±0.20 mg/m^3
NV**	0.49±0.03 mg/m^3	0.50±0.02 mg/m^3	2.54±0.00 mg/m^3	-	0.85±0.04 mg/m^3	1.72±0.20 mg/m^3
NV/MV ratio	75.4%	96.2%	149.4%	-	43.1%	63.7%
Season	Summer					
Experimental date	Jun.-Jul. 2014			Aug.-Sep. 2014		
Broiler age	1 week	2 weeks	4 weeks	1 week	2 weeks	4 weeks
MV*	0.47±0.21 mg/m^3	0.43±0.02 mg/m^3	0.54±0.02 mg/m^3	0.58±0.12 mg/m^3	0.33±0.05 mg/m^3	0.56±0.06 mg/m^3
NV**	0.58±0.32 mg/m^3	0.56±0.03 mg/m^3	0.77±0.26 mg/m^3	0.55±0.08 mg/m^3	0.34±0.02 mg/m^3	0.63±0.16 mg/m^3
NV/MV ratio	123.4%	130.2%	142.6%	94.8%	103.0%	112.5%

*MV refers to mechanically ventilated broiler house

**NV refers to naturally ventilated broiler house

From the TSP and PM10 concentrations at both broiler houses, most concentrations of airborne dust were temporarily decreased as the age of the broilers increased from 1 to 2 weeks. The highest dust concentrations were observed with broilers at the age of 4 weeks for most seasons. For example, mean TSP concentration of the MV broiler house at the age of 1 week was 1.17±0.63 mg/m^3. An 18% decrease in mean TSP concentration was observed at the age of 2 weeks (0.96±0.79 mg/m^3). However, a 152% increase was found at the age of 4 weeks (1.78±1.34 mg/m^3). The computed p-value was 0.03 ($p<0.05$) from the non-parametric one-way ANOVA using the Kruskal-Wallis test. Similarly, for the mean PM10 concentration of the MV broiler house, a decrease of 9% and an increase of 198% in the dust concentration were also observed at the experimental conditions for the ages of 2 and 4 weeks, respectively, based on the PM10 concentration of 0.66±0.35 mg/m^3 at the age of 1 week ($p<0.05$). These could be explained by the different ventilation rate applications and variable dust emission rates from the broilers according to the rearing stages. Winkel et al. (2015) introduced a regression equation to predict the PM10 emission rate from a broiler house in the Netherlands.

$$\mathrm{Y} = 0.013 \times a^{2.3855}\ (\mathrm{R}^2 = 0.89)$$

Where, a is the age of the broilers (days) and Y is the PM10 emission rate (mg/(h·animal)).

The emission rate of airborne dust from a livestock house can be usually defined as the multiplication of the concentration of airborne dust and the ventilation rate. Based on the assumption that the emission rate is generally dependent on the absolute quantities of the contaminant inside the facility (concentration), PM10 dust concentration per animal (mg/(m^3·animal)) can be derived by dividing the emission rate (mg/(h·animal)) into the ventilation rate (m^3/h) according to the dimensional analysis. In the case of ventilation management methods in a broiler house, a very little amount of ventilation rate is generally adopted for young broilers (~1 week old) to maintain a stable and proper thermal condition, and the ventilation rate is steadily increased as the broilers grows. For example, 0.034 AER/min was adopted for young broilers at the age of 11 days, 0.161 AER/min for broilers at the age of 18 days and 0.362 AER/min for broilers at the age of 26 days in the MV broiler house during the summer season (June-July, 2014). From the equation by Winkel et al. (2015) and the measured ventilation rate, the expected PM10 concentration was calculated. Table 4-7 shows the emission rate calculated by the equation, ventilation rate, and expected PM10 concentration for 30,000 broilers during the summer season.

Table 4-7 Expected PM10 concentration derived from equation of Winkel et al. (2015) and measured ventilation rate of mechanically ventilated broiler house.

Summer season (June-July 2014)				
Age of broiler	Emission rate (mg/(h·animal))	Ventilation rate (m^3/h)	Ventilation rate (AER/min)	Expected PM10 concentration (mg/m^3)
11 days	0.396	12,129.000	0.034	0.981
18 days	1.284	58,055.890	0.161	0.663
26 days	3.086	130,356.000	0.362	0.710
Summer season (August-September 2014)				
Age of broiler	Emission rate (mg/(h·animal))	Ventilation rate (m^3/h)	Ventilation rate (AER/min)	Expected PM10 concentration (mg/m^3)
7 days	0.135	5,821.920	0.016	0.695
14 days	0.705	130,356.000	0.362	0.162
27 days	3.376	304,164.000	0.845	0.333

The expected PM10 concentrations decreased as the age of the broilers increased from 1 to 2 weeks. The expected PM10 concentrations increased again as the age of broilers increased from 2 to 4 weeks. These observations could be caused by the discrepancies between the increment of the dust emission rate from the growth of broilers and dust removal abilities according to the increase of the ventilation rate. The decontamination rate of the ventilation system was more dominant than the dust emission rate for broilers at the age of 2 weeks with given environmental conditions. These derived relationships could support the tendencies of the measured TSP and PM10 concentrations according to the broiler age. Similarly, these tendencies were also found in the results of Vučemilo et al. (2008). Meanwhile, expected PM10 concentration at the age of 4 weeks had lower value than that of the experimental conditions at the age of 1 week. However, the highest dust concentrations were usually observed in the mentioned conditions. The mature broilers who have bigger bodies and more feathers generate a dustier environment. Even though Winkel et al. (2015) empirically introduced the mentioned equation from the relationship between ventilation and dust concentrations in the Netherlands, the experimental background of the study might not coincide with the situation in South Korea. Thus, the equation might not reflect all situations of the dust generation characteristics in South Korea. More consideration and related studies are needed to correct the suggested equation.

4.3.3. Periodic monitoring of inhalable and respirable particulate

Tables 4-8 and 4-9 shows the overall monitoring results of inhalable and respirable particulates in the MV and NV broiler houses, respectively according to the measurement height.

Table 4-8 Overall monitoring results of inhalable and respirable particulates according to measurement heights in experimental mechanically ventilated broiler house (Unit: mg/m^3).

Date	Height of worker's respiratory intake					
	Inhalable particulate (a)		Respirable particulate (b)		b/a (%)	
	AM±SD	GM(GSD)	AM±SD	GM(GSD)	AM	GM
Sep.24. 2013	2.36±0.61	2.28(1.29)	0.21±0.04	0.21(1.20)	9	9
Oct. 1. 2013	1.69±0.14	1.69(1.09)	0.15±0.01	0.15(1.09)	9	9
Oct.14. 2013	4.96±0.60	4.92(1.13)	0.65±0.04	0.65(1.06)	13	13
Dec. 3. 2013	4.37±0.78	4.29(1.22)	0.51±0.04	0.51(1.08)	12	12
Dec.10. 2013	2.59±0.32	2.58(1.13)	0.53±0.07	0.52(1.15)	20	20
Dec.20. 2013	3.42±0.18	3.42(1.05)	0.63±0.03	0.62(1.04)	18	18
Jun.17. 2014	0.76±0.30	0.70(1.54)	0.11±0.03	0.10(1.30)	14	15
Jun.24. 2014	1.94±0.30	1.92(1.17)	0.22±0.03	0.22(1.14)	12	12
Jul. 2. 2014	0.40±0.12	0.38(1.40)	0.11±0.01	0.11(1.11)	27	28
Aug.22. 2014	2.02±0.28	2.01(1.14)	0.34±0.02	0.33(1.06)	17	17
Aug.29. 2014	0.98±0.22	0.96(1.24)	0.12±0.01	0.12(1.13)	12	12
Sep.11. 2014	1.65±0.25	1.63(1.17)	0.15±0.03	0.15(1.20)	9	9
Date	Height of broilers					
	Inhalable particulate (a)		Respirable particulate (b)		b/a (%)	
	AM±SD	GM(GSD)	AM±SD	GM(GSD)	AM	GM
Sep.24. 2013	2.63±0.47	2.59(1.21)	0.23±0.05	0.23(1.27)	9	9
Oct. 1. 2013	2.97±1.10	2.71(1.59)	0.21±0.06	0.20(1.42)	7	7
Oct.14. 2013	7.66±1.52	7.52(1.21)	1.02±0.26	0.98(1.29)	13	13
Dec. 3. 2013	5.06±1.22	4.92(1.26)	0.60±0.04	0.60(1.06)	12	12
Dec.10. 2013	3.08±0.54	3.04(1.18)	0.51±0.10	0.50(1.22)	16	16
Dec.20. 2013	5.49±0.38	5.48(1.07)	0.80±0.03	0.80(1.03)	15	15
Jun.17. 2014	1.06±0.21	1.04(1.22)	0.13±0.01	0.13(1.11)	13	13
Jun.24. 2014	3.21±0.61	3.16(1.20)	0.31±0.02	0.31(1.08)	10	10
Jul. 2. 2014	0.64±0.11	0.63(1.19)	0.15±0.02	0.15(1.12)	23	24
Aug.22. 2014	2.80±0.68	2.72(1.28)	0.34±0.03	0.34(1.11)	12	13
Aug.29. 2014	1.34±0.19	1.33(1.15)	0.12±0.01	0.12(1.10)	9	9
Sep.11. 2014	2.70±0.99	2.53(1.43)	0.21±0.07	0.20(1.37)	8	8

Table 4-9 Overall monitoring results of inhalable and respirable particulates according to measurement heights in experimental naturally ventilated broiler house (Unit: mg/m^3).

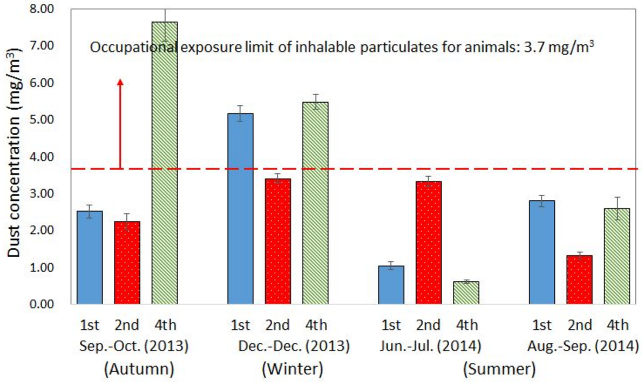
Date	Height of worker's respiratory intake					
	Inhalable particulate (a)		Respirable particulate (b)		b/a (%)	
	AM±SD	GM(GSD)	AM±SD	GM(GSD)	AM	GM
Sep.24. 2013	1.84±0.04	1.84(1.02)	0.250.00	0.25(1.02)	14	14
Oct. 1. 2013	1.11±0.06	1.11(1.06)	0.080.01	0.08(1.07)	8	8
Oct.14. 2013	8.86±1.07	8.79(1.13)	0.960.16	0.94(1.19)	11	11
Dec. 3. 2013	3.83±0.37	3.81(1.11)	0.590.05	0.59(1.10)	15	15
Dec.10. 2013	1.57±0.21	1.56(1.15)	0.330.02	0.33(1.07)	21	21
Dec.20. 2013	7.00±1.01	6.93(1.16)	0.760.04	0.76(1.05)	11	11
Jun.17. 2014	1.20±0.18	1.19(1.16)	0.150.01	0.14(1.07)	12	12
Jun.24. 2014	1.51±0.06	1.51(1.04)	0.200.00	0.20(1.02)	13	13
Jul. 2. 2014	0.48±0.12	0.47(1.29)	0.160.02	0.16(1.10)	33	34
Aug.22. 2014	1.68±0.40	1.64(1.26)	0.170.02	0.17(1.11)	10	10
Aug.29. 2014	1.88±0.65	1.80(1.33)	0.170.05	0.17(1.27)	9	9
Sep.11. 2014	1.84±0.48	1.78(1.31)	0.200.05	0.19(1.30)	11	11

Date	Height of broilers					
	Inhalable particulate (a)		Respirable particulate (b)		b/a (%)	
	AM±SD	GM(GSD)	AM±SD	GM(GSD)	AM	GM
Sep.24. 2013	3.13±0.19	3.12(1.06)	0.31±0.01	0.31(1.02)	10	10
Oct. 1. 2013	1.26±0.19	1.24(1.17)	0.10±0.01	0.10(1.14)	8	8
Oct.14. 2013	10.31±2.46	10.01(1.29)	1.11±0.32	1.06(1.38)	11	11
Dec. 3. 2013	5.52±1.92	5.21(1.42)	0.73±0.11	0.72(1.15)	13	14
Dec.10. 2013	3.48±1.05	3.28(1.44)	0.41±0.04	0.41(1.11)	12	12
Dec.20. 2013	8.16±0.84	8.11(1.11)	0.79±0.05	0.79(1.06)	10	10
Jun.17. 2014	1.32±0.15	1.32(1.11)	0.14±0.00	0.14(1.03)	11	11
Jun.24. 2014	3.38±0.96	3.24(1.34)	0.31±0.08	0.30(1.26)	9	9
Jul. 2. 2014	1.22±0.38	1.16(1.36)	0.16±0.02	0.16(1.16)	13	14
Aug.22. 2014	2.20±0.47	2.15(1.25)	0.18±0.03	0.17(1.23)	8	8
Aug.29. 2014	2.70±0.91	2.53(1.47)	0.24±0.05	0.24(1.27)	9	9
Sep.11. 2014	3.10±0.67	3.03(1.24)	0.26±0.05	0.26(1.22)	8	8

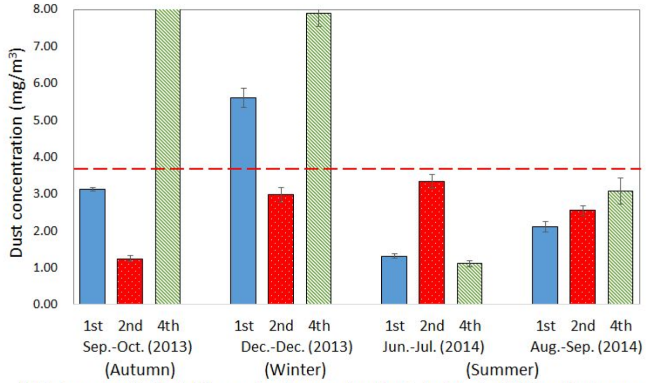
Figure 4-17 shows the inhalable particulate concentrations measured at the broiler's height in the MV and NV broiler houses. As shown in Figure 4-17 and Table 4-10, relatively higher concentrations of inhalable particulate were found in the NV broiler house than the MV broiler house. For example, in autumn, 3.13±0.19 mg/m^3 were observed at the age of 1 week in the NV broiler house, which is 119% higher than the MV broiler house (2.63±0.47 mg/m^3). A decrease in concentration of 1.26±0.19 mg/m^3 was found at the age of 2 weeks (2.97±1.10 mg/m^3, 42%), while 10.31±2.46 mg/m^3 at the age of 4 weeks (7.66±1.52 mg/m^3, 134%). These observations could be explained by the application of relatively high rearing density (113%) in the NV broiler house in comparison to the MV broiler house and the dehumidification effects of bedding materials due to excessive heating in the cold season. In interviews with the farmers, heating cost for the NV broiler house was generally 1.5~2.0 times higher than the MV broiler house. The higher cost is due to heat loss from leakage through the winch curtain openings. Heated air from kerosene heaters accelerated dehumidification of the bedding materials. Thus, dust potential from drier bedding materials could increase. Direct blowing effect and secondary turbulence effect by heaters could also produce the dispersion of the dust from animals and bedding materials. Finally, the effects of incoming sunlight in summer and the change of season, when the winch curtain openings were used, and sunlight coming through openings could desiccate the bedding materials. Therefore, an increase in dust potential could be expected as mentioned above. These mentioned facts also supported the higher observations in the NV broiler house than in the MV broiler house in the summer season (79~202%) (Table 4-10).

Parametric one-way ANOVA tests and their post-hoc tests were carried out to investigate the effect of seasonal changes on inhalable particulates measured at the broiler's height. As shown in Table 4-10, for the MV broiler house, ranks of Winter>Autumn>Summer were found for the age of 1 week (p-value=0.050), Winter>Summer ≥ Autumn for 2 weeks (p-value=0.592), and Autumn>Winter>Summer for 4 weeks (p-value=0.005). In the case of the NV broiler house, Winter>Autumn>Summer (p-value=0.164), Winter≥Summer>Autumn (p-value=0.22), and Autumn>Winter>Summer (p-value=0.003) were found for the ages of 1, 2, and 4 weeks, respectively. Inhalable particulates measured at the broiler's height showed different tendencies with previous studies according to the seasonal changes. The measurement locations were closer to the dust source, including the animals and bedding materials. Thus, discrepancies in tendencies might be estimated. However, more comprehensive approaches with various environmental factors are needed.

Partial results of the concentration of inhalable particulates usually measured during the autumn and winter seasons exceeded the recommended level for animals at 3.7 mg/m^3 (CIGR, 1994). Especially, an excess of 148 and 214% was observed with broilers at the age of 4 weeks during the winter season in the MV and NV broiler house, respectively. However, the observed data were acquired from the experimental conditions when activities of most broilers were very stable, while extremely high concentrations of airborne dust were generally found in following situations: the working activities of the farmers and the fluttering wings of the broilers. Therefore, it could be concluded that the broilers were generally exposed to an adverse environment for respiratory health and welfare.



(a) Measured inhalable particulates at broiler's height in MV broiler house



(b) Measured inhalable particulates at broiler's height in NV broiler house

Figure 4-17 Inhalable particulate concentrations measured at broiler's height in the mechanically ventilated broiler house (a) and naturally ventilated broiler house (b).

Table 4-10 Mean values of inhalable particulate concentrations measured at broiler's height in mechanically and naturally ventilated broiler houses.

Season	Autumn			Winter		
Experimental date	Sep.-Oct. 2013			Dec. 2013		
Broiler age	1 week	2 weeks	4 weeks	1st week	2 weeks	4 weeks
MV*	2.63±0.47 mg/m^3	2.97±1.10 mg/m^3	7.66±1.52 mg/m^3	5.06±1.22 mg/m^3	3.08±0.54 mg/m^3	5.49±0.38 mg/m^3
NV**	3.13±0.19 mg/m^3	1.26±0.19 mg/m^3	10.31±2.46 mg/m^3	5.52±1.92 mg/m^3	3.48±1.05 mg/m^3	8.16±0.84 mg/m^3
NV/MV ratio	119.0%	42.4%	134.6%	109.1%	113.0%	148.6%
Season	Summer					
Experimental date	Jun.-Jul. 2014			Aug.-Sep. 2014		
Broiler age	1 week	2 weeks	4 weeks	1 week	2 weeks	4 weeks
MV*	1.06±0.21 mg/m^3	3.21±0.61 mg/m^3	0.64±0.11 mg/m^3	2.80±0.68 mg/m^3	1.34±0.19 mg/m^3	2.70±0.99 mg/m^3
NV**	1.32±0.15 mg/m^3	3.38±0.96 mg/m^3	1.22±0.38 mg/m^3	2.20±0.47 mg/m^3	2.70±0.91 mg/m^3	3.10±0.67 mg/m^3
NV/MV ratio	124.5%	105.3%	190.6%	78.6%	201.5%	114.8%

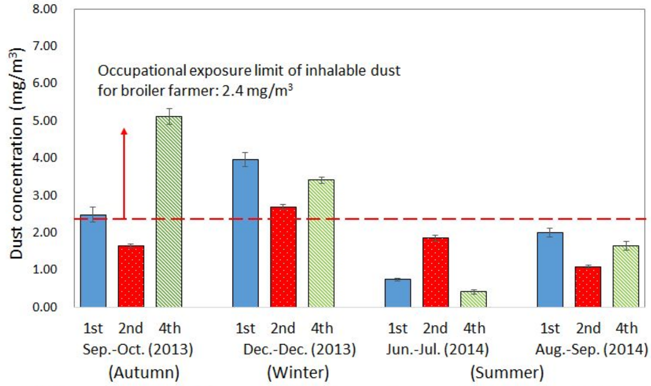
*MV refers to mechanically ventilated broiler house

**NV refers to naturally ventilated broiler house

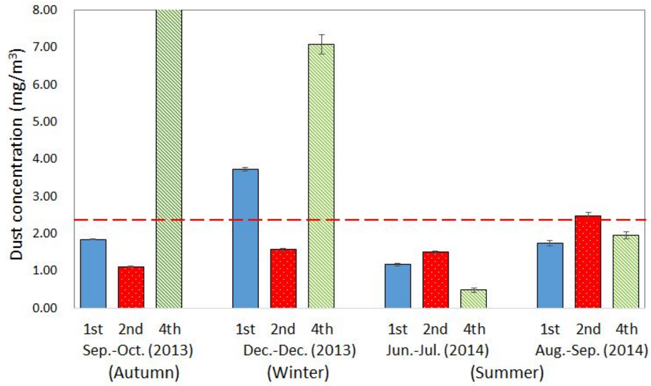
Figure 4-18 shows the results of inhalable particulates from the average height of the worker's respiratory intake in the MV and NV broiler houses, respectively. The measured results were typically lower than the broiler's height in both broiler houses: 56.9~89.7% for the MV broiler house and 39.3~90.9% for the NV broiler house. The lower values in the height of the worker's respiratory intake might be explained by the sedimentation rate of particulates with large AED due to the force of gravity. The sedimentation rate of relatively larger particles is greater. Therefore, relatively higher concentrations of inhalable particulates might be found in lower regions of the airspace. The lower values in the height of the worker's respiratory intake might be caused by the location of the dust source. From a number of previous studies, main dust sources are generally the animal, bedding materials, feces and feed particles. The effects of washing out from the ventilation system might be one of the primary reasons. Suspended dust located at a similar height to the ventilation system could be more effectively removed by the air streamline generated from the exhaust fans. More consideration using visualization experiments or aerodynamic approaches is still needed to exactly and fully understand the phenomena.

Parametric one-way ANOVA tests and their post-hoc tests were carried out to investigate the effect of seasonal changes on inhalable particulates measured at the average height of worker's respiratory intake. For the MV broiler house, the ranks of Winter>Autumn>Summer were found for the ages of 1 (p-value=0.047) and 2 weeks (p-value=0.060). However, Autumn>Winter>Summer was found for the age of 4 weeks (p-value=0.002). The experiment was carried out with broilers at the age of 22 days in winter season, while broilers at the age of 27 days for the autumn and 26 and 27 days for the summer season. Relatively small quantities of the particulates might be generated from immature broilers. It could be empirically estimated that if the winter experiment was conducted with identical conditions to the other seasons, the ranks of the concentration distribution might be Winter>Autumn>Summer as presented in other previous studies. Additional experiments should be conducted to confirm this inference.

In comparison with the occupational exposure limit of inhalable particulates with respect to the respiratory health of broiler farmers, it was noted that the partial measured concentration of inhalable particulates exceeded 2.4 mg/m^3 during the autumn and winter seasons when limited ventilation rate was adopted. Especially, most measured concentrations of inhalable particulates exceeded the recommended level in the cold season. An excess of 182, 108 and 143% were observed at the ages of 1, 2, and 4 weeks during the winter season in the MV broiler house, while an excess of 160 and 292% were observed at the ages of 1 and 4 weeks in the NV broiler house during identical periods. This meant that working activities in the facility where limited ventilation rate was used could be very harmful to the respiratory welfare of the farmers. An increase in broiler’s activity due to the worker’s action could cause a dustier environment than the mentioned results. Therefore, potential risks might be remarkably increased. Details will be presented in the following Section 4.3.4.



(a) Measured inhalable particulates at worker's height in MV broiler house



(b) Measured inhalable particulates at worker's height in NV broiler house

Figure 4-18 Inhalable particulate concentrations measured at worker's respiratory intake in the mechanically ventilated broiler house (a) and naturally ventilated broiler house (b).

Table 4-11 Mean values of inhalable particulate concentrations measured at average height of worker's respiratory intake in mechanically ventilated and naturally ventilated broiler houses.

Season	Autumn			Winter		
Experimental date	Sep.-Oct. 2013			Dec. 2013		
Broiler age	1 week	2 weeks	4 weeks	1st week	2 weeks	4 weeks
MV*	2.36±0.61 mg/m^3	1.69±0.14 mg/m^3	4.96±0.60 mg/m^3	4.37±0.78 mg/m^3	2.59±0.32 mg/m^3	3.42±0.18 mg/m^3
NV**	1.84±0.04 mg/m^3	1.11±0.06 mg/m^3	8.86±1.07 mg/m^3	3.83±0.37 mg/m^3	1.57±0.21 mg/m^3	7.00±1.01 mg/m^3
NV/MV ratio	78.0%	65.7%	178.6%	87.6%	60.6%	204.7%
Season	Summer					
Experimental date	Jun.-Jul. 2014			Aug.-Sep. 2014		
Broiler age	1 week	2 weeks	4 weeks	1 week	2 weeks	4 weeks
MV*	0.76±0.30 mg/m^3	1.94±0.30 mg/m^3	0.40±0.12 mg/m^3	2.02±0.28 mg/m^3	0.98±0.22 mg/m^3	1.65±0.25 mg/m^3
NV**	1.20±0.18 mg/m^3	1.51±0.06 mg/m^3	0.48±0.12 mg/m^3	1.68±0.40 mg/m^3	1.88±0.65 mg/m^3	1.84±0.48 mg/m^3
NV/MV ratio	157.9%	77.8%	120.0%	83.2%	191.8%	111.5%

*MV refers to mechanically ventilated broiler house

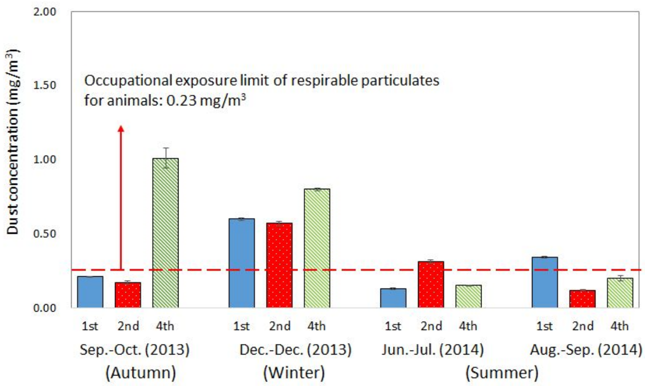
**NV refers to naturally ventilated broiler house

Figures 4-19 shows the respirable particulates measured at the broiler's height in both MV and NV broiler houses. The values acquired from the NV broiler house were higher than those from the MV broiler house during the summer season (100~200%). However, the data measured at the age of 1 week in August 2013 was 53% (Table 4-12). The discrepancies between the two broiler houses were not clear. As mentioned above, unfavorable air exchange in the NV broiler house, dehumidification effects, and increase in broiler's activity due to sunlight coming through the winch curtain openings might be primary causes for these qualitative differences during the summer season.

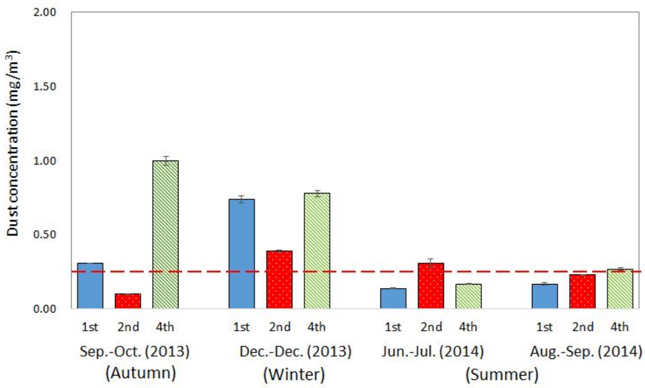
All concentrations of the respirable particulates measured during the winter season in both experimental broiler houses exceeded the occupational exposure limit for animals of 0.23 mg/m^3 (CIGR, 1994). For example, an excess of 347 and 339% was observed at the age of 4 weeks in the cold season in the MV and NV broiler houses, respectively. The limited application of ventilation could cause an increase in not only dust the concentrations but also the various pollutants (i.e., micro-organisms and gaseous matter within the facility) which were very vulnerable to the health of the animals. Decrease of productivity, symptoms of red eye and increased mortality in the winter season might be explained by these observations. An excess of the recommended level of respirable particulates for animals was also found in a few experimental conditions: situations with the age of 1 week when limited ventilation rate was adopted such as the autumn and winter seasons and with the age of 4 week broilers (mature broilers were raised) as given in Table 4-12.

Figure 4-20 shows the respirable particulate concentrations measured at an average height of the worker's respiratory intake in both experimental broiler houses. Most measured values from the NV broiler house were generally higher than those from the MV broiler house (Table 4-13). Most measured concentrations of the respirable particulates exceeded the recommended level for workers (0.16 mg/m^3)

(Donham et al., 2000). For example, excesses of 394 and 475% were observed at the age of 4 weeks in the cold season in the MV and NV broiler houses, respectively. Considering that the given measured data were acquired from the stable status of the animals, workers could easily be exposed to an extremely harmful environment to the respiratory system according to the working activities inside the facilities, especially during the winter season when a limited ventilation rate was used. Details in results will be discussed in the following Section 4.3.4.



(a) Measured respirable particulates at broiler's height in MV broiler house



(b) Measured respirable particulates at broiler's height in NV broiler house

Figure 4-19 Respirable particulate concentrations measured at broiler's height in the mechanically ventilated broiler house (a) and naturally ventilated broiler house (b).

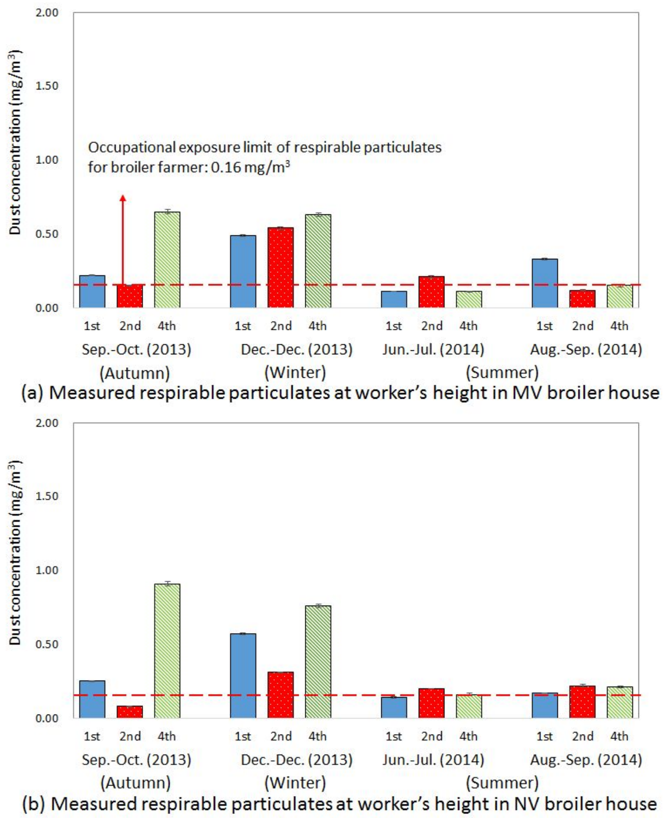


Figure 4-20 Respirable particulate concentrations measured at worker's respiratory intake in the mechanically ventilated broiler house (a) and naturally ventilated broiler house (b).

Table 4-12 Mean values of respirable particulate concentrations at broiler's height in mechanically and naturally ventilated broiler house.

Season	Autumn			Winter		
Experimental date	Sep.-Oct. 2013			Dec. 2013		
Broiler age	1 week	2 weeks	4 weeks	1st week	2 weeks	4 weeks
MV*	0.23±0.05 mg/m^3	0.21±0.06 mg/m^3	1.02±0.26 mg/m^3	0.60±0.04 mg/m^3	0.51±0.10 mg/m^3	0.80±0.03 mg/m^3
NV**	0.31±0.01 mg/m^3	0.10±0.01 mg/m^3	1.11±0.32 mg/m^3	0.73±0.11 mg/m^3	0.41±0.04 mg/m^3	0.78±0.05 mg/m^3
NV/MV ratio	134.8%	47.6%	108.8%	121.7%	80.4%	97.5%
Season	Summer					
Experimental date	Jun.-Jul. 2014			Aug.-Sep. 2014		
Broiler age	1 week	2 weeks	4 weeks	1 week	2 weeks	4 weeks
MV*	0.13±0.01 mg/m^3	0.31±0.02 mg/m^3	0.15±0.02 mg/m^3	0.34±0.03 mg/m^3	0.12±0.01 mg/m^3	0.21±0.07 mg/m^3
NV**	0.14±0.00 mg/m^3	0.31±0.08 mg/m^3	0.16±0.02 mg/m^3	0.18±0.03 mg/m^3	0.24±0.05 mg/m^3	0.26±0.05 mg/m^3
NV/MV ratio	107.7%	100.0%	106.7%	52.9%	200.0%	132.8%

*MV refers to mechanically ventilated broiler house

**NV refers to naturally ventilated broiler house

Table 4-13 Mean values of respirable particulate concentrations measured at average height of worker's respiratory intake in mechanically ventilated and naturally ventilated broiler houses.

Season	Autumn			Winter		
Experimental date	Sep.-Oct. 2013			Dec. 2013		
Broiler age	1 week	2 weeks	4 weeks	1st week	2 weeks	4 weeks
MV*	0.21±0.04 mg/m^3	0.15±0.01 mg/m^3	0.65±0.04 mg/m^3	0.51±0.04 mg/m^3	0.53±0.07 mg/m^3	0.63±0.03 mg/m^3
NV**	0.25±0.00 mg/m^3	0.08±0.01 mg/m^3	0.96±0.16 mg/m^3	0.59±0.05 mg/m^3	0.33±0.02 mg/m^3	0.76±0.04 mg/m^3
NV/MV ratio	119.0%	53.3%	147.7%	115.7%	62.3%	120.6%
Season	Summer					
Experimental date	Jun.-Jul. 2014			Aug.-Sep. 2014		
Broiler age	1 week	2 weeks	4 weeks	1 week	2 weeks	4 weeks
MV*	0.11±0.03 mg/m^3	0.22±0.03 mg/m^3	0.11±0.01 mg/m^3	0.33±0.02 mg/m^3	0.12±0.01 mg/m^3	0.15±0.03 mg/m^3
NV**	0.15±0.01 mg/m^3	0.20±0.00 mg/m^3	0.16±0.02 mg/m^3	0.17±0.02 mg/m^3	0.17±0.05 mg/m^3	0.20±0.05 mg/m^3
NV/MV ratio	136.4%	90.9%	145.5%	51.5%	141.7%	133.3%

*MV refers to mechanically ventilated broiler house

**NV refers to naturally ventilated broiler house

4.3.4. Inhalable and respirable particulate according to worker’s activities

Figures 4-21 and 4-22 show the example results of the inhalable and respirable particulate concentrations measured in December 2013 (Figure 4-21 (a) and Figure 4-22 (a)) and September 2014 (Figure 4-21 (b) and Figure 4-22 (b)) in the MV broiler house according to the measurement location and activities of the broilers. When famers entered the facility, the rapid motion of flapping wings by the herd of broilers was generally observed. Consequently, working activities of the farmers could lead to a dustier environment than in an ordinary environment or a stable status of the broilers. For example, when broilers were 22 days old in the MV facility during the winter season (Figure 4-21 (a)), 4.69 times higher concentration of inhalable particulates (mean value=24.25 mg/m^3) was found in contrast to the results with the broiler’s stable status (mean value=5.18 mg/m^3) at the broiler’s height, which is 655% more than recommended level for animals. In the case of the measurement results at the worker’s respiratory intake, 2.50 times higher value (mean value=9.87 mg/m^3) was observed. This was also 411% more than the recommended level for broiler farmers when considering respiratory health. For the results of the respirable particulates with the identical experimental conditions, relatively low rates of increment in dust concentration (2.48 and 1.90 times) were found at the measurement locations of the broiler’s and worker’s height than inhalable particulates according to the activity status of the broilers. In comparison with the recommended allowable exposure level of respirable particulates, it was noted that the measured values in December 2013 and September 2014 exceeded 0.16 mg/m^3 (582 and 328%). From the measured values of occupational dust according to the activity status of the broilers, it was obvious that the working activities of the farmers could cause adverse respiratory health conditions to both workers and animals.

The increment ratio of dust concentration according to the broiler's activity varied with the broiler's age. However, there were various factors affecting dust generation in the facility. For example, an average 121.8, 371.6 and 374.0% increases were found for inhalable particulates at the broiler's height according to the broiler's age, respectively in the change of season (autumn). Meanwhile, there was an average of 488.7, 148.2 and 193.6% increases for the winter season and 494.0, 415.2 and 1,854.2% increases for the summer season in the MV broiler house. From the non-parametric Kruskal-Wallis test, differences of the inhalable particulate concentrations measured at the broiler's height according to the animal's status were affected by the broiler's age (p-value=0.039). In the case of the worker's height, the computed p-value was 0.067. However, the increment tendencies were shown to be very complex according to the seasonal changes and broiler's age. Multiple factors, including number of broilers, water content of the bedding materials, local ventilation rate, activity level of the farmers and micro-climatic factors, could multiply the influence of the dust generation rate especially during conditions of increased broiler's activities. In my opinion, to quantitatively investigate the influence of the animal's activity on dust generation in the broiler house, experimental variables should be well controlled to restrict the random effects of the variables. A chamber experiment with limited volumes and conditions would be helpful.

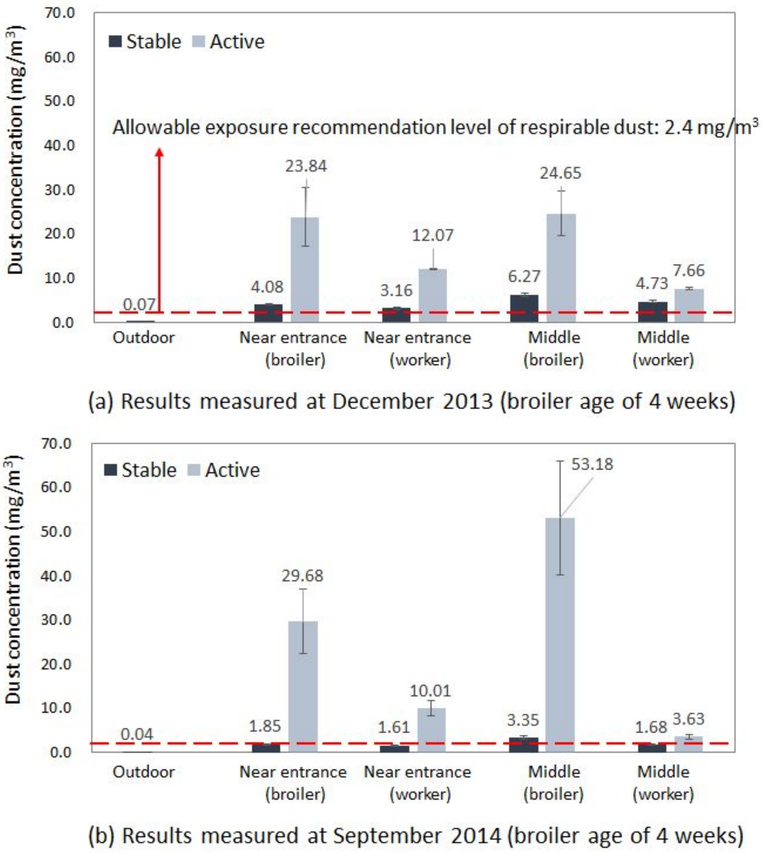


Figure 4-21 Results of inhalable particulate concentrations measured in December 2013 (a) and September 2014 (b) in MV broiler house according to increased broiler's activity.

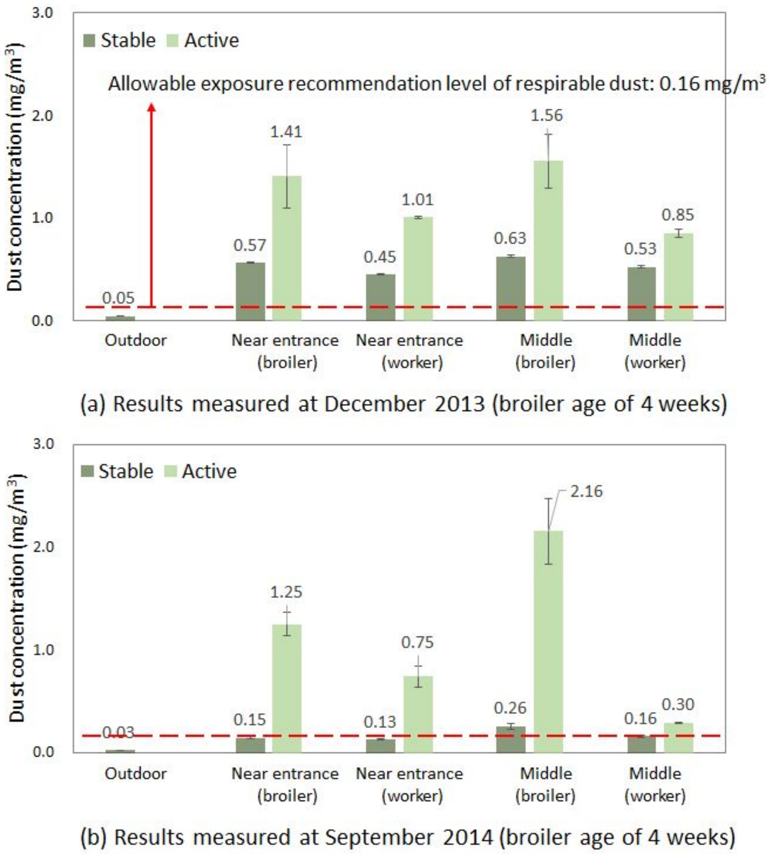


Figure 4-22 Results of respirable particulate concentrations measured in December 2013 (a) and September 2014 (b) in MV broiler house according to increased broiler's activity.

Considering all measured results with regards to the broiler's activity, it was noted that the increased activities of the broilers were statistically significant to the increase of the inhalable particulate at broiler's height (p-value=8.292e-06) and worker's height (p-value=6.192e-04), and the increase of respirable particulates at the broiler's height (p-value=3.598e-04) and worker's height (p-value=6.664e-04) in the MV broiler house. Similar results were also found in the NV broiler house. The inhalable particulates measured at the broiler's height had a p-value of 3.621e-05 ($p<0.05$) while the worker's height had a p-value of 0.002 ($p<0.05$). In the case of respirable particulates according to the broiler's activity, the computed p-values were

1.743e-04 and 0.017 ($p<0.05$) for each measurement height, respectively. All statistical analyses were carried out using the Kruskal-Wallis test. From the results, it was obvious that the work activities of farmers increased the dust generation rate in the facility and all measured values exceeded the recommended threshold levels. Before developing optimum dust control strategies in the mentioned situation, workers should wear personal protective equipment such as a respiratory mask. However, animals in the facility are still exposed to a harmful environment in regard to a healthy respiratory system. Urgent studies related to the suggestion of dust control strategies should be established.

Measurements of occupational dust during shipment working activities for mature broilers were also conducted two times: October 2013 in the NV broiler house and September 2014 in the MV broiler house. Dust concentrations were measured at two representative heights (1.5 and 1.0 m) when considering the working postures during shipment activities. 1.5 m referred to the standing posture of the workers, while 1.0 m referred to the bending posture of the workers to catch the broilers (Figure 4-23). When workers caught the broilers to load them into the truck's shipment cages, most of the broilers tried to escape quickly from the workers. A number of feathers and small particulates could be generated during these stages. Dispersed particulates could be easily seen by the naked eye. Tables 4-14 and 4-15 show the measurement results of inhalable and respirable particulates during the two shipment activities according to the measurement height.

(a) Dust measurement at 1.5 m height (b) Dust measurement at 1.0 m height

Figure 4-23 Dust measurement according to the shipment activities for mature broilers at 1.5 m height (a) and 1.0 m height considering average working height.

As shown in Tables 4-14 and 4-15, all measurement results exceeded the occupational exposure limit of both inhalable and respirable particulates for broiler farmers during shipment activities. The maximum of 36.36 mg/m^3 for inhalable particulates and 3.43 mg/m^3 for respirable particulates were instantaneously observed during the experiments. Concentrations of occupational dust acquired from the MV broilers house experiment of September 2014 were generally lower than the results from the NV broiler house experiment of October 2013. One of the possible reasons for these discrepancies might be the ventilation status during the shipment activities. In September 2014, all tunnel exhaust fans and side exhaust fans were fully operating, while all inlets, including sliding door, side plate openings, and a number of baffles were fully opened. In the case of experiments conducted in October 2013, all exhaust fans were operating and all openings including the sliding door and winch curtain openings were fully opened. However, the total systematic ventilation output of the NV broiler house was occupied only at the 9.7% level in contrast to the MV broiler house. In addition, the air exchange rate through the winch curtain openings might be unstable according to the outdoor wind environment. Therefore, effective removal of airborne dust in the NV broiler house might be relatively restricted.

From Tables 4-14 and 4-15, relatively higher dust concentrations were also found at the 1.0 m height when workers were bending their bodies to catch the broilers. Average of 4.0 and 3.4 times higher dust concentrations were measured at the lower level for inhalable and respirable particulate fractions. The relative distance of the dust source, including bedding materials and broilers, might cause these tendencies.

For the two events of the shipment activities, an average of 9 workers was included. However, only 5 workers wore a commercial yellow dust mask. Considering that an excess of 2,144% for the occupational exposure limit respirable particulates was observed in maximum, even short-term exposure to high concentration of the dust environment might increase the outbreak likelihood of respiratory diseases and other illnesses such as a cough, eye irritation, allergic reactions and asthma-like symptoms. Therefore, workers involved in shipment activities for broilers must wear personal protective equipment such as first-class respiratory masks. In addition, effective dust control strategies for shipment activities for mature broilers must be suggested as soon as possible to consider the working welfare of farmers.

Table 4-14 Measurement results of inhalable particulate concentrations according to experimental date (facility type) and measurement heights during shipment activities (Unit: mg/m^3)

Oct. 2013	Measurement heights				
	Outdoor	1.5 m	1.0 m	1.0 m	1.0 m
Max.	0.11	7.39	36.36	18.09	24.23
Min.	0.10	5.65	19.11	9.72	11.93
Mean	0.11±0.00	6.75±0.61	24.39±4.71	14.07±2.14	15.87±2.80
Sep. 2014	Measurement heights				
	Outdoor	1.5 m	1.5 m	1.5 m	1.0 m
Max.	0.07	3.69	3.87	3.45	7.28
Min.	0.06	1.75	2.15	1.23	5.97

Mean	0.07±0.00	2.82±0.54	3.16±0.49	2.41±0.83	6.40±0.34

Table 4-15 Measurement results of respirable particulate concentrations according to experimental date (facility type) and measurement heights during shipment activities (Unit: mg/m^3)

Oct. 2013	Measurement heights				
	Outdoor	1.5 m	1.0 m	1.0 m	1.0 m
Max.	0.08	0.88	3.43	1.64	2.51
Min.	0.07	0.75	1.91	0.93	1.34
Mean	0.07±0.00	0.82±0.04	2.53±0.38	1.29±0.19	1.82±0.35
Sep. 2014	Measurement heights				
	Outdoor	1.5 m	1.5 m	1.5 m	1.0 m
Max.	0.06	0.28	0.27	0.25	0.67
Min.	0.06	0.18	0.19	0.17	0.32
Mean	0.06±0.00	0.56±0.07	0.25±0.03	0.22±0.02	0.56±0.07

4.3.5. CFD-computed ventilation rate of experimental broiler houses

Table 4-16 and 4-17 show the results of the CFD-computed ventilation rates based on the TGD method in the MV and NV broiler houses, respectively. 2.6~6.9 times higher ventilation rate (AER/min) was applied to the NV broiler house in contrast to the ventilation rate application for the MV broiler house except for the last 4 experimental cases. Most of the prevailing wind conditions near the experimental farm were from the north wind series (north-northwest, north-west, and north-northeast). Therefore, unfavorable air exchange in the NV facility was predicted when considering the orientation of the building and direction of the prevailing wind. However, the CFD computed ventilation rate showed the opposite aspect for the given initial and boundary conditions. From the interviews with a consultant of the experimental farm who had managed the broiler yields and internal environment since June 2014, the broiler farmer manually and empirically set up excessive ventilation rates for the NV broiler house in order to eliminate abnormal indoor gas concentrations according to the insufficient air exchange. The excessive heating cost for the NV broiler house in the cold season in spite of the smaller volume size (about 45% more than the MV broiler house) and the number of broiler's heads could be explained by the ventilation operation status in these periods. After managing the ventilation rate for the NV facility by the consultant himself, the discrepancies of the CFD computed ventilation rate between the two facilities were not significant (1.1~1.2 times higher than the MV broiler house). However, one specific experimental situation in August 2014 was significant when the broilers were at the age of 2 weeks in the summer season. The 71% level of ventilation rate in the MV broiler house was calculated for the NV broiler house. At that time, the prevailing wind direction was the south-series. This direction was almost perpendicular to the longitudinal ways of the NV broiler house. However, ineffective air exchange was observed due to the arrangement of the MV broiler house at the leeward side. The pressure distribution at the leeward side affected the overall air exchange rate between the indoor and outdoor environments through the winch curtain openings. Related CFD computed air velocity and pressure distribution inside and outside of the NV broiler house is available in Park et al. (in review).

From the CFD computed ventilation rate in both experimental broiler houses, relatively low values of dust concentration might be predicted in the NV broiler house due to the excessive application of the ventilation rate by the broiler farmer. However, the measured dust concentrations especially in the cold season did not support conventional views on the relationship between ventilation rate and dust concentration. As mentioned earlier, excessive operating of kerosene heaters (1.5~2.0 times) in the NV broiler house might accelerate the effects of dehumidification on the bedding materials, and thus, dust potential could be increased in spite of the better performance of dust removal in the airspace. That is, it could be concluded that a single correlation between the dust level and environmental factors are restricted for understanding and explaining the whole phenomena related to dust concentration in the facility.

Table 4-16 CFD computed ventilation rate based on TGD method in mechanically ventilated broiler house according to experimental date and broiler's age.

	Ventilation rate (AER/min, m^3/h)		
Experimental date	Age of 1week	Age of 2 weeks	Age of 4 weeks
Sep.-Oct. 2013	0.015 (5,582.62 m^3/h)	0.051 (18,980.9 m^3/h)	0.070 (24,220.76 m^3/h)
Dec.-Dec. 2013	0.015 (5582.62 m^3/h)	0.035 (13,026.11 m^3/h)	0.041 (15,259.16 m^3/h)
Jun.-Jul. 2014	0.021 (7815.67 m^3/h)	0.110 (40,875.31 m^3/h)	1.000 (371,729.00 m^3/h)
Aug.-Sep.2014	0.160 (60,025.75 m^3/h)	0.960 (357,898.3 m^3/h)	1.830 (680,924.9 m^3/h)

Table 4-17 CFD computed ventilation rate based on TGD method in naturally ventilated broiler house according to experimental date and broiler's age.

	Ventilation rate (AER/min, m^3/h)		
Experimental date	Age of 1week	Age of 2 weeks	Age of 4 weeks
Sep.-Oct. 2013	0.091 (15,427.39 m^3/h)	0.268 (45,393.35 m^3/h)	0.428 (72,420.53 m^3/h)
Dec.-Dec. 2013	0.055 (9,283.97 m^3/h)	0.089 (15,129.98 m^3/h)	0.113 (19,205.31 m^3/h)
Jun.-Jul. 2014	0.145 (24,597.10 m^3/h)	0.470 (79,596.51 m^3/h)	1.165 (197,217.33 m^3/h)
Aug.-Sep.2014	0.169 (28,579.18 m^3/h)	0.684 (115,817.1 m^3/h)	1.929 (356,559.59 m^3/h)

4.3.6. Multiple regression analysis of measured inhalable and respirable particulate

Multiple regression analyses were also conducted on the basis of the measured occupational dust concentration, including inhalable and respirable particulates in the experimental MV and NV broiler houses. Multiple regression analyses for TSP and PM10 were not carried out when considering the partial missing values in the cold season due to the condensation problems of the measurement devices. To identify the independence among the experimental variables, a correlation test before selecting the proper variables for regression analysis and multi-collinearity as a test using VIF as a post hoc test were carried out. Tables 4-18 and 4-19 show the results of computed correlation coefficients among inhalable and respirable concentrations according to the measurement height and environmental variables in the MV and NV broiler houses, respectively. For the MV broiler house as given Table 4-18, the measured concentrations of inhalable and respirable particulates at the broiler's height showed reverse linear trends to the outdoor air temperature (R=-0.72, -0.83), outdoor absolute humidity level (R=-0.65, -0.74), indoor air temperature (R=-0.54, -0.66) and indoor absolute humidity level (R=-0.49, -0.44). Similar reverse linear trends to the mentioned variables were also found for inhalable and respirable particulate concentrations measured at the worker's respiratory intake. A number of previous studies have noted that the level of contaminants inside the livestock house generally and positively correlated with the indoor air temperature. However, dust measurements were periodically carried out for 13 months according to the rearing stage of the broiler, proper air temperature for the AOZ steadily decreased as the broilers grew, while ventilation rate was increased to remove surplus heat inside the facility. If the observations were conducted in a controlled environment situation, the level of airborne dust might be increased due to the buoyancy effects. However, opposite tendencies were found according to the time-serial changes in the indoor micro-climatic factors. The CFD computed ventilation rate also showed reverse linear trends to the dust concentration at each fraction and each measurement height.

However, correlation coefficient values were below -0.50 (0.39~ -0.48). Among the variables, weight of broilers was strongly and obviously correlated with the age of the broilers (R=0.99) and outdoor air temperature was also positively related with the outdoor absolute humidity level (R=0.92). In contrast to the conventional views on the relationship between the water content level of bedding materials and inhalable particulate concentrations, the water content levels did not statistically correlate with the occupational dust concentrations in the given data. Results of the correlation analysis between occupational dust concentrations and environmental variables according to the rearing stage of the broilers are given in Tables 4-20 (1 week), 4-21 (2 weeks) and 4-22 (4 weeks) for the MV broiler house, respectively. For the broilers whose ages were 1 and 2 weeks (Tables 4-20 and 4-21), the water content level showed the usual reverse linear relationship to the inhalable particulates measured at the broiler's height (R=-0.90 for 1 week old and -0.71 for 2 weeks old) and at the worker's height (R=-0.95, -0.95), and respirable particulates measured at the broiler's height (R=-0.81, -0.89) and worker's height (R=-0.78, -0.91) as reported in previous studies. However, these tendencies were reversed in the experimental conditions with broilers at the age of 4 weeks as shown in Table 4-22. All of the correlation coefficients for the relationship between the water content level and measured occupational dust in the given conditions were in the range of 0.60~0.77. When I consider all of the reported water content level results of the correlation coefficients, conventional views on the relationship between water content level and dust concentration were satisfactory for 1 and 2 weeks old broilers. However, the results were controversial for the mature broilers. These observations were also found for the results of the NV broiler house as shown in Tables 4-19 (all periods), 4-23 (1 week), 4-24 (2 weeks) and 4-25 (4 weeks). However, the correlation coefficients showed a somewhat different aspect with the broilers at the age of 2 weeks. In my opinion, the increase in feathers according to the growth of the broilers might cause a disturbance in the usual patterns of dust generation. The motion of flapping wings of mature broilers generated a considerable amount of airborne dust into the airspace, which might explain a number of failed cases of dust control techniques using a water spray in the broiler houses. Finding the critical point (inflection point) where the dust control strategy is still effective with respect to managing the water content level of the bedding materials according to the growth stage of the broilers could be a noteworthy research subject.

Table 4-18 Computed correlation coefficients among inhalable and respirable particulate concentrations according to the measurement heights and environmental variables in the mechanically ventilated broiler house.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Age of broilers (1)	1.00											
Weight of broilers (2)	0.99	1.00										
Ventilation rate (3)	0.52	0.53	1.00									
Outdoor air temperature (4)	-0.10	-0.12	0.41	1.00								
Outdoor absolute humidity (5)	-0.19	-0.21	0.11	0.92	1.00							
Indoor air temperature (6)	-0.75	-0.72	0.03	0.63	0.53	1.00						
Indoor absolute humidity (7)	-0.38	-0.42	-0.34	0.46	0.71	0.33	1.00					
Water content level (8)	0.71	0.66	0.14	0.06	0.09	-0.63	-0.01	1.00				
Inhalable particulate at broiler height (9)	0.21	0.26	-0.39	-0.72	-0.65	-0.54	-0.49	0.26	1.00			
Inhalable particulate at worker’s height (10)	0.05	0.11	-0.44	-0.73	-0.64	-0.42	-0.41	0.12	0.97	1.00		
Respirable particulate at broiler height (11)	0.25	0.29	-0.42	-0.83	-0.74	-0.66	-0.44	0.29	0.96	0.92	1.00	
Respirable particulate at worker’s height (12)	0.10	0.14	-0.48	-0.89	-0.80	-0.58	-0.39	0.12	0.90	0.89	0.97	1.00

Table 4-19 Computed correlation coefficients among inhalable and respirable particulate concentrations according to the measurement heights and environmental variables in the naturally ventilated broiler house.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Age of broilers (1)	1.00											
Weight of broilers (2)	0.99	1.00										
Ventilation rate (3)	0.66	0.67	1.00									
Outdoor air temperature (4)	-0.10	-0.12	0.40	1.00								
Outdoor absolute humidity (5)	-0.19	-0.21	0.12	0.92	1.00							
Indoor air temperature (6)	-0.67	-0.69	-0.06	0.57	0.45	1.00						
Indoor absolute humidity (7)	-0.36	-0.40	-0.36	0.19	0.41	0.30	1.00					
Water content level (8)	0.63	0.59	0.15	-0.11	-0.02	-0.64	-0.07	1.00				
Inhalable particulate at broiler height (9)	0.35	0.40	-0.20	-0.72	-0.64	-0.70	-0.46	0.40	1.00			
Inhalable particulate at worker's height (10)	0.39	0.43	-0.19	-0.67	-0.57	-0.74	-0.42	0.55	0.97	1.00		
Respirable particulate at broiler height (11)	0.50	0.56	0.71	-0.07	-0.32	-0.21	-0.52	0.24	0.34	0.34	1.00	
Respirable particulate at worker's height (12)	0.36	0.44	-0.06	-0.64	-0.60	-0.64	-0.44	0.38	0.89	0.90	0.48	1.00

Table 4-20 Computed correlation coefficients among inhalable and respirable particulate concentrations according to the measurement heights and environmental variables in the mechanically ventilated broiler house at the broiler's age of 1 week.

	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Ventilation rate (3)	1.00									
Outdoor air temperature (4)	0.58	1.00								
Outdoor absolute humidity (5)	0.39	0.97	1.00							
Indoor air temperature (6)	0.67	-0.06	-0.18	1.00						
Indoor absolute humidity (7)	0.27	0.93	0.99	-0.25	1.00					
Water content level (8)	0.47	0.91	0.84	-0.32	0.80	1.00				
Inhalable particulate at broiler height (9)	-0.06	-0.80	-0.84	0.64	-0.84	-0.90	1.00			
Inhalable particulate at worker's height (10)	-0.18	-0.78	-0.76	0.60	-0.74	-0.95	0.97	1.00		
Respirable particulate at broiler height (11)	0.05	-0.78	-0.86	0.65	-0.89	-0.81	0.98	0.89	1.00	
Respirable particulate at worker's height (12)	0.16	-0.69	-0.78	0.75	-0.82	-0.78	0.97	0.90	0.99	1.00

Table 4-21 Computed correlation coefficients among inhalable and respirable particulate concentrations according to the measurement heights and environmental variables in the mechanically ventilated broiler house at the broiler's age of 2 week.

	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Ventilation rate (3)	1.00									
Outdoor air temperature (4)	0.43	1.00								
Outdoor absolute humidity (5)	0.25	0.97	1.00							
Indoor air temperature (6)	0.14	0.88	0.97	1.00						
Indoor absolute humidity (7)	-0.76	-0.27	-0.02	0.20	1.00					
Water content level (8)	0.74	0.91	0.79	0.64	-0.62	1.00				
Inhalable particulate at broiler height (9)	-0.83	-0.58	-0.54	-0.53	0.29	-0.71	1.00			
Inhalable particulate at worker's height (10)	-0.76	-0.89	-0.82	-0.74	0.43	-0.95	0.87	1.00		
Respirable particulate at broiler height (11)	-0.60	-0.92	-0.91	-0.87	0.22	-0.89	0.84	0.97	1.00	
Respirable particulate at worker's height (12)	-0.53	-0.98	-0.96	-0.90	0.23	-0.91	0.73	0.95	0.98	1.00

Table 4-22 Computed correlation coefficients among inhalable and respirable particulate concentrations according to the measurement heights and environmental variables in the mechanically ventilated broiler house at the broiler's age of 4 week.

	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Ventilation rate (3)	1.00									
Outdoor air temperature (4)	0.85	1.00								
Outdoor absolute humidity (5)	0.61	0.93	1.00							
Indoor air temperature (6)	0.98	0.94	0.76	1.00						
Indoor absolute humidity (7)	-0.20	0.30	0.62	0.00	1.00					
Water content level (8)	-0.58	-0.26	-0.09	-0.49	0.21	1.00				
Inhalable particulate at broiler height (9)	-0.74	-0.77	-0.73	-0.79	-0.35	0.74	1.00			
Inhalable particulate at worker's height (10)	-0.73	-0.74	-0.69	-0.77	-0.32	0.77	0.99	1.00		
Respirable particulate at broiler height (11)	-0.87	-0.84	-0.73	-0.90	-0.18	0.74	0.98	0.97	1.00	
Respirable particulate at worker's height (12)	-0.89	-0.92	-0.83	-0.94	-0.23	0.60	0.94	0.93	0.98	1.00

Table 4-23 Computed correlation coefficients among inhalable and respirable particulate concentrations according to the measurement heights and environmental variables in the naturally ventilated broiler house at the broiler's age of 1 week.

	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Ventilation rate (3)	1.00									
Outdoor air temperature (4)	0.87	1.00								
Outdoor absolute humidity (5)	0.74	0.97	1.00							
Indoor air temperature (6)	0.63	0.38	0.16	1.00						
Indoor absolute humidity (7)	0.74	0.97	0.99	0.20	1.00					
Water content level (8)	0.90	0.99	0.96	0.35	0.96	1.00				
Inhalable particulate at broiler height (9)	-0.89	-0.90	-0.87	-0.21	-0.84	-0.94	1.00			
Inhalable particulate at worker's height (10)	-0.79	-0.91	-0.93	-0.05	-0.91	-0.94	0.97	1.00		
Respirable particulate at broiler height (11)	-0.35	-0.52	-0.64	0.51	-0.59	-0.58	0.73	0.81	1.00	
Respirable particulate at worker's height (12)	-0.34	-0.53	-0.66	0.52	-0.61	-0.59	0.72	0.82	0.99	1.00

Table 4-24 Computed correlation coefficients among inhalable and respirable particulate concentrations according to the measurement heights and environmental variables in the naturally ventilated broiler house at the broiler's age of 2 week.

	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Ventilation rate (3)	1.00									
Outdoor air temperature (4)	0.79	1.00								
Outdoor absolute humidity (5)	0.62	0.97	1.00							
Indoor air temperature (6)	0.32	0.72	0.75	1.00						
Indoor absolute humidity (7)	-0.99	-0.83	-0.67	-0.46	1.00					
Water content level (8)	0.51	0.41	0.40	-0.31	-0.38	1.00				
Inhalable particulate at broiler height (9)	0.13	-0.30	-0.49	-0.04	-0.17	-0.60	1.00			
Inhalable particulate at worker's height (10)	0.72	0.16	-0.06	-0.40	-0.62	0.54	0.36	1.00		
Respirable particulate at broiler height (11)	0.62	0.09	-0.09	-0.54	-0.50	0.67	0.19	0.97	1.00	
Respirable particulate at worker's height (12)	0.17	-0.47	-0.65	-0.76	-0.06	0.17	0.56	0.80	0.80	1.00

Table 4-25 Computed correlation coefficients among inhalable and respirable particulate concentrations according to the measurement heights and environmental variables in the naturally ventilated broiler house at the broiler's age of 4 week.

	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Ventilation rate (3)	1.00									
Outdoor air temperature (4)	0.89	1.00								
Outdoor absolute humidity (5)	0.67	0.93	1.00							
Indoor air temperature (6)	0.92	0.70	0.43	1.00						
Indoor absolute humidity (7)	-0.34	-0.06	0.19	-0.22	1.00					
Water content level (8)	-0.77	-0.64	-0.45	-0.92	-0.16	1.00				
Inhalable particulate at broiler height (9)	-0.77	-0.84	-0.78	-0.78	-0.34	0.90	1.00			
Inhalable particulate at worker's height (10)	-0.80	-0.86	-0.78	-0.78	-0.37	0.90	0.99	1.00		
Respirable particulate at broiler height (11)	0.66	0.30	-0.04	0.65	-0.88	-0.32	-0.07	-0.12	1.00	
Respirable particulate at worker's height (12)	-0.84	-0.85	-0.75	-0.86	-0.22	0.93	0.99	0.99	-0.21	1.00

From the correlation analyses and multi-collinearity tests using VIF values, outdoor air temperature seemed to be strongly correlated with the outdoor absolute humidity level for both experimental broiler houses. The weight of the broilers was also strongly related with the age of the broilers. Thus, the variables of the outdoor air temperature and the weight of the broilers were excluded from the multi-regression analyses for occupational dust measured at the broiler's height and worker's respiratory intake in the MV and NV broiler houses. The selected independent variables were the broiler's age (days), CFD computed ventilation rate (AER/min), outdoor absolute humidity level (kg/kg-da), indoor air temperature (℃), indoor absolute humidity level (kg/kg-da), water content level of the bedding materials (%), and activity status of the broilers. The activity status of the broilers was a nominal factor, which had a discrete distribution (0/1). Therefore, dummy variables were adopted to reflect the effect of the broiler's status according to the worker's entrance and work activities.

Table 4-26 and 4-27 shows the final results of the regression analyses for inhalable particulate concentrations measured at the height of the broiler's and worker's respiratory intake, respectively in the MV broiler house.

From the results of the multi regression analysis of inhalable particulates measured at the height of the broilers, the degree of contribution of the water content level toward the generation of inhalable particulates was very small (p-value=0.874). Therefore, the water content level of the bedding materials was excluded from the independent variables and the regression model was re-analyzed through the backward elimination process. Among the designed experimental variables, only the activity of the broilers was found to be the most significant variable with a p-value of 0.0016 ($p<0.05$). This indicated that vigorous movement and the motion of flapping wings of the broilers due to the work activities of the farmer could substantially contribute to the generation of inhalable particulates as observed in the field study.

However, other independent variables were not statistically significant toward the variation of inhalable particulates. From the regression model, the ranking of the degree of contribution of each variable to the inhalable particulate concentration was as follows: activity of broilers, age of broilers, indoor air temperature, ventilation rate, outdoor absolute humidity and indoor absolute humidity.

In the case of the inhalable particulate concentrations measured at the worker's respiratory height in the MV broiler house, the variable of water content level of the bedding materials was also excluded through the backward elimination process (p-value=0.766). The reason of excluding the water content level was explained by the results of the correlation analyses according to the broiler's age as mentioned earlier. As noted above, the water content level of bedding materials could effectively contribute to the reduction of dust concentration in the airspace. However, opposite tendencies were observed in the experimental conditions with broilers whose age was 4 weeks in both MV and NV broiler houses. The dust potential from the mature broilers with plenty of feathers might be more influential to the dust concentration in the airspace than the reduction effect of the water content level of bedding materials. From the normality test for residuals of the regression model using the Shapiro-Wilk test, the regression model for the variation of inhalable particulate concentrations measured at the worker's height was not satisfactory for the prerequisite of a normal distribution (p-value=0.003). Therefore, log transformation was carried out for the dependent variable of inhalable particulate concentration. The computed p-value from the corrected model using the Shapiro-Wilk test was 0.776. As shown in Table 4-27, activity of broilers (p-value=0.002), indoor absolute humidity (p-value=0.005) and ventilation rate (p-value=0.016) were found to be significant factors toward the generation of inhalable particulates. This indirectly indicated that work activities in the facility when minimum ventilation was used in the dry and cold season might be exposed to the high concentration of airborne dust in the MV broiler house. If I consider that the activity status of the broilers is not a controllable factor, temporal managing of the ventilation rate and humidity condition might be helpful to reduce the dust concentration. However, as mentioned earlier, increase of the ventilation rate can cause unfavorable thermal conditions of the AOZ and increase of indoor humidity is strongly related with the proliferation of the micro-organisms. Therefore, finding a proper control range for the two variables should carefully take precedence considering stability and suitability of the environmental factors.

Table 4-26 Computed regression coefficients, standard errors, t-values, and p-values from the multiple regression analysis of the inhalable particulate concentrations measured at broiler's height in mechanically ventilated broiler house.

Inhalable particulate	Multiple R^2	0.60	Adjusted R^2	0.46
	F-statistic	4.32	p-value	0.008
	Coefficient	Standard error	t-value	$Pr(>\|t\|)$
(intercept)	-62.30	55.79	-1.12	0.280
Age of broilers (day)	0.96	0.59	1.64	0.119
Ventilation rate (AER/min)	-3.57	4.68	-0.76	0.456
Outdoor A.H. (kg/kg-da)	-561.32	736.83	-0.76	0.457
Indoor air temperature (°C)	2.44	1.59	1.53	0.144
Indoor A.H. (kg/kg-da)	-851.15	998.79	-0.85	0.406
Broiler activity (binominal factor)	10.76	2.86	3.76	0.002**

Significance: 0 "***" 0.001 "**" 0.01 "*" 0.05 "." 0.1 " " 1

A.H. refers to absolute humidity level

Table 4-27 Computed regression coefficients, standard errors, t-values, and p-values from the multiple regression analysis of the inhalable particulate concentrations measured at worker's respiratory height in mechanically ventilated broiler house.

Inhalable particulate	Multiple R^2	0.64	Adjusted R^2	0.54
	F-statistic	6.35	p-value	0.001
	Coefficient	Standard error	t-value	Pr(>|t|)
(intercept)	0.60	3.13	0.19	0.851
Age of broilers (day)	0.05	0.04	1.20	0.244
Ventilation rate (AER/min)	-1.02	0.38	-2.66	0.016*
Indoor air temperature (°C)	0.07	0.10	0.72	0.481
Indoor A.H. (kg/kg-da)	-156.65	49.34	-3.18	0.005**
Broiler activity (binominal factor)	0.87	0.24	3.68	0.002**

Significance: 0 "***" 0.001 "**" 0.01 "*" 0.05 "." 0.1 " " 1

A.H. refers to absolute humidity level

Based on the corrected models, the linear regression equation derived for the inhalable particulate concentration according to the measurement height in the MV broiler house is given below. The R^2 and adjusted R^2 values were 0.60 and 0.46 for inhalable particulates measured at broiler's height and 0.58 and 0.54 for that measured at the worker's height, respectively. Here, activity of the broiler was a binominal factor. '0' refers to stable conditions of the broiler while '1' refers to active conditions due to the working activities.

$$\begin{aligned}\text{Inhalable particulate (broiler height)}\\ &= -62.304 + 0.960 \cdot \text{age of animals} - 3.565 \cdot \text{ventilation rate}\\ &- 561.317 \cdot \text{outdoor absolute humidiy} + 2.437 \cdot \text{indoor air temperature}\\ &- 851.148 \cdot \text{indoor absolute humidity} + 10.760 \cdot \text{broiler activity}\end{aligned}$$

$$\begin{aligned}\log\left(\text{Inhalable particulate (worker's respiratory height)}\right)\\ &= 0.595 + 0.047 \cdot \text{age of animals} - 1.021 \cdot \text{ventilation rate} + 0.069\\ &\cdot \text{indoor air temperature} - 156.645 \cdot \text{indoor absolute humidity} + 0.873\\ &\cdot \text{broiler activity}\end{aligned}$$

For example, from the derived linear equation and experimental conditions for October 2013, where the broiler's age was 27 days, the ventilation rate was 0.07 AER/min, indoor air temperature was 23.67°C and indoor relative humidity was 74.43%, only a 1.4% decrease in inhalable particulates at the worker's respiratory height could be estimated when an additional 10% of the ventilation rate was temporarily increased when broiler farmers entered the facility. Meanwhile, a 13.7% decrease occurred for the case when 5% of the indoor relative humidity level was increased with given identical conditions. These observations indirectly indicated that controlling the humidity level inside the facility would be more influential than adjusting the ventilation level when considering the effectiveness of dust reduction and the effects on the thermal conditions of the AOZ due to the increase in ventilation rate especially in the cold season.

Figure 4-24 depicts the estimated inhalable particulate concentrations at the height of the worker's respiratory intake when farmers entered the MV broiler house. The estimated inhalable particulate concentrations are derived from an equation in this thesis according to the ventilation rate, indoor relative humidity level and age of the broilers: (a) 7 days old (indoor air temperature was set at 29.5°C when considering the recommended thermal condition for broilers in South Korea), (b) 14 days old (indoor air temperature=27.5 ℃) and (c) 28 days old (indoor air temperature=22.0°C). The absolute humidity values were reflected in the figures through a transformation based on the psychometric chart using set-up air temperature and relative humidity levels. As mentioned earlier, the ventilation rate gave a minor effect on the inhalable particulate concentration while humidity level was very influential to the variation of the values. In contrast to the results from the experimental nursery pig house, adjusting the ventilation system was not effective in the MV broiler house. Controlling the humidity level might be one solution to reduce the respiratory risk of a dusty environment. Installing air filters or air cleaning devices inside the facility may be helpful. However, the effectiveness of these additional devices in the broiler houses is still in question with regard to the economic feasibility.

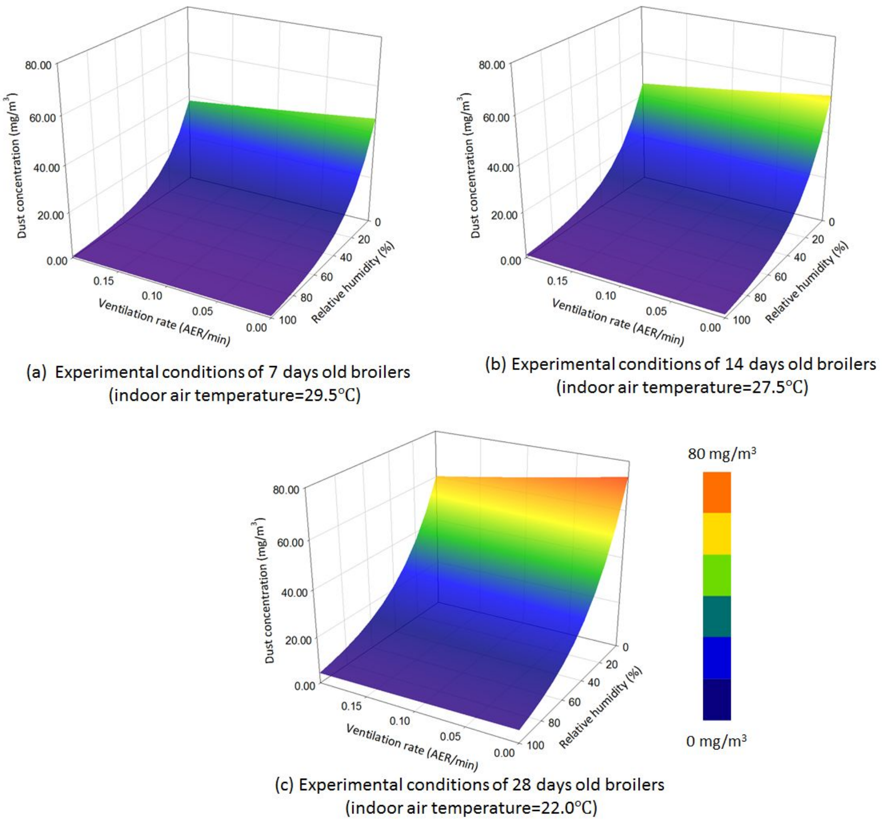


Figure 4-24 Estimated concentrations of inhalable particulate at height of worker's respiratory intake according to age of broilers in a mechanically ventilated broiler house.

From the multiple regression analysis of the respirable particulates measured at the broiler's height, the indoor absolute humidity level was excluded through the backward elimination process. Activity of the broilers was also found to be the most significant variable with a p-value of 0.004 ($p<0.05$). In contrast to the results of inhalable particulates in the MV broiler house, the variable of outdoor absolute humidity was an influential factor toward the variation of the respirable particulates (p-value=0.044). The computed statistics of the regression analysis for respirable particulates measured at the broiler's height are shown in Table 4-28.

In the case of the results of respirable particulate measured at the worker's height in the MV broiler house, indoor absolute humidity and water content level were excluded through the backward elimination process. From the normality test for residuals of the regression model using the Shapiro-Wilk test, the regression model for the variation of respirable particulate concentrations measured at the worker's height was not satisfactory for the prerequisite of a normal distribution (p-value=0.003). Therefore, a log transformation was carried out for the dependent variable of respirable particulate concentration. The computed p-value from the corrected model using the Shapiro-Wilk test was 0.436. From the statistical results in Table 4-29, the ranking of the degree of contribution toward the generation of respirable particulates was as follows: outdoor absolute humidity level, activity of broilers, ventilation rate, age of broilers and indoor air temperature.

Table 4-28 Computed regression coefficients, standard errors, t-values, and p-values from the multiple regression analysis of the respirable particulate concentrations measured at broiler's height in mechanically ventilated broiler house.

Respirable particulate	Multiple R^2	0.59	Adjusted R^2	0.44
	F-statistic	4.05	p-value	0.011
	Coefficient	Standard error	t-value	$Pr(>\|t\|)$
(intercept)	-3.81	3.22	-1.18	0.253
Age of broilers (day)	0.06	0.04	1.63	0.121
Ventilation rate (AER/min)	-0.36	0.31	-1.16	0.264
Outdoor A.H. (kg/kg-da)	-75.67	34.84	-2.17	0.044*
Indoor air temperature (°C)	0.13	0.10	1.28	0.217
Water content levels (%)	0.01	0.01	0.79	0.442
Broiler activity (binominal factor)	0.69	0.19	3.29	0.004**

Significance: 0 "***" 0.001 "**" 0.01 "*" 0.05 "." 0.1 " " 1

A.H. refers to absolute humidity level

Table 4-29 Computed regression coefficients, standard errors, t-values, and p-values from the multiple regression analysis of the respirable particulate concentrations measured at worker's respiratory height in mechanically ventilated broiler house.

Respirable particulate	Multiple R^2	0.76	Adjusted R^2	0.69
	F-statistic	11.27	p-value	4.866e-05
	Coefficient	Standard error	t-value	Pr(>$\|t\|$)
(intercept)	-5.97	2.82	-1.99	0.062.
Age of broilers (day)	0.08	0.03	2.50	0.022*
Ventilation rate (AER/min)	-0.97	0.29	-3.37	0.003**
Outdoor A.H. (kg/kg-da)	-117.94	27.15	-4.35	3.91e-04***
Indoor air temperature (°C)	0.15	0.09	1.72	0.103
Broiler activity (binominal factor)	0.67	0.18	3.78	0.001**

Significance: 0 "***" 0.001 "**" 0.01 "*" 0.05 "." 0.1 " " 1

A.H. refers to absolute humidity level

Based on the corrected model, the linear regression equations derived for respirable particulates according to the measurement height are given below. The R^2 and adjusted R^2 values were 0.59 and 0.44 for respirable particulates measured at the broiler's height and 0.76 and 0.69 for that measured at the worker's height, respectively.

$$\begin{aligned}\text{Respirable particulate (broiler height)} \\ &= -3.812 + 0.061 \cdot \text{age of animals} - 0.362 \cdot \text{ventilation rate} - 75.671 \\ &\cdot \text{outdoor absolute humidity} + 0.131 \cdot \text{indoor air temperature} + 0.008 \\ &\cdot \text{water content level} + 0.628 \cdot \text{broiler activity}\end{aligned}$$

$$\log(\text{Respirable particulate (worker's respiratory intake)})$$
$$= -5.597 + 0.083 \cdot \text{age of animals} - 0.972 \cdot \text{ventilation rate} - 117.939 \cdot \text{outdoor absolute humidity} + 0.154 \cdot \text{indoor air temperature} + 0.668 \cdot \text{broiler activity}$$

Table 4-30 and 4-31 shows the final results of the regression analyses for inhalable particulate concentrations measured at the height of the broiler's and worker's respiratory intake, respectively, in the NV broiler house.

From the results of the multiple regression analysis of the inhalable particulates measured at the height of the broilers, the degree of contribution of indoor air temperature (p-value=0.944), ventilation rate (p-value=0.897) and outdoor absolute humidity level (p-value=0.6894) were very small. Therefore, the mentioned variables were excluded from the independent variables and the regression model was re-analyzed through the backward elimination process. Among the designed experimental variables, only activity of the broilers was found to be the most significant variable with a p-value of 0.002 ($p<0.01$). This indicated that the vigorous movement and motion of flapping wings of the broilers due to the work activities of the farmer could contribute substantially to the generation of inhalable particulates as observed in the field study. However, other independent variables were not statistically significant toward the variation of inhalable particulates.

In the case of the inhalable particulate concentrations measured at the worker's respiratory height in the NV broiler house, the variables of outdoor absolute humidity (p-value=0.660) and indoor air temperature (p-value=0.642) were also excluded through the backward elimination process. As shown in Table 4-31, ventilation rate (p-value=0.010) and broiler activity (p-value=0.021) were found to be significant factors toward the generation of inhalable particulates. In contrast to the previous studies and observations in this thesis, the level of water content was positively correlated with the variation of inhalable particulates measured at the height of the workers in the NV broiler house. However, this variable was not significant (p-value=0.269). As noted earlier, the dust potential of mature broilers with plenty of feathers might influence the effectiveness of dust reduction from moist or damp bedding materials. Therefore, interpretation of this factor should be carefully handled. From the computed t-values and p-values, the ranking of variables in terms of their contribution toward the generation of inhalable particulates at the worker's respiratory height was as follows: ventilation rate, broiler's activity, age of broilers, indoor absolute humidity and the water content level of bedding materials.

Table 4-30 Computed regression coefficients, standard errors, t-values, and p-values from the multiple regression analysis of the inhalable particulate concentrations measured at broiler's height in naturally ventilated broiler house.

Inhalable particulate	Multiple R^2	0.511	Adjusted R^2	0.40
	F-statistic	4.71	p-value	0.009
	Coefficient	Standard error	t-value	Pr(>|t|)
(intercept)	12.55	14.32	0.88	0.392
Age of broilers (day)	0.22	0.28	0.79	0.438
Indoor A.H. (kg/kg-da)	-986.19	794.87	-1.241	0.231
Water content level (%)	0.09	0.15	0.60	0.556
Broiler activity (binominal factor)	11.10	3.12	3.56	0.002**

Significance: 0 "***" 0.001 "**" 0.01 "*" 0.05 "." 0.1 " " 1

A.H. refers to absolute humidity level

Table 4-31 Computed regression coefficients, standard errors, t-values, and p-values from the multiple regression analysis of the inhalable particulate concentrations measured at worker's respiratory height in naturally ventilated broiler house.

Inhalable particulate	Multiple R^2	0.64	Adjusted R^2	0.54
	F-statistic	6.152	p-value	0.002
	Coefficient	Standard error	t-value	$\Pr(>\|t\|)$
(intercept)	6.57	6.12	1.07	0.298
Age of broilers (day)	0.32	0.16	1.94	0.069.
Ventilation rate (AER/min)	-5.22	1.81	-2.89	0.010*
Indoor A.H. (kg/kg-da)	-598.52	337.99	-1.771	0.095.
Water content level (%)	0.08	0.07	1.14	0.27
Broiler activity (binominal factor)	3.35	1.32	2.53	0.02*

Significance: 0 "***" 0.001 "**" 0.01 "*" 0.05 "." 0.1 " " 1

A.H. refers to absolute humidity level

Based on the corrected models, the linear regression equation derived for the inhalable particulate concentrations according to the measurement height in the NV broiler house is given below.

$$\begin{aligned}\text{Inhalable particulate (broiler height)} \\ &= 12.552 + 0.219 \cdot \text{age of broiler} - 986.194 \cdot \text{indoor absolute humidity} \\ &+ 0.091 \cdot \text{water content level} + 11.096 \cdot \text{broiler activity}\end{aligned}$$

$$\text{Inhalable particulate (worker's respiratory height)} = 6.568 + 0.318 \cdot \text{age of broiler} - 5.216 \cdot \text{ventilation rate} - 598.522 \cdot \text{indoor absolute humidity} + 0.082 \cdot \text{water content level} + 3.348 \cdot \text{broiler activity}$$

From the multiple regression analysis of the respirable particulates measured at the broiler's height (Table 4-32), age of broiler, ventilation rate, water content level of bedding materials and activity of broilers were excluded through the backward elimination process. Log transformation for respirable particulate concentrations was also carried out according to the Shapiro-Wilk test results. Among the variables, outdoor absolute humidity was the most influential in the variation of respirable particulates at the broiler's height (p-value=0.096). Other variables were not statistically significant, and thus, the adjusted R^2 value was 0.26.

In the case of the results of respirable particulates measured at worker's height in the NV broiler house, age of broilers, ventilation rate, water content level of bedding materials, indoor absolute humidity level and activity of broilers were excluded through the backward elimination process. Log transformation for respirable particulate concentrations was also carried out according to the Shapiro-Wilk test results. As shown in Table 4-33, indoor air temperature (p-value=0.020) and outdoor absolute humidity level (p-value=0.031) were statistically significant in the variation of the dependent variable.

Table 4-32 Computed regression coefficients, standard errors, t-values, and p-values from the multiple regression analysis of the respirable particulate concentrations measured at broiler's height in naturally ventilated broiler house.

Respirable particulate	Multiple R^2	0.36	Adjusted R^2	0.26
	F-statistic	3.62	p-value	0.032
	Coefficient	Standard error	t-value	$Pr(>\|t\|)$
(intercept)	4.71	2.69	1.75	0.096.
Outdoor A.H. (kg/kg-da)	-63.71	42.37	-1.50	0.149
Indoor air temperature (°C)	-0.126	0.10	-1.31	0.206
Indoor A.H. (kg/kg-da)	-72.217	84.167	-0.86	0.402

Significance: 0 "***" 0.001 "**" 0.01 "*" 0.05 "." 0.1 " " 1

A.H. refers to absolute humidity level

Table 4-33 Computed regression coefficients, standard errors, t-values, and p-values from the multiple regression analysis of the respirable particulate concentrations measured at worker's respiratory height in naturally ventilated broiler house.

Inhalable particulate	Multiple R^2	0.51	Adjusted R^2	0.47
	F-statistic	10.56	p-value	7.398e-04
	Coefficient	Standard error	t-value	$Pr(>\|t\|)$
(intercept)	4.58	1.87	2.46	0.023*
Outdoor A.H. (kg/kg-da)	-67.61	29.06	-2.33	0.031*
Indoor air temperature (°C)	0.17	0.07	-2.54	0.020*

Significance: 0 "***" 0.001 "**" 0.01 "*" 0.05 "." 0.1 " " 1

A.H. refers to absolute humidity level

Based on the corrected model, the linear regression equations derived for respirable particulates according to the measurement height are given below.

$$\log(\text{Respirable particulate (broiler height)})$$
$$= 4.706 - 63.707 \cdot \text{outdoor absolute humidity} - 0.126$$
$$\cdot \text{indoor air temperature} - 72.217 \cdot \text{indoor absolute humidity}$$

$$\log(\text{Respirable particulate (worker's respiratory intake)})$$
$$= 4.585 - 67.609 \cdot \text{outdoor absolute humidity} - 0.174$$
$$\cdot \text{indoor air temperature}$$

4.3.7. Results of measured dust generation from bedding materials using chamber experiment

An additional simple chamber experiment was carried out to investigate the effects of water content in the bedding materials on dust generation. Table 4-34 shows the level of water content of bedding materials measured through KS F2306 test methods during the chamber experiment.

Table 4-34 Measured water content level of experimental bedding materials according to each designed experimental case

1st experiment		2nd experiment		3rd experiment	
Cases	Water content (%)	Cases	Water content (%)	Cases	Water content (%)
W0	0.00	W0	0.00	W0	0.00
W1	12.62	W1	29.67	W1	17.95
W2	17.12	W2	37.23	W2	21.47
W3	32.06	W3	54.19	W3	23.81

Figures 4-25 and 4-26 show measured trends of inhalable and respirable particulate fractions according to the magnitudes of mean air velocity inside the chamber and the water content level of bedding materials. The results were only displayed for the first chamber experiment.

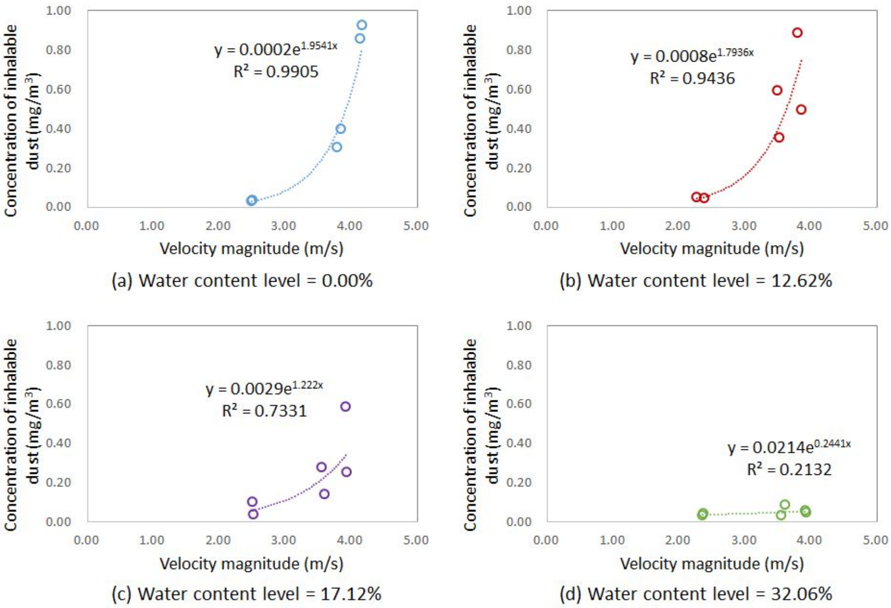


Figure 4-25 Measured trends of inhalable particulates versus mean air velocity magnitudes according to water content level of bedding materials (1st experiment).

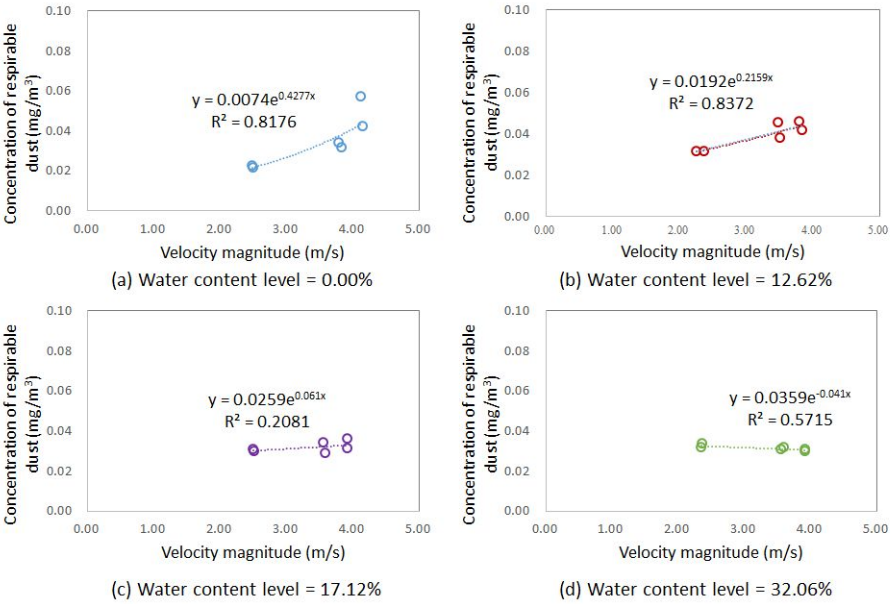


Figure 4-26 Measured trends of respirable particulates versus mean air velocity magnitudes according to water content level of bedding materials (1st experiment).

The exponential increase of dust concentration was generally observed as the mean air velocities increased. However, each slope gradually decreased as the experimental water content level increased. A relatively high speed of air velocity might be the driving force to bring about dust generation from bedding materials. However, high air velocity could not effectively contribute to the dust generation at specific water content conditions as shown in Figures 4-25 (d) and 4-26 (d). Extremely gentle slopes were found in the mentioned conditions.

The measured trends of inhalable and respirable particulate concentrations according to the experimental variable of air velocity in the chamber are given in Figure 4-27. The experimental condition of air velocity magnitude was expressed as a nominal variable (e.g., level-1, 2 and 3). It could be presumed that inhalable and respirable particulates were hardly dispersed from the bedding materials under water content experimental levels of 45 and 50%, respectively through extrapolation of each trend line in Figure 4-27. These reported values could be defined as a threshold water content level preventing particulates in each fraction from dispersion. From the chamber experimental results, it was also analogized that respirable particulate fractions could be generated from even more humid bed conditions.

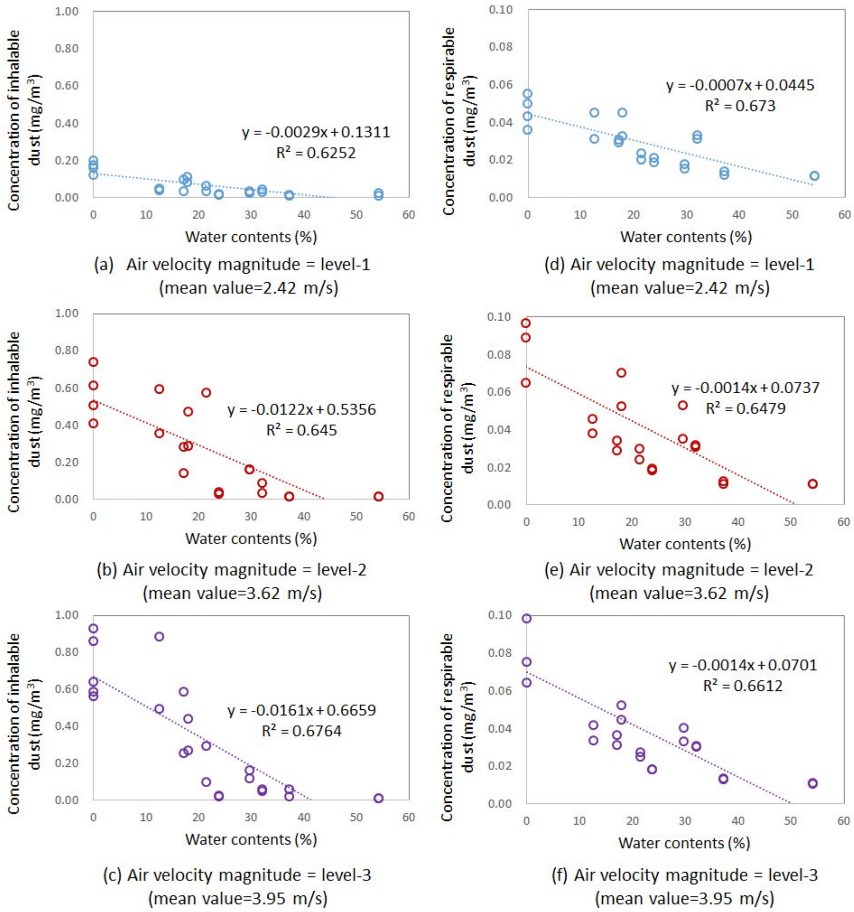


Figure 4-27 Trends of inhalable and respirable particulate versus experimental water content level according to air velocity magnitude inside chamber.

Multiple regression analyses were carried out to investigate the effect of each variable on dust generation and to predict the dispersion of airborne dust. For the inhalable particulate fractions, water content level (p-value=3.50e-11) and velocity magnitude (p-value=8.10e-21) were statistically influential for dust generation from bedding materials in the given experimental conditions (adjusted R^2=0.72), while only the variable of velocity magnitude was an influential factor for the generation of respirable particulate fractions (p-value=4.00e-04) (adjusted R^2=0.29). The computed p-value for water content was 0.1467 (Table 4-35). From the observation, it could be implied that the increase of water content in the bedding materials was more effective to reduce the generation of particulates with larger AED such as inhalable particulates. However, the particulates with relatively smaller AED such as respirable particulate fractions could be more easily defected from moist or damp bedding materials, which show more stickiness between particulates.

Table 4-35 Results of multiple regression analyses of concentrations of inhalable and respirable particulate according to water content levels and velocity magnitudes.

Inhalable particulates (adjusted R^2=0.72)				
	Coefficient	Standard error	t-value	Pr (>$\|t\|$)
Water contents (%)	-0.01	-0.00	-7.85	3.50e-11*** ($p<0.05$)
Velocity magnitude (m/s)	0.12	-0.01	13.29	8.10e-21*** ($p<0.05$)
Respirable particulates (adjusted R^2=0.29)				
	Coefficient	Standard error	t-value	Pr (>$\|t\|$)
Water contents (%)	3.0e-04	0.00	1.47	0.1467 ($p>0.05$)
Velocity magnitude (m/s)	3.0e-03	0.00	3.74	4.00e-04*** ($p<0.05$)
Significance: 0 “***” 0.001 “**” 0.01 “*” 0.05 “.” 0.1 “ ” 1				

If I consider that almost measured level of water content levels of bedding materials in the MV and NV broiler houses were beyond 40%, airborne dust in the experimental broiler houses might be generated not only from the bedding materials but also other various sources such as the animals, fallen feathers, feces and building materials. Especially, the water content level increased as growth of the broilers increased due to the accumulated feces and urine matter. However, the highest dust concentrations were generally found at the finishing stage of the broilers. This indirectly meant that dust potential from the animals and fecal matter were more dominant than other sources. From the SEM-EDX analyses, Cambra-Lopez et al.

(2010) mentioned that particulate matter smaller than a 2.5 μm diameter usually originated from feathers (28.4%), feces and urine (67.7%) and bedding materials (3.5%). Particulate matter in the range from 2.5 to 10 μm was also derived from feathers (17.2%) and feces (82.8%). Thus, it could be concluded that related follow-up experiments would be needed to exactly explain the relationship between dust generation and status of bedding materials when considering the variation of the components of bedding materials according to the rearing stages.

The experimental results implied the possibilities of controlling the level of airborne dust through the managing status of bedding materials. From the relationship between the water content level of bedding materials and surrounding air velocity magnitude, threshold water content levels could be derived to manage dust dispersion from the source. However, an absolute increase of water content level in bedding materials can cause another adverse health effect for both workers and animals. First, various micro-organisms such as endotoxin can be easily proliferated in humid conditions. Therefore, inhalation of bio-aerosols attached to dust particulates and deposition of these particulates in the respiratory airway can cause various respiratory related side effects. Second, the strength of odorous matters can be amplified due to the dissolution of ammonium in humid aerosols. Consequently, odorous matter not only irritates the respiratory airways but also brings about esthetic displeasure from workers and neighboring residents. Therefore, in my opinion, investigation to find proper ranges of the water content level must take precedence when considering the biological and chemical safety of workers and animals. However, temporarily increasing the moisture level in bedding materials during shipment activities for mature broilers can be an effective measure to reduce dust generation.

4.4. Conclusions

In this chapter, long-term and intensive field observations were conducted in commercial, mechanically ventilated broiler house and naturally ventilated broiler house, which are common type of facilities in South Korea. From field observations for experimental broiler houses, high dust concentrations, which exceeded the occupational exposure limit of inhalable and respirable particulates with regard to the respiratory health of broiler farmers, were usually observed during periods when broiler's activities increased as the work activities of the farmers. From the statistical analyses for experimental mechanically ventilated broiler houses, increase in activity of the broilers, indoor absolute humidity and ventilation were influential factors for inhalable particulates, while the activity of the broilers, outdoor humidity level, ventilation rate and age of broilers were influential factors for respirable particulate. In contrast to the nursery pig house, among the controllable factors, ventilation had minor effects on variation of the concentration of the occupational dust, whilst controlling of humidity level inside the facility was more effective manner for dust reduction strategies. For example, from the derived regression equations and specific experimental conditions, only a 1.4% decrease in inhalable particulates at the worker's respiratory height could be estimated when an additional 10% of the ventilation rate was temporarily increased when broiler farmers entered the facility. Meanwhile, a 13.7% decrease occurred for the case when 5% of the indoor relative humidity level was increased with given identical conditions. However, plenary application of mist spraying in the facility is not always recommended due to the biological hazards with regards to proliferation of the micro-organisms. Thus, investigations to find proper ranges of water consumptions for mist spraying must take precedence. For the naturally ventilated broiler house, ventilation rate and activity of broilers were influential to the inhalable particulates, while, indoor air temperature and outdoor humidity level were statistically significant to the variation of the respirable particulates. In contrast to the conventional views on relationship between water content levels of bedding materials and dust concentration, positive correlation was observed from given data for whole periods. Notwithstanding the negative correlation among factors was found for experimental conditions with young broilers (under 2 week olds), opposite tendencies were found for mature broilers who had plenty of feathers and showed vigorous motions of flapping wings. From the additional chamber experiment to investigate the effect of water contents of bedding materials on dust generation, water content levels of 45 and 50% were found as the threshold level for generation of the inhalable and respirable particulates, respectively. Restrictive and temporal droplets spraying on bedding materials might be reduce respiratory risk for workers during shipment activities.

Chapter 5. Identification of key factors for dust generation in cattle farms

5.1. Introduction

The monitoring of airborne dust, including TSP, PM10, inhalable and respirable particulates was carried out regularly at a commercial dairy cattle and Korean native cattle farms for five months. Due to the nationwide outbreak of FMD, dust monitoring at the cattle farms was carried out for a relatively short period in contrast to other types of livestock species. A number of previous studies reported that dust concentrations inside the cattle farms were generally lower than those of pig or poultry houses. In accordance with these mentioned facts, dust measurement in the experimental cattle farms was especially conducted according to the work activities of the farmers and feeding processes. To investigate any correlation between the dust concentration and various experimental variables, measurements of indoor and outdoor climates was also carried out. In contrast to the investigations with the experimental nursery pig house and the broiler houses, statistical approaches were not fully carried out due to the limited observed data. Therefore, simple comparative analyses and risk evaluation were conducted.

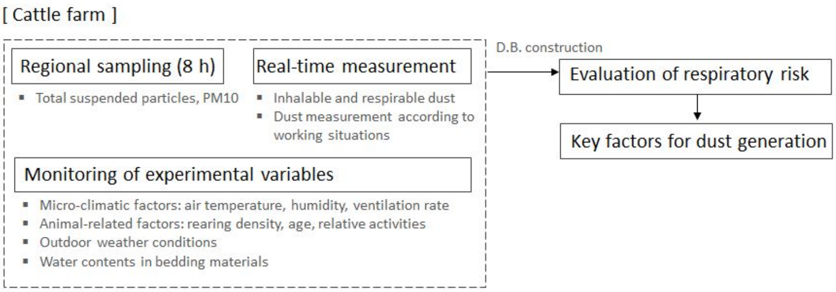


Figure 5-1 Overall research flow to find key factors for dust generation in experimental cattle farms.

5.2. Materials and methods

5.2.1. Experimental cattle farms

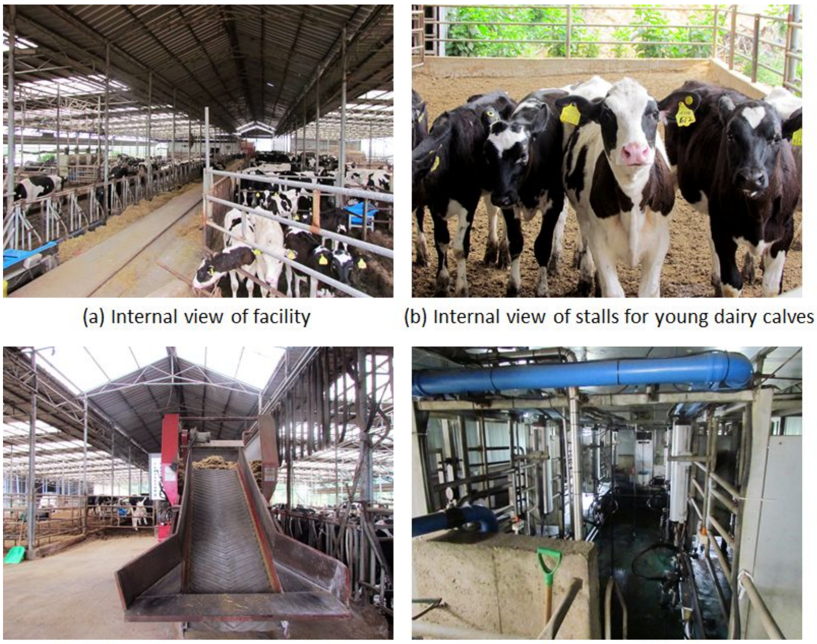
In South Korea, Korean native cattle farms (including beef cattle) have an 82.6% share of the total number of cattle farms, while dairy cattle farms occupy the remaining 17.4% (Statistics Korea, 2016). The measurement of airborne dust was carried out at both dairy cattle and Korean native cattle farms, which were the commercial and popular types in South Korea to evaluate the risk factors for respiratory health of cattle farmers. The experimental dairy cattle farm was located in Hwasan-ri, Ujeong-eup, Hwaseong City, Gyeonggi-do Province and the experimental Korean native cattle farm was located in Hwasu-ri, Ujeong-eup, Hwaseong City, Gyonggi-do Province. The Korean native cattle farm was 10.2 km away from the experimental dairy farm. Figure 5-2 shows the satellite views of the two experimental farms.

(a) Satellite view of experimental dairy cattle farm

(b) Satellite view of experimental Korean cattle farm

Figure 5-2 Satellite view of experimental dairy cattle farm (a) and Korean native cattle fam (b).

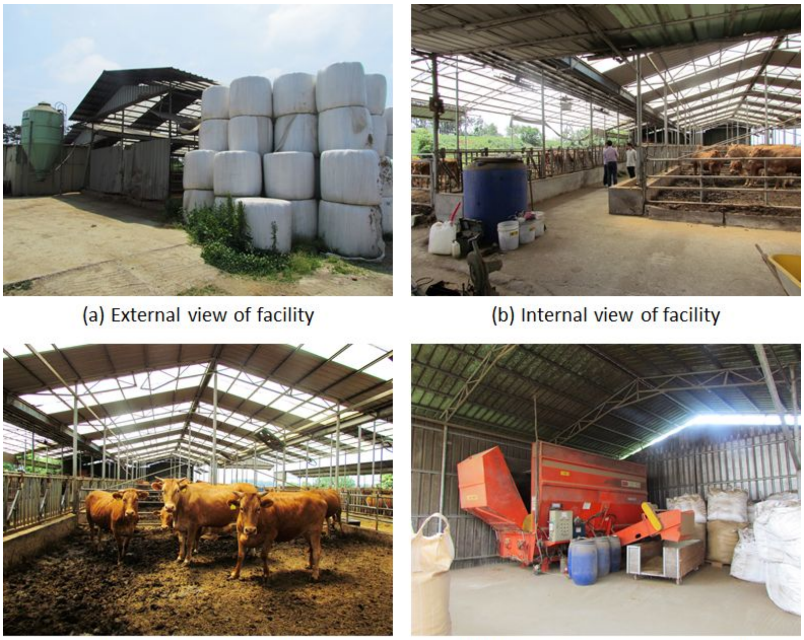
The size of the experimental dairy cattle farm was 40.0 m wide, 62.0 m long, 3.9 m high for the eaves and 5.5 m high for the ridge. Stalls for rearing calves were located at the left side based on the entrance and middle passage, while stalls for dairy cattle were located at the right side. 145 heads of cattle (60 dairy cattle and 85 rearing calves) were raised during the experimental periods. A 90 m^2 milking room was located near the entrance of the farm and its total milk production rate was reported as 2,300 liters per day. Natural ventilation was basically adopted through the full opening of the winch curtains though out the year. However, the winch curtains were temporarily closed during the winter season of severe cold weather conditions. 30 circulating fans with a diameter of 1.0 m (22,500 CMH) were installed beneath the inclined roof to effectively remove the various noxious gases emitted from the animals and their excretion. The circulating fans were usually operated when cattle excretion was washed out after the milking process and were also operated during the summer season by providing a chilling effects to alleviate thermal stress to the cattle. Two farmers including the owner and a foreign laborer were working on the experimental farm. The daily routine usually began at 5:30 am. The milking process was carried out two times per day (i.e., 6:00 am and 5:00 pm). TMR (Total mixed ration) mixing and feeding was at 7:00 am and 5:30 PM (only feeding) and the cleaning activities of the milking room and the stalls for dairy cattle were at 8:00 am and 7:00 pm. One movable TMR machine was installed near the entrance of the farm. The mixing process of feed materials, including cone, rice straw and various additives aiming to increase weight gain and enhance immunities was carried out inside the mixing machine. Then, feeding was automatically carried out following the rail installed at the central area of the passage. Figure 5-3 shows the internal views of the experimental dairy cattle farm.



(a) Internal view of facility
(b) Internal view of stalls for young dairy calves
(c) TMR machine for mixing feeds
(d) Internal view of milking house

Figure 5-3 Internal views of the experimental dairy cattle farm.

The size of the experimental Korean native cattle farm was 30.0 m wide, 40.0 m long, 5.0 m high for the eaves and 7.5 m high for the ridge. Six stalls with identical areas were installed for 95 heads of cattle (i.e., 93 Korean native cattle and 2 beef cattle). One stall operated as an ICU (intensive care unit). A side of the ICU stall was blocked by a stepped bundle of straw in order to protect animals from a strong and chilly wind. Natural ventilation was basically adopted through the full opening of the winch curtains throughout the year. However, the winch curtains were temporarily closed during the winter season. 24 circulating fans with a diameter of 1.0 m (22,500 CMH) were installed beneath the inclined roof to effectively remove the various noxious gases emitted from the animals and their excretion. The circulating fans were also operated during the summer season to reduce thermal stress of the animals. Only one farmer worked in the experimental Korean native cattle farm. The daily routine usually begun at 6:30 am, and finished at 6:00 pm. The mixing process of feed materials using a stationary TMR machine was carried out once every four days. The mixing was carried out for 2 hours. The mixed feed materials were manually supplied by the farmer with the help of a handcart. The feeding tasks were usually carried out two times per day at 10:00 am and 5:30 pm. After feeding, the farmer swept the fallen feed materials on the ground with a broom for 30 minutes. Figure 5-4 shows the external and internal views of the experimental Korean native cattle farm.



(a) External view of facility (b) Internal view of facility

(c) Internal view of stalls (d) TMR machine for mixing feeds

Figure 5-4 External and internal views of the experimental Korean native cattle farm.

5.2.2. Experimental instruments

5.2.2.1. Experimental instruments for dust monitoring

Area sampling for TSP and PM10 fractions, and real-time measurement of inhalable and respirable particulates in the experimental cattle farms were carried out using the same instruments that were used in dust monitoring for the nursery pig house as mentioned in Chapter 3. Details of the instruments can be found in Section 3.2.2.1.

5.2.2.2. Experimental instruments for environmental variables monitoring

Various experimental instruments for monitoring of the environmental factors were also used for comprehensive analyses related to dust generation from experimental cattle farms. HOBO sensors were used to measure the indoor air temperature and relative humidity. A portable weather station was installed to monitor outdoor environmental conditions such as wind speed, wind direction, solar radiation, rainfall, air temperature, and humidity. Details of instruments for monitoring the environmental variables can be found in Section 3.2.2.2.

5.2.3. Monitoring of airborne dust

Dust monitoring in the experimental dairy cattle farm and the Korean native cattle farm was simultaneously conducted from June 2015 to October 2015. The experiment was stopped in November 2015 to the present due to a nationwide outbreak of FMD in South Korea. To determine the TSP and PM10 concentrations through the area sampling in each experimental cattle farm, the PTFE membrane filters were fully desiccated for 24 hours and pre-weighed using an electronic balance instrument. Each filter was then housed in a 3-stage polystyrene cassette for TSP, while sampling PM10 in a PEM. The flow rates for the sampling of TSP and PM10 were 2 and 4 l/min for 8 hours, respectively. 9 experimental area sampling locations of TSP and PM10 were selected for the experimental dairy cattle farm. 1 dust sampling set was installed at the windward area of the farm. The windward area was selected from the observed wind data of the nearest KMA (Korean Meteorological Administration) weather station from the experimental farm over the past decade: 3 sets on the middle passage of the experimental farm; 1 set on the leeward area of the farm; 2 sets in the vicinity of the TMR machine; and 2 sets in the milking room (Figure 5-5).

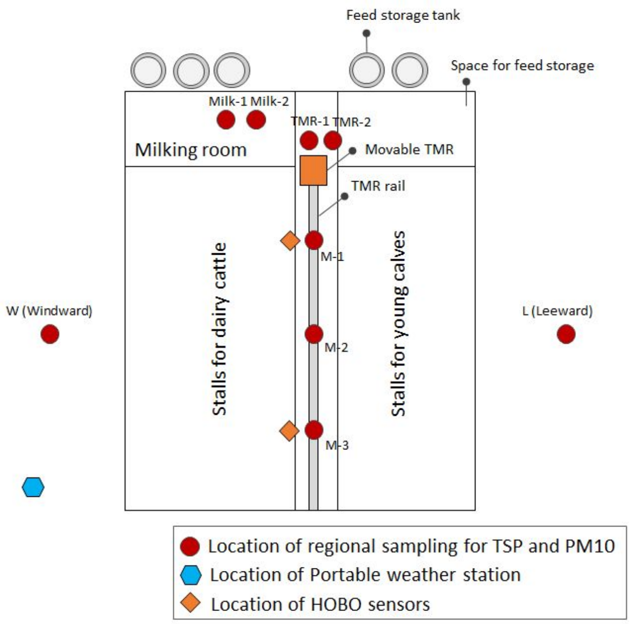


Figure 5-5 Location of area sampling for TSP and PM10, location of portable weather station and HOBO sensors in experimental dairy cattle farm.

In the Korean native cattle farm, 7 experimental locations were designed: 1 set of dust sampling devices was installed at the windward area of the farm; 2 sets on the middle passage of the experimental farm; 1 set in the vicinity of the ICU stall; 1 set on the leeward area of the farm; and 2 sets in the vicinity of the TMR machine (Figure 5-6). All of the dust sampling sets for TSP and PM10 were installed at a 1.5 height from the ground when considering the average working height of the farmers and their respiratory intake.

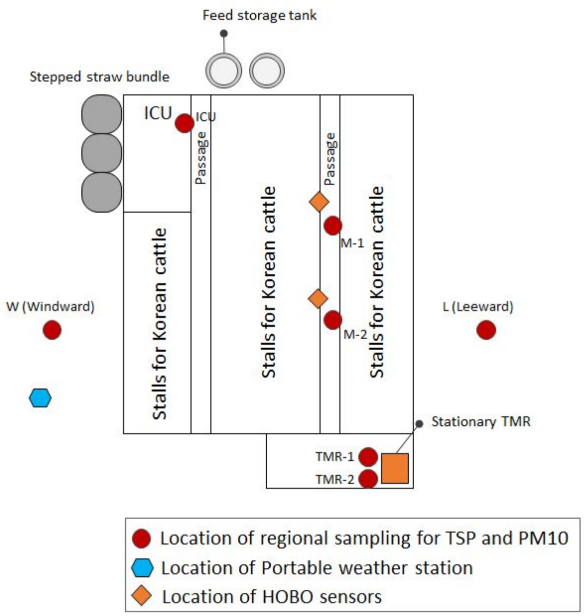


Figure 5-6 Location of area sampling for TSP and PM10, location of portable weather station and HOBO sensor in experimental Korean native cattle farm.

In the dairy cattle farm, area sampling of TSP and PM10 in the milking room, and in the vicinity of the TMR machine began at 6:00 am and finished at 8:00 am when considering the workers schedule. The sampling of the rest of TSP and PM10 were carried out for 8 hours from 9:00 am to 5:00 pm. In the experimental Korean native cattle farm, the concentrations of TSP and PM10 in the vicinity of the TMR machine were measured for 2 hours (from 8:00 am to 10:00 am). Measurements for the other area samplings were resumed at 10:30 am until 6:30 pm. Gravimetric measurement of the sampled TSP and PM10 dust concentrations were conducted in the same way as those in the nursery pig and broiler houses. Figures 5-7 and 5-8 show the experimental scenes of TSP/PM10 monitoring in the experimental cattle farms.

The concentration of inhalable and respirable particulates was measured using an Aerosol spectrometer at a height of 1.5 m according to the location and work activities of the farmers, such as TMR feeding, milking and clearing. Especially, measured occupational dust concentration during TMR processing were analyzed in details according to the mixing stages and supplying methods of the additives including rice straw, corns, and various chemical ingredients. Data was continuously recorded for 5~10 minutes and saved onto a memory card at intervals of 6 seconds. Figures 5-9 and 5-10 are photographs of occupational dust monitoring in the dairy cattle farm and Korean native cattle farm, respectively.

Figure 5-7 Experimental scenes of TSP/PM10 monitoring in dairy cattle farm.

(a) TSP/PM10 sampling during TMR process

(b) TSP/PM10 sampling at leeward

(c) TSP/PM10 sampling at middle passage

Figure 5-8 Experimental scenes of TSP/PM10 monitoring in Korean native cattle farm.

Figure 5-9 Experimental scenes of occupational dust monitoring in dairy cattle farm.

Figure 5-10 Experimental scenes of occupational dust monitoring in Korean native cattle farm.

5.2.4. Monitoring of experimental variables

Information regarding the number of cattle was provided regularly by the farm manager through interviews during dust monitoring. 145 heads of dairy cattle were raised at the experimental dairy cattle farm and 93 heads of cattle were raised at the experimental Korean native cattle farm. During all experimental periods, the increasing number of rearing cattle was only 3 and 2 at each experimental farm, respectively. The variation in rearing number was not significant. Therefore, it could be concluded that the mentioned factor might have less impact on the generation of airborne dust. To investigate the effects of the environmental factors on dust generation, various instruments were installed inside and outside the cattle farm. Two HOBO sensors were installed at the middle passage of each experimental farm in order to measure the air temperature and relative humidity. Data was recorded and stored every 5 seconds. A portable weather station was also installed at the open terrain of each cattle farm to simultaneously record outside weather conditions (Figure 5-5 and 5-6). Water contents of the bedding materials were also investigated through KS F2306 test methods with the identical process conducted in the investigation for broiler houses. Sieve-analysis test (KS F 2502) was also conducted to evaluate the size distribution of each feed material to investigate the relationship between mean diameter of the particulate and dispersed dust concentrations during TMR processing.

5.3. Results and discussions

5.3.1. Periodic monitoring of TSP and PM10

Table 5-1 shows the monitoring results of TSP and PM10 at the middle passage of the facility in the experimental dairy cattle and Korean native cattle farms.

Table 5-1 Overall monitoring results of TSP and PM10 measured at middle passage of the facility in the experimental dairy cattle and Korean native cattle farms (Unit: mg/m^3).

Date	Dairy cattle farm						b/a (%)	
	TSP (a)			PM10 (b)			AM	GM
	n	AM±SD	GM(GSD)	n	AM±SD	GM±GSD		
Jun.23. 2015	2	0.11±0.01	0.11(1.11)	1	0.09	0.09	85	85
Jul.13. 2015	2	0.07±0.01	0.06(1.26)	1	0.07	0.07	104	105
Aug. 7. 2015	3	0.13±0.04	0.12(1.36)	2	0.07±0.06	0.05	54	42
Aug.21. 2015	3	0.02±0.01	0.02(2.27)	0	-	-	-	-
Oct. 5. 2015	3	0.08±0.04	0.08(1.58)	2	0.06±0.02	0.06(1.32)	78	82
Oct. 6. 2015	3	0.08±0.03	0.07(1.58)	1	0.07	0.07	94	100
Date	Korean native cattle farm						b/a (%)	
	TSP (a)			PM10 (b)			AM	GM
	n	AM±SD	GM±GSD	n	AM±SD	GM±GSD		
Jun.23. 2015	2	0.26±0.10	0.25(1.50)	2	0.24±0.08	0.23(1.41)	91	92
Jul.13. 2015	2	0.13±0.03	0.13(1.26)	2	0.07±0.02	0.07(1.30)	58	58
Aug. 7. 2015	2	0.32±0.12	0.31(1.45)	2	0.18±0.03	0.18(1.16)	56	58
Aug.21. 2015	2	0.13±0.12	0.10(3.15)	1	0.1	0.10	80	108

Oct. 5. 2015	2	0.28±0.00	0.28(1.01)	2	0.20±0.03	0.20(1.16)	72	72
Oct. 6. 2015	2	0.29±0.22	0.25(2.33)	2	0.06±0.05	0.05(2.41)	22	22

n refers to number of subject.

Tables 5-2 and 5-3 show the monitoring results of the TSP and PM10 concentrations during work activities such as TMR processing and milking processing in the experimental dairy cattle farm and Korean native cattle farms, respectively.

Table 5-2 Overall monitoring results of TSP and PM10 measured during working activities such as TMR and milking processing in the experimental dairy cattle farm
(Unit: mg/m^3).

Date	TMR processing						b/a (%)	
	TSP (a)			PM10 (b)			AM	GM
	n	AM±SD	GM(GSD)	n	AM±SD	GM(GSD)		
Jun.23. 2015	2	0.79±0.26	0.77(1.39)	2	0.46±0.10	0.45(1.26)	58	59
Jul.13. 2015	2	0.38±0.05	0.37(1.15)	2	0.05±0.00	0.05(1.00)	15	15
Aug. 7. 2015	2	0.41±0.25	0.36(1.96)	2	0.07±0.03	0.07(1.63)	17	18
Aug.21. 2015	2	0.15±0.07	0.15(1.62)	2	0.05±0.02	0.05(1.53)	32	32
Oct. 5. 2015	1	0.18	0.18	1	0.07	0.07	41	41
Oct. 6. 2015	2	0.27±0.15	0.24(1.85)	1	0.19	0.19	70	77
Date	Milking processing						b/a (%)	
	TSP (a)			PM10 (b)			AM	GM
	n	AM±SD	GM(GSD)	n	AM±SD	GM(GSD)		
Jun.23. 2015	2	0.140.04	0.14(1.35)	2	0.140.05	0.14(1.40)	102	101
Jul.13. 2015	1	0.09	0.09	1	0.09	0.09	98	98
Aug. 7. 2015	2	0.070.06	0.06(2.39)	2	0.06±0.07	0.03(6.43)	85	51
Aug.21. 2015	2	0.070.07	0.05(3.66)	2	0.02±0.02	0.01(2.92)	27	30
Oct. 5. 2015	2	0.120.00	0.12(1.02)	2	0.07±0.01	0.07(1.17)	57	57
Oct. 6. 2015	2	0.270.03	0.27(1.13)	2	0.19±0.06	0.19(1.37)	72	71

n refers to number of subject.

Table 5-3 Overall monitoring results of TSP and PM10 measured during working activities such as TMR processing in the experimental Korean native cattle farm (Unit: mg/m^3).

Date	TMR processing						b/a (%)	
	TSP (a)			PM10 (b)			AM	GM
	n	AM±SD	GM(GSD)	n	AM±SD	GM(GSD)		
Jun.23. 2015	2	3.04±1.50	2.85(1.67)	2	0.36±0.43	0.20(5.51)	12	7
Jul.13. 2015	2	0.65±0.53	0.53(2.57)	2	0.23±0.17	0.20(2.23)	35	37
Aug. 7. 2015	2	1.81±0.13	1.81(1.08)	2	0.88±0.00	0.88(1.00)	48	49
Aug.21. 2015	2	5.90±6.45	3.74(4.28)	2	1.35±1.24	1.03(2.99)	23	27
Oct. 5. 2015	2	10.38±10.75	7.06(3.75)	2	5.58±4.67	4.50(2.61)	54	64

n refers to number of subject.

In this thesis, relatively lower values were generally found in the area sampling of the TSP and PM10 concentrations according to the measurement location and work activities in the experimental dairy cattle farm and the Korean native cattle farm in contrast to the experimental results from the nursery pig and broiler houses. An excessive occupational exposure limit for inhalable and respirable particulates when considering the respiratory health of livestock farmers and animals were occasionally found according to specific situations, which include the feed supply, work activities of farmers and the increase in animal activities in the experimental nursery pig house and broiler houses. However, those specific situations were seldom observed in the two experimental cattle farms. The excessiveness of the mentioned situations was partially observed in area sampling from the Korean native cattle farm during TMR processing. The recommended occupational exposure limit of the organic dust when considering the respiratory welfare of cattle farmers has not been reported. Thus, the occupational exposure limits for pig farmers (2.5 mg/m^3 for inhalable particulate fractions and 0.23 mg/m^3 for respirable particulate fractions) were used to evaluate the potential risk of respiratory health of workers as a reference. Table 5-4 briefly shows the measured results of mean TSP and PM10 concentrations from the nursery pig house, fattening pig house (Kwon et al., 2013), mechanically ventilated broiler house, naturally ventilated broiler house, dairy cattle farm and Korean native cattle farm during all experimental periods. Arithmetic mean values of TSP and PM10 were listed regardless of the seasonal changes.

Table 5-4 Comparison of average values of TSP and PM10 concentrations according to species (Unit: mg/m^3).

	Nursery pig house		Fattening pig house*	
	TSP	PM10	TSP	PM10
Ave.	1.15±0.48	0.63±0.32	0.61±0.28	0.41±0.18
	Mechanically ventilated broiler house		Naturally ventilated broiler house	
	TSP	PM10	TSP	PM10
Ave.	1.29±1.02	1.00±0.78	1.14±0.62	0.78±0.64
	Dairy cattle farm		Korean native cattle farm	
	TSP	PM10	TSP	PM10
Ave.	0.09±0.05	0.08±0.02	0.23±0.08	0.14±0.07

Ave. refers to averaged value

Data of fattening pig house (Kwon et al., 2013)

For example, Table 5-4 shows that the measured TSP and PM10 concentrations from area sampling in the dairy cattle farm occupied 7.8 and 12.9% of the results from the nursery pig house, 14.6 and 20.0% of the results from the fattening pig house, 6.9 and 8.1% of the results from the mechanically ventilated broiler house and 7.9 and 10.4% of the results from the naturally ventilated broiler house. TSP and PM10 concentrations from the Korean native cattle farm were 256 and 175% higher than those from the dairy cattle farm. However, the measured results were still lower than other livestock species as mentioned above. These observations corresponded with the results of Takai et al. (1998) who commented that relatively lower level of particulates were generally observed in the cattle farm in contrast to other livestock species. Therefore, it could be interpreted that the potential risk of being exposed to a harmful dust environment in a cattle farm might be lower than other livestock species. However, contradictory experimental results were also found in real-time measurement of occupational dust in a specific experimental situation, such as TMR processing. Details will be discussed in Section 5.3.3. Figure 5-11 shows example results of TSP and PM10 concentrations according to the measurement location and work activities measured in June (a) and October (b) of 2015 in the experimental dairy cattle farm.

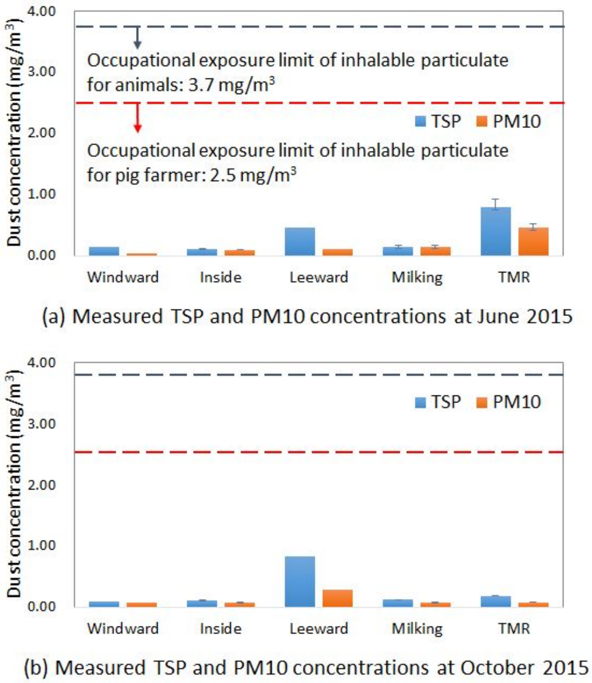


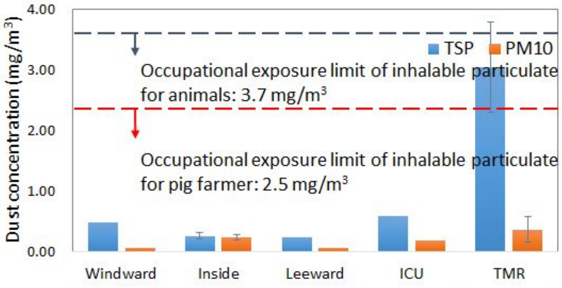
Figure 5-11 Measured TSP and PM10 concentrations according to measurement locations and working places in experimental dairy cattle farm.

The westerly prevailing wind series were mostly observed from a portable weather station that was installed in open terrain near the experimental dairy cattle farm. Based on the results from the windward location in June 2015, about 3.29 and 2.75 times higher TSP (0.46 mg/m^3) and PM10 (0.11 mg/m^3) concentrations were observed at the leeward measurement location (Figure 5-11 (a)). In the case of the results from monitoring in October 2015 (Figure 5-11 (b)), 9.11 times higher TSP concentration (0.82 mg/m^3) and 4.00 times higher PM10 concentration (0.28 mg/m^3)

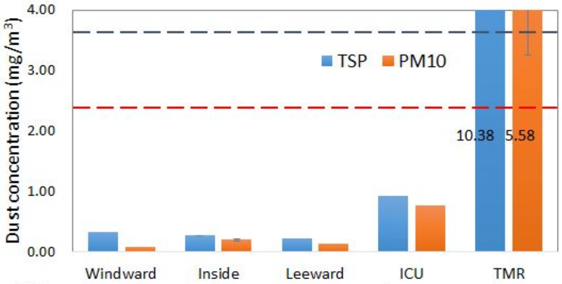
were found at the leeward location in contrast to the results from the windward location. The floor surface of the stalls for the mature dairy cattle located near the windward area was covered with concrete materials and usually under wet conditions. Water cleaning after the milking process to remove fecal residues above the ground occurred two times per day. However, the floor surface of stalls for rearing calves was composed of loose soil type beds, including saw dust and dried feces. Thus, the potential of dust generation might be higher than the aforementioned dairy stalls. Hoof actions due to the movement of the calves usually generates plenty of dust in the airspace. The dust was dispersed enough to be observed by the naked eye. A list of facts could support the results of higher observations at the leeward regions of the experimental dairy cattle farms. These observed tendencies also corresponded with the results of many preceding studies (Purdy et al., 2009). TSP and PM10 concentrations at the leeward location measured in October 2015 (Figure 5-11 (a)) were 178 and 254% higher than those measured at the identical location in June 2015. In the case of environmental variables, the mean air temperature (27.7℃), mean relative humidity (71.2%) and mean water content level ($17.6\pm2.7\%$), which were randomly sampled from the top soils of bedding materials in stalls for rearing calves, were recorded in June 2015. However, mean air temperature (19.6℃), relative humidity (55.7%) and water content level for bedding materials ($16.3\pm3.5\%$) were recorded in October 2015. There were no significant differences between the measured water content levels ($p>0.05$). However, about 30% of the relative humidity level was steadily recorded after 1:00 pm in October 2015, which meant that dry conditions were favorable for dust generation. In addition, frequent accesses by veterinarians and farmers were observed due to the activities related to the birthing process in October 2015. These work activities caused an increase in the activities of the animals and might also contribute to a higher dust concentration near the leeward regions. From the mentioned observations, the leeward regions of cattle farms might be risky areas for the respiratory health of farmers. Therefore, farmers at the mentioned locations could be exposed to a harmful dust environment during work activities that are related to management of the facilities and checking the status of animals.

In the case of TSP and PM10 concentration measured in June 2015, the highest values were obtained near the TMR machine despite the short-term sampling (0.79 mg/m^3, 0.46 mg/m^3). The results were 5.64 and 3.29 times higher than the results from the milking house. An excessive occupational exposure limit was not found. However, there were possibilities of being exposed to a dustier environment during TMR processing. Relatively lower TSP (0.14 mg/m^3) and PM10 (0.14 mg/m^3) concentrations were observed in the milking house (June 2015). These results might be presumed effects of moist or damp conditions in the air space. For example, the relative humidity level inside the milking house in June 2015 was about 93.7%, which increased and peaked gradually to 95.1%, and then decreased again as the milking process progressed. These could be explained by the influences of fecal and urine materials on the ground surface, the exhalation emitted by dairy cattle and the regular breast washing before and after the milking process for each dairy cattle. A relatively lower dust level was also observed during other experimental periods. It could be estimated that humid micro-climate conditions for the mentioned situations might have a negative impact on the degree of dust generation.

Figure 5-12 shows example results of TSP and PM10 concentrations according to the measurement location and work activity measured in June (a) and October (b) of 2015, respectively, in the experimental Korean native cattle farm.



(a) Measured TSP and PM10 concentrations at June 2015



(b) Measured TSP and PM10 concentrations at October 2015

Figure 5-12 Measured TSP and PM10 concentrations according to measurement locations and working place in experimental Korean native cattle farm.

The results of the TSP and PM10 concentrations were more complex than those of the experimental dairy cattle farm. For example, the measured TSP concentration at the windward location was 2.1 times higher than that of the leeward location (0.23 mg/m^3). However, PM10 concentration of an identical value (0.06 mg/m^3) was found at both windward and leeward locations in June 2015 (Figure 5-12 (a)). For the results from the experiment conducted in October 2015 (Figure 5-12 (b)), TSP concentration at the windward location (0.32 mg/m^3) was slightly higher than that of the leeward location (0.23 mg/m^3). However, PM10 concentrations at the windward and leeward locations were 0.09 and 0.14 mg/m^3, respectively. The prevailing wind direction near the experimental Korean native cattle farm was the north wind series in October 2015. The pre-designed measurement location according to the prevailing wind direction did not coincide with the wind environment at that time. However, unusual tendencies were observed in the experiment conducted in June 2015 even though the arrangement of pre-designed measurement locations (i.e., windward and leeward) were in agreement with the prevailing wind direction of the westerly wind series at that time. These phenomena could be explained by the specific experimental situation of the Korean native cattle farm. A bundled straw wall was built near the ICU stall located at the windward region location to prevent the direct chilling effect of strong winds on weak calves. Thus, due to the disturbance of smooth air exchange, recirculated airflow and generation of backflow could be predicted at these mentioned areas. The observation of a relatively higher level of dust concentration near the ICU stall could be demonstrated by these situations.

In the case of the measurement results near the stationary TMR machine, relatively higher dust concentrations of TSP of 3.04±0.75 mg/m^3 and PM10 of 0.36±0.21 mg/m^3 in June 2015, and TSP of 10.38±5.38 mg/m^3 and PM10 of 5.58±2.33 mg/m^3 in October 2015 were found in comparison to other measurement locations. The TSP concentrations in June 2015 and October 2015 went beyond the recommended level for pig farmers by 122 and 415%, respectively. These tendencies in the experimental Korean native cattle farm were strongly related to the operation process of the TMR machine and the mechanism of feed supply. Details will be discussed in Section 5.3.3.

5.3.2. Periodic monitoring of inhalable and respirable particulate

Table 5-5 shows the monitoring results of inhalable and respirable particulates at the middle passage of the facility, and the windward and leeward locations in the experimental dairy cattle farm.

Table 5-5 Overall monitoring results of inhalable and respirable particulate at middle passage of the facility, windward area and leeward area in the experimental dairy cattle farm (Unit: mg/m^3).

Date	Middle passage of the facility					
	Inhalable particulate (a)		Respirable particulate (b)		b/a (%)	
	AM±SD	GM(GSD)	AM±SD	GM(GSD)	AM	GM
Sep.24. 2013	0.08±0.01	0.08(1.11)	0.05±0.00	0.05(1.04)	65	65
Oct. 1. 2013	0.00±0.00	0.00(1.13)	0.00±0.00	0.00(1.08)	77	78
Oct.14. 2013	0.07±0.00	0.07(1.05)	0.06±0.00	0.06(1.01)	76	76
Dec. 3. 2013	0.06±0.01	0.06(1.28)	0.01±0.00	0.01(1.05)	21	22
Dec.10. 2013	0.24±0.05	0.23(1.23)	0.04±0.00	0.04(1.07)	16	17
Dec.20. 2013	0.24±0.04	0.23(1.19)	0.03±0.00	0.03(1.10)	11	11
Date	Windward location					
	Inhalable particulate (a)		Respirable particulate (b)		b/a (%)	
	AM±SD	GM(GSD)	AM±SD	GM(GSD)	AM	GM
Sep.24. 2013	0.06±0.01	0.06(1.16)	0.05±0.00	0.05(1.03)	81	82
Oct. 1. 2013	0.02±0.00	0.02(1.15)	0.02±0.00	0.02(1.13)	92	96
Oct.14. 2013	0.09±0.02	0.09(1.30)	0.06±0.00	0.06(1.02)	63	96
Dec. 3. 2013	0.01±0.00	0.01(1.22)	0.01±0.00	0.01(1.02)	70	82
Dec.10. 2013	0.06±0.01	0.06(1.26)	0.03±0.00	0.03(1.01)	53	87
Dec.20. 2013	0.04±0.00	0.04(1.11)	0.03±0.00	0.03(1.06)	72	92
Date	Leeward location					
	Inhalable particulate (a)		Respirable particulate (b)		b/a (%)	
	AM±SD	GM(GSD)	AM±SD	GM(GSD)	AM	GM
Sep.24. 2013	2.74±1.51	2.33(1.82)	0.05±0.01	0.05(1.17)	2	2
Oct. 1. 2013	0.26±0.02	0.26(1.07)	0.07±0.00	0.07(1.01)	28	28
Oct.14. 2013	0.17±0.03	0.16(1.18)	0.03±0.00	0.03(1.02)	19	19
Dec. 3. 2013	0.61±0.08	0.60(1.15)	0.04±0.00	0.04(1.01)	6	6
Dec.10. 2013	1.23±0.12	1.23(1.10)	0.01±0.00	0.01(1.06)	1	1
Dec.20. 2013	1.66±0.12	1.65(1.08)	0.03±0.00	0.03(1.03)	2	2

Figure 5-13 shows the results of inhalable and respirable particulate concentrations from the experimental dairy cattle farm in July and August 2015. Results of 53.4 and 19.7 times higher concentration of inhalable particulates than those of the windward location were found at the leeward measurement location, which is similar to the noted TSP and PM10 observations. However, there were no significant differences in the measured respirable particulate fractions in July 2015 (0.04 and 0.06 mg/m^3) and August 2015 (0.02 and 0.04 mg/m^3) according to the measurement location (i.e., windward and leeward regions).

The peak values in both inhalable and respirable particulate fractions were generally observed inside the stalls for rearing calves. 126.1 and 8.75 times higher inhalable and respirable particulate concentrations were especially observed in the inside stalls in contrast to the results from the aisle (height of average respiratory intake of the workers) in July 2015 as shown in Figure 5-13 (a) and (b). These observations could be estimated by the increase in dust generation rate due to the frequent hoof actions on the bedding materials by rearing calves. These observations were also strongly related to the measured values at the leeward location, which was caused by the influences of loose soil type bedding materials and the activities of calves inside the stalls. Predominant variations in dust concentrations were found for inhalable particulate fractions. It could be concluded that the activities of livestock were more likely to affect the dispersion of particulates with larger AED. These mentioned tendencies agreed closely with Pearson & Sharples (1995) with respect to the behavior of the larger particulates in a pig house, and the observations in this thesis from the experimental nursery pig house and the mechanically and naturally ventilated broiler houses.

For a comparison of occupational exposure limits of inhalable and respirable particulates with the respiratory health of pig farmers, excesses of 107 and 404% for inhalable particulate fractions were observed at the leeward location (2.67±1.15 mg/m^3) and the inside stalls for rearing calves (10.09±2.51 mg/m^3), respectively in July 2015. For measured respirable particulate fractions on an identical experimental date, the dust concentration from the stalls (0.35±0.19 mg/m^3) was approximately

152% higher than the recommended concentration. From the experiments conducted in July 2015, an excess of 272% was found in the inside stalls when considering the recommendation of inhalable particulates for animals. However, no excesses were found for the level of workers and animals in October 2015.

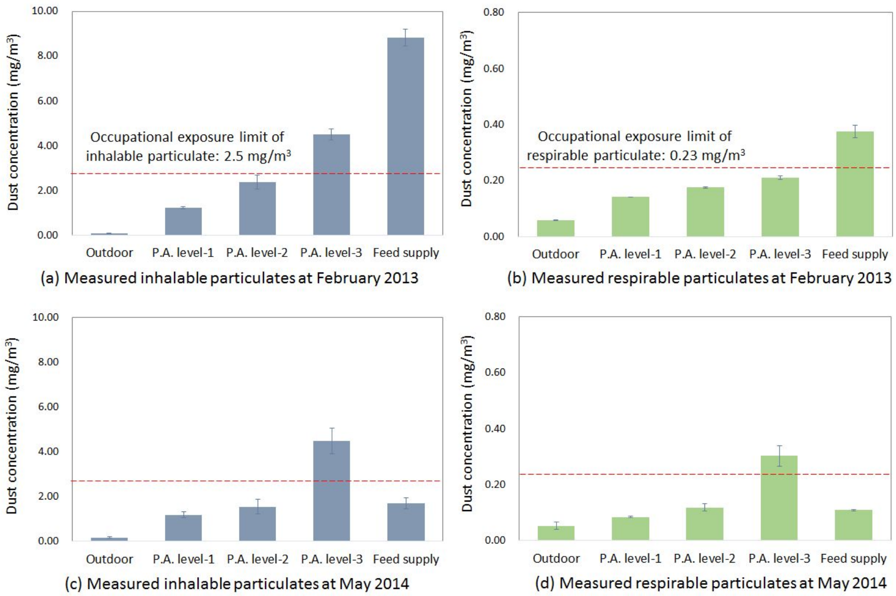


Figure 5-13 Measured inhalable and respirable particulates according to measurement locations in experimental dairy cattle farm at July 2015 ((a) and (b)) and August 2015 ((c) and (d)).

As noted earlier, relatively higher dust concentrations for both fractions were generally found at the leeward location and inside the stalls for rearing calves due to the dust potentials of loose bedding materials and hoof actions of animals. Figure 5-14 depicts the trends of inhalable and respirable particulate concentrations at the leeward location and stalls versus water content levels of bedding materials during all experimental periods. A reverse linear trend between the variables was found for the inhalable particulate fractions from the leeward location (R^2=0.44) and stalls (R^2=0.67), respectively. However, specific trends were not observed for the respirable particulate fraction from the leeward location (R^2=1.0e-05) and stalls (R^2=0.21), respectively. These observations could also imply the possibility of controlling dust generation through managing the status of the bedding materials. However, an absolute increase of the water content of bedding materials is strongly related to the proliferation of micro-organisms such as endotoxin as noted in the results parts for the chamber experiment using bedding materials at broiler houses (Section 4.3.7.). Thus, biological and chemical approaches must take precedence in order to investigate the relationship between water content level in the beds and health effects on workers and animals. From the results of the chamber experiment for bedding materials in a broiler house, a water content level of 45% was suggested as a threshold level for the generation of the inhalable particulate fractions. However, about 70% was referred for bedding materials in dairy cattle farms. Bedding materials in cattle farms were usually composed of fine particulates such as saw dust and dried fecal materials, while bedding materials in broiler houses were generally composed of rice husks, and floating leaves, which have relatively larger AED. Therefore, the composition of bedding materials and their size might affect the degree of dust generation according to the level of water content. Related future studies are still needed to introduce proper management plans and strategies for controlling the generation of dust.

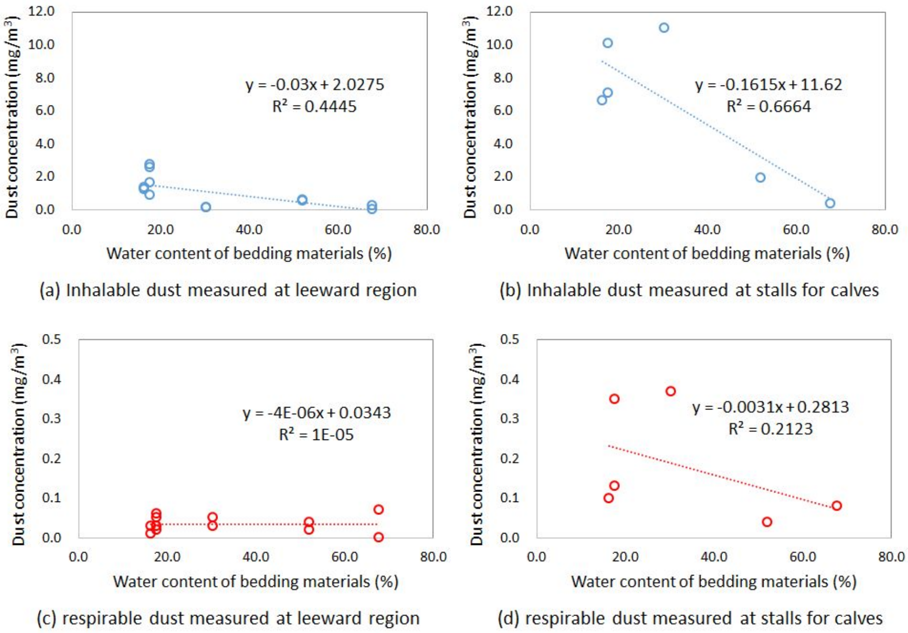


Figure 5-14 Measured occupational dust versus water contents of bedding materials in experimental dairy cattle farm.

Table 5-6 shows the monitoring results of inhalable and respirable particulates at the middle passage of the facility, and the windward and leeward locations in the experimental Korean native cattle farm.

Table 5-6 Overall monitoring results of inhalable and respirable particulate at middle passage of the facility, windward area and leeward area in the experimental Korean native cattle farm (Unit: mg/m^3).

Date	Middle passage of the facility					
	Inhalable particulate (a)		Respirable particulate (b)		b/a (%)	
	AM±SD	GM(GSD)	AM±SD	GM(GSD)	AM	GM
Sep.24. 2013	0.60±0.38	0.52(1.69)	0.08±0.02	0.08(1.22)	13	15
Oct. 1. 2013	0.14±0.01	0.14(1.06)	0.12±0.00	0.12(1.02)	86	86
Oct.14. 2013	0.19±0.15	0.15(1.98)	0.06±0.01	0.06(1.20)	34	43
Dec. 3. 2013	0.09±0.04	0.08(1.47)	0.06±0.00	0.06(1.04)	61	66
Dec.10. 2013	0.51±0.26	0.42(2.12)	0.03±0.01	0.03(1.31)	6	7
Dec.20. 2013	0.23±0.37	0.13(2.57)	0.03±0.01	0.03(1.17)	13	23
Date	Windward location					
	Inhalable particulate (a)		Respirable particulate (b)		b/a (%)	
	AM±SD	GM(GSD)	AM±SD	GM(GSD)	AM	GM
Sep.24. 2013	0.04±0.01	0.04(1.13)	0.04±0.00	0.04(1.04)	91	92
Oct. 1. 2013	0.00±0.00	0.00(1.16)	0.00±0.00	0.00(1.15)	77	96
Oct.14. 2013	0.06±0.01	0.06(1.17)	0.05±0.00	0.05(1.05)	85	60
Dec. 3. 2013	0.06±0.00	0.06(1.07)	0.05±0.00	0.05(1.05)	96	71
Dec.10. 2013	0.08±0.04	0.07(1.80)	0.02±0.01	0.02(1.39)	23	62
Dec.20. 2013	0.03±0.03	0.03(1.54)	0.02±0.00	0.02(1.10)	66	45
Date	Leeward location					
	Inhalable particulate (a)		Respirable particulate (b)		b/a (%)	
	AM±SD	GM(GSD)	AM±SD	GM(GSD)	AM	GM
Sep.24. 2013	0.40±0.26	0.32(2.09)	0.06±0.01	0.06(1.12)	14	17
Oct. 1. 2013	0.42±0.41	0.31(2.10)	0.10±0.00	0.10(1.02)	24	33
Oct.14. 2013	1.15±1.55	0.84(1.97)	0.08±0.04	0.08(1.37)	7	9
Dec. 3. 2013	0.33±0.16	0.29(1.70)	0.05±0.00	0.05(1.08)	16	18
Dec.10. 2013	0.93±1.82	0.24(5.00)	0.04±0.03	0.04(1.47)	4	16
Dec.20. 2013	0.20±0.13	0.17(1.77)	0.07±0.00	0.07(1.07)	34	40

Figure 5-15 shows the results of inhalable and respirable particulate concentrations from experimental Korean native cattle farm in July and August 2015. Due to the safety issues, dust measurements from the inside stalls were not carried out after consultation with the farm owner. The results of 6.6 and 5.6 times higher concentrations of inhalable particulates were found at the leeward locations in comparison with the results from windward locations, respectively. However, clear differences in respirable particulate fractions were not observed according to the measurement location with respect to the direction of prevailing winds in July (0.04 and 0.06 mg/m^3) and August 2015 (0.04 and 0.06 mg/m^3). Relatively high concentrations of inhalable particulates were also found at the ICU stall for weak calves in July 2015 (5.76 ± 2.88 mg/m^3) and August 2015 (1.31 ± 0.52 mg/m^3). However, distinct differences in respirable particulate fractions were not found in July 2015. The reasons for showing higher dust concentrations near the ICU stall were already commented in the above section. In other words, thermal comfort for weak calves could be anticipated by installing bundled straw stacks near the ICU stall. However, accumulation of contaminant due to the unfavorable air exchange might also happen as a trade-off.

For a comparison of occupational exposure limits with the respiratory health of pig farmers, the excess average 128% for inhalable particulate fractions was observed at the ICU stall (3.21 ± 5.76 mg/m^3) and their variations were relatively larger (max=23.04 mg/m^3) in July 2015. From this observation, it could be concluded that the work activities in the space where unfavorable air exchange could be expected, such as the ICU stall, might be critical to the respiratory health of workers. On the contrary, measurement results of inhalable particulates at the ICU stall in August 2015 did not exceed the recommendation for both workers and animals. In the case of respirable particulate fractions during all experimental periods, excesses of the recommendation were not found.

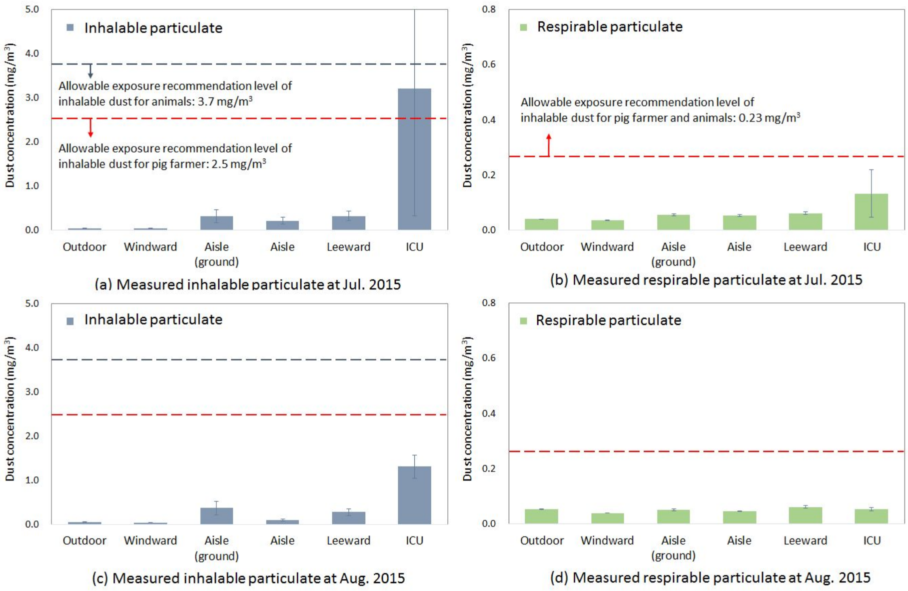
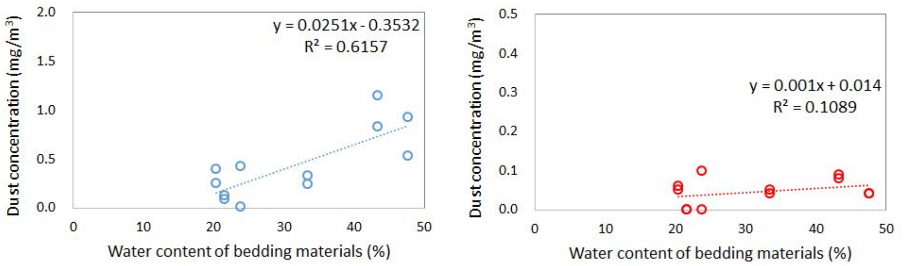


Figure 5-15 Measured inhalable and respirable particulates according to measurement locations in experimental Korean native cattle farm at July 2015 ((a) and ((b) and August ((c) and (d)).

Figure 5-16 shows the trends of inhalable and respirable particulate concentrations at the leeward location versus the water content levels of bedding materials at the Korean native cattle farm during all experimental periods. For a comparison to the results from the experimental dairy cattle farm, linear progression of inhalable particulate was found according to the increase in water content levels in the bedding materials (R^2=0.62). However, no specific trends for respirable particulate fractions were observed (R^2=0.11). These unusual tendencies could be explained by the experimental situations in the target facility. As shown in Figure 5-8 (b), low hills covered with vegetation were located 1.2~1.4 m above the ground on the boundaries of the farms (leeward side). These topographical characteristics at the leeward side of the farm might be a windbreak for preventing the dispersion of airborne contaminants. This could be explained by the observations of accumulated particulates on the surface of vegetation at the lower parts of the hills. When I consider these experimental situations at the Korean native cattle farm, dispersed particulates from the bedding materials of stalls were initially accumulated on the surface of the vegetation at the leeward side. These accumulated particulates could then be dispersed again by wind blowing effects. Therefore, it could be concluded that the results given in Figure 5-16 (a) might be affected by the disturbance effect of vegetation.



(a) Inhalable dust measured at leeward region (b) Respirable dust measured at leeward region

Figure 5-16 Measured occupational dust versus water contents of bedding materials in experimental Korean native cattle farm.

5.3.3. Inhalable and respirable particulate according to worker' s activities

TMR processing such as mixing and distribution of various feed stuffs was generally carried out for 2 hours every early morning in the experimental dairy cattle farm. Various feed materials were supplied into the TMR machine in sequential order. Table 5-7 shows the mean diameter of each spherical feed material (d50) measured through a sieving test (KS F 2502 method) and Malvern Mastersizer (MS3000, Malvern Instrument Ltd., UK) for the experimental dairy cattle farm. If the feed particles had geometrical shape of elongated type (i.e., pellet and rice straw), average longitudinal length was alternatively measured. # 2 feed materials were composed of foam of powder such as, silicate, sodium and probiotics. These fine particulates were manually loaded into a handcart by workers and then supplied to the TMR machine. # 1 (rice straw), # 3 (corn) and # 5 (cotton seed hull pellet) feed materials were directly supplied into the TMR machine, while # 4 (mixture of rice straw, corn and beans) feed materials for mature dairy cattle were regularly and directly supplied from vehicles of the Korean Federation of Livestock. Distribution of mixed TMR feed materials was automatically carried out along the rails installed at the central aisle of the farm.

Table 5-7 Representative feed materials used in experimental dairy cattle farm and their information.

No.	Type	Information	d50 (mm)
# 1	Rice straw	Dried rice straw, feed components Development of ruminant stomach Energy source	2.77*
# 2	Additives	Silicate: enhancement of immune system Sodium: promotion of urinary calculus discharging Probiotics: reduction of odor strength, improvement of digestion effectiveness, and etc.	0.06 0.06 0.38
# 3	Corn	Feed components	6.58
# 4	Mixture of rice straw, corn and beans	Supplied from Korean Federation of Livestock Cooperatives, feed materials for mature dairy cattle	-
# 5	Cotton seed hull pellet	Feed components	34±2.3**

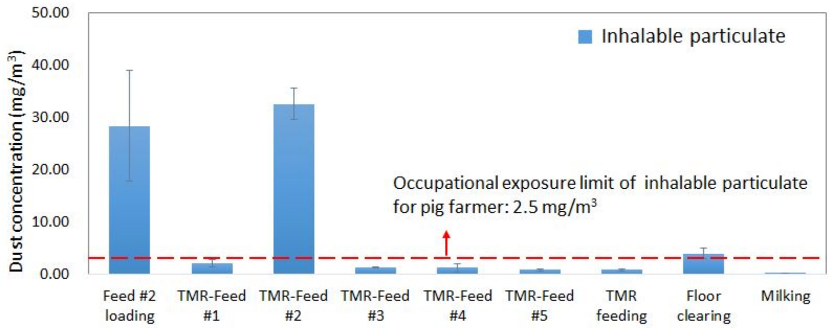
* Mean length of randomly sampled fragment of rice straws

** Mean length of randomly sampled pellets

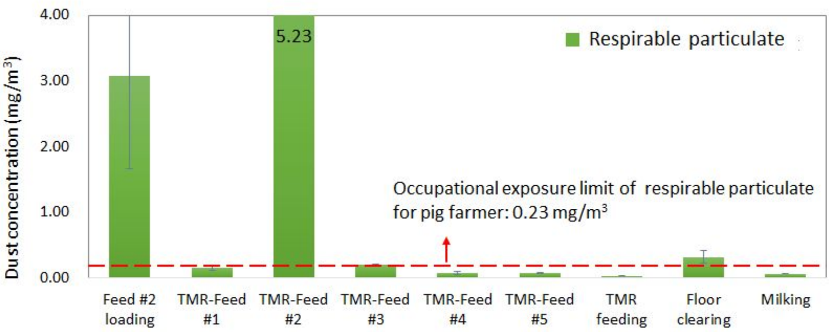
Figure 5-17 and Tables 5-8 and 5-9 show the measured inhalable and respirable particulate concentrations according to TMR processing and work activities during all experimental periods at the experimental dairy cattle farm. Each value plotted in Figure 5-17 refers to the observed maximum value during the experimental period. As shown in Figure 5-17, relatively higher concentration of inhalable particulates were observed during the work activities related to the # 2 feed materials, such as the loading of powder materials in the handcart (28.39±21.17 mg/m^3) and loading into the TMR machine using an inclined rail (32.54±5.99 mg/m^3). Excesses of 11.4 and 13.0 times than the occupational exposure limit of inhalable particulates were detected for mentioned situations related to the # 2 feed materials, respectively. The maximum concentration of inhalable particulates during the real-time measurement was 72.78 mg/m^3 for the loading of # 2 feed materials in the handcart, and 39.83 mg/m^3 for loading into the TMR machine. A cloud of dust was seen by the naked eye during the mentioned work activities. In the case of respirable particulates, there was an excess of 13.4 (3.08±2.83 mg/m^3) and 22.7 (5.23±1.45 mg/m^3) times for recommendation level for respirable particulate fractions when considering the respiratory health of workers. Therefore, the possibility of manifestation of instantaneous respiratory symptoms such as frequent cough, stuffiness and sore throats might be dramatically increased during work activities with very fine particulates (~0.38 μm). On the contrary, in the case of work related to # 1, 3, 4 and 5 feed materials of whose AED were relatively larger, the momentary excesses of the recommendation level for inhalable and respirable particulate were occasionally found, but the mean dust concentrations were below the occupational exposure limits for both dust fractions.

The workers usually swept away feed residues on the ground surface for 5~10 minutes after the termination of TMR processing. An average 4.00±1.98 mg/m^3 of inhalable particulates (1.6 times higher than the recommendation level) and 0.31±0.19 mg/m^3 of respirable particulates (1.3 times higher) were found. During the milking process, maximum inhalable particulates (0.35 mg/m^3) and respirable particulates (0.07 mg/m^3) were observed. As noted earlier, the relative humidity level was maintained above 90% due to the frequent breast washing process of dairy cattle before and after the automatic milking process. It could be concluded that the potential of dust generation from the wet surface inside the milking house were considerably eliminated.

In contrast to the results of monitoring occupational dust by measurement location, frequent excesses of the recommendation levels were found during work activities at the dairy farm. The values exceeded the results from the experimental nursery pig and the broiler houses. However, two farmers in the experimental dairy cattle farm did not wear a respiratory mask and they developed frequent dry cough and phlegm during the work activities related to # 2 feed materials. Therefore, wearing personal protective equipment must be recommended for these situations and introducing effective dust control strategies are needed.



(a) Inhalable particulate according to feed materials during TMR processing and working activities



(b) respirable particulate according to feed materials during TMR processing and working activities

Figure 5-17 Measured occupational dust concentrations according to kinds of feed materials during TMR processing and working activities in experimental dairy cattle farm.

Table 5-8 Measured maximum inhalable particulate concentrations according to working activities in dairy cattle farm during all experimental periods (Unit: mg/m^3).

	# 2 loading	# 1 feed	# 2 feed	# 3 feed	# 4 feed
Max.	78.78	3.64	39.83	1.97	6.21
Min.	1.47	0.06	24.49	1.10	0.24
Mean	28.4±21.2	2.1±1.2	32.5±6.0	1.3±0.2	1.3±1.6
	# 5 feed	TMR feeding	Floor clearing	Milking	
Max.	1.61	1.44	8.12	0.35	
Min.	0.45	0.10	1.85	0.14	
Mean	0.9±0.4	0.8±0.4	4.0±2.0	0.2±0.1	

Table 5-9 Measured maximum respirable particulate concentrations according to working activities in dairy cattle farm during all experimental periods (Unit: mg/m^3).

	# 2 loading	# 1 feed	# 2 feed	# 3 feed	# 4 feed
Max.	10.59	0.25	7.33	0.26	0.30
Min.	0.20	0.03	3.61	0.17	0.03
Mean	3.08±2.83	0.15±0.08	5.23±1.45	0.20±0.03	0.07±0.06
	# 5 feed	TMR feeding	Floor clearing	Milking	
Max.	0.09	0.04	0.73	0.07	
Min.	0.06	0.02	0.10	0.05	
Mean	0.07±0.01	0.03±0.01	0.31±0.19	0.06±0.00	

In the experimental Korean native cattle farm, TMR processing, including mixing and distribution of feed materials was carried out once every four days. A stationary TMR machine was used to mix the feed materials in sequential order. The distribution of mixed feeds was manually conducted by the farmer with the help of handcarts. Table 5-10 shows the feed material information used at the experimental Korean native cattle farm.

Table 5-10 Representative feed materials used in Korean native cattle farm and their information.

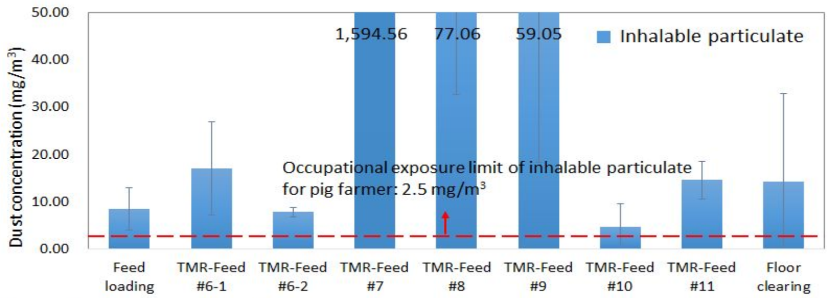
No.	Type	Information	d50 (mm)
# 6-1	Puffed grain	Supply of carbohydrate materials Supplied using large size gunnysack	3.56
# 6-2	Puffed grain	Supply of sugar and carbohydrate contents Supplied using long plastic bag	3.56
# 7	Pulverized corn	Feed components	1.95
# 8	Pulverized wheat brp	Supply of vitamin B and E	0.58
# 9	Additives	Probiotics Lime Tofu Pureed soybean soup	0.38 - - -
# 10	Rice straw	Feed components	-
# 11	Rice flour and snack	Supply of sugar and carbohydrate contents	-

6 feed materials (puffed grain) were usually supplied by using large size gunny sacks and long plastic bags. The dust measurement was conducted according to the supply method. Most feed materials were generally supplied by means of free falling. After hanging the bags filled with feed materials in the air above the TMR machine, the cattle farmer would cut the bottom of the hanging bags, and then the feed materials were directly supplied into the stationary TMR machine.

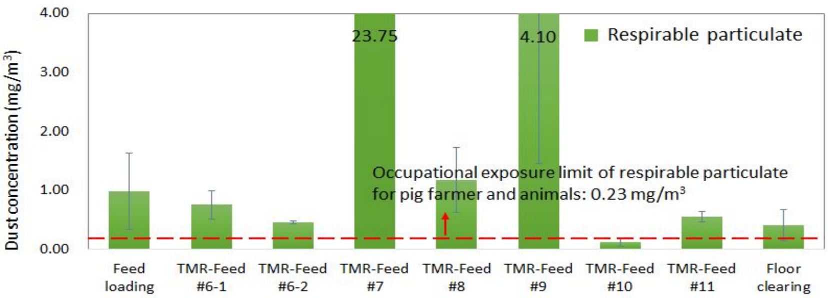
Figure 5-18 and Tables 5-11 and 5-12 show the measured inhalable and respirable particulate concentrations according to TMR processing and work activities during all experimental periods at Korean native cattle farm. Each value plotted in Figure 5-18 refers to the observed maximum value during the experimental periods. As shown in Figure 5-18, measured inhalable and respirable particulate concentrations exceeded the occupational exposure limits according to the kinds of feed materials and work activities. In the case of # 6 feed materials, maximum inhalable particulate of 109.64 mg/m^3 was observed when the feed materials were supplied using large size gunnysacks by means of “free falling.” However, approximately 46% of that was found when the feed materials were supplied using a long plastic bag. This might be caused by the differences of the falling distance from the bags to the TMR. Similar tendencies were found in Section 3.3.4. for the effect of installation height of the feed supply pipe on dust generation in the experimental nursery pig house.

Considerably higher inhalable particulate concentrations were observed (mean=1,594.56$\pm$1,375.23 mg/m^3 and maximum=5,317.67 mg/m^3) during the supply of # 7 feed materials (pulverized corn) whose mean diameter (d50) was 1.95 mm. There was an excess of 637.8 times the recommended inhalable particulate concentration for pig farmers. During TMR processing for these particulates, a dust cloud was seen by the naked eye and the deposition of particulates on the outer surface of the TMR machine and the shoulder of workers were also easily found. From an interview with a cattle farmer, he commented that eye irritation, frequent dry cough, and phlegm symptoms were always induced after the work activities related to fine particulates. Inhalable particulate concentrations of 77.06$\pm$88.83 mg/m^3 (excess of 30.8 times for recommendation) and 59.05$\pm$81.54 mg/m^3 (excess of 23.6 times) were also observed during TMR processing with # 8 (d50=0.58 mm) and # 9 (d50 of probiotics=0.38 mm) feeding materials. In spite of TMR processing with very fine particulates of probiotics, relatively lower dust concentrations were observed than for # 7 and 8 feed materials because of the effects of moisture from tofu and pureed soybean soup during the mixing of # 9 feed materials. In comparison to the experimental results from the dairy cattle farm, 3.5 and 1.3 times higher concentrations of inhalable (mean=14.14$\pm$37.72 mg/m^3 and maximum=710.42 mg/m^3) and respirable (mean=0.40$\pm$0.52 mg/m^3 and maximum=1.82 mg/m^3) particulates were observed during the floor clearing of deposited particulates on the ground surface.

From the measurement results of the experimental Korean native cattle farm, it could be concluded that the supply method of feed materials considerably contributed to the quantity of dust generation. That is, the supply of feed materials through the “free falling” method was more favorable to disperse particulates into the airspace than the supply of feed materials using inclined rails. Controlling the falling distance of particulates, adjusting supply order of particulates (supply of dried and fine particulates after finishing loading of moist or damp materials), and the additional application of a dust control strategy such as water spraying might be helpful to reduce the degree of dust generation during TMR processing. However, engineering-based approaches are still needed to be considered in future research.



(a) Inhalable particulate according to feed materials during TMR processing and working activities



(b) respirable particulate according to feed materials during TMR processing and working activities

Figure 5-18 Measured occupational dust concentrations according to kinds of feed materials during TMR processing and working activities in experimental Korean native cattle farm.

Table 5-11 Measured maximum inhalable particulate concentrations according to working activities in Korean native cattle farm during all experimental periods (Unit: mg/m^3).

	Feed loading	# 6-1 feeds	# 6-2 feeds	# 7 feeds	# 8 feeds
Max.	37.53	109.64	31.69	5,315.67	255.57
Min.	0.74	1.28	2.36	115.76	6.21
Mean	8.5±9.0	17.0±19.9	7.8±6.4	1,594.6±1,375.2	77.1±88.8
	# 9 feeds	# 10 feeds	# 11 feeds	Floor clearing	
Max.	358.71	61.61	33.56	170.42	
Min.	5.39	0.11	4.51	0.25	
Mean	59.1±81.5	4.7±9.5	14.6±8.0	37.7±18.9	

Table 5-12 Measured maximum respirable particulate concentrations according to working activities in Korean native cattle farm during all experimental periods (Unit: mg/m^3).

	Feed loading	# 6-1 feeds	# 6-2 feeds	# 7 feeds	# 8 feeds
Max.	5.52	2.46	0.79	55.46	4.16
Min.	0.19	0.12	0.05	0.22	0.24
Mean	0.98±1.30	0.75±0.48	0.45±0.16	23.75±18.69	1.17±1.10
	# 9 feeds	# 10 feeds	# 11 feeds	Floor clearing	
Max.	19.89	0.91	0.82	1.82	
Min.	0.15	0.03	0.11	0.05	
Mean	4.10±5.30	0.12±0.13	0.55±0.18	0.40±0.52	

5.4. Conclusions

For the experimental cattle farms, statistical analyses were not carried out due to the limited research periods and outbreak of FMD. Relatively low dust concentrations were observed in the experimental dairy cattle and Korean native cattle farm according to the measurement locations. For example, TSP and PM10 concentrations from area sampling in the dairy cattle farm occupied 7.8 and 12.9% of the results from the nursery pig house, 14.6 and 20.0% of the results from the fattening pig house, 6.9 and 8.1% of the results from the mechanically ventilated broiler house and 7.9 and 10.4% of the results from the naturally ventilated broiler house. TSP and PM10 concentrations from the Korean native cattle farm were 256 and 175% higher than those from the dairy cattle farm. However, the measured results were still lower than other livestock species. In the case of the monitoring of occupational dust, such as inhalable and respirable particulates, relatively low dust concentrations were also measured at two experimental cattle farms. Dust concentrations for inhalable particulates measured at the leeward location were usually higher than those at the windward location. A substantial quantity of the dust concentrations that exceeded the occupational exposure limit for respiratory health of workers were occasionally found especially during hoof actions of the animals and TMR process for feed particulates. Maximum inhalable particulates of 78.78 mg/m^3 and respirable particulates of 10.59 mg/m^3 were observed when # 2 feed materials (mixture of powder type materials) were manually loaded into a handcart by workers in the experimental dairy cattle farm. In the case of experimental Korean native cattle farm, maximum inhalable particulates of 5,315.67 mg/m^3 and respirable particulates of 55.46 mg/m^3 were found when # 7 feed materials (pulverized corn, d50=1.95 mm) were suppled into a stationary TMR machine. In comparison to the supply method of the feed materials, “free-falling” method generated dustier environment than feed supply method using inclined rail of a TMR machine. Falling distance of the particulates was also strongly related to the dust concentration during the TMR processing. Water content of bedding materials also related to the dispersion of the larger particulates such as inhalable particulate fractions by hoof actions of the animals. Therefore, it could be concluded that adjusting the feed supply method during TMR processing and controlling the water content of bedding materials could be effective and practical solution for dust control in the cattle farms.

Chapter 6. Conclusions

6.1. General conclusions

In the livestock fields, various dust removal techniques, such as water or oil droplet spraying, electrostatic dust collectors, fabric or metallic filtration, and mechanical air cleaning units have been used to improve the indoor air quality of livestock facilities. However, the use of dust removal techniques by livestock farmers is limited due to the questionable efficiencies of dust removal, maintenance issues, and economic feasibility. Introducing an effective and practical strategy for airborne dust reduction is challenging for agricultural engineers. There is ultimately a need to improve the respiratory welfare of livestock farmers as well as the animals, and to increase livestock productivity. An investigation of the main factors contributing to the generation of airborne dust is needed to provide the background for introducing a practical and successful dust reduction strategy. Especially in South Korea, in spite of the demand of legislation or regulation pertaining to the occupational exposure limit in the primary industries, such as agriculture, only few studies related to dust concentration in livestock houses are available. In this thesis, long-term and intensive field observations were conducted in a commercial, mechanically-ventilated nursery pig house, mechanically and naturally ventilated-broiler houses, and dairy cattle and Korean native cattle farms, which are common types of facilities in South Korea.

From field observations and statistical analyses for experimental nursery pig house, controlling the ventilation rate was determined to be the most significant factor for the generation of TSP and PM10. For inhalable particulates, the activity of animals, the number of animals, and the ventilation rate were influential factors. The ventilation rate, indoor air temperature, and activity of animals were influential factors for respirable particulates. Considering the economic feasibility and thermal comfort of the animal-occupied zone, controlling the number of animals and the thermal environment are not practical solutions for the reduction of dust generation. Therefore, ventilation could be a key factor for improving the IAQ of an experimental nursery pig house. High dust concentrations, which exceeded the occupational exposure limit of inhalable and respirable particulates with regard to the respiratory health of pig farmers, were observed during periods when feed was supplied and the animals were actively moving. These observations emphasize that pig farmers should wear personal protective equipment (e.g., a respiratory mask) when working in the facility, especially during the supply of feed. From the statistically derived equations for predicting dust concentrations in the different size fractions and for various experimental factors measured in the nursery pig house, a computational fluid dynamics study was also conducted to evaluate the dust removal efficiencies of a conceptual ventilation configuration using a pipe-exhaust system based on the Eulerian-Eulerian multiphase model. From our CFD results, it was obvious that the combined use of a pipe-exhaust system and conventional roof-exhaust duct system effectively reduced the inhalable particulates with a defined aerodynamic equivalent diameter of 20 μm in the airspace. Particulates larger than 20 μm were rapidly settled out of the airspace and deposited on the ground due to gravity and greater settlement velocity. These behaviors of the larger particulates corresponded with previous field observations. However, dust reduction efficiencies of respirable particulates were very restricted due to the physical behavior of the smaller particulates in the airspace.

In the case of the field observations and statistical analyses for experimental mechanically-ventilated broiler houses, increase in activity of the broilers, indoor absolute humidity and ventilation were influential factors for inhalable particulates, while the activity of the broilers, outdoor humidity level, ventilation rate and age of broilers were influential factors for respirable particulates. In contrast to the nursery pig house, among the controllable factors, ventilation had minor effects on the variation of the occupational dust concentration, while controlling the humidity level inside the facility was a more effective manner for dust reduction strategies. For example, from the derived linear equation and specific experimental conditions, only a 1.4% decrease in inhalable particulates at the worker's respiratory height could be estimated when an additional 10% of the ventilation rate was temporarily increased when broiler farmers entered the facility. Meanwhile, a 13.7% decrease occurred for the case when 5% of the indoor relative humidity level was increased with given identical conditions. However, plenary application of mist spraying in the facility is not recommended due to the biological hazards with regards to the proliferation of micro-organisms. Thus, investigations to find proper ranges of water consumption for mist spraying must take precedence. For the naturally-ventilated broiler house, ventilation rate and activity of broilers were influential to the inhalable particulates, while indoor air temperature and outdoor humidity level were statistically significant to the variation of the respirable particulates. From the additional chamber experiment for investigating the effect of water contents of bedding materials on dust generation, water content levels of about 45 and 50% was found as the threshold levels for inhalable and respirable particulates, respectively. Restrictive and temporal droplet spraying on bedding materials might reduce respiratory risk for workers during shipment activities.

For the experimental cattle farms, statistical analyses were not carried out due to the limited research periods and the outbreak of foot-and-mouth disease. As in a number of previous reports, relatively low dust concentrations were observed in the experimental dairy cattle and Korean native cattle farms according to the measurement locations. However, substantial quantities of the dust concentrations that exceeded the occupational exposure limits for the respiratory health of workers were occasionally found especially during the hoof actions of the animals and the total mixed ration (TMR) process for feed particulates. Water content of bedding materials were also strongly related to the dispersion of the larger particulates such as inhalable particulate fractions. In the case of TMR processing, size of the feed materials and supply method were related to the level of dust concentration.

6.2. Future research

In this thesis, considering the research budget and time constraints, the relative P.A. level was introduced to reflect the influence of the movement of animals on dust generation in a nursery pig house, while binominal factors of broiler's activity were used for both experimental broiler houses. The qualitative and quantitative evaluation of the movement of the animals and the hygiene status of the slatted floor using a mathematical procedure (e.g., object tracking and image sensing) would enhance the reliability of the dust prediction equations. In this study, field observations were carried out in a single commercial livestock house according to the species and according to the time, cost and preventive measures against livestock diseases. Notwithstanding the popularization of standard design of the livestock facilities, each facility has different physical properties such as the dimensions of the buildings and the systematic composition of the ventilation configurations, while considering the economical and practical reasons. Therefore, as the next step, the development of experimental variables showing the physical characteristics of other types of livestock houses are needed to construct comprehensive predictive models of dust concentration at a national scale.

As mentioned in the results Section 4.3.2. for dust monitoring in the experimental broiler houses, reliability problems were found during the sampling process of TSP and PM10 in the winter season. Droplets were observed by the naked eye on the inside and outside parts of the dust sampling devices. Consequently, THIS resulted in disturbance of the air streamline of the sampling devices due to the formation of cohesive particulates, especially at the location of the air pathway. These phenomena might be caused by sudden air temperature variation when the research team entered the studied facility. Cold and dry air conditions are usually observed outside the facility in the winter season while warm and humid air conditions are created inside the facility. The manufacturing company for the dust sampling devices recommended the application of a hot wire near the sampling tube. However, these techniques have seldom been applied in the livestock fields due to budget constraints and practicality. When considering the preventive measures for livestock epidemics, all sampling devices were disinfected before and after the experiments and the sampling tube was discarded. Some researchers used additional accessories for regulating incoming air conditions and preventing condensation problems. However, these devices are not practical for field observations due to their size and operation methods. One possible solution for dust sampling in livestock houses can be the design of an experimental chamber that can control the inside air temperature and humidity level. Before starting the experiments, preparation of sampling devices in the chamber with identical air conditions in the livestock houses may be helpful to reduce condensation problems. Related future studies are still needed.

Based on the validated CFD simulation model in this thesis, the following five issues are needed to optimize the performance of the suggested method: an adjustment of the various ventilation rates of the pipe-exhaust system; a test of the installation of the feed supply pipe and exhaust pipe; a practical field application of this system; an investigation of the influence of the suggested ventilation systems on micro-climatic factors such as air temperature and humidity level; and design optimization and additional installing of the accessories (a kind of barrier) at the exit area of the feed supply pipe to prevent excessive dispersion from the particulates near the feeder, which is in reference to the practical dust control cases for a conveyer belt in other industries. In addition, future application of the exact dust distribution from the source using log-normal distribution or Rosin-Rammler's distribution from the intensive field experiment can improve the reliability of the numerical models.

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국 문 초 록

축산 시설 내 분진은 시설 내부의 공기 질 (Indoor air quality, IAQ) 하락을 야기시키며 작업자 및 경제동물의 호흡기 건강을 위협하는 요소로 작용한다. 또한 분진은 악취, 유해가스 등과 같은 가스상 물질을 인근 지역으로 수송하여 심미적 불쾌감을 야기시키거나 건강상 이상을 초래하기도 하며 각종 가축 질병의 공기 중 확산 매개체로도 작용한다. 따라서 축산 시설의 공기 질 개선은 가축의 생산성, 작업자의 산업 보건, 주민의 거주 안정성 등과 귀결되는 중요한 요소로 간주될 수 있다. 따라서 축산 시설 내부의 적정 공기 질 관리를 위하여 우선 축종 별, 상황 별 분진 발생 수준을 측정하고 분진 농도 및 다양한 환경 변수들간의 상호 관계를 규명하고 발생 메커니즘을 이해하는 것이 매우 중요하다. 그러나, 국내의 경우 축산 시설 내부에서 발생하는 분진 수준에 대한 관측 결과가 매우 부족하며 국내, 국외를 통틀어 다양한 환경 변수들에 의한 효과를 복합적으로 규명한 사례가 매우 부족한 실정이다. 또한 시설 내부의 미기상 환경을 좌우하는 환기에 대한 효과 역시 이를 정량적으로 접근한 사례가 매우 제한적인 실정이다. 이에 본 논문에서는 국내 대표적 유형의 축산 시설을 대상으로 축종 별 분진 및 환경 변수에 대한 현장 관측, 통계 분석, 수치 해석 등의 기법을 토대로 분진 발생에 대한 주요 메커니즘을 규명하고자 하였다.

2장에서는, 논문에 대한 기틀을 다지고 연구 방법론의 적정성을 평가하기 위하여 “축산 시설 내부에서의 분진 발생원,” “분진 발생 영향 인자,” “작업자, 동물, 인근 지역 사회에 분진이 미치는 영향,” “농업 분야에서의 CFD 기법을 이용한 최근 연구 동향,” “CFD 기법을 이용한 분야 별 분진 거동 해석 관련 연구 동향,” “분진 거동 해석을 위한 연구 방법론” 등에 대한 연구사 검토를 실시하였다.

3장에서는, 국내 대표적인 유형의 강제환기식 자돈사를 대상으로 TSP, PM10, 흡입성 및 호흡성 분진, 그리고 각종 환경 변수들에 대한 정기 모니터링을 수행하고 분진 발생과 관련한 주요 메커니즘을 규명하고자 하였다. 현장 관측 및 통계 분석을 토대로, 환기가 TSP 및 PM10 농도에 대한 주요 인자로, 동물의 활동성, 사육두수, 환기가 흡입성 분진에 대한 주요 인자로, 그리고 환기, 내부 온도, 동물의 활동성이 호흡성 분진에 대한 주

요 인자로 도출되었다. 국내 양돈 농가의 경영 현실 및 경제성 등을 고려할 때 사육 두수에 대한 관리 대비 환기 조절이 분진 저감에 있어 보다 효과적인 대책이 될 수 있을 것이라 판단되었다. 이와 관련하여 전산유체역학 기법을 이용하여 “파이프 배기 시스템”을 새로이 제안하고 해당 환기 시스템의 운영 방안 등에 따른 분진의 거동 모의 및 저감 효율을 평가하고자 하였다. 분진에 대한 해석은 Eulerian−Eulerian multiphase 모델에 의거하여 수행하였으며 기존의 덕트 배기 시스템과 파이프 배기 시스템을 조합하여 운영할 때 평균 입경 20 μm의 분진의 경우 사료 공급 시 최대 31.0%의 저감 효과를 보이는 것으로 나타났다.

4장에서는, 국내 대표적인 유형의 강제환기식 육계사 및 윈치커튼식 육계사를 대상으로 TSP, PM10, 흡입성 및 호흡성 분진, 그리고 각종 환경 변수들에 대한 정기 모니터링을 수행하고 분진 발생과 관련한 주요 메커니즘을 규명하고자 하였다. 환기량의 경우, 전산유체역학 기법을 이용하여 실제 현장의 풍환경 조건을 구현하고 추적가스기법을 적용하여 정량적인 값을 제시하고자 하였다. 현장 관측, 수치 해석 및 통계 분석을 토대로 강제환기식 계사의 경우 동물의 활동성 증가, 내부 절대 습도, 환기량 순으로 흡입성 분진 농도 변이에 영향을 미치는 것으로 나타났으며 외부 절대 습도, 동물의 활동성, 환기량, 일령이 호흡성 농도에 대한 유의한 영향을 미치는 것으로 관측되었다. 강제환기식 계사의 경우, 3장 돈사 결과와는 달리 환기로 인한 분진 저감 효과는 두드러지지 않았으며, 시설 내부 공기 중 수분 함량을 조절하는 것이 보다 효과적인 분진 저감에 효과적일 것으로 판단되었으나 시설 내부의 수분 증가는 각종 바이러스 등의 증식과 밀접한 관련이 있으므로 생물학적 안정성 등을 고려한 후속 연구가 뒷받침되어야 될 것으로 판단되었다. 한편, 자연환기식 계사의 경우 환기량, 동물의 활동성이, 그리고 내부 온도 및 외부 절대 습도가 각각 흡입성 및 호흡성 분진 농도에 대한 주요 영향 인자로 판별되었다. 계사의 바닥재를 이용하여 바닥재의 수분 함량에 따른 분진 비산 관련 메커니즘 규명을 위한 챔버 실험을 추가로 수행하였으며 그 결과, 각각 45, 50% 함수비가 흡입성 및 호흡성 분진 비산과 관련한 일종의 임계 함수비로 산출되었다.

5장에서는 국내 대표적인 유형의 유우사 및 한우사를 대상으로 시기별 작업 형태 별 분진 모니터링을 수행하였다. 국외 연구 사례와 마찬가지

로 국내 역시 타 축종 대비 상대적으로 매우 낮은 수준의 분진 농도가 관측되었으나 TMR 사료 작업 등과 같은 일부 작업 시기 시 작업자의 폐기능을 고려한 분진의 허용 노출 기준을 쉽게 초과하는 것으로 관측되었다. TMR 작업 시 분진의 발생 수준은 각 사료 입자의 입경 크기, 사료의 공급 방식 등과 밀접한 관련이 있는 것으로 나타났으며 작업 형태에 대한 개선 등을 통하여 분진 발생 수준을 저감하는데 기여할 수 있을 것이라 판단되었다.

주요어: 동물 복지, 전산유체역학, 축산 시설 호흡성 분진, 회귀 분석,
흡입성 분진

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