공학박사학위논문

DEVELOPMENT AND SEASONAL DEMONSTRATION OF AIR RECIRCULATED VENTILATION SYSTEM FOR PIG HOUSE BASED ON ICT TECHNOLOGY

ICT 기반의 양돈시설 공기재순환 환기시스템 개발 및 계절별 실증 연구

2023년 2월

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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

JUN-GYU Kim

FEBRUARY 2023

I certify that I have read this dissertation and that in my opinion it is fully adequate, in scope and quality, as dissertation for the degree of Doctor of Philosophy.

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Abstract

The demand for meat and other livestock products has increased rapidly accounting to about 39.4% of the total agricultural production in South Korea (MAFRA, 2020). In the pig industry, the number of rearing heads per farm is increasing every year due to intensive pig production with mechanization and automation. However, the pig production increase caused a lot of contaminants accumulated inside compared to other livestock facilities (Kwon et al., 2016). This also resulted to difficulties in maintaining the stability and uniformity of the rearing environment in large-sized pig houses. The ventilation is generally operated to control the rearing environment inside the pig houses. However, there are many difficulties in proper ventilation operation in pig houses. In many farms, minimum ventilation rate is performed to minimize the inflow of cold air to maintain the optimum temperature in winter season. Also, there is a reason for reluctance to increase the ventilation rate. The epidemic airborne diseases can be spread through the air and the environmental problems can occur near the pig farm when the harmful gases and odors are dispersed from the pig farm. Accordingly, interest in technology that can improve the external environment as well as the rearing environment inside the pig house is increasing.

There are four major issues that need to be solved in pig house; 1) rearing environment for pig productivity, 2) energy cost, 3) livestock disease, and 4) ammonia and odor emission. The air recirculated ventilation system (ARVS) has been proposed as a method to improve the internal environment of pig houses, prevent livestock disease, and minimize the emission of harmful gas and odor. The main purpose of the ARVS was to minimize the inflow of external air for preventing

the disease and increasing the energy efficiency. It can also minimize complaints from residents by reducing odors and harmful gases emitted from the pig house. The ventilation rate can be increased without additional energy input because the metabolic energy inside the pig room can be reused. Through this, there was an advantage that the internal growth environment can be improved

1) The ARVS reuses the heat energy of the exhausted air, and it was possible to increase the ventilation rate in cold winter season. Accordingly, the rearing environment could be improved and the energy can be saved by reducing the use of heating device. 2) Also, the ARVS can minimize the emission of harmful gas and odor by removing the gas and odor using wet scrubber module while the amount of exhausted air can be decreased. 3) It can block the livestock disease by reducing the inflow and outflow of external air, and to suppress the growth of bacteria through ARVS sterilization devices. Such an ARVS was applied to an actual farm to evaluate the internal rearing environment, external environmental load, and pig productivity.

The manuscript was divided into six chapters. As a first step of addressing the issues on livestock facility, Chapter 2 included literature review that builds the manuscript foundation and suggested the suitability of the study. The review included literature on main problems of rearing environment in pig house, external environmental of pig house, cooling methods of pig house, and air recirculation technology.

In Chapter 3, it was intended to present the results of the analysis of internal environmental problems in the experimental pig house where the air-recirculated ventilation system will be installed. The data for system installation were collected through field experiments at the experimental pig house where the environmental factors, ventilation rate, and operating information were measured. Based on these monitoring data, the main environmental problems of the target pig house were analyzed. The results of monitoring data analysis were used for the improving internal environment through the application of the air re-circulated ventilation. However, in reality, it is impossible to conduct experiments with artificially changing various environmental conditions while raising pigs on the farm, and qualitative and quantitative visualization of the air flow and various environmental factors was also difficult. In order to overcome these limitations, the computational fluid dynamics (CFD) simulation mod-el for the target pig house was designed, and then environmental analysis was conducted with the computed CFD results. The environment data inside and outside the pig house were measured through seasonal field experiments, and they were also used as input data and validation data for the CFD simulation. In addition, the improvement and applicability of the air-recirculated ventilation system were evaluated compared with the existing system by adding the module of the air-recirculated ventilation system in the CFD simulation model.

In Chapter 4, the internal environment of pig houses installed with ARVS was evaluated and the optimal model of ARVS was designed using the numerical model developed in this study. The internal environment of the pig house was analyzed based on the various balance equations. The ARVS could consist of various modules. Based on the numerical model developed in this study, the internal environment of the pig house was evaluated. In addition, it was attempted to derive the optimal design standard of the ARVS.

In Chapter 5 & 6, such an ARVS was applied to an actual farm to evaluate the internal rearing environment, external environmental load, and pig productivity according to the season (winter, spring and summer). Then, the evaluations of the

cooling methods were conducted in summer. 1) The capacity of the general cooling system required for temperature was calculated. 2) The water temperature and chiller capacity required for evaporative cooling were calculated using the wet scrubber. Finally, 3) as a windchill cooling method, the ventilation system was improved to increase the velocity near the piglet zone.

The ARVS developed in this study was able to solve all four issues of livestock industry: 1) rearing environment, 2) energy save, 3) livestock disease, and 4) complex odor. The developed system should be optimized and upgraded in order to be installed at other farms. Also, by expanding the ARVS, it will be possible to contribute to the development of the pig industry.

Keywords : Air recirculated ventilation system, Complex odor, Computational fluid dynamics, Energy, Livestock disease, Numerical model, Pig house, Rearing environment

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Abbreviations

A	Total heat radiant area (m^2)
a_1-a_4	Coefficients of automatically control algorithm
A3EL	Aero-Environmental & Energy Engineering Laboratory
AcSEC	Artificially controlled smartfarm engineering center
ARVS	Air recirculated ventilation system
c	Specific heat of air (cal·kg^{-1}·°C^{-1})
c_o	Outdoor concentration of carbon dioxide (ppm)
C_a	Specific heat capacity (W·kg^{-1}·K^{-1})
c_a	Carbon dioxide generation rate of the piglets (kg·hr^{-1}·head^{-1})
c_i	Internal concentration of carbon dioxide (ppm)
C_p	Specific heat at a constant pressure of internal air (kcal·kg^{-1}·°C^{-1})
CFD	Computational fluid dynamics
CV	Coefficient of variant of the RMSE
CV	Control value of inverter (Hz)
CVS	Conventional ventilation system
DBMS	Database management system
E_{hum}	Contribution of humidity to the ET
E_{vel}	Contribution of velocity to the ET
EAMR	External air mixing ratio
EBRT	Empty bed retention time
ELISA	Enzyme-linked immunosorbent assay
ERR	Energy recycling rate
ET	Effective temperature
FMD	Foot-and-mouth disease
g	Gravity acceleration (m·s^{-2})

i	Cartesian coordinated indices
IgA	Immunoglobulin A
ICT	Information and communications technology
IoT	Internet of things
j	Cartesian coordinated indices
k	Cartesian coordinated indices
m	Weight of the piglets (kg)
m	Mass of air (kg)
n	Feed intake constant
n_i	Internal concentration of ammonia gas (ppm)
N	Number of piglets (head)
MBE	Mean bias error
M_t	Measured value at hour t
MWPS	Midwest plan service
Δp	Pressure changes in the porous medium (Pa)
P_t	Predicted valued at hour t
PCR	Polymerase chain reaction
PCV-2	Porcine circovirus type 2
PEDV	Porcine epidemic diarrhea virus
PM10	Particulate matter 10
PPV	Porcine parvovirus
PRRSV	Porcine reproductive and respiratory syndrome virus
Q	Ventilation rate ($\mathrm{m^3 \cdot s^{-1}}$)
Q	Calorie of the air (cal)
Q_l	Flow rate of the recirculated water ($\mathrm{L \cdot min^{-1}}$)
Q_{solar}	Flow rate of solar hot water ($\mathrm{L \cdot min^{-1}}$)
q_s	Sensible heat production of piglets ($\mathrm{kcal \cdot hr^{-1} \cdot head^{-1}}$)

q_{tot}	Sensible heat production of piglets (kcal·hr^{-1}·head^{-1})
RH	Air relative humidity (%)
RMSE	Root mean square error
RPM	Revolutions per minute
R_1	Internal resistance factor
R_2	Viscous resistance coefficient
SAEW	Slightly acidic electrolyzed water
s_T	Sink or source term (W·m^{-3})
SIV	Swine influenza virus
t_{hi}	Air temperature before passing the heat exchange module (°C)
t_{ho}	Air temperature after passing the heat exchange module (°C)
t_i	Air temperature inside the piglet room (°C)
T_{in}	Average air temperature inside the piglet room (°C),
t_o	Outdoor air temperature (°C)
T_{out}	External air temperature (°C)
t_l	Temperature of recirculation water (°C)
T_{low}	Low temperature standards according to the piglet age (°C)
t_{solar}	Temperature of solar hot water (°C)
$t_{solar+l}$	Mixed temperature of recirculated water and solar hot water (°C)
t_l	Temperature of recirculated water (°C)
t_r	Water temperature before passing the heat exchange module (°C)
t_v	Inflow air temperature from the ARVS (°C)
t_{wi}	Air temperature before passing the wet scrubber module (°C)
t_{wo}	Air temperature after passing the wet scrubber module (°C)
TGEV	Transmissible gastroenteritis virus
TSP	Total suspended particles
T	Time (s)

T	Temperature (K)
ΔT	Difference of air temperature (℃)
u	Velocity components (m·s^{-1})
U	Total heat transfer coefficient (kcal·m^{-2}·℃$^{-1}$·hr^{-1})
UV	Ultraviolet
v	Velocity flowing in the porous medium (m·s^{-1})
v_c	Specific volume of the carbon dioxide (m^3·kg^{-1})
v_n	Specific volume of the ammonia gas (m^3·kg^{-1})
VBA	Visual basic for applications
w	Variable fan operation rate (dimensionless)
w_a	Absolute humidity of the wet scrubber module (kg·kg-da^{-1}·hr^{-1})
w_e	Absolute humidity of the outdoor air (kg·kg-da^{-1}·hr^{-1})
w_a	Moisture generation rate of the piglets (kg·kg-da^{-1}·hr^{-1}·head^{-1})
w_e	Moisture generation rate in a humid place (kg·kg-da^{-1}·hr^{-1}·head^{-1})
w_i	Internal absolute humidity of the piglet room (kg·kg-da^{-1}·hr^{-1})
w_{wi}	Absolute humidity before passing the wet scrubber module (kg·kg-da^{-1})
w_l	Absolute humidity of recirculation water (kg·kg-da^{-1})
w_{wo}	Absolute humidity after passing the wet scrubber module (kg·kg-da^{-1})
w_v	Absolute humidity of the inlet air of the piglet room (kg·kg-da^{-1}·hr^{-1})
x	Position vector in tensor notation
x_m	Mixing ratio of the outdoor air
δ	Kronecker delta
η	removal efficiency of the wet scrubber module
η_s	Adiabatic saturation efficiency (%)
η_t	Heat exchange efficiency (%)
λ	Evaporative latent heat of water (kcal·kg^{-1})
λ	Thermal conductivity (W·m^{-1}·K^{-1})

μ	Viscosity coefficient of the air ($kg \cdot m^2 \cdot s^{-1}$)
ρ	Air density at the inlet ($kg\ m^{-3}$)
ρ_d	Air density at the outlet ($kg\ m^{-3}$)

Chapter 1. Introduction

1.1. Study background

The livestock industry in South Korea has been an important industry in agriculture over a long time. The domestic livestock industry continues to grow due to the increase in the demand for meat, accounting for about 39.4% of the total agricultural production (MAFRA, 2020). In particular, in the pig industry, which occupies the highest proportion in the livestock industry, the number of rearing heads per farm is increasing every year, while the number of pig farms is decreasing due to the enlargement and intensive production of pig houses. Since Korea is located in the middle of the northern temperate zone, the four seasons are distinct. In addition, recent climate change is causing changes in the agricultural system, and it becomes more difficult to maintain the proper environment for animals in the open field. In 2020, among pig farms in South Korea, closed-type pig house accounted for 66%, and opened-type pig house accounted for 30% (MAFRA, 2020). In addition, the proportion of closed-type pig house was increasing every year, and most standards of pig house design recommend closed type. Even in pig house, in order to increase pig production, since the pig facilities are getting larger and larger, it is very important to control the internal environment in these closed-type pig house. Compared with other livestock facilities, pig houses generally have a lot of pollutants such as dust, odor, and harmful gas accumulated inside the pig house. As the size of the pig house increases, it is becoming more and more difficult to maintain the appropriate environment inside the pig house due to the occurrence of problems related to the stability and uniformity of the internal environment. Therefore, the demand for technologies of controlling and managing the internal environment of the pig house has been continuously increased. The ventilation is generally operated to control the rearing environment inside the pig houses. The conventional ventilation type is a method in which the air inside the pig house and the external air are exchanged directly using the exhausted fan. However, there are many difficulties in proper ventilation operation in pig houses. In many farms, minimum ventilation rate is performed to minimize the inflow of cold air to maintain the optimum temperature in winter season. Also, there is a reason for reluctance to increase the ventilation rate. Accordingly, interest in technology that can improve the external environment as well as the rearing environment inside the pig house is increasing. The epidemic airborne diseases can be spread through the air and the environmental problems can occur near the pig farm when the harmful gases and odors are dispersed from the pig farm. In addition, extreme high temperature can occur in summer season, which can cause heat stress to pigs. Therefore, it is important to create the appropriate rearing environment using heating and cooling devices in winter and summer. However, operating heating and cooling devices could dramatically increase consumption of fossil fuels and electricity.

Although the pig industry has been actively automated and mechanized by applying integrated information and communication technology (ICT) in recent years, it is still difficult to solve the fundamental problems of the pig farms (MAFRA, 2020). Accordingly, disputes between local residents and farm owners constantly occurred considering various environmental and social problems in pig industry. Representative issues to be solved in pig facilities include 1) improvement of the internal rearing environment, 2) energy save, 3) livestock disease prevention, and 4) reduction of odor and harmful gas emissions.

The thermal environment inside the pig house consists of the sensible and latent heat generation of pigs and loss through ventilation and heat conduction from the wall. In particular, heat accumulation can occur inside the pig house even if the maximum ventilation is operated during summer. Exposure to a high temperature environment for an extended period results in a 7 °C increase in a pig’s body temperature. In addition, the feed intake of pigs can be reduced by half when the temperature inside the pig house increases from 20 °C to 30 °C (Godyń et al., 2020). High stress in pigs was also found to increase the pig mortality from about 5000 heads in 2014 to 40,000 heads in 2018 (KDCA, 2020). Low temperatures also affect pig productivity. Pigs maintain their body temperature through metabolism. Therefore, the feed efficiency can be lowered because the metabolism can be increased when the air temperature near the pigs is lowered. Accordingly, it is not recommended to allow in a lot of cold air from outdoors in the winter season. In order to increase the pig productivity in summer and winter, it is essential to maintain the appropriate internal temperature. If additional air conditioners such as heaters and coolers are operated for temperature control, the energy input can be increased. Accordingly, although the minimum ventilation is operated in the winter season to maintain the temperature, other environmental conditions (e.g., humidity, dust, gas and odors) inside the pig house can be poor, leading to reduced pig immunity and the possibility of increased rates of respiratory diseases (Huynh et al., 2005). Therefore, it is essential to increase the ventilation rate while maintaining the appropriate temperature inside the pig house.

In order to control the internal rearing environment according to the season, the heating and cooling system can be required. Ventilation was generally used to as a method to improve indoor air pollution, but the loss of heating and cooling energy generated during ventilation may be large. As an alternative to this, the need for heat recovery ventilation research to utilize the loss of ventilation energy was increasing (Kang, 2006). The heating energy loss rate in winter was 70-90%, mostly due to ventilation (Krommweh et al., 2014). Therefore, energy consumption was inevitable to clean the polluted air inside the pig house while properly maintaining the air temperature inside the pig house. In order to prevent global warming, there was a report that the scale of carbon dioxide emission should be reduced to 50-65% of that of 2000 by 2050 (Pachauri & Reisinger, 2007). Horticulture was the dominant source of carbon dioxide emissions from agriculture (Kim & Lee, 2009). This was because the amount of energy input such as briquettes and diesel for heating was high due to facility cultivation. In the case of rice, it was because the agricultural machinery was used for a long time during the cultivation process and the consumption of diesel was high accordingly. In the case of livestock, it was estimated that the carbon dioxide emission of beef cattle and dairy farming was high. The input of gasoline and diesel was higher than that of other livestock, and the emission of pig farms was very low, about 5.5% of livestock (Kim & Lee, 2009). However, as extreme climatic conditions were becoming more frequent, the demand for heating and cooling was increasing, and it was also important to reduce the energy consumption of pig farms to reduce the carbon emission.

Especially, the livestock disease control is very important for stable farm operation in winter. Large economic damage can occur during outbreaks of livestock infectious diseases (Seo et al., 2015). In addition, if immunity is weakened, it can decrease the appetite and activity amount of pigs. There are three routes by which foot-and-mouth disease (FMD) can be transmitted by livestock aerosols and surface contact to respiratory organs (Weber & Stilianakis, 2008); 1) direct contact with an infected animal, 2) indirect contact with the structure inside the pig room, workers, vehicles and equipment, and 3) airborne spread through airflow. However, the airborne spread of livestock disease can be very difficult to prevent due to the invisible of airflow. Therefore, many pig farms were reluctant to make flow in external air directly using the conventional ventilation type.

In addition, there are various problems not only inside but also outside the pig house. One of the main functions of ventilation in the pig house is to keep the proper environment inside the pig house by exhausting the polluted air. However, harmful gases and odors emitted by ventilation fans can affect the external environment. There are reports that ammonia causes soil acidification and can be oxidized to sulfuric acid and nitrification in the air to generate secondary inorganic aerosols (Conti et al., 2020). An increase in civil complaints about livestock odors and harmful gas emissions represents a big obstacle to the development of the pig industry. Therefore, there is a need for a technology capable of managing the environment inside and outside the pig house.

The air recirculated ventilation system (ARVS) has been proposed as a method to improve the internal environment of pig houses, save the energy cost, prevent livestock disease, and minimize the emission of harmful gases and odors. The main purpose of the ARVS is to minimize the inflow of external air to prevent disease and increase the energy efficiency. It also minimizes complaints from residents by reducing odors and harmful gases emitted from the pig house. The ventilation rate can be increased without additional energy because the metabolic energy inside the pig house can be reused. Through this, there is the advantage that the internal growth environment can be improved.

The operation principle of the ARVS starts with sufficiently washing the internal air through the wet scrubber module wherein a certain amount of air is exhausted while a certain amount of air is mixed with fresh air and flows back into the system. These air recirculation technologies are mainly being studied in the industrial environment to save the cost of cooling and heating buildings. Accordingly, various studies have been conducted to apply the air recirculation technology to pig houses and devise a method of recirculated air to remove dust by using a fabric filter and an electrostatic dust collector. For example, Park et al. (2017) simulated the effect of the concentration of the pollutant in the pig house using mass and energy balance equations. Meanwhile, Mostafa et al. (2017) applied a wet scrubber to the air recirculation system and reported that the wet scrubbing technique can reduce both ammonia and dust concentration without a negative effect on pigs.

The previous studies analyzed the removal efficiency of dust and gas by applying an air recirculated system; however, it is insufficient to simultaneously evaluate the rearing environment of pigs, such as the air temperature, humidity, gas concentration, dust, and so on. Therefore, a complex analysis of various environmental factors is required. Additionally, the ARVS should be designed as a system in which the ventilation rate and external air mixing ratio (EAMR) should be controlled in real time according to the various environmental conditions inside and outside the pig house. Therefore, it was necessary to apply the ARVS in order to simultaneously solve the four representative problems of pig facilities.

1.2. Objective of thesis

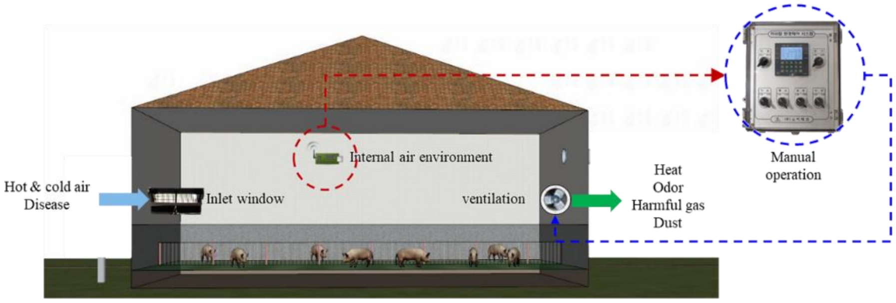
The research has been conducted for a total of 5 years since 2018. The overall schematic diagrams of the conventional ventilation system (CVS) of pig house and ARVS of pig house are shown in Figure 1-1. Figure 1-1 (a) shows the structure of a

CVS operated in a pig house. It is a system that controls the ventilation rate based on the internal temperature, and then exhausts internal heat, moisture, gas, and dust while the external fresh air come into the pig house. On the other hand, Figure 1-1 (b) shows the schematic diagram of various modules in the ARVS installed at a pig house such as the wet scrubber module, the external air mixing module with disease sterilizer, and the heat exchange module controlled by ICT. It was expected that the representative four problems aforementioned would be solved through ARVS.

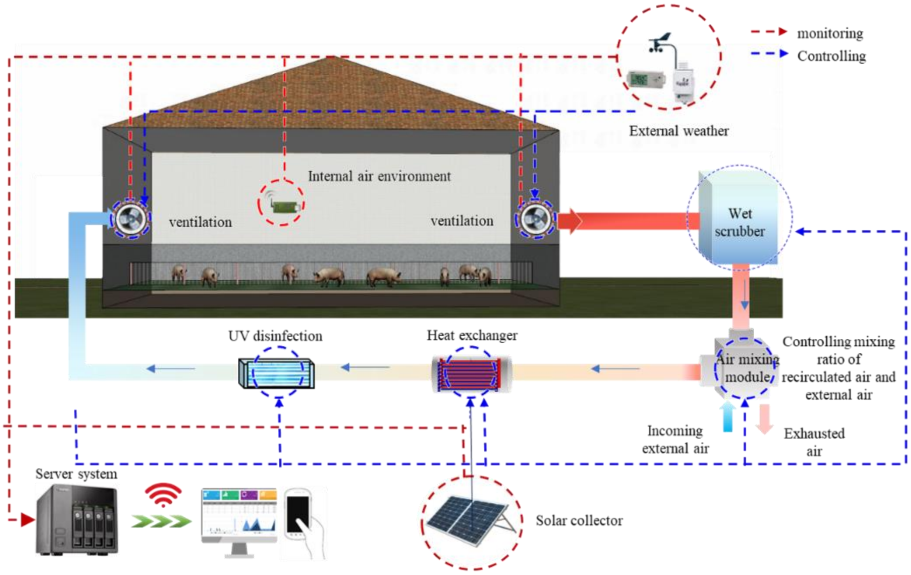
1) The ARVS reuses the heat energy of the exhausted air, and it was possible to increase the ventilation rate in cold winter season. Accordingly, the rearing environment could be improved and the energy can be saved by reducing the use of heating device.

2) Also, ARVS can minimize the emission of harmful gas and odor by removing the gas and odor using wet scrubber module while the amount of exhausted air can be decreased.

3) It can block the livestock disease by reducing the inflow and outflow of external air, and to suppress the growth of bacteria through ARVS sterilization devices. Therefore, the aim of this study was to develop the ARVS that solve the four problems of pig farm and to conduct the validation experiment to evaluate the rearing environment, energy efficiency, livestock disease and odor emission.



(a) Conventional ventilation system (CVS)



(b) Air recirculated ventilation system (ARVS)

Figure 1-1 Schematic diagram of the conventional ventilation system (CVS) and the developed air recirculated ventilation system (ARVS).

The manuscript was divided into six chapters. As a first step of addressing the issues on pig farm, Chapter 2 included literature review that builds the manuscript foundation and suggested the suitability of the study. The review included literature on main problems of internal and external environment of pig farms, such as air temperature, relative humidity, ammonia gas, complex odor, and livestock disease, the air recirculation technologies, and cooling methods of pig house in summer.

Chapter 3 discussed about the internal environment problems in the experimental pig house where the ARVS will be installed. The data for system installation were collected through field experiments at the experimental pig house where the environmental factors, ventilation rate, and operating information were measured. Based on these monitoring data, the main environmental problems of the target pig house were analyzed. The results of monitoring data analysis were used for the improving internal environment through the application of the ARVS. However, in reality, it is impossible to conduct experiments with artificially changing various environmental conditions while raising pigs on the farm, and qualitative and quantitative visualization of the air flow and various environmental factors was also difficult. In order to overcome these limitations, the computational fluid dynamics (CFD) simulation model for the target pig house was designed, and then environmental analysis was conducted with the computed CFD results. The environment data inside and outside the pig house were measured through seasonal field experiments, and they were also used as input data and validation data for the CFD simulation. In addition, the improvement and applicability of the ARVS were evaluated compared with the existing system by adding the module of the ARVS in the CFD simulation model.

Chapter 4 focused on the analysis of the aerodynamic environment of pig house in various environmental conditions using CFD simulation. This study conducted field surveys and literature review to identify representative problems about aerodynamic environment in the pig house. The validation of CFD model was conducted by comparing between the measured and computed data. From the validated CFD model, analysis of aerodynamic environment was performed in various environmental conditions.

Chapter 5 discussed about optimum combination of modules in ARVS. The main modules in ARVS were the wet scrubber module, the outdoor air mixing module, and the heat exchange module. The analysis according to the combination of the various modules was conducted for selecting optimum module combination. In order to evaluate the combination of modules, it was necessary to analyze various environmental conditions. Therefore, the internal environment of pig houses installed with ARVS was evaluated and the optimal model of ARVS was designed using the numerical model developed. The internal environment of the pig house was analyzed based on the various balance equations. The ARVS could consist of various modules. Based on the numerical model developed, the internal environment of the pig house was evaluated. In addition, it was attempted to derive the optimal design standard of the ARVS.

Chapter 6 and 7 evaluated the validation experiment results after installing the ARVS on the experimental pig house. It is necessary to evaluate the performance of the ARVS developed based on the results of the previous chapters and then comprehensively validating the improved rearing environment, decreased harmful gas emission, and increased pig productivity through seasonal experiment. In the chapter 6, the results of validation experiments for winter season were analyzed. Through this, the performance and effects of ARVS were evaluated. In chapter 7, the analysis of the validation experiments on spring and summer season were conducted in the same way. Additionally, the experiments for cooling methods in summer were discussed. Finally, based on the analysis results of seasonal ARVS experiments, the representative problems in pig farm to be solved were discussed.

Chapter 2. Literature review

2.1. Main problems of rearing environment in pig house

Due to the presence of four distinct seasons in Korea, the problems of air temperature inside the pig house occur annually. The thermal environment inside the pig house consists of the sensible and latent heat generation of pigs and loss through ventilation and heat conduction from the wall. In particular, heat accumulation can occur inside the pig house even if the maximum ventilation is operated during summer. As the ambient temperature and the frequency of hot days increased due to climate change, heat stress of pig farm and economic impacts were of increasing concern (Schauberger et al., 2019; Valiño et al., 2010). Pigs are particularly susceptible to heat stress because they lack functional sweat glands and have small lungs that reduce their ability to disseminate heat by panting (D'Allaire et al., 1996). Therefore, it is very important to manage the thermal environment inside the pig house in summer. The thermal environment inside the pig house consists of the sensible and latent heat generation of pigs, and loss through the ventilation and heat conduction from the wall. In particular, heat accumulation can occur inside the pig room even if maximum ventilation was operated during summer. Exposure to high temperature environment for long time resulted to a 7°C increase in pig’s body temperature. In addition, the feed intake of pigs can be reduced by half when the temperature inside the pig room increases from 20°C to 30°C (Godyń et al., 2020). Heat stress results in a higher rate of secondary bacterial infections due to a compromised intestinal defense mechanism (Pearce et al., 2013). The economic loss caused by such heat stress of pigs was also enormous. The pig industry of USA lost hundreds of millions of dollars annually due to heat stress (Parois et al., 2018).

Meanwhile, in summer climate of South Korea, the humid environment was also a problem. In South Korea, the rainy season occurs every summer, and the weather conditions are hot and humid. When the humidity is high, the possibility of developing respiratory diseases of pigs may increase (Gordon, 1963), and if the temperature is high, the effect of humidity may be greater (Huynh et al., 2005). Therefore, the cooling methods were necessary to satisfy the pigs' thermal demand.

Low temperatures also affect pig productivity. Pigs maintain their body temperature through metabolism. Therefore, the feed efficiency can be lowered because the metabolism can be increased when the air temperature near the pigs is lowered. Accordingly, it is not recommended to allow in a lot of cold air from outdoors in the winter season. In order to increase the pig productivity in summer and winter, it is essential to maintain the appropriate internal temperature. If additional air conditioners such as heaters and coolers are operated for temperature control, the energy input can be increased.

Accordingly, although the minimum ventilation is operated in the winter season to maintain the temperature, other environmental conditions (e.g., humidity, dust, gas and odors) inside the pig house can be poor, leading to reduced pig immunity and the possibility of increased rates of respiratory diseases (Huynh et al., 2005). For this reason, ammonia concentrations inside the pig house are usually maintained 0-40 ppm (Heber et al., 2005). High ammonia concentrations could increase symptoms such as coughing, sneezing, salivation, excessive tearing, loss of appetite, and lethargy (Philippe et al., 2011). This could be fatal not only to the pigs, but also to the workers inside the farm (Kwon et al., 2016). Also, high humidity and high concentration of gas can increase the risk of respiratory diseases in pigs (Chantziaras et al., 2020). If the rearing environment is not suitable, the piglets can be stressed.

The high stress in pig was also found to increase pig mortality from about 5,000 heads in 2014 to 40,000 heads in 2018 (KDCA, 2020).

Therefore, it is essential to control the internal environment through sufficient ventilation even in cold winter season. In order to increase the ventilation rate in cold winter, there is a way to use an additional heating device to maintain internal air temperature. If additional air conditioners, such as heater and radiator, are operated for temperature control, the energy input can be increased (Jung et al., 2017). The heating energy loss rate in winter in pig house was 70 to 90% mostly due to ventilation (Krommweh et al., 2014). Since extreme low temperature in winter can occur frequently in South Korea, a solution to reduce the heating costs is necessary.

Especially, the livestock disease control is very important for stable farm operation in winter. Large economic damage can occur during outbreaks of livestock infectious diseases (Seo et al., 2015). In addition, if immunity is weakened, it can decrease the appetite and activity amount of pigs. There are three routes by which foot-and-mouth disease (FMD) can be transmitted by livestock aerosols and surface contact to respiratory organs (Weber & Stilianakis, 2008); 1) direct contact with an infected animal, 2) indirect contact with the structure inside the pig room, workers, vehicles and equipment, and 3) airborne spread through airflow. However, the airborne spread of livestock disease can be very difficult to prevent due to the invisible of airflow. Therefore, many pig farms were reluctant to make flow in external air directly using the conventional ventilation type.

2.2. External environment of pig house (ammonia and complex odor emission)

There are various problems not only inside the pig house but also outside the pig house. One of the main functions of ventilation in the pig room is to keep the proper environment inside the pig room by exhausting the polluted air. However, harmful gases and odors emitted by ventilation fans can affect the external environment. Livestock facilities occupied a large proportion of ammonia emissions. There were reports that ammonia causes soil acidification and can be oxidized to sulfuric acid and nitrification in the air to generate secondary inorganic aerosols (Conti et al., 2020). The main source of ammonia gas is the rapid hydrolysis of urea of urine by the faecal enzyme urease leading to ammonium formation in an aqueous medium (Cortus et al., 2006). Another source of ammonia gas is the degradation of undigested proteins, but this way is slow and of secondary importance (Zeeman, 1991). The urease is a cytoplasmic enzyme largely present in faecal bacteria (Mobley & Hausinger, 1989). In livestock facilities, it is present in abundance on fouled surfaces like floors, pits and walls (Ni et al., 1999). Therefore, the ammonia generation rate could be affected by the cleanliness inside the pig house. Urease activity is affected by temperature with low activity below 5-10°C and above 60°C (Sommer et al., 2006). Urease activity is also affected by pH with optimum ranging from 6 to 9. As such, various previous studies on ammonia generated from manure have been conducted. Ammonia generated inside the pig house could be emitted to the outside through ventilation. There is also a complex odor as harmful substance emitted from pig house. As civil complaints about livestock odor and harmful gas emissions are increasing, it is a big obstacle to the development of the pig industry (Kim et al., 2013). Complaints related to livestock odor accounted for 26.7% of all complaints of odor, and the number of complaints from local residents due to livestock odor was increasingly rapidly (ME, 2019). Livestock odor emitted from pig house include ammonia (NH_3), hydrogen sulfide (H_2S), methane (CH_4), carbon dioxide (CO_2), and volatile organic matter (VOCs). NH_3 and H_2S are the main odor generating substances (Kim et al., 2012).

Various researches have been conducted to reduce ammonia and odor emission. Most researches have mainly evaluated the efficiency of additives (chemical and biological methods) or reduction facilities (biofilters, manure circulation system and so on) to reduce the livestock odor (Choi et al., 2015; Ha & Kim, 2019; Hartung et al., 2001; Lim et al., 2012; McCrory & Hobbs, 2001; Melse & Hol, 2017; Wang et al., 2009). Yoo et al. (2010) studied the effect of reducing odors from manure using microbial probiotics. Jeong et al. (2019) applied soil microorganisms to the liquid manure circulation system to improve the efficiency of reducing odors generated from manure and compared the effect with the existing liquid manure circulation system. However, in these researches, the efficiency was calculated by measuring the concentration of complex odors in the pig house, but the evaluation of the spread of livestock odor to the outside was not considered (Ha & Kim, 2015; Kim et al., 2013). Accordingly, Yeo et al. (2019) conducted an evaluation of the spread of complex odors around the pig house considering the internal environment and weather conditions. Also, Hong et al. (2011) developed and validated Computational fluid dynamics model to simulate the spread of livestock odor considering the weather conditions. As researches on the spread of harmful odors outside the pig house were being actively conducted, the reduction of odors and civil complaints was important.

2.3. Cooling methods of pig house in summer season

A cooling device was essential to prevent high temperature stress in summer season. A very important goal when cooling a facility is to prevent the flow of heat from the outdoors to the indoor (Firfiris et al., 2019). It is also important to efficiently dissipate the calories of pigs generated inside the pig house. From a thermodynamic point of view, cooling of an indoor environment can be managed with sensible cooling: an adiabatic mixture of air with different temperatures, cooling with dehydration and evaporation (Firfiris et al., 2019). Sensible cooling includes the removal of heat without affecting the humidity of the indoor environment. However, the sensible heat cooling device can have high electricity consumption, complicated equipment, and low performance (Yoo et al., 2015). Accordingly, in pig farms, evaporative cooling pads were generally used as a cooling method because of their economic advantages (Obando et al., 2020). Although there were many methods available, the evaporative cooling pad was continuously demonstrated as effective (Chen et al., 2011; Malli et al., 2011; Shukla et al., 2008). However, since the performance of the evaporative cooling system largely depends on the external air conditions, there was a problem that the performance of the evaporative cooling system was lowered in South Korea where the temperature and humidity were high in summer (Yoo et al., 2015). In particular, if the humidity environment inside the pig house is not appropriate, it may adversely affect the growth.

There is a method of adjusting the windchill temperature in order to simultaneously satisfy the temperature and humidity environment of pigs. All livestock may experience passive evaporative heat loss on both skin and respiratory surface (Hillman, 2009). Increased air velocity at pig lying area affects the immediate thermal vicinity of the animals, causing increased convective heat losses from their bodies and therefore expanding the thresholds of their perceived thermo-neutral zone (wind-chill effect) (Wellock et al., 2003; Zhang & Bjerg, 2017). Pexas et al. (2021) concluded that both the shower cooling method and windchill cooling method can significantly reduce the impact on the environment while improving farm profitability. Therefore, it was necessary to reduce the air temperature by windchill cooling method to prevent internal high temperature while satisfying the pigs' thermal demand.

2.4. Air recirculation technology

Air recirculation technology is a technology that minimizes the inflow of outside air and uses the internal air which is cleaned by a wet scrubber system. The reason for using the recirculated air is to reuse the thermal energy inside the pig house. This technology is widely investigated in industrial environments to save air conditioning costs by recycling the energy inside buildings (Besant & Simonson, 2000; Burton, 2004; Ekinci et al., 2006; Hall et al., 1987; Park & Seo, 2018; Ziegler et al., 2016). In particular, standards for air recirculation have been developed in general industrial processes, and the allowable concentration standards for hazardous substances in reused air are suggested (ANSI, 2007). If air recirculation technology is applied to pig houses, it is possible to minimize the possibility of livestock infectious diseases because it can block the airborne transmission of disease (Donham, 1991). Since the pig house can be operated and managed in a closed state, the infectious diseases through wild animals can be minimized. In the winter season, minimum ventilation is operated to reduce the heating load in the pig house, and as a result, the breeding environment in the pig house, such as the high level of dusts and various harmful gases, can be very poor. The ARVS can improve the breeding environment by increasing the ventilation rate and using the recirculated air. Also, it is possible to minimize the emission of odors from the pig house. Accordingly, various research has been conducted to apply air recirculation technology to pig houses (Alvarado & Predicala, 2017; Anthony et al., 2015; Anthony et al., 2014; Anthony et al., 2017; Park et al., 2017). Lau et al. (1996) devised a method of recirculating air by removing dust by using a fabric filter and an electrostatic dust collector. Although the concentration of dust in pig houses could be reduced by up to 60% or more, it was difficult to satisfy the allowable concentration standards. Anthony et al. (2017) analyzed the concentration of dust and carbon dioxide inside the pig house when the air recirculation system was applied in farrowing pig room, and reported that the air recirculation system can be an alternative to prevent the deterioration of workers' health. Wenke et al. (2018) analyzed that when a filter was installed in the air recirculation system, the dust concentration was the lowest and the pig's lung health was excellent. Peters et al. (2015) evaluated the performance by applying the shaker dust collector to the air recirculation system, and Park et al. (2017) simulated the effect of the concentration of pollutants in the pig house using mass and energy balance equations. Mostafa et al. (2017) applied an air scrubber module to the air recirculation system, and reported that wet scrubber technology can reduce both ammonia gas and dust concentrations and has no negative effect on pigs. Despite the re-search in the application of air recirculation system in pig house, there are few studies that evaluate the internal environment such as air temperature, humidity, gas, dust, and odor. In addition, previous researches on air scrubber systems have been conducted to evaluate the effect in terms of deodorizing and reducing harmful gases in pig houses. However, there is no current research that focuses on designing an air conditioning system to prevent livestock disease by recirculating air. In particular, there are no present study related to analyzing the complex environment inside and outside the pig house through installation of ARVS including the wet scrubber module to improve the internal environment, re-duce energy load, improve energy recovery rate, and reduce exhaust gas and odor.

Chapter 3. Analysis of representative problems through field experiment and aerodynamic analysis using CFD simulation for evaluating applicability of system

3.1. Introduction

This chapter intends to present the results of the analysis of internal environmental problems in the experimental pig house where the ARVS will be installed. The data for system installation were collected through field experiments at the experimental pig house where the environmental factors, ventilation rate, and operating information were measured. Based on these monitoring data, the main environmental problems of the target pig house were analyzed. The results of monitoring data analysis were used for the improving internal environment through the application of the air recirculated ventilation. However, in reality, it is impossible to conduct experiments with artificially changing various environmental conditions while raising pigs on the farm, and qualitative and quantitative visualization of the air flow and various environmental factors was also difficult. In order to overcome these limitations, the CFD simulation model for the target pig house was designed, and then environmental analysis was conducted with the computed CFD results. The environment data inside and outside the pig house were measured through seasonal field experiments, and they were also used as input data and validation data for the CFD simulation. In addition, the improvement and applicability of the ARVS were evaluated compared with the existing system by adding the module of the ARVS in the CFD simulation model.

3.2. Materials and methods

The internal environment of the target pig house was analyzed through field experiments and CFD simulations (Figure 3-1). The measured data in the target pig house include the air temperature, humidity, gas (ammonia, carbon dioxide), and ventilation rate. Additionally, the external weather was monitored by the meteorological station installed in the target experimental pig farm. Based on these data, the analysis of seasonal problems occurring inside the pig house was conducted. In addition, the measured data were used as input data and validation data for the CFD simulation. The model for the ARVS was integrated into the developed CFD model where the ventilation rate and EAMR of the ARVS were used to evaluate CFD calculation. The ARVS was installed on the real experimental piglet house, and seasonal validation experiments were conducted. In this paper, applicability was evaluated through the CFD simulation for the ARVS, and the validation results of the real farm will be analyzed in the next sections of the paper.

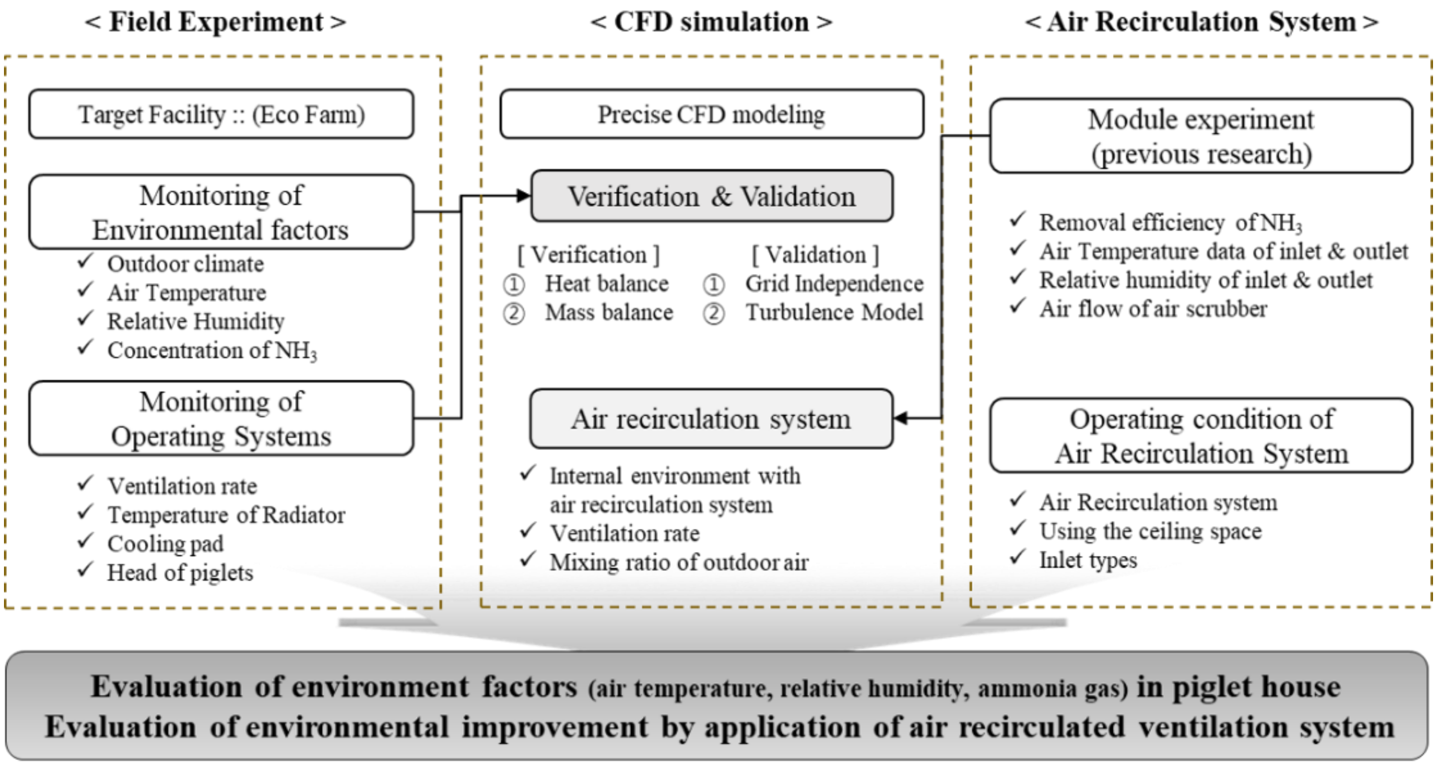


Figure 3-1 Flowchart of the analysis of internal environment for the development of the ARVS.

3.2.1. Target pig house

A mechanically ventilated pig house in Sunchoen EcoFarm (34°55’17” N, 127°22′8″ E), Jeollanam-do, South Korea, was selected as the target pig house where the ARVS would be installed. About 980 piglets aged between 3 and 11 weeks were raised in the experimental pig house (Figure 3-2) during the period of the study. The dimension of the facility is 10.55 m in width, 31.25 m in length, and 2.6 m in height. There was a ceiling space 1.2 m high above the pig house, and a corridor with a width of 1.25 m outside the pig houses. The stocking density was found to be 0.35 $m^2 \cdot head^{-1}$, which was higher than the Korean stocking density standard of 0.24 $m^2 \cdot head^{-1}$. The outdoor air can enter through the corridor windows openings and through the 5 rows of 7 ceiling slots at the top of each pig zone. Identical types of side exhaust fans and chimney exhaust fans with 141.6 CMM each were installed in the experimental pig house (COCO-630A, Dong-sung Cocofan. Ltd., Gyeonggi-do, Korea). The required ventilation rate according to the number of piglets was 509.6 CMM, and the recommended ventilation rate in winter and summer was 101.2 CMM and 762 CMM, respectively (MWPS, 1983).

The ARVS was installed in the experimental pig house in December 2021. In the existing ventilation system, external air flowed into the ceiling space from the corridor and then flowed into the pig house through the ceiling slots. The air inside the pig house was then exhausted from the outside through the chimney exhaust fan. Whereas the side exhaust fan was used only for maximum ventilation rate in summer, in general, only the chimney exhaust fan was used for operating ventilation. When the ARVS was applied, only the side exhaust fans were used for ventilation. The air inside the pig house could pass through the wet scrubber module to remove the ammonia gas, dust, and odors. The mixture of cleaned air and external air would then be recirculated again in the pig house. An experiment and simulation studies were also conducted on individual modules to determine the optimal design characteristics of the ARVS by Aero-Environmental & Energy Engineering Laboratory (A3EL) research team. The removal efficiency of the ammonia gas calculated through the module experiment was used as an input data in the CFD model of this study. Based on these results, the internal environment of the pig house was evaluated according to the ventilation rate and EAMR. Because the Ultraviolet (UV) module was used for the sterilization effect of air, it does not affect the internal environment. Additionally, the solar module is operated only when temporary heating was needed in the winter. Therefore, both the UV module and solar module are not considered in the analysis of the internal environment.

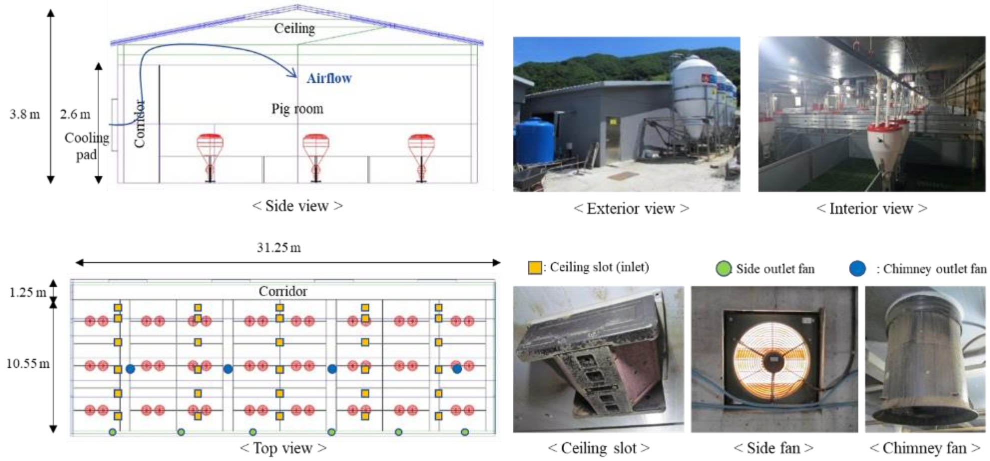


Figure 3-2 The structure and ventilation system of the experimental pig house.

3.2.2. Field experiment

The environmental data such as the heat, moisture, ammonia level, and ventilation rate were measured through field experiments from January 2019 to December 2021. Based on the measured data, the internal environmental analysis and validation of the CFD model were conducted. A total of 980 piglets which were about 7 weeks of age were raised inside the target experimental pig house. To measure the internal air temperature and relative humidity, temperature and humidity sensors (SH-VT260VS, Sohatech, Seoul, Korea) were installed at 9 points inside the pig house at a height of 1 m. The same temperature and humidity sensors were also installed in the corridor. A wireless temperature and humidity sensor (UX-100-03, MA, USA) were also installed at difficult-to-reach sampling areas such as the pig house entrance and ceiling where the installation of wired sensors was difficult. The installation location of each sensor is as follows (Figure 3-3). A weather station was installed outside the pig house to measure the outside temperature, humidity, and wind speed in real time. In order to measure the ammonia concentration, complex gas meters (MultiRAE IR, RAE System, California, USA) were installed at 6 sampling points. Calibrated readings from gas detector tubes (GV-110s, GASTEC, Kanagawa, Japan) were used to measure the ammonia concentration inside the pit because it is impossible to measure the ammonia concentration using the complex gas meters inside the pit while pigs are being raised. In the case of a ventilation fan, the ventilation rate may be lower than the design fan performance depending on the age of the fan, the shape of the internal structure and the inlet type, and so on (Park et al., 2018). Therefore, the actual ventilation rate of the exhaust fan was quantified by measuring the difference between the inside and outside static pressure of the exhaust fan according to the operating condition and linking it with the actual electricity consumption. The relationship between the static pressure difference inside and outside the facility and the ventilation rate are shown in Equation 1 (Liu & Liu, 2012). Using a differential pressure sensor (Manometer, TSI, Minnesota, USA), the static pressure of the exhaust fan was measured. The measurement location was in front of the exhaust fan (inside the piglet house) and outside duct of exhaust fan.

$$\triangle \mathrm{P} = (\frac{\rho}{\rho_d})(a_0 w^2 + a_1 Q w + a_2 Q^2) \qquad \text{Equation 3-1}$$

where ρ is the air density at the inlet (kg·m^{-3}), ρ_d is the air density at the outlet (kg·m^{-3}), Q is the ventilation rate (m^3·s^{-1}), and w is the variable fan operation rate (dimensionless). The difference in static pressure inside and outside the exhaust fan was measured.

The difference in static pressure inside and outside the exhaust fan was measured. The fan performance curves by the design fan curve and the actual measured airflow rate are shown in Figure 3-4. Considering this reduction in airflow rate of the fan, the boundary conditions of the CFD model were used from the relational expression shown in Table 3-1. In addition, the actual ventilation rate was measured in real time at the pig house based on the conversion result of the actual airflow rate according to the static pressure applied to the exhaust fan. As a result of the measurement, the airflow rate was decreased by about 19% compared to the design ventilation rate.

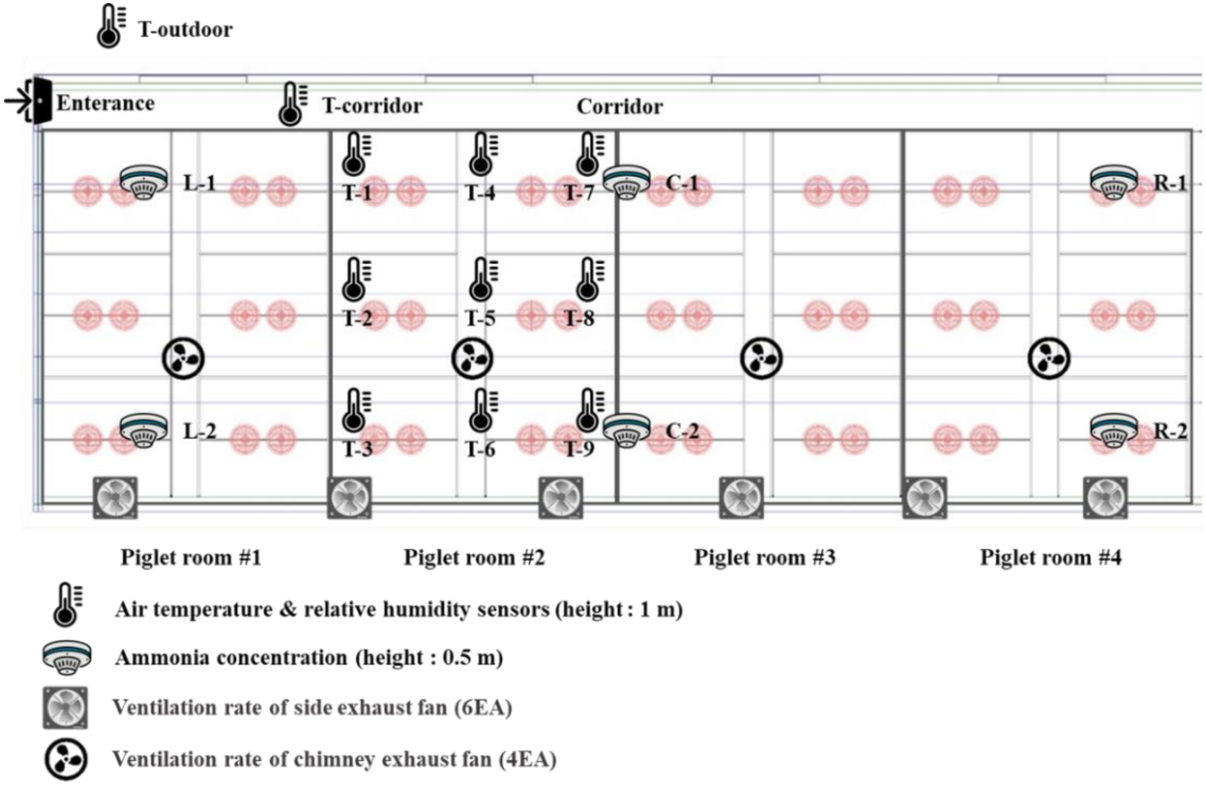


Figure 3-3 Installation location for each sensor inside the experimental pig house.

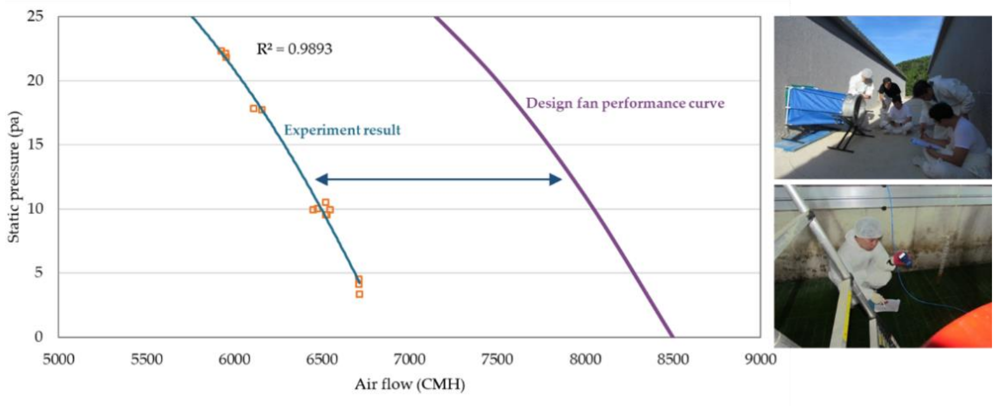


Figure 3-4 Calculation of the airflow reduction based on the measured data of static pressure.

Table 3-1 Results from measuring the ventilation rate of exhaust fan in the experimental pig house.

Static pressure (Pa)	Flow rate (CMH)		Reduction rate (%)
	Design	Actual	
0	8497	6835	19.6
10	8061	6499	19.4
20	7488	6046	19.3
30	6778	5478	19.2
40	5931	4787	19.3

3.2.3. Computational fluid dynamics (CFD)

CFD is a technology that obtains numerical solutions for physical quantities such as the pressure, force, and temperature or visualizes physical and chemical phenomena through computer simulation. The environmental conditions or theoretical equations can be easily applied to perform simulation through a CFD model, and only steady-state analysis and transient-state analysis can be computed. CFD simulation is widely used in fluid phenomena including heat transfer, mass transfer, and chemical reaction, mainly in mechanical, chemical engineering, manufacturing, and industrial fields. In addition, CFD simulation is being used in various buildings such as greenhouses and livestock houses to estimate the heating and cooling, ventilation, wind load, odor dispersion, and so on. The equation required to analyze fluid and energy flows from CFD are nonlinear simultaneous partial differential equations obtained by applying the law of conservation of mass, momentum, and energy. The mass conservation equation can be applied regardless of whether the flow is steady, viscous, or compressible, and can be expressed as Equation 3-2. The momentum conservation equation is known as the Navier–Stokes equation, and it is expressed as Equation 3-3. The energy conservation equation can be defined as Equation 3-4 as an equation that stipulates the relationship of energy converted between physical systems.

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}\left(\rho u_j\right) = 0 \qquad \text{Equation 3-2}$$

Conservation of momentum equation:

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_i u_j) = \frac{\partial}{\partial x_j}\left[-p\delta_{ij} + \mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] + \rho g_i \quad \text{Equation 3-3}$$

Conservation of energy equation:

$$\frac{\partial}{\partial t}(\rho C_a T) + \frac{\partial}{\partial x_j}(\rho u_j C_a T) - \frac{\partial}{\partial x_j}(\lambda \frac{\partial T}{\partial x_j}) = s_T \qquad \text{Equation 3-4}$$

Where, C_a is the specific heat capacity (W·kg^{-1}·K^{-1}), g is the gravity acceleration (m·s^{-2}), s_T is the sink or source term (W·m^{-3}), x is the position vector in tensor notation, T is the temperature (K), t is the time (s), u is the velocity components (m·s^{-1}), ρ is the air density (kg·m^{-3}), δ is the Kronecker delta, λ is the thermal conductivity (W·m^{-1}·K^{-1}), and i, j and k are the Cartesian coordinated indices. In this study, Design Modeler and ANSYS Meshing (ANSYS Inc., USA) were employed in the pre-processing stage, while ANSYS FLUENT (ANSYS Inc., USA) was employed in the main-processing stage.

3.2.4. Experimental procedure

In this study, the internal environmental factors were measured in the experimental pig house, and the result of the analysis was later applied for the development of the ARVS. In addition, since it was difficult to analyze the aerodynamics and various conditions inside the pig house with live pigs, the CFD simulation modelling technique was additionally used to analyze the internal environment according to the ventilation rate and ventilation types. The CFD model was validated based on the measured data to evaluate the accuracy and reliability of the CFD model. In addition, it was attempted to evaluate the applicability of the ARVS and to predict the environmental distribution.

3.2.4.1. Data construction for analysis of the internal environment of the piglet room

The air quality (temperature, humidity, gas, and so on) inside and outside the pig house was measured every 5 s and stored at average of 5 min interval measurements in the database. The database also stored the power consumption of the exhaust fan, which was measured and converted into an equivalent ventilation rate. According to the ventilation conditions, the collected data were evaluated for whether ventilation was properly operated seasonally. The real-time measurements obtained by the installed sensors were also stored in the database. Each datum was monitored through a program built on the website. The data collection for big data construction was conducted using an open-source client program (HeidiSQL). HeidiSQL is a piece of DBMS (database management system) software that enables efficient data storage and management for communication between users and databases and supports search and data operation. The sensor values defined in each sensor were matched to build real-time and continuous data. Since it was difficult to analyze and visualize the collected raw data in the direction of users, a program that can automatically collect and systematically visualize the data was coded and used in this study.

3.2.4.2. Data processing method of measured data

A time synchronization was conducted because the time of the collected data may be different depending on the time setting of each sensor. In addition, data filtering was needed since unnecessary redundant data can be collected in the data-collection process. Using the C language string function, duplicate data removal and time synchronization programs were designed and installed. In the data-collection field, the sensor ID can be defined by the developer. However, in the data-collection process, it is necessary to process the data defined in a row to fit each field row in order to improve the data-collection efficiency. Therefore, the first data-processing operation was conducted using the R program. After the first processing, the data were classified into fields according to the location and type of each sensor, and data visualization was conducted to analyze data easily. For data visualization, Excel and VBA (Visual Basic for Applications) program codes were used, and since the data collection period was long, visualization was made possible by dividing it into seasons, factors, and days. In this study, the time points corresponding to seasonal internal environmental problems and the cause analysis were found among the environmental monitoring results of the pig house. The data were divided into time series, and the internal environmental factors and ventilation rate were comparatively analyzed.

3.2.4.3. Design and validation of CFD simulation model

The process of developing the CFD model was conducted as follows: (1) design of the geometry, (2) meshing, (3) input of boundary conditions, and (4) calculation of the CFD model. However, the development CFD simulation model has various uncertainties. First, uncertainty in the design of geometry may occur when the shape of the actual pig house is simplified for simulation or some shapes are excluded. In this study, all internal structures of the pig house were designed similarly except for thin pipes and wires that did not significantly affect the airflow, and the actual shape of the pigs were designed to be the size of a 7-week-old piglet. In addition, the ventilation structure was designed to have the same shape as the real pig house to reduce uncertainty as much as possible. Second, in the mesh design stage, it is important to design the grid distance as efficiently as possible. The larger the grid interval, the faster the simulation computation, but the resolution of the calculation results may be lowered and the accuracy may be lowered. In this study, the optimal number of grids was determined by the grid independence test comparing the calculation speed according to the shape and number of grids. The grid was designed by maintaining the skewness value, which is an indicator of grid quality. Third, the uncertainty may occur depending on the value input as the boundary conditions. The environmental variables to be analyzed in this study were heat, moisture, gas, and airflow. The input values of boundary conditions for each environmental variable were values measured in the field and values obtained by theoretical equations. Therefore, the similarity between the values measured in the field and the simulation results calculated based on the values obtained from the theoretical equations was confirmed. Additionally, different calculation equations are applied depending on the turbulence model to simulate the airflow. In the turbulence model, the types and methods of solving the equations are different depending on the CFD model. Therefore, by performing calculations according to various turbulence models, the turbulence model simulated most similar to the data measured in the field was selected as the final model. Finally, in the calculation stage, it can be divided into a steady-state and a transient state depending on the timing of the simulation. Since heat and gas generation per hour are applied, the transient state was simulated to consider the time interval.

To reduce the uncertainty of the CFD model simulation and improve the accuracy, verification of whether field-measured data was suitable for boundary conditions, and comparison with theoretical equations was conducted. Additionally, validation to improve the accuracy of simulation results was conducted through comparison of CFD computed results and field measured data. The theoretical verification was conducted with the thermal environment and the gas environment, which were the most important factors in the internal boundary condition.

When verifying the thermal environment, the boundary condition of the CFD model was applied based on the temperature data measured in the field, and the heat generation was compared with the simulation result and the heat generation rate of piglets provided by (CIGR, 2002). To simulate the heat generation rate of piglets in the CFD model, the surface condition of a piglet was divided into the surface of skin for body heat and the surface of the mouth for respiration. Both the heat transfer in the air and conduction to the floor inside the pig house were ignored, and only heat generated by latent heat and sensible heat was considered. In the case of a gas environment, the generation rate per unit time in the pit space of the CFD model was simulated based on ammonia data measured inside the pig house, and verification of the boundary condition was conducted compared with the amount of ammonia generated according to the domestic emission factor.

In order to improve the accuracy of CFD simulation, the grid independence test and turbulence model test were conducted to increase the computational efficiency of the model. For the grid independence test, a grid size with sufficient quality was selected by comparing the calculation time according to the number of grids of the model and the skewness of the grid. Additionally, based on the temperature data measured in the piglet house, the turbulence model was selected by conducting comparative validation according to the turbulence models. Finally, CFD models were computed based on the models which were conducted for verification of boundary conditions and validation of grid independence test and turbulence models.

3.2.4.4. Boundary conditions of CFD simulation model

The boundary conditions finally used for the calculation of the CFD simulation model designed in this study is shown in the Table 3-2. The heat, moisture, and gas generation were applied as values determined through verification, and ventilation rates were applied in consideration of the fan load. The heat source inside the piglet house was simulated by the pig’s body surface and breathing. For the surface temperature of the pig, the actual measured value of the surface temperature of the pig was applied. Since the temperature of the pig’s breathing air is equal to the body temperature, the sensible heat caused by respiration was applied as the body temperature of the piglets in the boundary condition. Additionally, the moisture generation rate was included in the respiration of piglets (Figure 3-5).

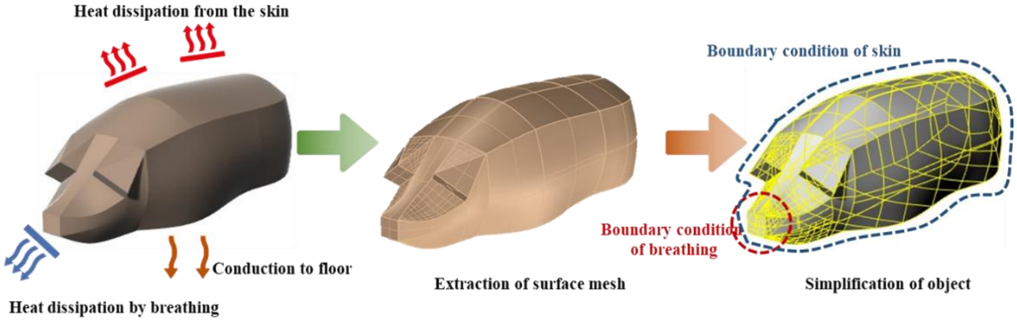


Figure 3-5 Calculation of the airflow reduction based on the measured data of static pressure.

Moisture and ammonia generation rates from the manure were simulated to generate and diffuse from the pit space located at the bottom of the piglet house. The moisture generation rate was applied in consideration of the ratio between the size of the pig house used in the previous study and the size of the pig house applied in this study (Hayes et al., 2013). In addition, the ammonia generation rate was converted to the ammonia concentration measured in the experimental piglet house and applied in the CFD model. The moisture and ammonia gas should pass through the pit slot on the bottom to diffuse from the pit space. The airflow can be resisted by the structure of the pit slot. Therefore, the floor of the pig house was designed as a porous medium for the efficiency of the calculation considering the effect of diffusion of moisture and ammonia gas inside the pit. When passing through the area of the porous medium, the element resisting the flow in the x-, y-, and z-axis directions can be calculated and expressed through Equation 3-5 (Bjerg et al., 2008). Considering the shape of the pit, the airflow in the vertical direction exists and the air flow in the horizontal direction is limited.

$$\Delta \mathrm{p} = 0.5 \times R_1 \times \rho \times v^2 + \mu \times R_2 v \qquad \text{Equation 3-5}$$

where Δp is the pressure change in the porous medium (Pa), R_1 is the internal resistance factor, R_2 is the viscous resistance coefficient, ρ is the density of air ($kg{\cdot}m^{-3}$), v is the velocity flowing in the porous medium ($m{\cdot}s^{-1}$), and μ is the viscosity coefficient of the air ($kg{\cdot}m^2{\cdot}s^{-1}$).

When the ARVS is applied to the validated CFD model, the inlet and outlet of the pig house can have the outlet and inlet wet scrubber module applied, respectively. Therefore, the environmental values of the air exhausted from the pig house were converted by the characteristics of the wet scrubber module, and the air was mixed with the external air. When analyzing the ARVS, the heat, moisture, and gas generation rate of the validated CFD model were equally applied. If an ARVS is installed, the performance of the equipment can be assumed to be its own capacity, and it can be operated by controlling the ventilation rate and the EAMR. Additionally, the removal efficiency of the wet scrubber module depends on the ventilation rate, type of fills, type of recirculation water, and so on. Therefore, for CFD simulation, the characteristics of the wet scrubber module should be numerically applied. In this study, the results of previous research on each module of the A3EL research team were used. After determining the characteristics of the wet scrubber module based on the experimental results for various variables (type of nozzles, fills, recirculation water, and so on), in the CFD simulation, the removal efficiency of 77, 64, 54, and 49% were assumed depending on the ventilation rate of 25, 50, 75, and 100%. The condition of the air passing through the wet scrubber can converge to the temperature of the recirculation water with a relative humidity at 100%. The recirculation water is initially the same as the temperature of the groundwater, but it can converge to a certain temperature in contact with the air inside the pig house. When the initial temperature inside the pig house was assumed to be 30°C and with a relative humidity of 60%, it converges to about 24℃ based on repeatedly calculating the heat exchange. Therefore, the recirculation water temperature was set to 24℃ in the CFD simulation model. The boundary conditions applied to the CFD model are shown in Table 3-2.

Table 3-2 Boundary conditions of CFD simulation.

Types		Values	Units
Outdoor temperature (TAC : 5%)	Winter	-8	℃
	Summer	33	
Air temperature inside the corridor	Winter	10	℃
	Summer	31	
Heat production	Surface temperature of piglets	39.7	℃
	Breathing capacity	0.28	$m^3 \cdot s^{-1}$
Moisture production of piglets		1.7	$g \cdot h^{-1} \cdot kg^{-1}$
Moisture generation rate of manure		2.8	$g \cdot h^{-1} \cdot kg^{-1}$
Ammonia generation rate of manure		211.4	$g \cdot h^{-1}$
Ventilation rate	Validation	0.6	min^{-1}
	Winter	0.12	
	Summer	0.92	
Solver		Pressure-based solver	-
Numerical algorithm		SIMPLE algorithm	-
Time condition		Steady state	-
Operating pressure		1.1325	Pa
Gravitational acceleration		9.81	$m \cdot s^{-2}$
Air density		1.225	$kg \cdot m^{-3}$
Air viscosity		1.7894×10^{-5}	$kg \cdot m^{-1} \cdot s^{-1}$
Ammonia density		0.6894	$kg \cdot m^{-3}$
Ammonia viscosity		1.015×10^{-5}	$kg \cdot m^{-1} \cdot s^{-1}$
H_2O density		0.5542	$kg \cdot m^{-3}$
H_2O viscosity		1.34×10^{-5}	$kg \cdot m^{-1} \cdot s^{-1}$

3.2.4.5. Case studies of CFD simulation

In this study, an analysis of the internal environment and seasonal problems of the target pig house was conducted based on the data measured in the field experiment. CFD simulation was used to aerodynamically analyze the causes of these problems. First, the main environmental problems such as internal temperature, humidity, and gas were analyzed based on the computed results of the CFD simulation (Table 3-3). It is necessary to compare the difference according to the operating conditions of the ventilation (ventilation rate, inlet type, and so on) to suggest the improvement method for these problems. Therefore, the CFD model that was previously analyzed in the winter season was used to analyze the operating condition when the ventilation rate was increased and the radiator was added. In addition, the evaluation according to the ceiling slot condition was conducted to analyze the internal uniformity as shown in Table 3-3. Finally, at the same ventilation rate, the internal environment of the pig house was comparatively analyzed based on the computed results when the ARVS was applied. To evaluate the applicability of the ARVS, the internal rearing environment was analyzed according to the ventilation rate and EAMR. The total number of case studies for the CFD simulation was 37.

Table 3-3 Case studies of the CFD simulation in this study.

Purpose	Experimental variables	Cases
Analysis of the internal environment by season	Outdoor weather condition: winter & summer	2
Analysis of internal environment according to the increase of ventilation rate using radiator in winter season	Ventilation rate: 0.06, 0.12, 0.18, 0.24, 0.3 min^{-1} Radiant values of radiator: 0, 500, 600, 650 W	20
Analysis of internal environment according to the ceiling slot conditions	Open conditions of ceiling slots: 3 types Ventilation rate: 0.12, 0.24 min^{-1}	6
Analysis of the internal environment according to the operating conditions of the air recirculation system	Ventilation rate: 0.2, 0.6, 0.9 min^{-1} Mixing ratio of outdoor air: 25, 50, 75%	9

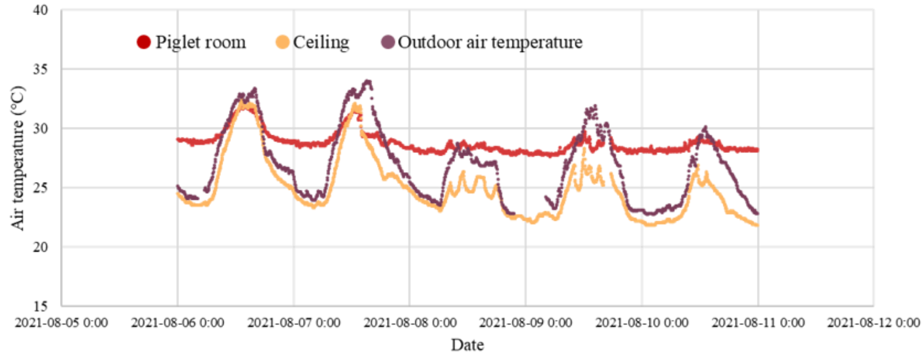
3.3. Results and discussions

3.3.1. Analysis of internal measurement data of piglet house in summer and winter season

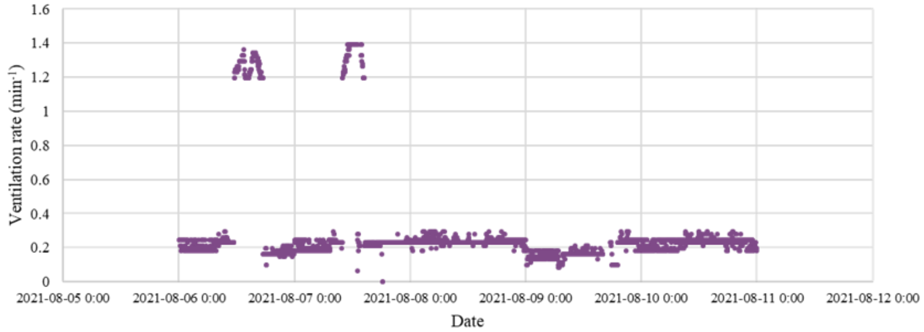
3.3.1.1. Results of summer season

Figure 3-6 shows the air temperature, ventilation rate, and gas measurement results inside the pig house in summer. The aim for temperature of the experimental piglet house was about 28 °C. The chimney exhaust fan was operated according to the internal temperature. When the weather was hot, additional ventilation was operated using the side exhaust fans to increase the ventilation rate. The highest temperature outdoors on 6th and 7th August was kept high at about 34 °C, and the lowest temperature at nighttime showed a temperature distribution of 24 °C. Due to the hot weather outside, as shown in Figure 3-6 (b), the ventilation rate was temporarily high. As the ventilation rate increased, the air exchange rate was high, so the temperature inside the pig house was greatly affected by the external air. As a result, a ventilation rate of 1.4 min^{-1} during the daytime was operated, and the air temperature inside the ceiling and the pig house reached about 33 °C. If the target temperature rises by 5 °C compared to the target temperature of 28 °C, there may be a problem that the daily weight gain of piglets decreases by about 16.8% from 467.6 $\mathrm{g \cdot day^{-1}}$ to 388.6 $\mathrm{g \cdot day^{-1}}$ (Fuller, 1965). Because the experimental pig house did not use the additional cooling system, the method to lower the temperature inside the pig house was limited in the current operation method. At nighttime, the target temperature was kept close to 28 °C with a low ventilation operation of 0.2 min^{-1} despite an external temperature of 25 °C due to the heat production of the piglets. During the daytime on 8th and 9th August, the external temperature was 27 °C and

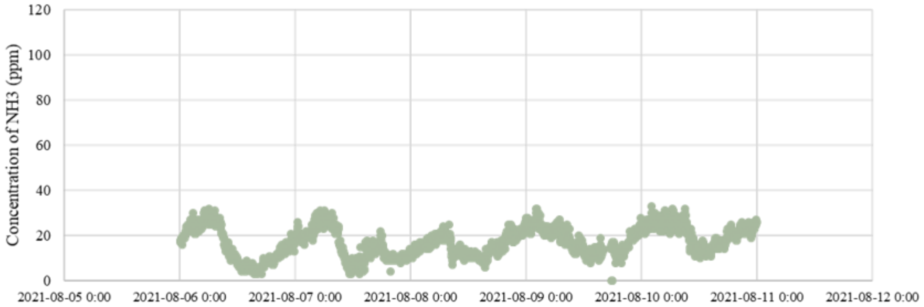
32 ℃, respectively, but the low ventilation rate led to less air exchange inside the pig house and the target temperature could be maintained. In the case of the ceiling space, which is an inflow path of external air, an average of 26 ℃ was maintained, lower than the temperature inside and outside the pig house. The roof of the experimental pig house was made of 175 mm hard urethane panels, which is more than double the recommended thickness of 75 mm in the southern region of Korea (MAFRA, 2020). Accordingly, due to the high thermal insulation effect, the heat accumulation inside the ceiling space did not occur significantly, and the temperature was maintained lower than the outside and inside of the pig house. Figure 3-6 (c) shows the measured data of the ammonia concentration inside the piglet house. During the daytime on 7 August, when the ventilation rate was temporarily increased, the concentration of ammonia gas was as low as about 6 ppm, but it was maintained at around 20 ppm during the summer season due to the overall low ventilation operation. When the external temperature rose greatly, the farmer tried to prevent the internal high temperature stress by artificially increasing the ventilation rate. However, there was a problem that the air temperature rose because there was no cooling system. In order to resolve these problems, ventilation with a cooling system controlled according to the temperature distribution inside and outside is required. It is expected that high temperature stress can be prevented by operating the ARVS equipped with a wet scrubber method that has a cooling effect in this experimental pig house. In addition, the internal ammonia gas could not be removed because of the low ventilation rate. Therefore, it is possible to improve the gas environment by increasing the ventilation rate through the ARVS.



(a) Air temperature (piglet room, ceiling and outdoor)



(b) Ventilation rate of piglet room



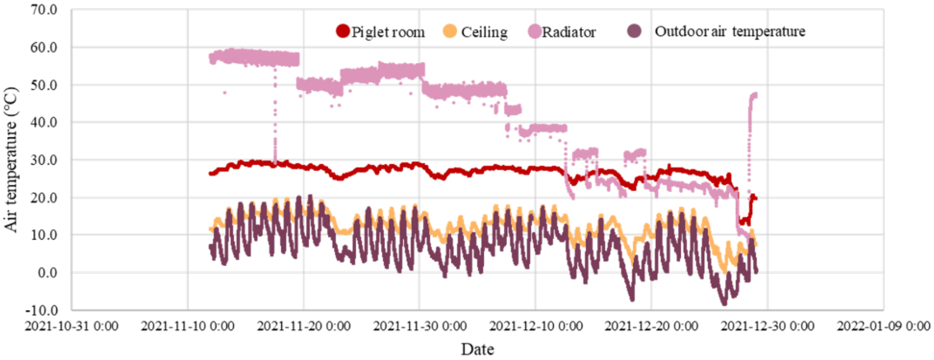
(c) Concentration of NH_3 in piglet room

Figure 3-6 The air temperature, ventilation rate, and ammonia gas results measured in experimental piglet house in summer season. Data analysis period of August 6 (5 weeks piglet) when heat stress was occurred.

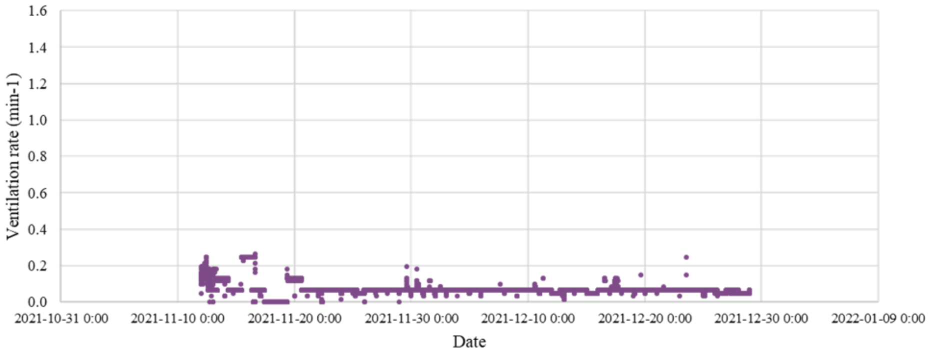
3.3.1.2. Results of winter season

Figure 3-7 shows the temperature, ventilation rate, and gas measurement results inside the pig house in winter. The pig breeding period was from 12 November to 28 December 2021. The standard operating temperature was maintained at 30 ℃ initially and lowered by 1 ℃ every week to 25 ℃ at the end of rearing period. To maintain the internal temperature in the piglet house, the radiator was operated in stages according to the age of the week, and the operating temperature of the radiator is shown in Figure 3-7 (a). The set temperature of the radiator was lowered every week, but as the weight and heat production of internal pigs rose, the temperature inside the pig house was maintained within a deviation of 2 ℃. It is considered that the internal air temperature was well operated by maintaining the internal temperature of the pigs from about 30 ℃ to about 26 ℃. During the rearing period, the external temperature was formed at about 20 ℃ during the daytime, and the difference in air temperature between the outdoor and inside of the ceiling was maintained at about 1 ℃. Meanwhile, during the nighttime, the temperature dropped sharply, and the external temperature dropped to a minimum of −10 ℃. However, the ceiling space was able to maintain a temperature higher than 0 ℃ due to the excellent insulation of the roof. During the winter season, the minimum ventilation rate was maintained at around 0.07 min^{-1}, which was lower than the minimum ventilation rate of 0.12 min^{-1} based on the Midwest Plan Service (MWPS) standards (MWPS, 1983). Therefore, the proper temperature inside the piglet house was maintained through the body heat produced by the piglets, the operation of the radiator, and the operation of the minimum ventilation rate. At the beginning of rearing, the concentration of carbon dioxide gas and ammonia gas inside the pig house were 1200 ppm and 38 ppm, respectively. In this experimental piglet house, manure was not cleaned before raising piglets and ventilation was not operated. Therefore, the gas state inside the piglet house was higher than the allowable atmospheric carbon dioxide concentration of about 300 ppm, and the ammonia gas concentration was as high as about 38 ppm. In the first week, the exhaust fan was operated at the ventilation rate of 0.2 min^{-1}, and the internal ammonia concentration was lowered to about 10 ppm because the amount of gas emitted was larger than the generation rate. This showed a similar trend to the ammonia concentration in the summer operating with a ventilation rate of 0.2 min^{-1}. However, since 20th November, the ventilation rate was operated at 0.07 min^{-1}, and the concentration of internal carbon dioxide and ammonia gas showed a continuous increase. The amount of carbon dioxide generated was closely related to the respiration of pigs, and the amount of respiration of pigs was positively correlated with internal air temperature and raising period (Van Ouwerkerk & Pedersen, 1994). Theoretically, sufficient ventilation should be operated to lower the gas concentration as the age of the piglets increases. However, in this experimental piglet house, the internal gas environment was maintained very poorly because less ventilation was operated for maintaining the air temperature. Accordingly, since the ventilation rate was low, the ammonia gas concentration was measured to be above the allowable gas concentration of 20 ppm. As the age of the piglets increased, the gas generation rate in the manure increased, so the internal ammonia concentration eventually increased by more than 50 ppm. It was necessary to lower the ammonia concentration through sufficient ventilation because this could greatly reduce the feed efficiency and immunity of piglets.

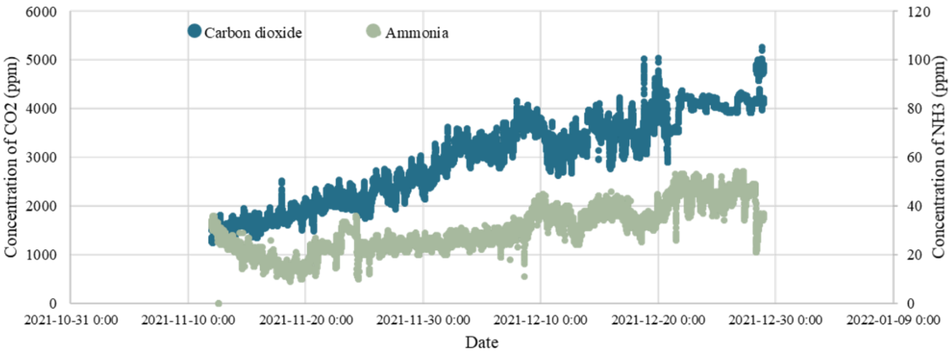
In this experimental piglet house, ventilation was hardly operated to maintain the internal air temperature in winter. Therefore, it was concluded that the application of the ARVS is necessary to improve the gas environment by increasing the ventilation rate. In addition, the air discharged through the ARVS could be advantageous in resolving complaints because the odors and harmful gases can be reduced. It also has an advantage in preventing the inflow and outflow of infectious livestock diseases in the winter.



(a) Air temperature (piglet room, ceiling and outdoor)



(b) Ventilation rate of piglet room



(c) Concentration of NH_3 in piglet room

Figure 3-7 The air temperature, ventilation rate, and ammonia gas results measured in experimental piglet house in winter season.

3.3.2. Verification and validation of CFD simulation model

3.3.2.1. Verification of boundary conditions

To verify the boundary condition input value of the CFD simulation, the calculated value based on the theoretical equations and the calculated value using the CFD simulation model were compared and analyzed. First, in order to verify the boundary condition for the thermal environment, the heat production of the simulation model was calculated (Table 3-4). In general, the flow of internal thermal energy in a piglet house is heat generated by animals, the conduction of external solar energy by walls, and heat transfer to the ground. The roof and walls of the experimental pig house were not exposed to the outside and were adjacent to the corridor, the ceiling space, and other pig houses. Additionally, the thickness of the wall was more than twice that of the standard pig house. Therefore, in this study, the heat transfer from walls and floors and heat transfer by external solar radiation were not considered. In a previous study, the heat production of pigs was considered as body heat on the pig's surface to simulate sensible heat production (Seo et al., 2008). Since the short-term behavior of air, heat, and gas in a transient state was analyzed to simulate the heat generated over time, in this CFD model, not only the body heat of the piglet but also the heat production per hour through the respiration of the piglet was considered. In the CFD model applying the temperature data measured in the field, the total energy by respiration was calculated to be 26567 W, and the heat flux generated from the pig's surface was multiplied by the surface area to calculate the heat production of 9235 W. Therefore, the total heat production of 35803 W, which was the sum of the two calculated results, was derived (Table 3-4). Next, to verify the heat production based on the theoretical equation, 35476 W was derived by multiplying the total heat production value, the sum of latent heat and sensible heat, by the actual number of piglets based on the heat production of piglets provided by CIGR (CIGR, 2002). Therefore, since the error between the two calculated values was within 0.9%, it was considered that the internal thermal environment was appropriately simulated in the CFD model to which respiration and surface heat were applied based on the data measured in the field.

Table 3-4 CFD computed results of respiration and body heat production of piglets and calculated results of theoretical heat production.

Conditions	Parameter	Heat generation rate	Unit
CFD computed data	(a) Breath of piglets	26567.6	W
	(b) Body heat of piglets	9235.5	W
	(a) + (b) Total	35803	W
Theoretical calculation	Total heat production	94.8	$W \cdot kg^{-1}$
	Latent heat production	58.6	$W \cdot kg^{-1}$
	Sensible heat production	36.2	$W \cdot kg^{-1}$
	980 head × 20 kg × SHP	35476	W

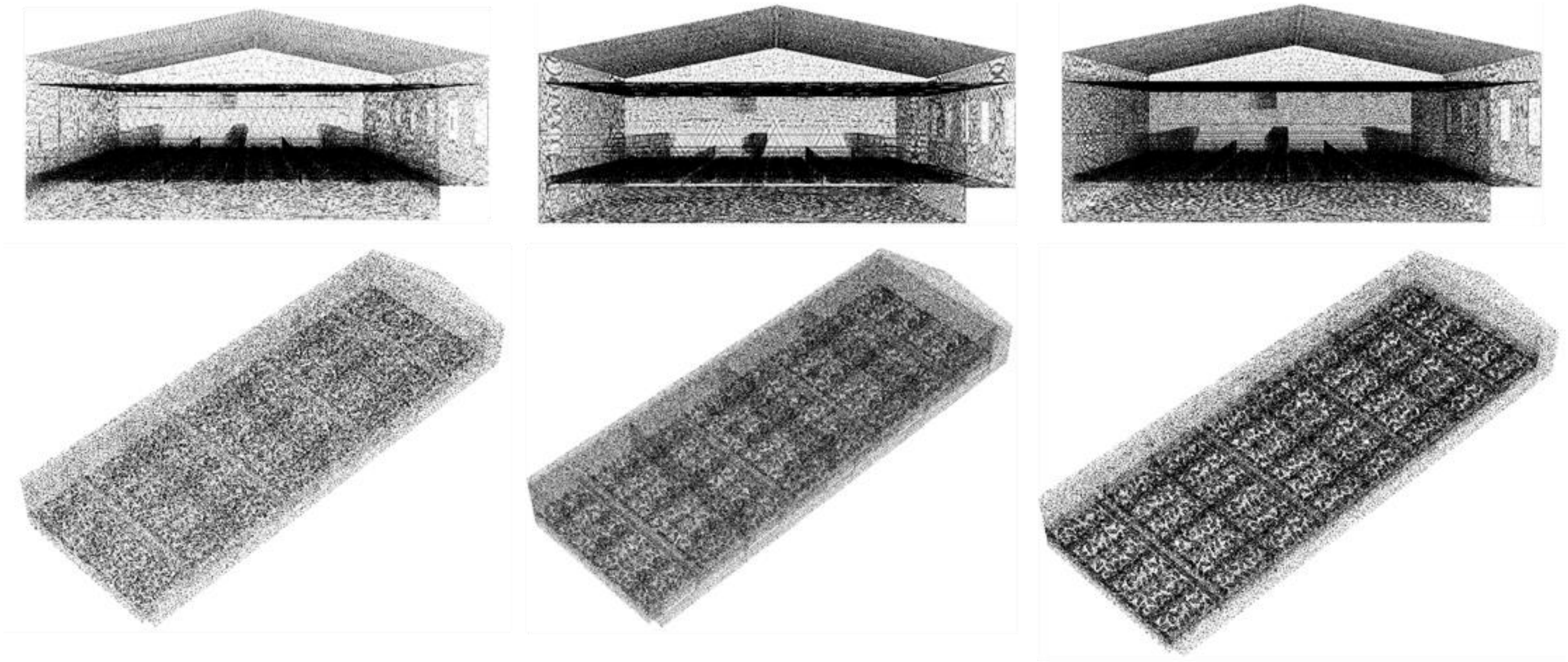
The ammonia generation rate in pig houses differs depending on the air temperature inside the pig house and the surface flow rate of manure (Aarnink, 1997). The method of constantly generating the ammonia gas on the surface of the manure in the CFD simulation model was inappropriate for simulating the diffusion of ammonia by the air flow because the constant flow rate was fixed. Therefore, in this study, boundary conditions were set so that ammonia values were diffused in the pit space according to the surrounding concentration and flow rate. In addition, the ammonia concentration value calculated in the CFD model was analyzed and compared with the domestic ammonia emission factor. The domestic emission factor is 1.89 $kg \cdot animal^{-1} \cdot yr^{-1}$ based on piglets. As shown in Table 3-5, the amount of ammonia generation rate inside the experimental piglet house was calculated. The ammonia concentration (ppm) measured in the experimental piglet house was listed according to time, and the hourly generation rate was calculated using the volume and ammonia density in the pit space. In this case, the ammonia generation rate was 2.82×10^{-7} kg·m^{-3}·s^{-1}, and the emission factor standard was 2.98×10^{-7} kg·m^{-3}·s^{-1}. The error between the two values was calculated to be within 5%. Therefore, it is considered sufficient to be applied as a CFD boundary condition.

Table 3-5 Ammonia generation rate of CFD computed results and emission factor of domestic standard.

Conditions	Parameter	Gas generation rate	Unit
CFD computed data	Concentration of NH_3 in pit slurry	2.82×10^{-7}	kg·m^{-3}·s^{-1}
Theoretical calculation	Emission factor of piglet	2.98×10^{-7}	kg·m^{-3}·s^{-1}

3.3.2.2. Validation of CFD simulation model for computational efficiency

The geometry of the experimental piglet house was sufficiently designed since the locations of all inlet and outlet ports except for the pit shape were patterned based on the actual design of the piglet house. In order to design the mesh of the CFD model, a grid independence test was conducted by comparing the calculation speed of the basic model according to the size and number of grids. First, the optimal grid size was selected by comparing the basic model calculation time according to the number of grids with skewness, a statistical index indicating grid quality. In general, as the number of grids in the model increases, the accuracy of the calculation results improves. Errors were found when larger grids were used. However, as the number of grids increases, the computation load increases rapidly, and the accuracy does not significantly improve beyond a certain number of grids and skewness quality. Skewness according to the number of grids is shown in Figure 3-8, and the grid size was corrected for optimal operation of the model. The results according to the number of grids and the calculation speed according to the grid size are shown in Figure 3-9. In this study, when the number of grids was about 6.9 million, the skewness value was designed as 0.92 and the minimum value of orthogonal quality was 0.213, and these grid conditions were used for calculating the CFD model.



Skewness : 0.84
Elements : 2,298,850

Skewness : 0.92
Elements : 6,975,444

Skewness : 0.93
Elements : 10,677,502

Figure 3-8 Results of the meshing of CFD model according to the size and number of girds.

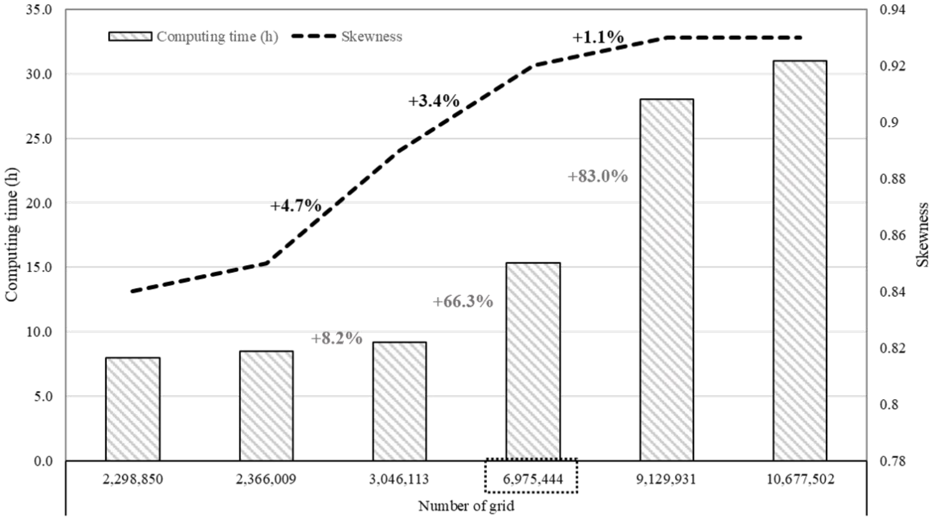


Figure 3-9 Optimization results according to the total number of grids, skewness, and computing time according to the grid size of the model.

3.3.2.3. Validation of CFD simulation model for improvement of uncertainty variables

Using the model in which the boundary condition verification for the experimental piglet house has been completed, the validation was conducted based on the measured data in the experimental piglet house. The accuracy of the model was improved by conducting comparative validation according to the turbulence model based on the May 2020 field measurement data. At the time of the field experiment, the external air temperature was 27.3°C, the humidity was about 60%, and the ventilation was operated at 0.6 min^{-1}. Internal air temperature data of the piglet house were used for the validation data, and the Realizable k-ε, Standard k-ε, RNG k-ε, and Standard k-ω were used as validation variables for the turbulence models. The difference between the computed data and the measured data according to the turbulence model is shown in Table 3-6. The external air entering the corridor of pig house was at a temperature of 27.3°C. As the heat was lost through the floor and walls inside the corridor, the temperature was lowered to about 25°C, and the air flowed into the piglet house through the ceiling space of the piglet house. The heat of the piglet house was transferred to the ceiling, and the air temperature rose again and recovered to an average of 27°C in the ceiling space. This showed a tendency to recover heat while moving from the corridor to the opposite of the corridor. Accordingly, the temperature distribution of T-1, T-4, and T-7 was lower than that of the opposite sides (T-3, T-6, and T-9) due to the inflow of fresh air, which was the closest to the corridor. In addition, the lowest temperature distribution was shown in T-2, T-5, and T-8, where the airflow was formed by the exhaust fan because the heat inside the piglet house was discharged well. Among the turbulence models, the RNG k-e model, which had the smallest error with field measurement data, showed results within 2% of error. Therefore, in this study, the RNG k-e model was selected as the turbulence model.

Table 3-6 Measured and CFD computed air temperature and error according to the turbulence models.

		T-1	T-2	T-3	T-4	T-5	T-6	T-7	T-8	T-9
Measured data	Temp (℃)	30.6	30.7	31.1	30.7	30.5	30.9	30.5	30.3	30.8
Realizable k-e	Temp (℃)	31.5	31.5	31.5	31.6	31.5	31.5	31.6	31.4	31.4
	Error (%)	2.9	2.7	1.4	2.8	3.2	1.9	3.7	3.7	2.0
Standard k-e	Temp (℃)	31.5	31.3	31.5	31.3	31.2	31.5	31.4	31.6	31.4
	Error (%)	2.8	2.1	1.4	1.9	2.2	1.9	3.1	4.2	2.0
RNG k-e	Temp (℃)	31.1	31.2	31.4	31.1	31.0	31.4	31.0	30.9	31.2
	Error (%)	1.5	1.5	1.0	1.4	1.7	1.7	1.9	1.9	1.5
Standard k-w	Temp (℃)	31.6	31.1	31.0	31.5	31.5	31.4	31.5	31.3	31.5
	Error (%)	3.1	1.3	0.2	2.5	3.3	1.6	3.5	3.2	2.4

The location of measurement and measured data of ammonia concentration are shown in Figures 3-10 and 3-11. The measured ammonia concentration was lower near the entrance than near the exhaust fan. It is considered that the concentration difference occurred because the fresh air in the corridor first entered from the location close to the corridor among the ceiling slots. The concentration of the side parts (L1, L2, R1, R2) was measured to be 7 ppm higher than the central part of the piglet room, and a concentration of 20 ppm or more occurred on the left side (L1. L2). The CFD simulation results showed that the left and right concentrations were symmetric, but in the field measurement data, the R1 and R2 points were lower than the L1 and L2 points. This difference occurred because of the difference in the manure condition inside the pit. Since the experimental piglet room was operated as an all-in–all-out system, the manure condition on both sides of the pit was also different. Accordingly, the difference in ammonia concentration occurred, and it was not realistic to consider this situation in CFD. In addition, as the piglets age, the condition of the manure becomes almost the same. Therefore, the CFD simulation was conducted assuming that all the manure conditions were similar.

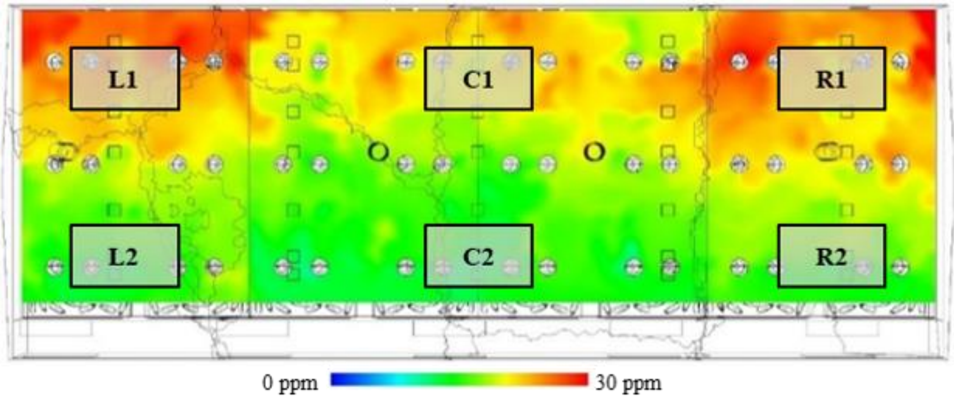


Figure 3-10 Computed results of ammonia concentration inside the experimental piglet room.

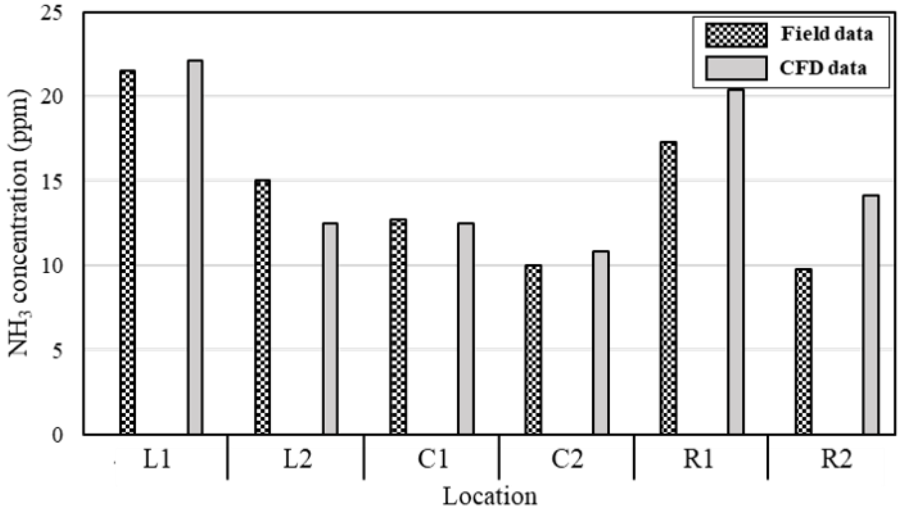


Figure 3-11 Ammonia concentration data of measurement and CFD computed results for each location inside the experimental piglet room.

3.3.3. Analysis of the CFD computed results

3.3.3.1. CFD computed results according to the outdoor climate

The results of the CFD simulation for the winter season in Korea are shown in Figure 3-12 (a). In the case of the external temperature of 10°C, the simulation was computed under the conditions of the minimum ventilation rate (0.07 min^{-1}), and the temperature and ammonia contours at the height of the piglet zone are shown in Figure 3-12. In this case, the average air temperature inside the piglet house was maintained at an appropriate level (about 29°C). This showed similar results to the previous field measured results in the winter season. An approximately 22°C air temperature was computed when the air flowed in from the corridor passed through the ceiling space. A temperature distribution of about 25°C was shown at the lower part of the ceiling slot close to the corridor. Since this cannot be measured using the temperature sensor in the field, the aerodynamic analysis of the internal environment distribution was conducted through CFD simulation. The air was heated while moving to the exhaust fan, so it was possible to prevent low temperature stress inside the piglet house. The heat source inside the piglet house was the piglet's heat production and radiator heating. Because this simulation was the result of computing the thermal environment of 5-week-old piglets without operating the radiator, operating the minimum ventilation rate was a suitable condition for the piglets. However, if the piglets have high heat production, the amount of weight gain due to feed intake may decrease due to the increase in the metabolic rate. Accordingly, the farmers try to reduce the heat production of the piglets by operating the radiator.

In the case of the ammonia concentration, it was confirmed that the ammonia concentration accumulated as the distance from the corridor was increased, and the concentration was high on both sides of the piglet house. Unlike the ammonia concentration measured in the field, the distribution of ammonia concentration around the piglet zone showed a maximum of 40 ppm of the internal deviation, and the area where the ammonia concentration was improperly distributed was more than 65% of the entire piglet house. Since the air temperature of the inlet is important for controlling the thermal environment, the location and distribution of the inlet are important. However, in the case of ammonia gas, the location where inlet was and the ventilation rate of the fan should be considered. The chimney exhaust fan and the ceiling slots installed in the center of the experimental piglet house were located at sufficient intervals, but the ceiling slots installed close to both walls were located adjacent to the chimney exhaust fan. This may cause a problem that the fresh air flowing into the side of the piglet house is not sufficiently supplied to the piglet zone and discharged through the exhaust fan. The average ammonia concentration inside the piglet house was 40.1 ppm, which was a very dangerous level, and it was predicted that the productivity decrease due to the high concentration of gas could occur when the minimum ventilation was operated in the winter season. Therefore, it was judged that the operation of the minimum ventilation rate in winter did not sufficiently remove the internal ammonia gas, and it was necessary to increase the ventilation rate using the ARVS.

The results of CFD simulation for the summer season (outdoor temperature of 34°C) in Korea are shown in Figure 3-12 (b). In the experimental piglet house, the maximum ventilation of 1.4 min^{-1} was operated even in summer when it was extremely hot, and 0.2 min^{-1} was usually used. In this study, the CFD models were computed under the condition of the maximum ventilation rate, and the air temperature near the piglet zone was maintained at an average of 32.05°C. In general, in summer, a high ventilation rate is maintained to remove the heat inside piglet house. However, when the outdoor weather conditions are very hot, the inflow air should be cooled. In the experimental piglet house, the external air was flowed in and the air temperature was lowered by 2℃ in the corridor. Due to the high ventilation rate, the air inside the piglet house was replaced quickly, and the internal air temperature converged to about 32℃. If the average temperature inside the piglet house is maintained above 32℃, productivity may be lowered due to the high temperature stress, so it is considered that a cooling device was necessary. Since the wet scrubber module of the ARVS is a method of cleaning air through water, the cooling effect on the same principle as a cooling pad can be expected. Meanwhile, in the case of ammonia gas, it was confirmed that the internal ammonia concentration was maintained below an appropriate level with an average of 8.12 ppm because the ammonia gas was sufficiently discharged with a high ventilation rate. This was a result similar to the internal concentration as a result of the field experiment.

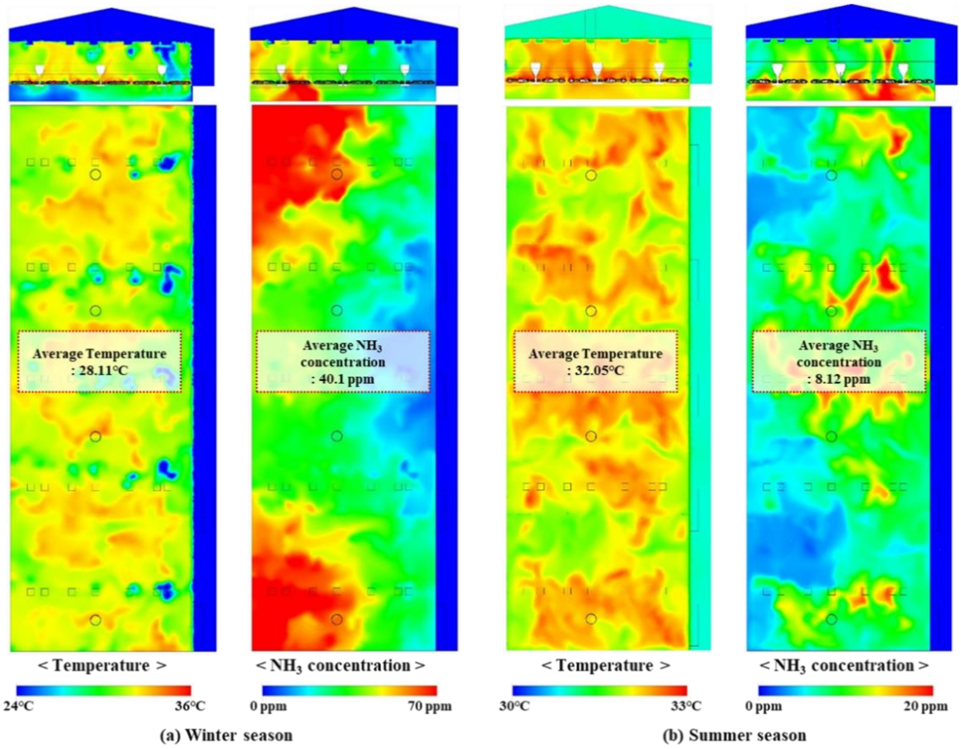
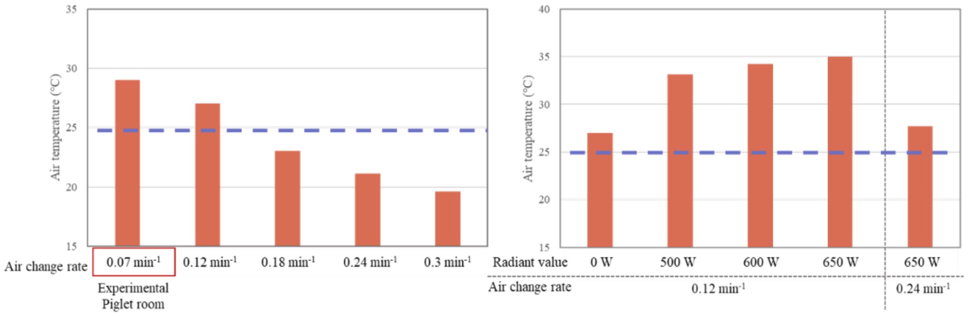


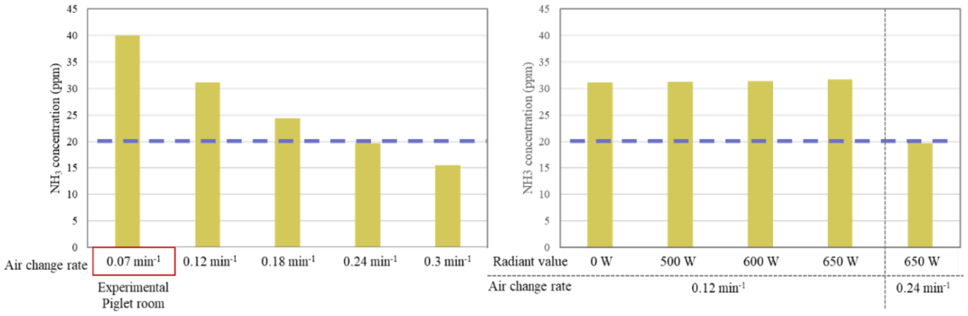
Figure 3-12 CFD computed results of visualization of the internal air temperature and ammonia concentration contour of the experimental piglet room in winter and summer season.

3.3.3.2. Results of CFD simulation for internal environment improvement (ventilation rate and radiator)

Figure 3-13 shows the computed results according to the ventilation rate and the use conditions of the radiator. The ventilation rate of 0.07 min^{-1} in the actual ventilation rate operated in the experimental piglet house, and the minimum ventilation rate based on the MWPS according to the breeding head conditions is 0.12 min^{-1}. In the experimental piglet house, the ventilation rate was lower than the recommended ventilation rate, and accordingly, the temperature inside the piglet house can be maintained at 28°C, but it was found that the internal ammonia concentration accumulated up to 40 ppm. However, even when operated with the recommended minimum ventilation rate of 0.12 min^{-1}, the internal ammonia concentration was about 31 ppm (Figure 3-13 (c)). It was judged that it would be difficult to improve the environment inside the piglet house by operating the recommended minimum ventilation rate. Accordingly, it was attempted to predict the required ventilation rate to reduce the ammonia concentration by computing the increase in ventilation rate. The result of CFD simulations according to the ventilation rate at 0.18 min^{-1}, 0.24 min^{-1}, and 0.3 min^{-1} showed that the internal temperature decreased to 23°C, 21°C, and 19°C on average, respectively, while the ammonia concentrations were reduced from 40 ppm to 24 ppm, 19 ppm, and 15 ppm, respectively. The result confirmed that the ventilation rate should be more than 0.25 min^{-1} to reach the allowable ammonia concentration of 20 ppm. However, since the temperature inside the piglet house was less than 20°C, there was a limit to increasing the ventilation rate in winter. Therefore, in order to reduce the harmful gas by increasing the ventilation rate, it is necessary to supplement heat by using a heating device. The heating system was analyzed based on the actual conditions of the radiator installed in the experimental piglet house. The radiator was assumed to have a standard heat radiant value of 522 W, 600 W, and 650 W based on the heat radiant area of the radiator installed in the experimental piglet house. In the case of using the radiator, it was analyzed that at the minimum ventilation rate of 0.2 min^{-1} at which the ammonia concentration was maintained properly, the temperature of the radiator can be maintained up to 27°C only when the radiant value was 650 W. It is most suitable to control the internal environment by increasing the ventilation rate and the radiator to 650 W. Since the use of the radiator requires energy consumption, it is considered that the ARVS is needed to control the internal environment by maximizing energy efficiency.



(a) Air temperature near the piglet zone (Ventilation rate) (b) Air temperature near the piglet zone (Radiator)



(c) NH_3 concentration near the piglet zone (Ventilation rate) (d) NH_3 concentration near the piglet zone (Radiator)

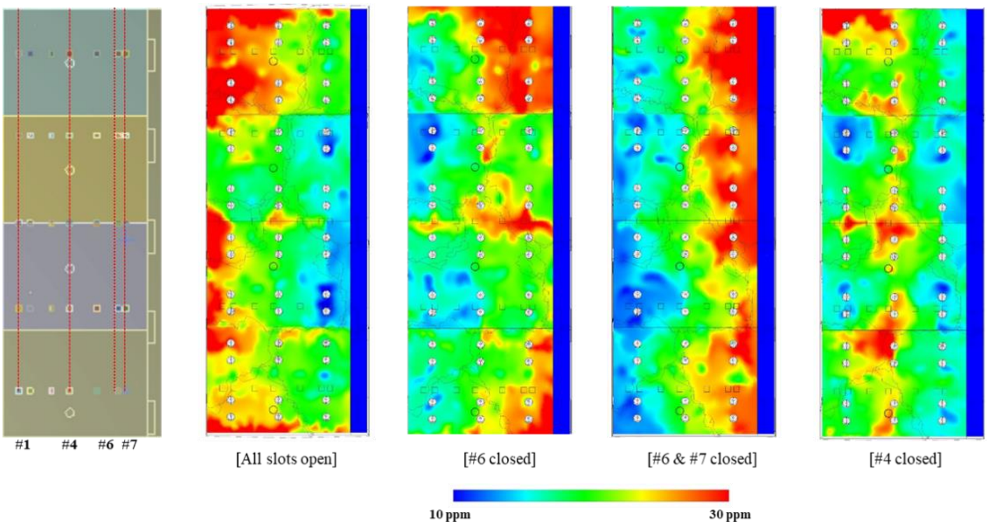
Figure 3-13 The computed results of internal temperature and ammonia concentration inside the experimental piglet room according to the ventilation rate and radiator conditions.

3.3.3.3. Results of CFD simulation for internal environment improvement (ceiling slots)

The improper design of ceiling slots can result in high ammonia gas accumulation in various locations inside the pig house when a low ventilation rate is operated. Therefore, the aerodynamic analysis of the inlet and outlet was conducted through CFD simulation, and improvement methods were evaluated by varying the conditions of ceiling slots. Table 3-7 shows the results of the internal average temperature and ammonia concentration according to the opening conditions of the ceiling slots. The existing ceiling slots were not installed at uniform intervals, and the #1 and #7 slots on both sides are located at abnormally narrow intervals (Figure 3-14). It may thus be difficult to remove harmful gas near the piglet zone because the inflow of air could not be made uniformly. In addition, #4 was a slot located on the same line as the chimney fan, which was the location most affected when the negative pressure of the chimney fan was formed. There was a risk that the harmful gas inside the piglet house could not be discharged and the fresh air could be immediately exhausted. In the results of Table 3-7, cases 1 to 3 were computed results with the same ventilation rate of 0.12 min^{-1}, and cases 4 to 6 were computed results with a ventilation rate of 0.25 min^{-1}. In the case of a low ventilation rate, there was no significant difference in the internal average ammonia concentration according to the condition of ceiling slots. In the case of cases 4 to 6, the ammonia concentration was reduced by about 6% depending on the ceiling slots' opening condition, but there is no significant effect in reducing the amount of ammonia inside the piglet house. The ammonia concentration was greatly affected by the ventilation rate, whereas the internal ammonia concentration distribution was significantly different according to the ceiling slot conditions. When all slots were opened, fresh air from the corridor flowed in from #7 first, the ammonia concentration was kept low around #7, and the ammonia concentration increased toward the opposite side of the corridor. When the ventilation was operated by closing ceiling slots #6 and #7, ammonia was removed by inflowing fresh air to the opposite side of the corridor, but the air on the corridor side was not sufficiently replaced, resulting in a high ammonia concentration. Therefore, it was difficult to solve the ammonia gas accumulation problem even if slots #6 and #7 were closed to guide the incoming air to the opposite side of the corridor. On the other hand, when ceiling slot #4 adjacent to the chimney fan was closed, the ammonia concentration inside the piglet house was uniformly low. This was because fresh air inflowed to both ends of the piglet house so that fresh air could flow into the whole piglet house, and internal ammonia gas could be discharged at the chimney exhaust fan. Therefore, to minimize the high accumulation area of ammonia gas inside the piglet house, it was necessary to consider the location of the ventilation fan and the inlet. In addition, to reduce the concentration of ammonia gas inside the piglet house, it was important to improve the air exchange rate by increasing the ventilation rate.

Table 3-7 CFD computed results of air temperature and ammonia concentration according to the opening conditions of the ceiling slots and ventilation rate.

No.	Variable factors of CFD simulation (ceiling slot conditions and ventilation rate)	Avg Temp (°C)	Avg Ammonia concentration (ppm)
1	Ceiling slot (#6): closed Ventilation rate: 0.12 min^{-1}	25.82	31.17
2	Ceiling slot (#6, #7): closed Ventilation rate: 0.12 min^{-1}	25.9	31.83
3	Ceiling slot (#4): closed Ventilation rate: 0.12 min^{-1}	25.57	31.67
4	Ceiling slot (#6): closed Ventilation rate: 0.25 min^{-1}	21.12	19.07
5	Ceiling slot (#6, #7): closed Ventilation rate: 0.25 min^{-1}	21.28	18.95
6	Ceiling slot (#4): closed Ventilation rate: 0.25 min^{-1}	20.91	17.8



[All slots open] [#6 closed] [#6 & #7 closed] [#4 closed]

Figure 3-14 Distribution of ammonia concentration inside the experimental piglet room according to the opening conditions of ceiling slots.

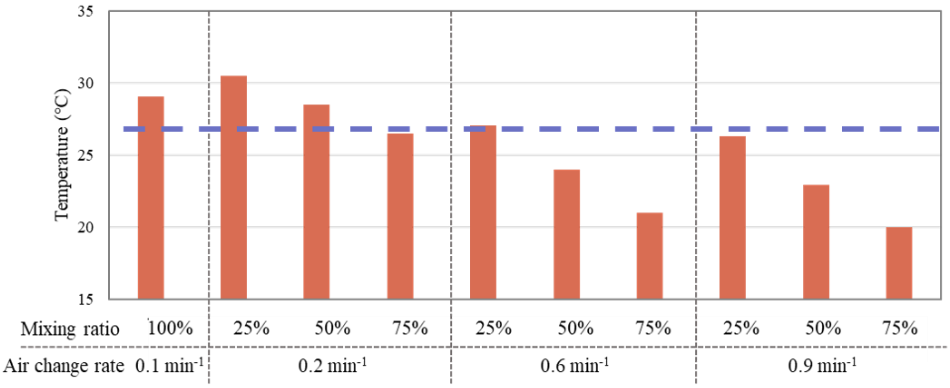
3.3.3.4. Analysis of the internal environment of experimental piglet room applying ARVS

Even though the inside temperature was properly maintained using a low ventilation rate during the winter season using the existing ventilation, the amount of ammonia concentration inside the piglet house was very high. The ammonia concentration was properly maintained but there was a risk of high temperature stress when no cooling device was used. In this study, the ARVS was used to maintain the proper environment inside the piglet house and to evaluate the applicability of the system to reduce odors and harmful gases without temperature problems. In order to evaluate the ARVS, the internal temperature and ammonia concentration of the experimental piglet house were evaluated according to the ventilation rate and EAMR. The removal efficiency of the ammonia gas may change depending on the configuration of the wet scrubber and the pH condition of the cleaning solution. The research team has conducted a removal efficiency test according to the conditions of the cleaning solution prior to the full operation of the system. The results revealed that utilizing an acid solution will give a removal efficiency of about 8–90% while a groundwater cleaning solution has 60% removal efficiency. Therefore, the two removal efficiencies were used as calculation conditions in CFD model. Figure 3-15 shows the internal temperature and ammonia concentration according to the ventilation rate (0.1, 0.2, 0.6, and 0.9 min^{-1}) and EAMR when the ARVS was applied. In the case of the minimum ventilation rate of 0.1 min^{-1}, the ARVS was not used, and the EAMR was set to 100%. As a result of CFD calculation, it was predicted that the ammonia gas environment would be poor when the ARVS was not used, with an internal temperature of about 28°C and an ammonia concentration of 40 ppm due to the low ventilation rate (Figure 3015 (a)). In the case of using the ARVS, the temperature of the incoming air was higher than the external air, with the advantage that the temperature inside the piglet house did not decrease rapidly. Therefore, it was possible to reduce the internal ammonia concentration by increasing the ventilation rate, and the internal environment of the piglet house could be improved by appropriately controlling the ventilation rate and the EAMR.

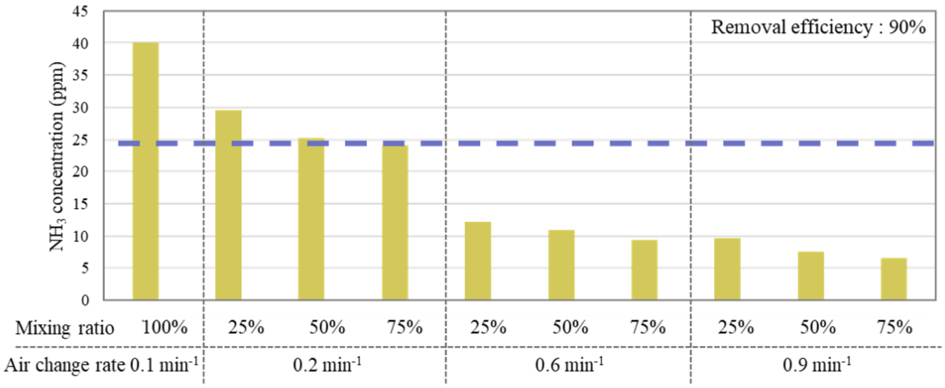
When the ventilation rate was increased to 0.2 min^{-1}, the internal temperature of the piglet house was maintained at an appropriate level when all 25, 50, and 75% EAMRs were applied. As the mixing ratio of the outdoor air increased, the air temperature near the piglet zone could be lowered. However, when operating the ventilation rate of 0.2 min^{-1}, even if 75% of the external air was mixed, the temperature of the remaining 25% of the recirculated air was high, so it was possible to maintain the appropriate level of temperature inside the piglet house. On the other hand, when the ventilation rate and EAMR were increased, the inflow of the external air increased. This resulted in the air temperature decreasing to 25°C inside the piglet house. Therefore, it was necessary to control the ventilation rate at 0.2 to 0.6 min^{-1} and to maintain the temperature properly by controlling the EAMR of the ARVS in real time.

The ammonia concentration was analyzed according to the ventilation rate, EAMR, and removal efficiency (Figure 3-15 (b), (c)). When the ventilation rate was operated at 0.2 min^{-1} in the experimental piglet house, the internal ammonia concentration was reduced but still did not reach the allowable concentration of 20 ppm, although the removal efficiency was 90%. When the ventilation rate was increased to 0.6 min^{-1}, the ammonia concentration was maintained at an appropriate concentration level. This was because the amount of air cleaned in the wet scrubber module increased with the increase in fresh external air. There was no significant difference in ammonia removal when the ventilation rate was increased further. The appropriate ammonia concentration could be maintained because the ventilation rate was sufficient compared to the ammonia generation rate inside the piglet house. On the other hand, as the ventilation rate and EAMR are increased, the internal temperature could be lowered. Therefore, the wet scrubber with a removal efficiency of 90% could maintain an appropriate environment with a ventilation rate of 0.6 min^{-1} and an EAMR of about 25%. In actual operation, it was possible to reduce the carbon dioxide that could not be removed using the wet scrubber module by controlling the EAMR according to the outdoor weather conditions.

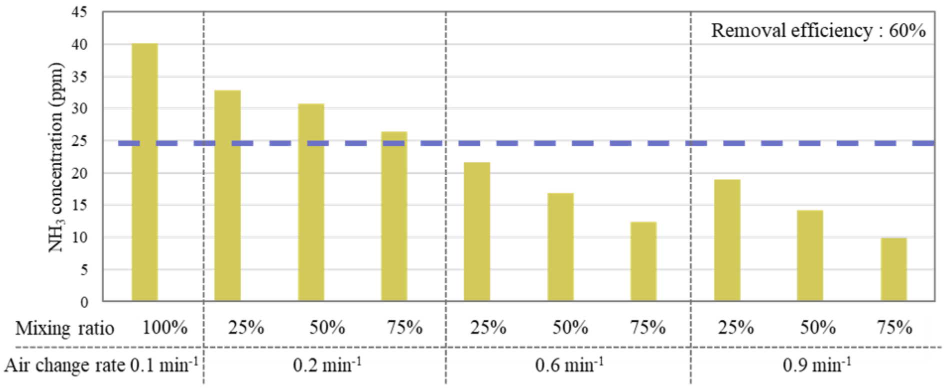
In the condition of the removal efficiency of 60%, the ammonia concentration was not satisfied at the ventilation rate of 0.2 min^{-1}. However, as the ventilation rate and outdoor air mixing ratio increased, the internal ammonia concentration could be maintained below the allowable concentration (20 ppm). Since the amount of ammonia removed was smaller than when the removal efficiency was 90%, the ammonia removal according to the EAMR showed a greater effect. However, if the ventilation rate was sufficiently increased, the internal ammonia concentration could be maintained at 10–15 ppm. Therefore, it was expected that the temperature and ammonia gas environment inside the piglet house could be optimally maintained through the ARVS if the ventilation rate and EAMR were properly operated according to the removal efficiency and outdoor weather conditions.



(a) Air temperature near the piglet zone when using air scrubber



(b) NH_3 concentration near the piglet zone when using air scrubber (90%)



(c) NH_3 concentration near the piglet zone when using air scrubber (60%)

Figure 3-15 CFD computed results of temperature and ammonia concentration inside the experimental piglet room according to the ventilation rate and EAMR using the ARVS.

3.4. Conclusions

In this study, the main problems of the internal environment inside the pig house were identified through the field experiments and CFD simulation of the experimental piglet house. The accuracy and computational efficiency of the CFD model were validated based on the field measurement data, and case studies were conducted based on the validated CFD model. Based on the CFD computed results, various aerodynamic analyses were conducted according to various conditions such as outdoor weather conditions, the ventilation rate, and inlet types. In addition, by applying the ARVS to the developed CFD model, the suitability of the ARVS was evaluated according to the ventilation rate, EAMR, and removal efficiency.

The result of the field experiment showed that the maximum ventilation rate during the high temperature period was increased in summer with a high of about 33°C. During this period, it was found that the ventilation rate was not sufficiently increased, and the gas environment was not properly maintained. To maintain the internal air temperature in winter, it was found that less than the recommended minimum ventilation rate was operated, resulting in an unsuitable gas environment with an ammonia gas concentration of above 40 ppm.

Through CFD simulation, the main problems that occurred due to the ventilation rate and inlet types of the experimental piglet house were identified. To reduce the high gas concentration environment, it was essential to increase the ventilation rate. The result of analysis according to the use of the radiator showed that it was possible to properly maintain the internal gas when the ventilation rate was increased by operating the radiator at 630 W or more. For the uniformity inside the experimental piglet house, the inlet conditions of the ceiling slots were analyzed.

It was also found that the location of the ceiling slots in the experimental piglet house was not appropriate. The internal uniformity could be improved by preventing direct flow to the chimney exhaust fan by closing the center (#4) of the ceiling slots.

Finally, the usability of the ARVS was evaluated to improve the existing problems based on the developed CFD model. Compared to the existing ventilation system, the ventilation rate could be increased by about four times or more, and if the ventilation rate and EAMR were automatically controlled according to the outdoor environment and removal efficiency conditions, the rearing environment inside the piglet house could be maintained properly. Additionally, it has the advantage of reducing harmful gases discharged outside and preventing diseases.

Meanwhile, one of the parts that could not be considered in this CFD simulation was the internal carbon dioxide concentration. Since the carbon dioxide does not dissolve well in water, the ARVS cannot remove carbon dioxide, so if carbon dioxide is not sufficiently discharged, it may cause abnormalities in the respiratory and circulatory systems of piglets. Considering this, it was necessary to properly maintain the gas environment by controlling the EAMR in real time.

Chapter 4. Determination of the optimal module combination of ARVS using the numerical model

4.1. Introduction

Air recirculation technology is a technology that minimizes the inflow of external air and uses the internal air which is cleaned by a wet scrubber system. The reason for using the recirculated air is to reuse the thermal energy inside the pig house. This technology is widely investigated in industrial environments to save air conditioning costs by recycling the energy inside buildings (Besant & Simonson, 2000; Burton, 2004; Ekinci et al., 2006; Hall et al., 1987; Park & Seo, 2018; Ziegler et al., 2016). In particular, standards for air recirculation have been developed in general industrial processes, and the allowable concentration standards for hazardous substances in reused air are suggested (ANSI, 2007). If air recirculation technology is applied to pig houses, it is possible to minimize the possibility of livestock infectious diseases because it can block the airborne transmission of disease (Donham, 1991). Since the pig house can be operated and managed in a closed state, the infectious diseases through wild animals can be minimized. In the winter season, minimum ventilation is operated to reduce the heating load in the pig house, and as a result, the rearing environment in the pig house, such as the high level of dusts and various harmful gases, can be very poor. The ARVS can improve the rearing environment by increasing the ventilation rate and using the recirculated air. Also, it is possible to minimize the emission of odors from the pig house. Lau et al. (1996) devised a method of recirculating air by removing dust by using a fabric filter and an electrostatic dust collector. Although the concentration of dust in pig houses could be reduced by up to 60% or more, it was difficult to satisfy the allowable concentration standards. Anthony et al. (2017) analyzed the concentration of dust and carbon dioxide inside the pig house when the air recirculation system was applied in farrowing pig room, and reported that the air recirculation system can be an alternative to prevent the deterioration of workers' health. Wenke et al. (2018) analyzed that when a filter was installed in the air recirculation system, the dust concentration was the lowest and the pig's lung health was excellent. Peters et al. (2015) evaluated the performance by applying the shaker dust collector to the air recirculation system, and Park et al. (2017) simulated the effect of the concentration of pollutants in the pig house using mass and energy balance equations. Mostafa et al. (2017) applied an air scrubber module to the air recirculation system, and reported that wet scrubber technology can reduce both ammonia gas and dust concentrations and has no negative effect on pigs.

Despite the research in the application of air recirculation system in pig house, there are few studies that evaluate the internal environment such as air temperature, humidity, gas, dust, and odor. In addition, previous researches on air scrubber systems have been conducted to evaluate the effect in terms of deodorizing and reducing harmful gases in pig houses. In particular, there are no present study related to analyzing the complex environment inside and outside the pig house through installation of ARVS including the wet scrubber module to improve the internal environment, reduce energy load, improve energy recovery rate, and reduce exhaust gas and odor.

Modules applicable to the ARVS could be combined in various ways depending on the purpose. However, there was a limit to conduct the experiment which combinations of various modules are proper. In addition, the system design is only optimal when capacity is sufficient to maintain the indoor environment of the pig house. Therefore, it was necessary to develop the numerical model and conduct the analysis according to various module combinations. In this study, the internal environment of pig houses installed with ARVS was evaluated and the optimal model of ARVS was designed using the numerical model developed in this study. The internal environment of the pig house was analyzed based on the various balance equations. The ARVS could consist of various modules. Based on the numerical model developed in this study, the internal environment of the pig house was evaluated. In addition, it was attempted to derive the optimal design standard of the ARVS.

4.2. Materials and methods

In this study, a numerical model was developed for the optimal design of the ARVS. First, the numerical model was developed to calculate the internal environment such as heat, moisture, and gas balance equations inside the pig house (Figure 4-1). The model of the recirculating air required iterative calculation because the environment inside the pig house was calculated by the balance equations after the air was used again. This iterative calculation was conducted many times according to the various environmental conditions. Therefore, the calculation to predict the environment inside the piglet room was developed as a numerical model. For the validation of the designed numerical model, the measured data of the thermal environment inside the experimental piglet room were used. Heat loss was selected as a thermal environment validation variable. The calibration was conducted according to the amount of heat loss to reduce the error value between the computed result and the measured temperature data. In developing the numerical model, the configuration of the ARVS such as the wet scrubber module, external air mixing module, heat exchange module, and solar module were considered. These modules linked to the numerical model of base module that completed the validation of the thermal environment. Based on these results, numerical model calculations were conducted according to external weather conditions. The internal environment of the pig house was evaluated, and an optimal design for the experimental piglet room was suggested.

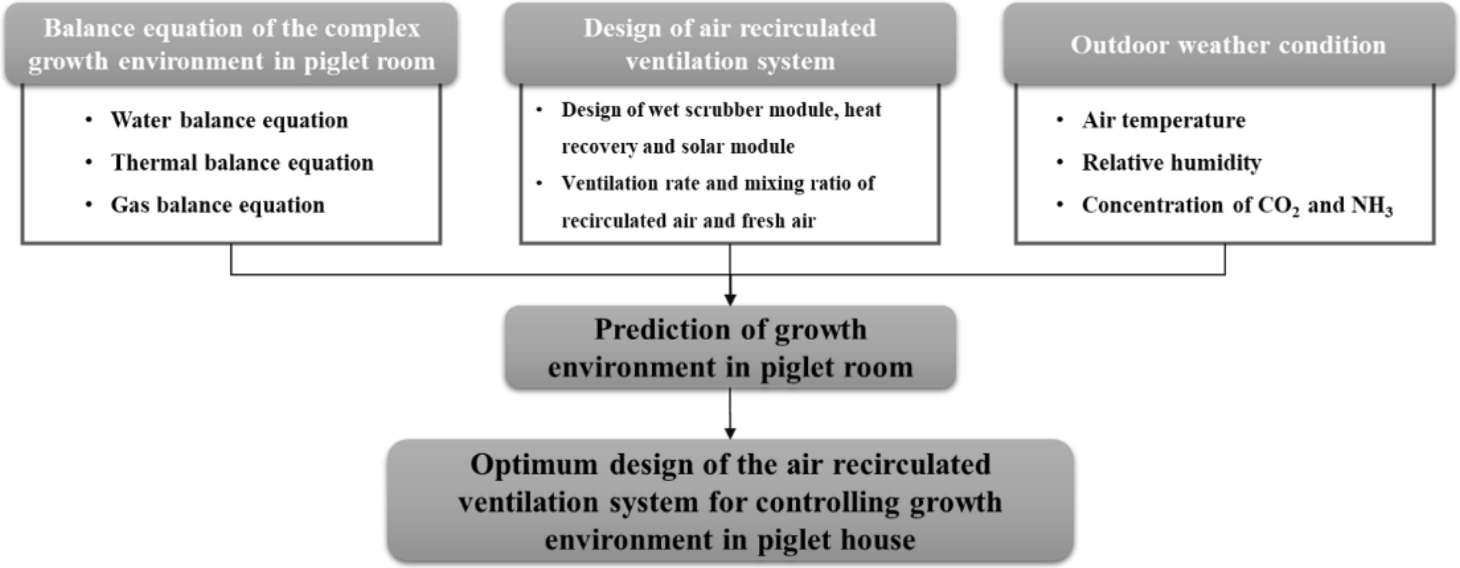


Figure 4-1 Flow chart for numerical model of ARVS.

4.2.1. Target facility

Using the result of this study, an actual ARVS developed will be installed in a real farm. Thus, the main purpose of this study was to suggest an optimal design based on a combination of several modules that will provide optimal design of the ARVS. In order to determine the optimal design of the ARVS in this study, the validation and calculation of the numerical model were conducted first in the test bed. The target test bed for the numerical design of the ARVS was in Artificially Controlled Smartfarm Engineering Center of A3EL (AcSEC-A3EL) located at the College of Agriculture and Life Sciences, Pyeongchang Campus, Seoul National University (latitude 37°54′87′′N, longitude 128°43′57′E). The target facility was designed according to the 2016 Pig House Architectural Design Manual (MAFRA, 2016) (Figure 4-1). In general pig farms, access is limited due to the livestock disease control. Also, it is impossible for researchers to artificially set the experimental environment because the farmers are reluctant to change their operating environment inside the pig house. To overcome the limitations of the field experiments in an actual pig farms, the target facility was constructed so that all indoor and outdoor environmental factors could be artificially controlled. The reason why AcSEC-A3EL were selected as the experimental pig room in this study was to first design the ARVS numerically, and then to manufacture all the modules of the ARVS based on the results from the numerical design later. After the manufactured module was installed in the target facility, experiments were conducted to validate and supplement the results of this study. After validation of this scale-down stage, the developed ARVS will be installed in the actual pig farm. Through this scale-down development stage, it was attempted to prevent failures or problems that could occur in advance.

Figure 4-1 below is a schematic diagram of the experimental piglet room. It was assumed that a total of 174 piglets (7-weeks old) were raised based on rearing density of 0.3 $m^2 \cdot head^{-1}$. Three-dimensional artificial piglets were also added in the experimental piglet room to reflect realistic airflow. The size of the experimental piglet room was 6.7 m in width, 9.5 m in length, and 2.5 m in height according to the domestic standards. The floor of the experimental piglet room consisted of a plastic pit. The heat inside the piglet room can be exchanged through the wall. The total heat radiant area of the wall was 196.5 m^2 and the wall of the experimental piglet room was equipped with the thermal insulation plate type (No. 1), so the thermal conductivity was set to 0.036 $W \cdot m^{-1} \cdot {}^{\circ}C^{-1}$ in the numerical model of this study. Various outlets such as chimney exhaust fan, sidewall exhaust fan, and pit exhaust fan were installed inside the experimental piglet room. Also, various inlets such as sidewall slot, ceiling slot, and pit inlet were installed. In this study, the chimney exhaust fan and the side slots were used for the experiment. The actual airflow rate at the outlets were measured with the pressure sensor, and it was designed to remotely and quantitatively monitor the real-time ventilation rate. In addition, heat, moisture, and gas generators were installed in the slurry pit under the floor of the experimental piglet room, so it was possible to experiment while artificially controlling the heat, moisture, and gas generation rate of the piglets.

Table 4-1 Characteristics of numerical procedure for validation of CFD model.

Contents	Value
Heads of piglets	174
Weight of each piglet (kg)	15
Daily feed energy	3.44
Total heat (kcal·hr^{-1}·head^{-1}) (in 34.5℃)	79
Sensible heat (kcal·hr^{-1}·head^{-1}) (in 34.5℃)	25
Latent heat (kcal·hr^{-1}·head^{-1}) (in 34.5℃)	54

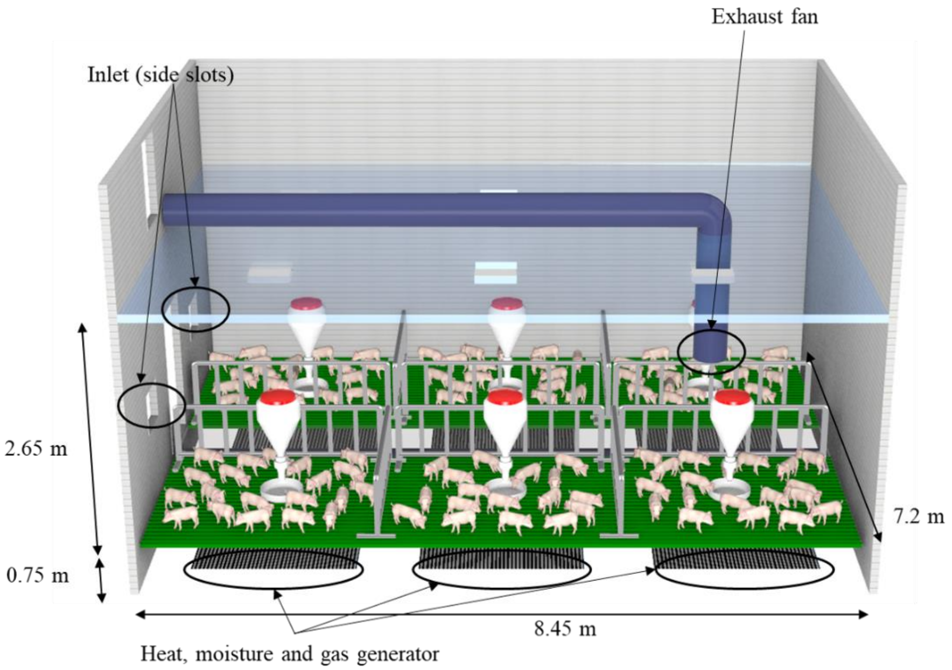


Figure 4-2 Schematic view of target piglet room at Artificially controlled Smartfarm Engineering Center of Aero-Environmental & Energy Engineering Laboratory (AcSEC-A3EL), Seoul National University, Korea.

4.2.2. Balance equations of environment inside the experimental piglet room

In this study, the rearing environment inside the experimental piglet room was simulated considering the air temperature, moisture, and gas balance equations. The change of state of humid air was calculated using the equation specified in the ASHRAE Hand-book - Fundamentals (ASHRAE, 2017). The heat generation of the electricity use and sensible heat loss due to water evaporation were excluded from the calculation because only the heat produced by the piglets should be considered in the thermal balance equation. Accordingly, the thermal balance equation included the inflow and outflow of heat by ventilation, the sensible heat production of piglets, and the wall conduction. Moisture and gases generated inside the piglet room are mainly from the manure and floors. Accordingly, to quantify the heat, moisture, and gas balance equations, it was necessary to determine the heat, moisture, and gas generation rate inside the piglet room.

The total heat production of piglets can be expressed as Equation 4-1. Also, sensible heat production can be expressed as Equation 4-2 (CIGR, 2002). The heat production of piglets can be changed depending on the air temperature near the piglets because the piglets maintain homeostasis. Therefore, the equation of the heat production considering the piglet's weight and feed intake constant includes the correction equation according to the air temperature near the piglets. The change of the heat production based on the 20°C of air temperature was applied as a linear equation.

$$q_{tot} = 0.00086 \times [7.4m^{0.66} + \{1 - (0.47 + 0.003 \cdot m)\} \times (7.4nm^{0.66} - 7.4m^{0.66}) \times \{1000 + 12 \times (20 - t_i)\}] \qquad \text{Equation 4-1}$$

Where, q_{tot} is the total heat production of piglets (kcal·hr^{-1}·head^{-1}), m is the weight of the piglets (kg), n is feed intake constant, and t_i is the air temperature inside the piglet room (°C)

$$q_s = 0.00062\{1000 + 12(20 - t_i)\} - 1.15{t_i}^6 \times 10^{-7} \qquad \text{Equation 4-2}$$

Where, q_s is the sensible heat production of piglets (kcal·hr^{-1}·head^{-1}).

The moisture generation rate of the piglets can be calculated from the latent heat generation and the evaporative latent heat of water, which is shown in Equation 4-3. In addition, the moisture generation rate from the manure and bottom of the piglet room was calculated using Equation 4-4 (Hayes et al., 2013). The moisture generation rate of the floor was determined by considering the ratio of the size of the piglet zone in the previous study to the size of the piglet zone in this study.

$$w_a = \left(\frac{q_{tot} - q_s}{\lambda}\right) \qquad \text{Equation 4-3}$$

Where, w_a is the moisture generation rate of the piglets (kg·kg-da^{-1}·hr^{-1}·head^{-1}) and λ is the evaporative latent heat of water (kcal·kg^{-1}).

$$w_e = \frac{3.6(0.224t_i - 2.5469)}{N} \qquad \text{Equation 4-4}$$

Where, w_e is the moisture generation rate in a humid place (kg·kg-da^{-1}·hr^{-1}·head^{-1}).

The ammonia generation rate in the piglet room should consider various factors such as the number of piglets, manure treatment facilities, feed intake, internal air temperature, the surface flow rate of manure, and pH. Therefore, in this numerical model, the ammonia generation rate inside the piglet room was determined to be 0.000216 $\mathrm{kg \cdot hr^{-1} \cdot head^{-1}}$ according to the results of report (NIER, 2013). In general, the concentration of carbon dioxide has a high correlation with the respiration rate of livestock. As the respiration increases, the exhalation rate increases, resulting in an increase in carbon dioxide emissions. Therefore, the carbon dioxide generation rate was applied by considering the number of piglets. Therefore, the carbon dioxide generation rate of the piglets can be expressed as Equation 4-5 considering the respiration rate according to the heat production of the piglets (Van Ouwerkerk & Pedersen, 1994).

$$c_a = \frac{2.3\times10^{-4} q_{tot}}{v_c} \qquad \text{Equation 4-5}$$

Where, c_a is carbon dioxide generation rate of the piglets ($\mathrm{kg \cdot hr^{-1} \cdot head^{-1}}$) and v_c is specific volume of the carbon dioxide ($\mathrm{m^3 \cdot kg^{-1}}$).

In this study, various design conditions of the ARVS were considered. The air condition inside the piglet room for each environmental condition was calculated considering the temperature, moisture, and gas concentration balance equations. In the calculation, the air inside the piglet room is discharged and then pass through the ARVS. After that, the air flows into the piglet room. The air flowing into the piglet room passes through the ARVS including a heat exchange module, a wet scrubber module, an external air mixing module (controlling recirculated air and external air), and a solar module. The total inflow air is equal to the sum of the recirculated air and the external inflow air. The external inflow air is the same as the amount of exhausted air from the external air mixing module. From the thermal balance equation considering the heat production of piglets and the heat conducted through the wall, the air temperature inside the piglet room can be expressed as Equation 4-6 (Nam, 2018).

$$t_i = t_v - \frac{v_a \times \{q_s \cdot N - A \cdot U \cdot (t_i - t_o)\}}{QC_p} \qquad \text{Equation 4-6}$$

Where, t_v is the inflow air temperature from the ARVS (°C), v_a is the specific volume of the air inside the piglet room ($m^3 \cdot kg^{-1}$), A is the total heat radiant area (m^2), U is the total heat transfer coefficient ($kcal \cdot m^{-2} \cdot {}^{\circ}C^{-1} \cdot hr^{-1}$), N is the number of piglets (head), t_o is the outdoor air temperature (°C), Q is the ventilation rate ($m^3 \cdot hr^{-1}$), and C_p the specific heat at a constant pressure of internal air ($kcal \cdot kg^{-1} \cdot {}^{\circ}C^{-1}$).

Even in the case of moisture, the moisture-containing air inflows to the piglet room after passing through the ARVS. The factor that affects the inflow of air is the wet scrubber module using the nozzles that spray water. Therefore, the amount of moisture in the air passing through the wet scrubber module and the moisture generation rate in the piglet room were considered. The amount of moisture inside the piglet room can be calculated with the following moisture balance equation (Nam, 2018) (Equation 4-7).

$$w_v = w_i - \frac{v_a (w_a + w_e) N}{Q} \qquad \text{Equation 4-6}$$

Where, w_v is the absolute humidity of the inlet air of the piglet room (kg·kg-da^{-1}·hr^{-1}), w_i is the internal absolute humidity of the piglet room (kg·kg-da^{-1}·hr^{-1}), w_a is the absolute humidity of the wet scrubber module (kg·kg-da^{-1}·hr^{-1}), and w_e is the absolute humidity of the outdoor air (kg·kg-da^{-1}·hr^{-1}).

In the case of the gas, the change of gas concentration occurs according to the mixing ratio of the external air and the gas removal efficiency of the wet scrubber module regardless of the characteristic of the ARVS. Ammonia gas can be removed in the wet scrubber module. However, carbon dioxide cannot be removed in the wet scrubber module (Zhao et al., 2011). Therefore, in the ammonia gas balance equation, the EAMR and the ammonia gas removal efficiency of the wet scrubber module were considered. The concentration of carbon dioxide can be calculated by considering the EAMR. The two balance equations can be expressed as Equation 4-8, 4-9 (Nam, 2018). In this study, it was assumed that the ammonia gas removal efficiency of the wet scrubber module was 80% (Zhao et al., 2011). In addition, according to the 2016 standards of the piglet house (MAFRA, 2016), 20 ppm of ammonia concentration and 5,000 ppm of carbon dioxide concentration were set as the limiting gas concentrations to evaluate the ARVS.

$$n_i = \frac{10^6 v_n n_a N}{Q \cdot \{1-(1-x_m)(1-\eta)\}} \qquad \text{Equation 4-8}$$

$$c_i = \frac{10^6 c_a v_c N}{Q x_m} + c_o x_m \qquad \text{Equation 4-9}$$

Where, n_i is the internal concentration of ammonia gas (ppm), v_n is the specific volume of the ammonia gas (m^3·kg^{-1}), x_m is the mixing ratio of the outdoor air, η is the removal efficiency of the wet scrubber module, c_i is the internal concentration of carbon dioxide (ppm), and c_o is the outdoor concentration of carbon dioxide (ppm).

4.2.3. Design equation of the ARVS

The ARVS applied to the piglet room was a method in which the air exhausted from the piglet room was reused after cleaning in the wet scrubber module. Therefore, it was necessary to clean the exhausted air to optimally control the air temperature, humidity and gas concentration. In this study, various devices were investigated, and the suitability of the module was evaluated considering the economic feasibility such as installation and operating costs. Based on these results, the wet scrubber module, the external air mixing module, the heat exchange module, and the solar module were selected as the ARVS. Although the UV system was not a device for environmental control, it was also included in the module to be installed for disease control.

Based on the design equations of the ARVS, the wet scrubber module, external air mixing module, heat exchange module, and solar heat exchanger module were implemented. Through these, the air temperature and relative humidity, and gas concentration inside the piglet room were evaluated. For the change in the state of the wet air, the equations for the change in the state of the wet air was referred to in the ASHRAE Handbook – Fundamentals (ASHRAE, 2017). When the air passes through the wet scrubber module, the air temperature and relative humidity can change. Equation 4-10 and 4-11 show the change in wet air when the air exhausted from the piglet room passes through the wet scrubber module (Hundy, 2016). According to the previous experimental results of the wet scrubber module, the adiabatic saturation efficiency was assumed to be 70%.

$$t_{wo} = t_{wi} - \eta_s \times (t_{wi} - t_l) \qquad \text{Equation 4-10}$$

$$w_{wo} = w_{wi} - \eta_s(w_{wi} - w_l) \qquad \text{Equation 4-11}$$

Where, t_{wo} is the air temperature after passing the wet scrubber module (°C), t_{wi} is the air temperature before passing the wet scrubber module (°C), η_s is the adiabatic saturation efficiency (%), t_l is the temperature of recirculation water (°C), w_{wo} is the absolute humidity after passing the wet scrubber module ($\text{kg}\cdot\text{kg-da}^{-1}$), w_{wi} is the absolute humidity before passing the wet scrubber module ($\text{kg}\cdot\text{kg-da}^{-1}$), and w_l is the absolute humidity of recirculation water ($\text{kg}\cdot\text{kg-da}^{-1}$) (based on 100% relative humidity).

The heat exchange module and solar module all operate by sensible heat exchange. The Equation 4-12 expressed the temperature exchange efficiency of each module. The temperature exchange efficiency coefficients were applied based on the results measured in the experiment. As a result of measuring the efficiency according to the flow rate, the average temperature exchange efficiency of 60% was calculated and applied in the numerical model. The heat storage tank is one of the equipment components of the solar module. The average temperature of hot water inside the heat storage tank was maintained at 60°C depending on the daytime solar radiation. Therefore, it was assumed that the hot water flow rate was 5 $\text{L}\cdot\text{min}^{-1}$ and applied to the calculation as shown in Equation 4-13 below. Finally, the temperature and absolute humidity of the air mixed with the outdoor air were calculated based on the psychrometric chart.

$$t_{ho} = t_{hi} - \eta_t \times (t_{hi} - t_r) \qquad \text{Equation 4-12}$$

$$t_{solar+l} = \frac{t_{solar} \times Q_{solar} + t_l \times Q_l}{Q_{solar} + Q_l} \qquad \text{Equation 4-13}$$

Where, t_{ho} is the air temperature after passing the heat exchange module (°C), t_{hi} is the air temperature before passing the heat exchange module (°C), η_t is the heat exchange efficiency (%), t_r is the water temperature before passing the heat exchange module (°C), $t_{solar+l}$ is mixed temperature of recirculated water and solar hot water (°C), t_{solar} is the temperature of solar hot water (°C), t_l is the temperature of recirculated water (°C), Q_{solar} is the flow rate of solar hot water ($\mathrm{L \cdot min^{-1}}$), and Q_l is the flow rate of the recirculated water ($\mathrm{L \cdot min^{-1}}$).

4.2.4. Numerical design condition of the ARVS

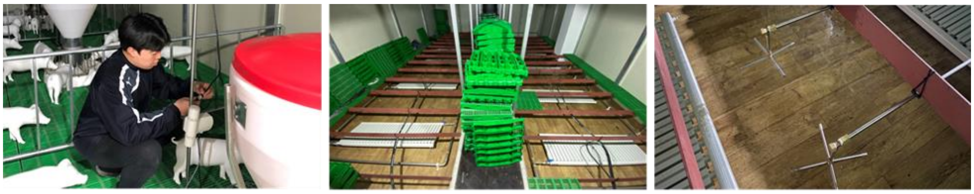
In this study, the numerical model of the ARVS was developed to evaluate the environmental condition inside the piglet room when the ARVS was installed. The numerical model was designed based on the temperature, moisture and gas balance equations of the piglets and the ARVS modules. Python was used as the programming language, and the numerical model was developed using the PyCharm (Ver. 2019.2.1., JetBrains Inc., Czech Republic) software. The first condition considered in developing the numerical model was the structure of the ARVS. The module of the ARVS consists of the wet scrubber module, the external air mixing module, the heat exchange module, and the solar module. Depending on the configuration of the module, the rearing environment inside the piglet room can vary. As previously mentioned, carbon dioxide cannot be reduced in wet scrubber module (Zhao et al., 2011), thus, in this study, no module that can reduce carbon dioxide was considered in the ARVS. Since carbon dioxide can be continuously accumulated by the respiration of the piglets, it was essential to inflow the external air for carbon dioxide balance. Therefore, to evaluate the combination of each module, the wet scrubber module and external air mixing module were selected as basic modules for controlling the carbon dioxide. The wet scrubber module was a device that can reduce the concentration of dust, odors, and harmful gases in the exhausted air from the piglet room. The external air mixing module was a device that conducts the mixing of the air according to the mixing ratio of the recirculated air and external air. In other words, the amount of the exhausted air was equal to the total amount of exhausted air from the piglet room excluding the amount of recirculated air. Also, it was equal to the amount of the inflow of air from the outside of the piglet room. The odors and harmful gases in the exhausted air should be removed. Therefore, the numerical model was developed to mix the outdoor air after passing through the wet scrubber module. On the other hand, the heat exchanger module and the solar module were selected as system variable conditions.

4.2.5. Validation of the numerical model of the ARVS

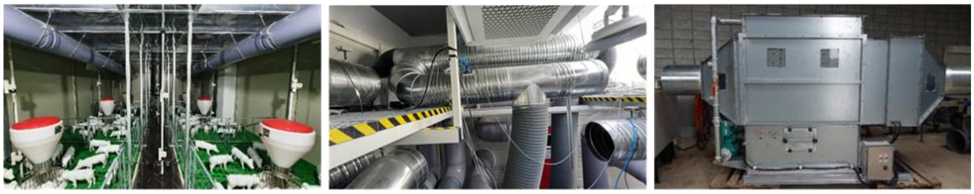
The validation experiment was conducted using the basic module of the ARVS in the testbed experimental piglet room (Figure 4-3). The numerical model of the ARVS was validated based on the thermal environment data for the basic module combination. The thermal environment simulation factors of the numerical model were the heat production of piglets, heat loss from the wall, temperature change due to recirculation water, and outdoor air inflow according to the EAMR. The radiator was installed for generating the same heat production of the piglets, and the ventilation system and wall shape were considered the same as in the numerical model. The heat loss with uncertainty can be caused by infiltration or wall heat loss. In addition, since the ARVS is a semi-closed duct system, the ventilation rate can be reduced by the fan load. Since this was difficult to quantify in the numerical model, it was selected as variable factor and validation was conducted based on the measured data of temperature. Validation of the ventilation and wall heat loss for the basic module was conducted. The validation of uncertainty about other modules was not considered in the numerical model because the experimental data was used for the additional heat exchange and solar module. The thermal environment validation experiment of the basic module was conducted from August to September 2021. The validation experiment process was as follows. The heat production of the piglets was 4698 W based on the total number of the piglets (174 heads) assumed in this study (CIGR, 2002).

First, the radiator was operated using this condition, and the initial temperature inside the piglet room was maintained at 34.5°C. After that, the ARVS was operated, and the outdoor air with 15°C entered into the experimental piglet room under the condition of the EAMR of 10%. The exhaust fan was operated with a ventilation rate of 100 CMM (0.5 min^{-1}) until the air temperature inside the experimental piglet room converges. As the input value of the numerical model, the ventilation structure conditions were set to be the same, and the basic heat production was set to be the same as the number of breeding heads. The validation variables were the amount of heat loss with uncertainty, and the case studies of the numerical model were selected according to the infiltration and ventilation rate. Generally, it is recommended that the crack area is within 10% of the total area in pig houses (MAFRA, 2016). In this study, the ventilation rate considering the infiltration was applied as the standard of 10%. As a result of measuring the pressure while the exhaust fan was operated, the loss of ventilation rate was about 20%. Therefore, as shown in the Table 4-2, the calculation of the numerical model for validation was conducted based on the six experimental conditions considering the infiltration rate and ventilation rate.

Descriptive statistics shown in the Table 4-3 were used for statistical analysis of the measured data and computed data of the experimental piglet room. Measured data and computed data were listed as time-series data. Therefore, mean bias error (MBE) was used to calculate the error according to the same time interval. In addition, root mean square error (RMSE) and coefficient of variant of the RMSE (CV), which indicate accuracy, were used.



(a) Heat and moisture generation inside the experimental piglet room



(b) Combined modules for air recirculated ventilation system

Figure 4-3 Measurement of air temperature for validation of numerical design of ARVS.

Table 4-2 The input value of boundary conditions in the numerical model for thermal environment validation.

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Infiltration rate (%)	10	5	1	10	5	1
Ventilation rate (CMM)	100			80		

Table 4-3 Summary of descriptive statistics used for the analysis.

Descriptive statistics	Acronyms	Equations
Mean Bias Errors	MBE (%)	$\mathrm{MBE} = \frac{\sum_t (\overline{P_t} - \overline{M_t})}{\sum_t \overline{M_t}} \times 100$
Root Mean Square Error	RMSE	$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{t=1}^{n}(P_t - M_t)^2}$
P_t : Predicted valued at hour t M_t : Measured value at hour t		

4.2.6. Case studies with the numerical model of the ARVS

The efficiency of the ARVS was evaluated under various environmental conditions according to the configuration of the ARVS. The outdoor temperature, relative humidity, ventilation rate, and the EAMR were considered as the environmental conditions, and these are shown in Table 4-4. A total of 10800 cases were analyzed according to the combination of the ARVS module and environmental conditions. The condition of recirculating air only with the wet scrubber module was defined as the base module, and the EAMR could be controlled. The internal environment was analyzed according to the configuration of each heat exchange module, EAMR, and solar module. In the case of the heat exchange module, it could be used as a method of exchanging heat with the air inside the piglet room (Figure 4-4 ①) and a method of exchanging heat with the external air (Figure 4-4 ②).

After the combination of the modules was selected, the external air condition was determined as a variable factor to calculate according to various environmental conditions. The meteorological data obtained from Wonju-si, Gangwon-do (37°20'23", 127°55'5") were used. The environmental conditions were set to include both extreme external air temperature and relative humidity by sorting the data based on the meteorological data of the experimental piglet house. A total of 11 conditions of air temperature (-10, -5, 0, 5, 10, 15, 20, 25, 30, 35, 40°C) at intervals of 5°C was set to include the highest temperature and lowest temperature for outdoor temperature conditions. Also, a total of 6 conditions of relative humidity (50, 60, 70, 80, 90, 100%) at intervals of 10% were set to include the highest and lowest relative humidity.

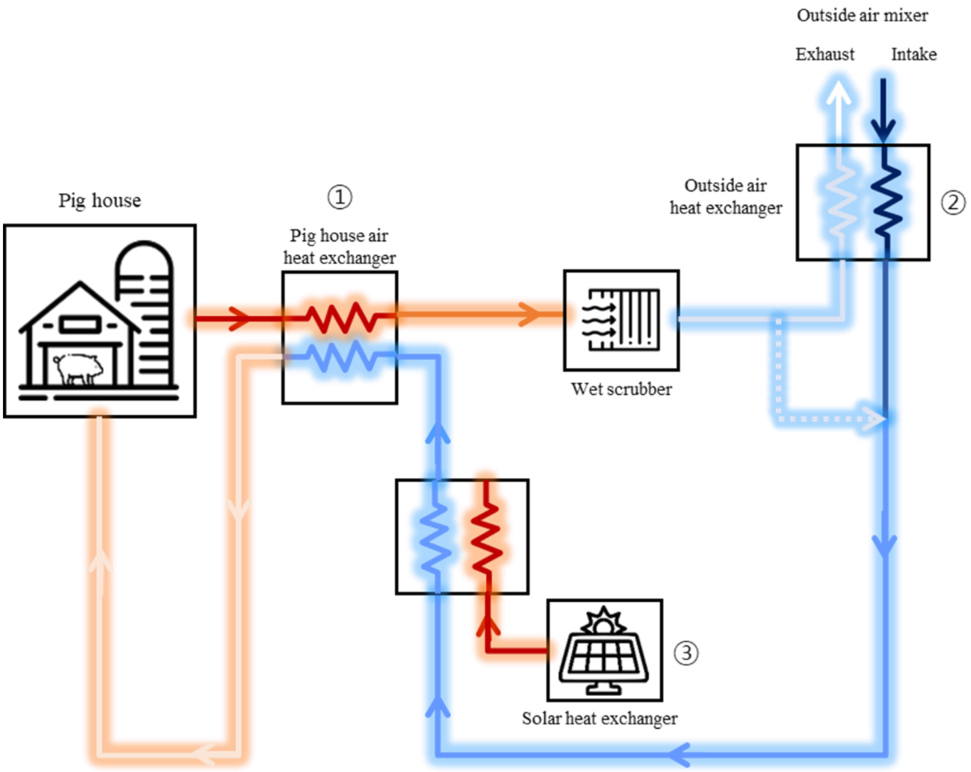


Figure 4-4 Schematic diagram of the ARVS for designing the numerical model.

Table 4-4 Total cases to determine optimal ARVS.

Schematic diagram of the ARVS	
System 1	Basic module
System 2	Basic module + ①
System 3	Basic module + ②
System 4	Basic module + ③
System 5	Basic module + ①, ②
System 6	Basic module + ①, ③
System 7	Basic module + ②, ③
System 8	Basic module + ①, ②, ③
Environmental conditions	
External air temperature (℃)	−10, −5, 0, 5, 10, 15, 20, 25, 30, 35, 40
External air relative humidity (%)	50, 60, 70, 80, 90, 100
Ventilation rate (CMM)	40, 70, 100, 130, 160
EAMR (%)	10, 30, 50, 70, 90
Total cases	
10800	

4.3. Results and discussions

4.3.1. Design and validation of the numerical model of the ARVS

The algorithm of the numerical design of the ARVS is shown in Figure 4-5. First, the air exhausted from the piglet room passes through all modules of the ARVS. All heat exchange and entropy conditions were considered (Figure 4-5 (A)), and the air condition before the inflow of the piglet room was calculated based on balance equations (Figure 4-5 (B)). The air that passed through the ARVS inflows to the piglet room. According to the module combinations, the cleaned air and external air will be mixed in the external air mixing module, and the air temperature, humidity, and gas concentration can be calculated. Next, the air condition inside the piglet room was calculated from the balance equation of thermal, moisture, and gas by considering the reused air, the generation rate of environmental factors inside the piglet room, and heat exchange through the internal structure and the wall. The calculation of the numerical model was repeated until the calculated temperature, moisture, and gas of the air inside the experimental piglet room and the air exhausted from the piglet room converge, and the final result was analyzed (Figure 4-5 (C)). The final result derived in this way means the rearing environment inside the experimental piglet room when the combination of each module was applied. As shown in Table 4-4, for the numerical model of the ARVS, a total of 8 combined systems were designed. It was designed to calculate for all environmental conditions and to repeatedly calculate 1350 cases for each system at once through parallel processing. In a total of 10800 cases, iteration operation was performed until A and C became the same value (Figure 4-5).

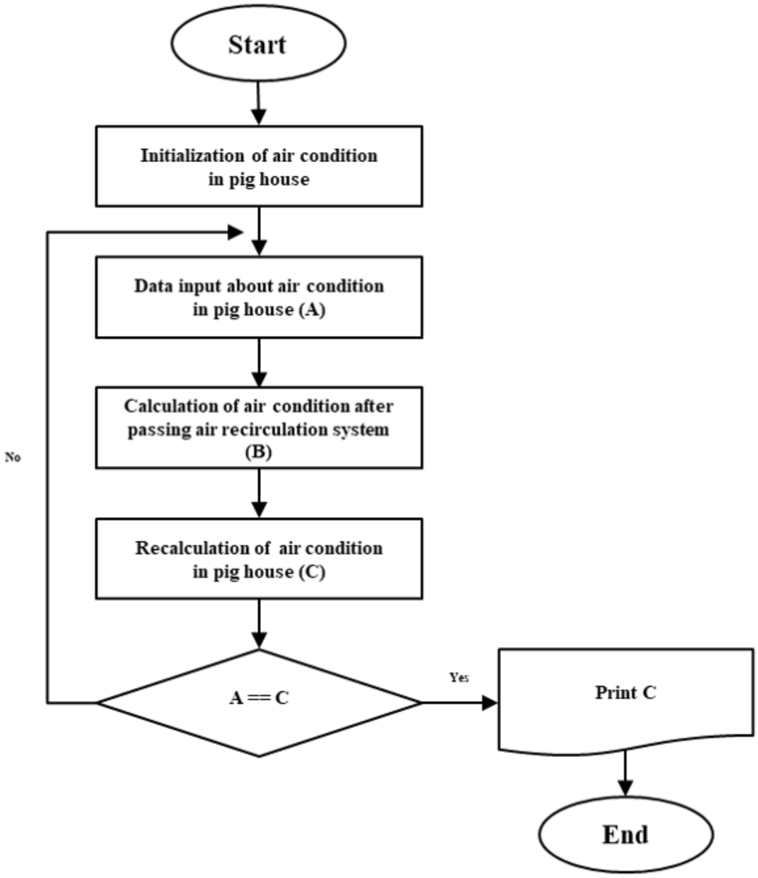


Figure 4-5 Algorithm of the numerical design of the ARVS.

The validation result of the numerical model of the ARVS is shown in Figure 4-6. By generating the heat of 174 piglets using the radiator, about 4698 W of heat dissipation was maintained as sensible heat production in the experimental piglet room. After that, the ARVS was operated and the internal temperature was maintained until a steady state was reached. Then, measured data of air temperature was used to compare with computed data of numerical model according to the variable values.

In Figure 4-6, the measured air temperature converged from the initial temperature value of 34.5°C to a temperature of about 33.5°C over time. The amount of internal heat generated and the amount of heat loss converged due to the inflow of external air. As a result of calculating the validation model, case 1 converged to a temperature of 30.2℃, and there was a large difference compared to the measured air temperature. In case 1, the ventilation rate was set to 100 CMM and the infiltration rate was 10%, so the amount of external air inflow was very large. Accordingly, the air temperature convergence was observed the lowest. In case 2 and case 3, the numerical model was calculated by reducing the infiltration rates to 5% and 1%, respectively. As a result of the calculation, the convergence temperature slightly increased to 30.6℃ and 31.2℃, respectively. On the other hand, in case 4, case 5, and case 6 where the ventilation rate was lowered considering the load of the exhaust fan, the convergence temperature was calculated as 32.7℃, 33.1℃, and 33.5℃, respectively. In the case of the lowest infiltration rate, the predicted result was the most similar to the measured temperature data. The reason for this was that the experimental piglet room had better airtightness compared to the general pig house, and there was almost no infiltration, so the effect of the heat loss due to infiltration was insignificant. In addition, when the load of exhaust fan was considered, the thermal environment similar to the measured data was calculated. The load of the exhaust fan is easy to occur because the structure of the ARVS is a closed-loop duct ventilation system. In particular, the fan load was an important factor in the validation of this numerical model because the airflow loss due to the fan load can be about 10 to 20 times higher than the infiltration of the wall and cracks. Therefore, in case 6, where the load of the exhaust fan was considered and the effect of the infiltration rate was reduced, the convergence value of the numerical model was the most similar to the results of the thermal environment inside the experimental piglet room. In addition, MBE and RMSE were calculated to be 0.23%

and 0.11, respectively (Table 4-5), and based on these, it was determined that the thermal environment was the most suitable for validation. When the developed numerical model will be applied to other pig houses, the influence factors of fan load and infiltration should be considered.

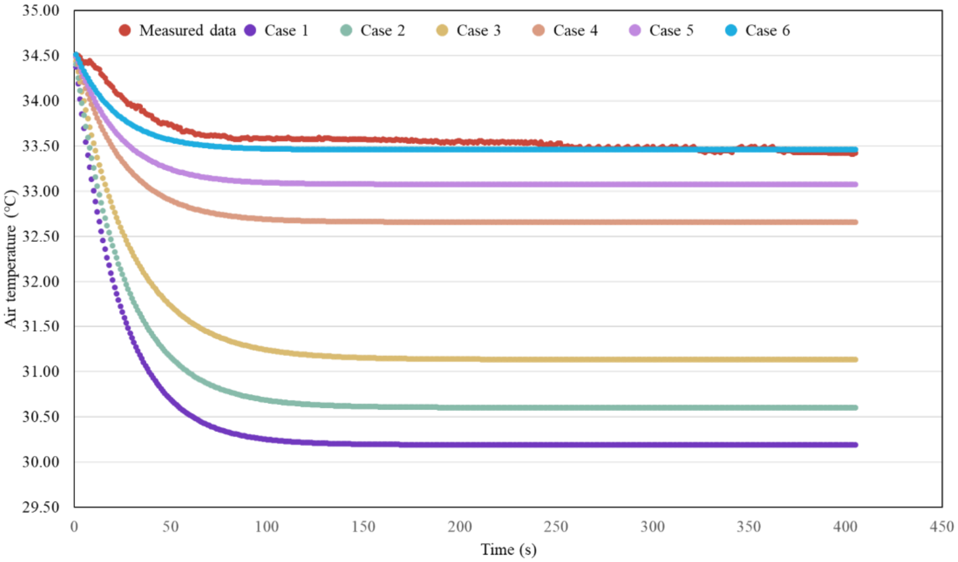


Figure 4-6 Thermal environment of the measured data and calculation data of the numerical model according to the ventilation rate and infiltration rate.

Table 4-5 Results of MBE and RMSE statistics of calculation results according to the ventilation rate and infiltration rate.

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
MBE (%)	9.38	6.59	8.15	2.45	1.29	0.23
RMSE	3.19	2.78	2.25	0.83	0.44	0.11

4.3.2. The results of the gas concentration according to the ventilation rate EAMR

The gas concentration inside the piglet room was first analyzed from the validated numerical model of the ARVS. The gas concentration was designed assuming that there was no change in concentration even if it passed through the heat exchange module of the piglet room, the heat exchange module of external air, and the solar module. Therefore, the gas concentration could be changed according to the total ventilation rate and the EAMR. In addition, the ammonia gas concentration was designed to decrease when it passed through the wet scrubber module while the carbon dioxide gas was designed to remain the same even after passing through the wet scrubber module. According to this design, the gas concentration can be calculated with the same as the result of the basic module (ARVS with only wet scrubber module) regardless of the module configuration of the ARVS. Therefore, in this study, the gas environment according to the ventilation rate and EAMR was analyzed first.

The results of the gas concentration according to the ventilation rate and EAMR are shown in Figure 4-7. According to the results of the gas concentration, it was confirmed that ammonia gas and carbon dioxide gas were formed higher than the allowable concentration standard under some conditions. When the ventilation rate was operated at 40 CMM, the ammonia gas concentration exceeded the allowable standard even when the EAMR was increased to the maximum. Even when the EAMR was increased, the internal gas concentration continued to accumulate. This was because the internal gas generation rate was higher than the gas emission according to the minimum ventilation rate. From these results, the ventilation rate should be maintained at 70 CMM or more to reduce the ammonia gas concentration.

In the case of carbon dioxide gas, when the ventilation rate was 40 CMM, the allowable concentration standard was exceeded using the 27% or less EAMR. Also, when the ventilation rate was 70 CMM, the allowable standard was exceeded using the 18% or less EAMR (Figure 4-7). From these results, it was found that to operate the ARVS, the ventilation rate should be maintained at 40 CMM or higher, and the EAMR should be maintained over 20% with 40 CMM.

Based on the calculation results of this numerical model, it was possible to determine the standard of ventilation rate and EAMR to maintain the gas environment properly. In the case of ammonia gas, the removal efficiency can be changed depending on the design of the wet scrubber capacity, structure, ventilation rate, and recirculating water condition. Therefore, to optimally operate the ARVS, the wet scrubber design considering the specifications of pig house should be first made, and the proper ventilation rate and EAMR can be operated after the appropriate capacity standard is determined. On the other hand, the proper operation of ventilation rate and EAMR for the carbon dioxide should be determined first because it is impossible to reduce the concentration of the carbon dioxide using the wet scrubber.

Accordingly, it should be operated at over 70 CMM, which is higher than the minimum ventilation rate (about 20 CMM) (MWPS, 1983) to maintain the proper gas concentration. When operated under these conditions, the ARVS can properly maintain the gaseous environment inside the piglet room. In addition, there is an advantage that harmful gases emitted outside can be reduced. Even if the EAMR is maintained at about 60%, the air exhausted to the outside can be less than the amount exhausted from the general pig house because the ammonia gas can be removed by the wet scrubber. In particular, since the amount of gas emission can be further reduced according to the removal efficiency and internal gas concentration, the ARVS can be effective in reducing the emission of harmful gases to the outside.

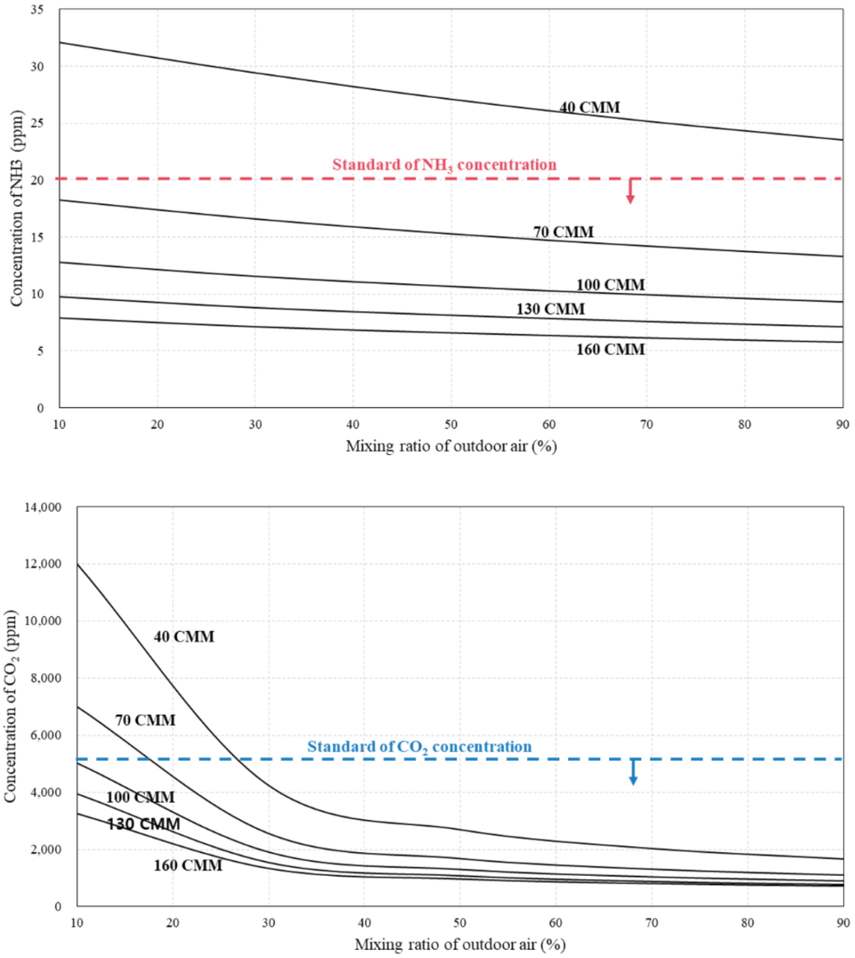


Figure 4-7 Computed results of the numerical model according to the ventilation rate and EAMR.

4.3.3. Air temperature and relative humidity results in the experimental piglet room with the ARVS

When the ARVS was applied according to the calculation conditions, the computed results of the internal environment are shown in Table 4-6. In this study, among a total of 10800 cases, the results of the summer season (external temperature of 35°C), the winter season (external temperature of −5°C), and the mild season (external temperature of 15°C) were selected as representative results. Also, the fixed values of the numerical model were the relative humidity of 90% and the ventilation rate of 160, 100, and 70 CMM. Although it was recommended as a minimum ventilation rate (20 CMM) in the winter season, this was an improper condition that did not improve the gas environment, so it was excluded from the analysis results. The optimum temperature range was assumed to be 28-32°C, and the optimum humidity range was assumed to be 60-85% (MAFRA, 2016).

In the summer season when the external temperature was 35°C, the air temperature inside the piglet room was very high regardless of the configuration of the ARVS module. Because the external air temperature was very high, the air temperature blown by the ventilation system remained at 35°C which resulted in difficulties in lowering the internal temperature to an appropriate level. Also, it was impossible to lower the temperature without a cooler because the inside of the piglet room was heated by the heat production of the piglets. The effect of reducing the air temperature by the recirculation water was considered. However, the air temperature was increased due to the internal heat generation, resulting in an average temperature inside the piglet room 2°C higher than the inflow air temperature. The wall heat transfer in the numerical model can be calculated according to the internal and external temperature difference, wall thickness, and thermal conductivity (wall characteristics). In the case of summer with a high ventilation rate, heat exchange has the greatest effect on the ventilation rate than the wall heat transfer. Accordingly, in summer, as the EAMR at 35°C was lower than the internal temperature, the air temperature inside the piglet room was decreased. Compared to system 1 using only the wet scrubber module, the overall higher temperature was maintained in the systems using other modules. When the internal temperature in summer was lower than the external temperature, the inflow temperature was reduced in combinations such as systems 2 and 3 using a heat exchanger. However, because the actual temperature inside the piglet room was simulated higher, the use of the heat exchanger increased temperature. Therefore, the combination of a heat exchanger and solar heat was not suitable in summer. The method was required to lower the internal temperature by operating the cooling device or by frequently replacing the recirculation water to keep the water temperature low. In Korea, the hot season occurred from June to August, and the number of days when the external temperature exceeds 35°C is less than 10 days. Therefore, it is advantageous to maintain the maximum ventilation rate and to increase the EAMR as much as possible when using the ARVS in the hot season. If the internal temperature is lower than the external air, it may be more advantageous to lower the temperature of the incoming air through the heat exchanger than to increase the EAMR.

On the other hand, in Korea, relative humidity is often high during the rainy season. When the relative humidity of the external air in the hot season was 90%, the internal relative humidity was all simulated in a humid state. In the piglet room, moisture may be continuously generated inside the piglet room due to the piglet’s respiration and evaporation of moisture from the manure. In this case, since there was no device to remove moisture, moisture should be managed through sensible heat change in air condition. It can be suitable to drop the saturated water vapor pressure by generating condensed water through cooling and dehumidification.

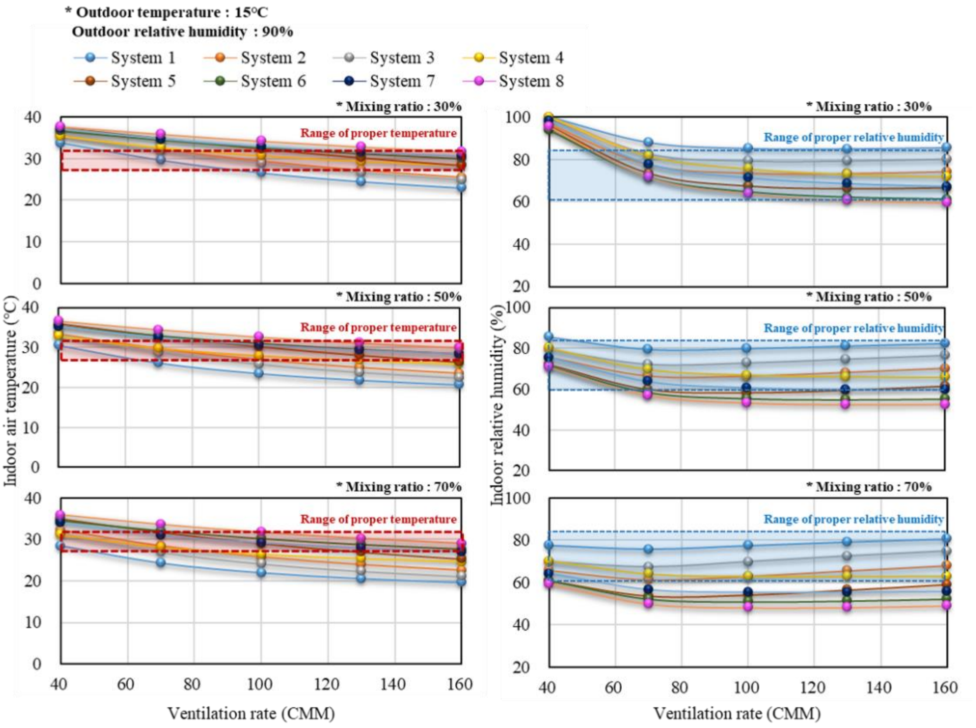


Figure 4-8 The air temperature and relative humidity inside the experimental piglet room according to the ventilation rate and the external air mixing ratio (external air temperature 15°C, external air relative humidity 90%).

When the external temperature was 15°C, it was possible to maintain the proper temperature inside the piglet room even if only one module was added along with the basic module including the wet scrubber module. The Figure 4-9 illustrates the graph showing the results according to the ventilation rate and EAMR. In the case of system 1, when the air passed through the wet scrubber module and mixed with external air, it was mixed with air at 15°C, so the temperature of the incoming air was low. In particular, when the EAMR was low, it was possible to properly maintain the internal temperature of the piglet room. However, when the ventilation rate was maintained above 100 CMM, it became below the appropriate temperature range. In addition, as the EAMR increased, it became less than the appropriate temperature range in most combinations of modules. As shown in Table 4-6, when the EAMR was increased to 90%, it was simulated that the internal temperature was lowered to 21℃ when operating at 70 CMM ventilation rate. The higher the EAMR, the greater the amount of discharging the thermal energy inside the piglet room to the outdoor. In the case of systems 2, 3, and 4, since internal heat energy was reused through the heat exchanger, an appropriate temperature could be maintained inside the piglet room even when the EAMR was increased. In addition, systems 5, 6, 7, and 8 were also found to be able to sufficiently maintain the proper temperature inside the piglet room by controlling the EAMR. In particular, during the mild weather condition, the relative humidity inside the piglet room can also be maintained properly. Therefore, it was analyzed that the system in which modules such as a heat exchanger and solar heat module were added could maintain the internal thermal environment properly by controlling the ventilation rate and EAMR according to the external air conditions.

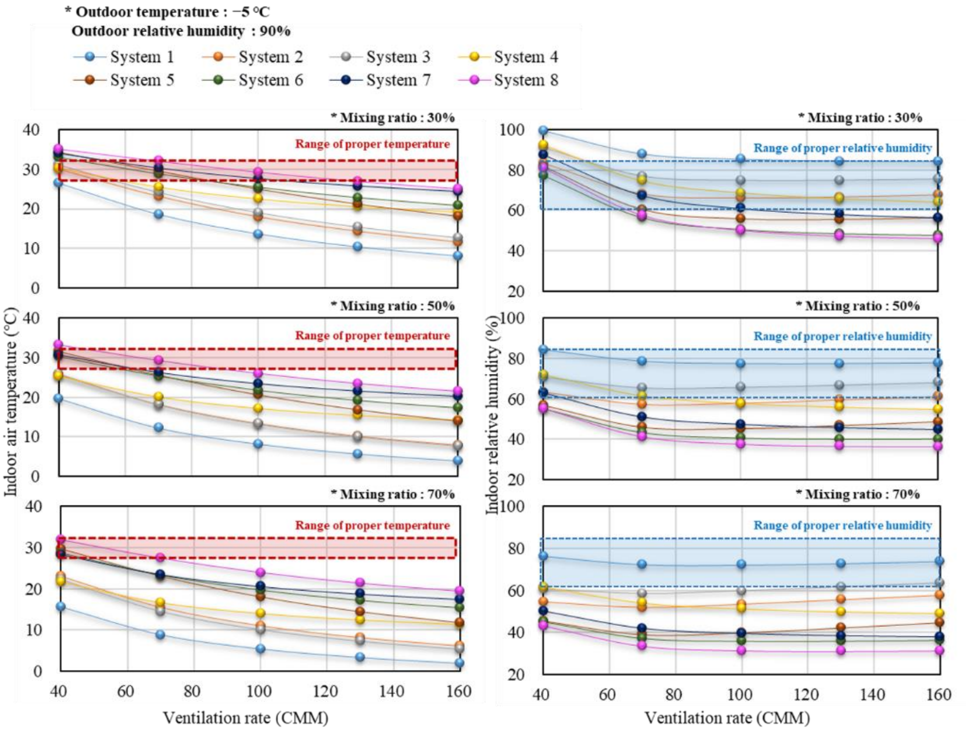


Figure 4-9 The air temperature and relative humidity inside the experimental piglet room according to the ventilation rate and the external air mixing ratio (external air temperature −5℃, external air relative humidity 90%).

In the case of system 1, which used only the wet scrubber module, the temperature inside the piglet room decreased rapidly as the EAMR increased during the cold season when the external temperature was −5℃. When the EAMR was set to 10%, the temperature inside the piglet room converged to a proper condition because the inflow of low temperature air was minimized. However, when the EAMR was maintained at 30% or more, the temperature inside the piglet room was low resulting to a risk of low temperature stress. In system 2, 3, and 4, the internal temperature converged to about 33.4, 34.2, 34.2℃ when the mixing ratio was 10%. However, since it was necessary to increase the EAMR to improve the gas environment, it was difficult to maintain the proper temperature in system 2, 3, and

4 that add a single module. On the other hand, when two or more modules were used together with the wet scrubber module as in systems 5, 6, 7, and 8, the temperature increased about 5°C when the EAMR was low, but it increased to 19.4°C when the EAMR was high. In particular, in the case of system 8, which used all three modules, it was confirmed that the temperature inside the piglet room was maintained properly even if the EAMR was increased to 50%. Among systems 2, 3, 6, and 7 with different heat exchanger installation arrangements, the temperature inside the piglet room of systems 2 and 7 was about 1.2°C higher. Therefore, when only one heat exchanger module was used, it was advantageous to install the heat exchanger after the wet scrubber module. The reason for this was to not lose thermal energy by the recirculation water while passing through the wet scrubber module. It was desirable to apply two or more ARVS modules together with the wet scrubber module to improve the temperature inside the piglet room during the cold season. In addition, in the case of using two modules in a system combination, the system 7 combination was most advantageous. When the EAMR needed to be increased to improve the internal gas environment, the air temperature inside the piglet room can be decreased. Therefore, in consideration of the internal temperature, the EAMR should be controlled in real-time, so that the internal gas environment can be properly maintained at the same time. Even if the relative humidity of the external air in winter was high, since the temperature can rise due to heat exchange, the saturated vapor pressure of the air increased. Accordingly, the relative humidity was lowered, and the internal moisture environment could be properly maintained. In addition, if the inside of the pig house is in a dry state, there is an advantage that humidification is possible by a wet scrubber module. Therefore, it was possible to properly maintain the moisture environment inside the piglet room in winter through the ARVS.

Table 4-6 Computed results of internal air temperature and relative humidity of the piglet room with the ARVS according to the external conditions, ventilation rates, and mixing ratio of external air.

External Temp (℃)	Ventilation rate (CMM)	EAMR (%)	System 1		System 2		System 3		System 4		System 5		System 6		System 7		System 8	
			Temp (℃)	RH (%)	Temp (℃)	RH (%)	Temp (℃)	RH (%)	Temp (℃)	RH (%)	Temp (℃)	RH (%)	Temp (℃)	RH (%)	Temp (℃)	RH (%)	Temp (℃)	RH (%)
35	160	10	38.7	100	39.1	100	39.2	100	39.2	100	39.5	100	39.4	100	39.6	100	39.6	100
		30	37.3	98	37.8	95	37.7	96	38.0	95	38.3	94	38.4	93	38.4	94	38.7	92
		50	36.5	94	37.2	91	36.8	93	37.4	91	37.6	89	38.0	88	37.7	90	38.2	87
		70	36.3	92	37.0	89	36.4	91	37.1	88	37.4	87	37.8	85	37.4	87	37.9	85
		90	36.2	90	37.0	87	36.3	90	37.0	87	37.2	86	37.8	83	37.2	86	37.8	83
15	100	10	34.5	100	36.0	100	36.5	100	36.6	100	37.7	100	37.2	100	37.9	100	38.1	100
		30	26.6	85	29.4	73	28.9	79	30.7	76	32.3	67	32.8	65	33.0	71	34.2	64
		50	23.5	80	27.0	66	25.8	73	28.0	67	30.2	58	31.0	55	30.6	61	32.6	53
		70	22.0	77	25.8	63	24.1	70	26.4	63	29.0	54	30.1	51	29.2	56	31.7	48
		90	21.0	76	25.0	61	23.1	68	25.3	61	28.3	52	29.6	48	28.2	52	31.1	45
-5	70	10	31.0	100	33.4	100	34.2	100	34.2	100	36.0	100	35.3	100	36.3	100	36.6	100
		30	18.5	88	23.2	68	24.1	77	25.5	75	29.5	60	28.8	57	30.3	68	32.1	57
		50	12.2	79	18.2	57	18.1	65	20.0	62	25.6	46	25.4	43	26.3	51	29.3	41
		70	8.8	72	15.5	52	14.4	58	16.6	54	23.1	39	23.3	37	23.5	42	27.4	33
		90	6.7	68	13.8	48	12.0	54	14.1	49	21.4	35	22.0	33	21.4	36	26.1	29

4.3.4. Example of optimal operation for ARVS

In this study, using the numerical model of the ARVS, the internal thermal environment, moisture environment, and gas environment were simulated according to module combination, ventilation rate, and EAMR. When operating the ARVS, the internal temperature, humidity, and gas conditions could all be different depending on the module combination and external weather conditions. Therefore, it was necessary to determine the ventilation rate and EAMR to maintain an appropriate temperature, humidity, and gas environment according to the system combinations and external weather conditions. The ventilation rate and EAMR were determined to maintain the appropriate concentration of ammonia and carbon dioxide gas inside the experimental piglet room. Assuming that the proper temperature was maintained inside the piglet room using this ventilation rate, the EAMR should be determined based on this ventilation rate. Since it was impossible to remove the carbon dioxide with the wet scrubber module, increasing the EAMR should be accompanied. Additionally, if the EAMR and ventilation rate were maintained, the relative humidity inside the piglet room could also be predicted using numerical model. In this study, when the external air temperature was −5°C and the relative humidity was 90%, the optimal operation plan for the ARVS (system 1 and system 7) was analyzed (Figure 4-10).

For example, when system 1 was installed, it was confirmed that the ventilation rate of 70 CMM or more should be operated to maintain the proper gas environment. When the ventilation rate was 70 CMM, the EAMR should be set to 12% to maintain the air temperature inside the piglet room at 30°C as shown in the left chart of Figure 4-10. The relative humidity inside the piglet room was 99% with this operating condition. If system 1 was installed and the ventilation rate was maintained at 130 CMM, even if the EAMR was controlled, the air temperature inside the piglet room could not be maintained at 30℃. On the other hand, when system 7 was installed, the EAMR should be set to 32% with the ventilation rate at 70 CMM to maintain the air temperature inside the piglet room at 30℃. Because the system 7 used the heat exchanger and solar module, it could use more external air than system 1. Therefore, it was determined that system 7, which could use more external air, could be easier to control the gas environment, even if the same temperature was maintained. In addition, if system 7 was operated with this condition, the relative humidity inside the piglet room would be 66%. If system 7 was installed and the ventilation rate was 130 CMM, the EAMR should be set to 25% to maintain the air temperature inside the piglet room properly. The relative humidity inside the piglet room could be 70% with this condition.

In this way, it was possible to calculate the ventilation rate and EAMR to properly maintain the air temperature, relative humidity, and gas environment inside the piglet room depending on the module combination of the target facility. In addition, the numerical model developed in this study could be used according to the external weather conditions to determine the necessary module combination and operation condition when installing the ARVS.

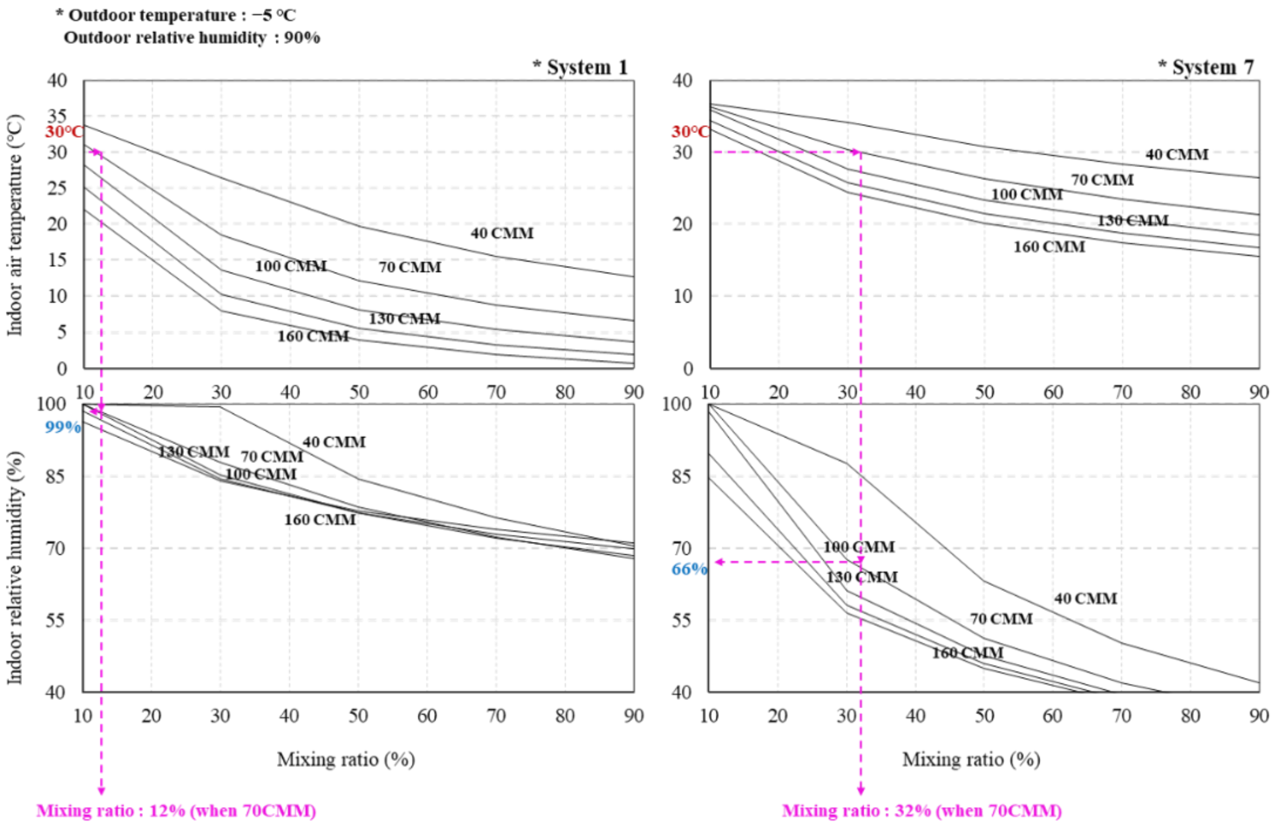


Figure 4-10 Example of optimal operation method for ARVS (System 1, System7).

4.4. Conclusions

In this study, an optimal numerical model for predicting the internal rearing environment of piglet house was developed to suggest a design and operation plan for the ARVS. This numerical model was designed based on various balance equations, and the environment inside the piglet room was calculated according to the heat, moisture, and gas generation mechanisms of the ARVS. Therefore, the developed numerical model could be used generally through farm information such as farm size, age, and weather condition.

To validate the thermal environment of the developed numerical model, field experiment was conducted at the experimental testbed where the ARVS and modules were installed. The uncertainty of the numerical model considering internal heat generation and heat loss was selected as a validation variable, and comparative validation was conducted with the thermal environment data of the experimental piglet room in AcSEC-A3EL. Heat transfer with uncertainty was infiltration caused by infiltration and the air flow can decrease due to the fan load. As a result of considering 20% reduction in ventilation fan load and 1% of infiltration rate in the numerical model, MBE and RMSE with air temperature data inside the experimental piglet room were calculated to be 0.23% and 0.11, respectively. In the case of additional modules, the removal efficiency, heat exchange efficiency, and solar thermal efficiency for each module were considered based on the field experiment data. For a new module, various conditions can be considered if the numerical model is modified through additional experiments.

As a result of calculating the numerical model, the ventilation rate of 40 CMM or more was advantageous to properly maintain the gas environment. Also, when operated with the ventilation rate of 70 CMM or more, the EAMR could be sufficiently lowered. On the other hand, in the case of ammonia gas, it was removed by the wet scrubber module, but in the case of carbon dioxide, it was necessary to maintain the EAMR over a certain amount because the carbon dioxide cannot be removed using wet scrubber module.

In the case of system 1 using a single module, the air temperature was higher than that using other modules in summer season. Also, in the case of system 2 and 3 using the heat exchanger module, the proper air temperature could not be maintained because the air temperature of the inlet was increased. Therefore, it was necessary to additionally use the cooling device in the hot season. In the case of the external weather condition with high relative humidity, all of the internal relative humidity was simulated in an over-humid state, so the reduction of moisture content through refrigeration dehumidifier was necessary. When the external air temperature was 15°C, if the EAMR was increased by 50% or more, the internal air temperature was lowered to an appropriate level. The system using the heat exchanger and solar module can effectively use the internal thermal energy of the piglet room and maintain the air temperature properly. In the winter season, low temperature stress can occur inside the piglet room when using the system 1, except when the EAMR was 10%. When using a heat exchanger and solar module, the EAMR could be increased up to 50%. It was advantageous to use a heat exchanger and solar module at the same time. In particular, in systems 2, 3, 6, and 7 with different heat exchanger combination, the system 3 and 7, in which the heat exchanger was installed after the wet scrubber module, was more advantageous for maintaining air temperature in winter season.

From these results, the operation plan of the ARVS can be suggested using this numerical model. Based on the optimal design of this study, scale-up experiment and application of the ARVS will be conducted.

Chapter 5. Application of system in real pig farm and evaluation of pig productivity in winter season

5.1. Introduction

The demand for meat and other livestock products has increased rapidly accounting to about 39.4% of the total agricultural production in South Korea (MAFRA, 2020). In the pig industry, the number of rearing heads per farm is increasing every year due to intensive pig production with mechanization and automation. However, the pig production increase caused a lot of contaminants accumulated inside compared to other livestock facilities (Kwon et al., 2016). This also resulted to difficulties in maintaining the stability and uniformity of the rearing environment in large-sized pig houses. The ventilation is generally operated to control the rearing environment inside the pig houses. However, there are many difficulties in proper ventilation operation in pig houses. In many farms, minimum ventilation rate is performed to minimize the inflow of cold air to maintain the optimum temperature in winter season. Also, there is a reason for reluctance to increase the ventilation rate. The epidemic airborne diseases can be spread through the air and the environmental problems can occur near the pig farm when the harmful gases and odors are dispersed from the pig farm. Accordingly, interest in technology that can improve the external environment as well as the rearing environment inside the pig house is increasing. There are four major issues that need to be solved in pig house; 1) rearing environment for pig productivity, 2) energy cost, 3) livestock disease, and 4) ammonia and odor emission.

The ARVS has been proposed as a method to improve the internal environment of pig houses, prevent livestock disease, and minimize the emission of harmful gas and odor. The main purpose of the ARVS was to minimize the inflow of external air for preventing the disease and increasing the energy efficiency. It can also minimize complaints from residents by reducing odors and harmful gases emitted from the pig house. The ventilation rate can be increased without additional energy input because the metabolic energy inside the pig room can be reused. Through this, there was an advantage that the internal growth environment can be improved. Through CFD simulation analysis, the applicability of the ARVS has already been evaluated in chapter 3.

The operation principle of the ARVS starts with sufficiently washing the polluted air exhausted through the wet scrubber module. Then, certain amount of the cleaned air is exhausted while the rest amount of the cleaned air is mixed with incoming external air and then flows back to the system. The amount of air to be replaced is the amount calculated by the algorithm based on the measured environmental data in the piglet room. In order to apply these technologies, it is necessary to monitor internal and external environmental factors in real time with high-tech ICT. In addition, the efficiency of this system could be maximized by precisely controlling the ventilation rate and EAMR.

It was expected that the representative four problems aforementioned would be solved through ARVS. 1) The ARVS reuses the heat energy of the exhausted air, and it was possible to increase the ventilation rate in cold winter season. Accordingly, the rearing environment could be improved and the energy can be saved by reducing the use of heating device. 2) Also, ARVS can minimize the emission of harmful gas and odor by removing the gas and odor using wet scrubber module while the amount of exhausted air can be decreased. 3) It can block the livestock disease by reducing the inflow and outflow of external air, and to suppress the growth of bacteria through

ARVS sterilization devices. In chapter 3, seasonal problems were identified through field experiments at the experimental pig house to evaluate the applicability of the ARVS, and developed the CFD model to aerodynamical analysis. The ARVS applicability to maintain the internal rearing environment was evaluated by applying the ARVS to the developed model. In addition, for installation and operation on the actual pig house, it was evaluated the optimal combination and operation plan for each module of the ARVS based on numerical model in chapter 4. It was necessary to evaluate the performance of the ARVS developed based on the results of the previous studies and then comprehensively validating the improved rearing environment, decreased harmful gas emission, and increased pig productivity through seasonal experiment. Therefore, in this chapter, such an ARVS was applied to an actual farm to evaluate the internal rearing environment, external environmental load, and pig productivity.

5.2. Materials and methods

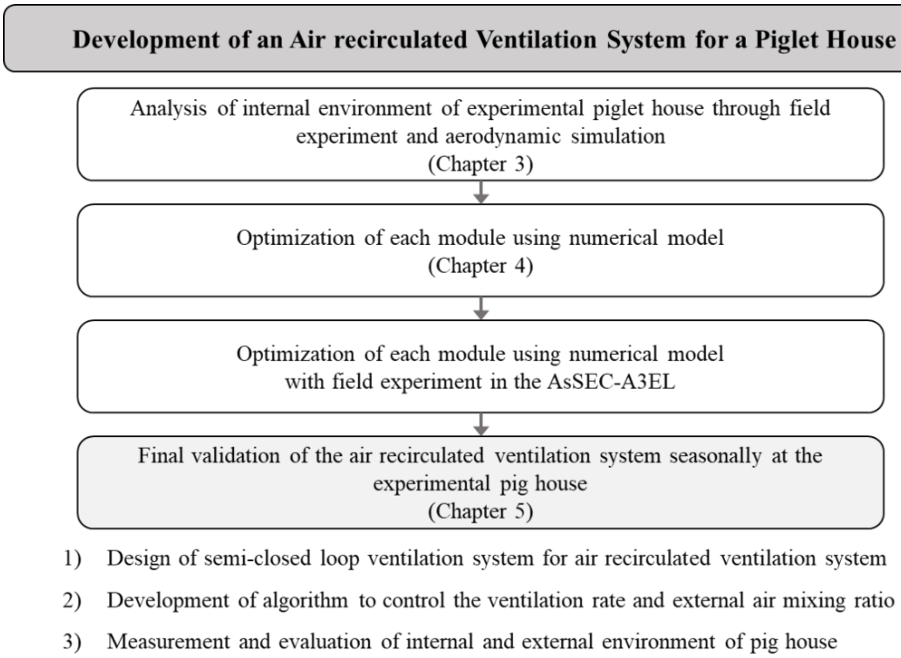


Figure 5-1 Flowchart of the development process of the ARVS. To design the ARVS for piglet house, the evaluation of applicability and optimal design were conducted on chapter 3 and 4. Finally, the validation experiments were conducted in this chapter.

The research has been conducted for a total of 5 years since 2018. The overall ARVS was developed in four steps as follows (Figure 5-1).

1) The analysis of environmental problems and improvement were first conducted through seasonal field experiments and CFD modelling at the experimental pig farm where the ARVS was finally installed (chapter 3).

2) Optimized design for each module of ARVS using numerical model and overall integrated system design were conducted (chapter 4). The individual upscaling of modules such as wet scrubber module, solar energy module and air mixing module were conducted at the AcSEC-A3EL.

3) The validation was conducted after the design of the upscaled modules were optimized and manufactured, and then installed at the AcSEC-A3EL as scale-up experiments. Based on this, algorithm for real-time monitoring and integrated control were designed. Then, the wet scrubber module was also validated on a real piglet room.

In this chapter, 4) the finally developed full-scaled ARVS was installed at Ecofarm (experimental pig house), and the final validation studies and modification were conducted by season. Validation experiments for winter were conducted, and improvement of the environment in piglet room was evaluated (chapter 5). Also, the operation manual was made after applying the algorithm for automatic control of the system. Next, the validation experiments for spring and summer season were conducted (chapter 6).

5.2.1. Target facilities

5.2.1.1. The experimental piglet room of conventional ventilation type

A mechanically ventilated pig house in Sunchoen EcoFarm (34°55’17“N, 127°22’8” E), Jeollanam-do Province, South Korea was selected as the target pig house where the ARVS was installed. About 960 piglets with ages between 3 and 10 weeks were raised in the experimental pig room (Figure 5-2) during the period of the study. There were two piglet room of the same size. One piglet room was selected as the experimental group, and ARVS was installed in this piglet room. Another piglet room was selected as a control group, and the CVS was installed. There was about a month difference between rearing period. In the ARVS piglet room the piglets were bred for 50 days from Jan to Feb. On the other hand, in the CVS piglet room, the piglets were bred from Dec to Jan.

The dimension of the facility was 10.55 m in width, 31.25 m in length and 2.6 m in height. There was a ceiling space at the top of the piglet room and the height of ceiling space was 1.2 m. Also, there was a corridor with a width of 1.25 m outside the piglet rooms. The stocking density was found to be 0.35 $m^2 \cdot head^{-1}$, which was higher than the Korean stocking density standard of 0.24 $m^2 \cdot head^{-1}$. The external air can enter through the corridor windows openings and through the 5 rows of 7 ceiling slots at the top of each pig zone. Identical types of side exhaust fans and chimney exhaust fans with 141.6 CMM each were installed in the experimental pig house (COCO-630A, Dongsung Cocofan. Ltd, Korea). The required ventilation rate according to the number of piglets was 509.6 CMM, and the recommended ventilation rate in winter and summer was 101.2 CMM and 762 CMM, respectively (MWPS, 1983). Radiator heating system was used in the CVS piglet room. The heat sinks were heated with hot water to increase the air temperature inside the CVS piglet room.

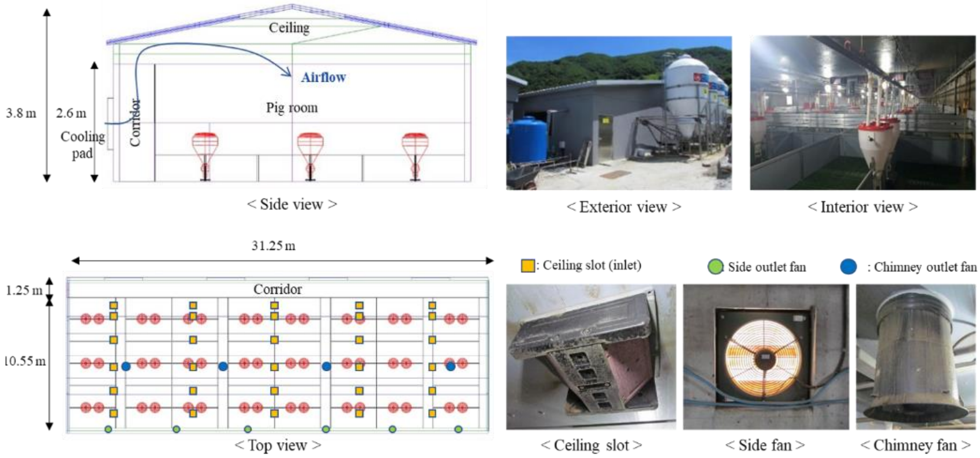


Figure 5-2 The structure and ventilation system of the CVS piglet room.

5.2.1.2. The experimental piglet room of ARVS

Figure 5-3 is an overall schematic diagram of the experimental piglet room with ARVS. The ARVS piglet room and CVS piglet room were located side by side in the same pig house. In the chapter 4, the optimal combination of modules in ARVS was suggested based on the computed results of the numerical model. First, the air inside the piglet room could be exhausted through the outlet ducts. This air moves to the wet scrubber module through the round ducts (600 mm). Inside the wet scrubber module, the air can be cleaned and passed to the external air mixing module. Some air can be exhausted according to the EAMR of automatically controlled standard. The remaining cleaned air enters the heat exchanger module. Here, a coil connected to the heat storage tank of the solar heat module was installed. Solar heating module was used as an auxiliary heating system in case of very cold weather, and it was very economical equipment for less than 4000 USD. And the external air in the corridor can be mixed with the recirculated cleaned air according to the EAMR. The amount of air equal to the amount exhausted to the outside can be inflowed. Finally, the air enters the piglet room uniformly through the inlet ducts. The process of ARVS development proceeded as follows. 1) A semi-closed loop ventilation system was designed to control the internal ventilation rate and EAMR of the ARVS. 2) A wet scrubber module that can clean the recirculated air was installed. 3) A coil that can increase the air temperature using solar hot water from the solar heating module was designed and installed in the heat exchange module. Finally, 4) equipment to control the pH of the circulating water used in the wet scrubber module and UV sterilizers were installed.

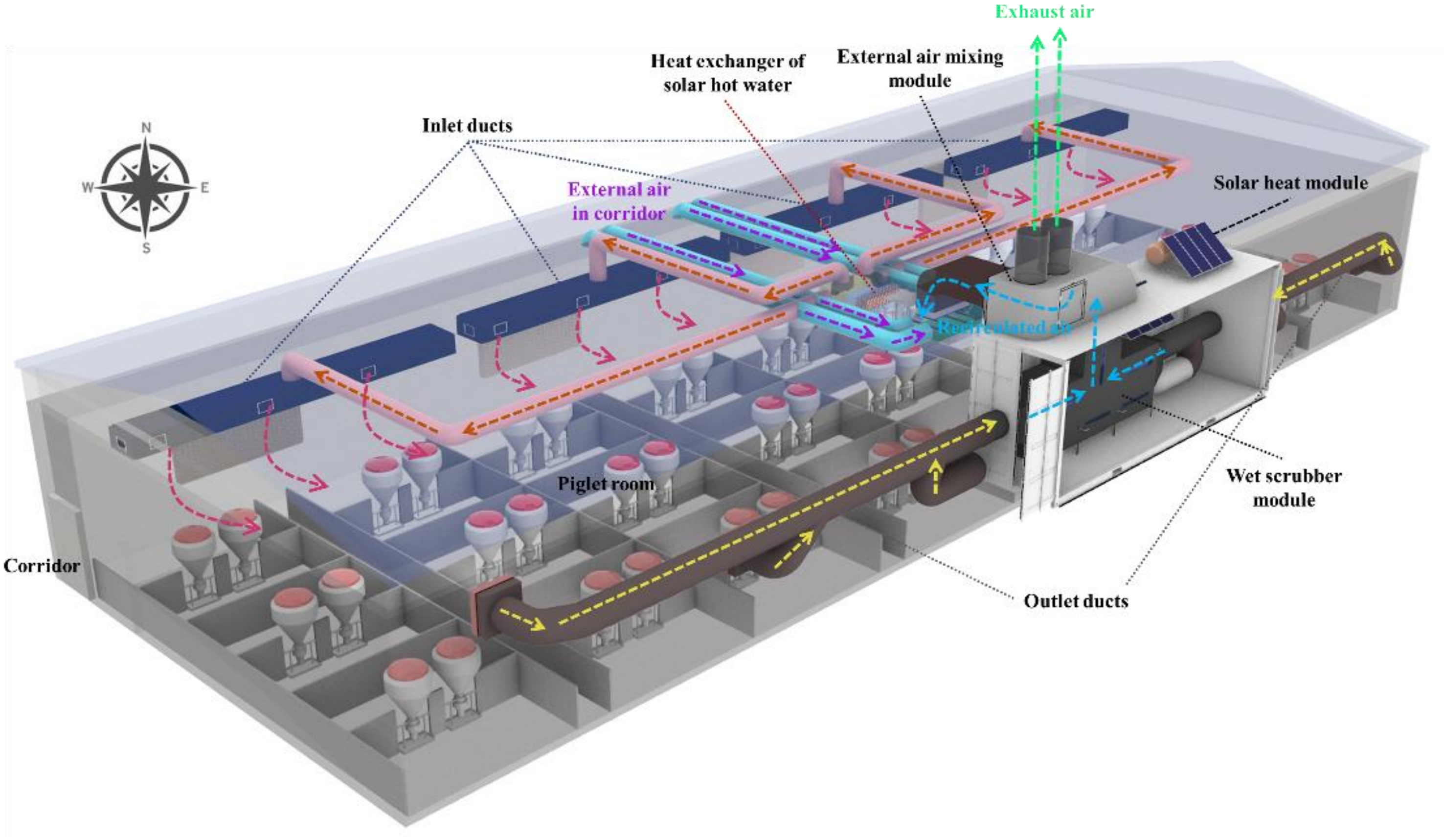


Figure 5-3 Overall schematic diagram of the experimental piglet room with ARVS installed.

5.2.2. Experimental methods and procedure

The experimental procedure in this study was shown in Figure 5-4. First, the design and installation of ARVS proceeded. System installation was completed in December 2021 for conducting seasonal validation experiments in 2022. Next, during the piglet rearing period, various internal and external environmental data, weight gain, and disease data were collected. Finally, the collected data were analyzed to evaluate the performance of ARVS.

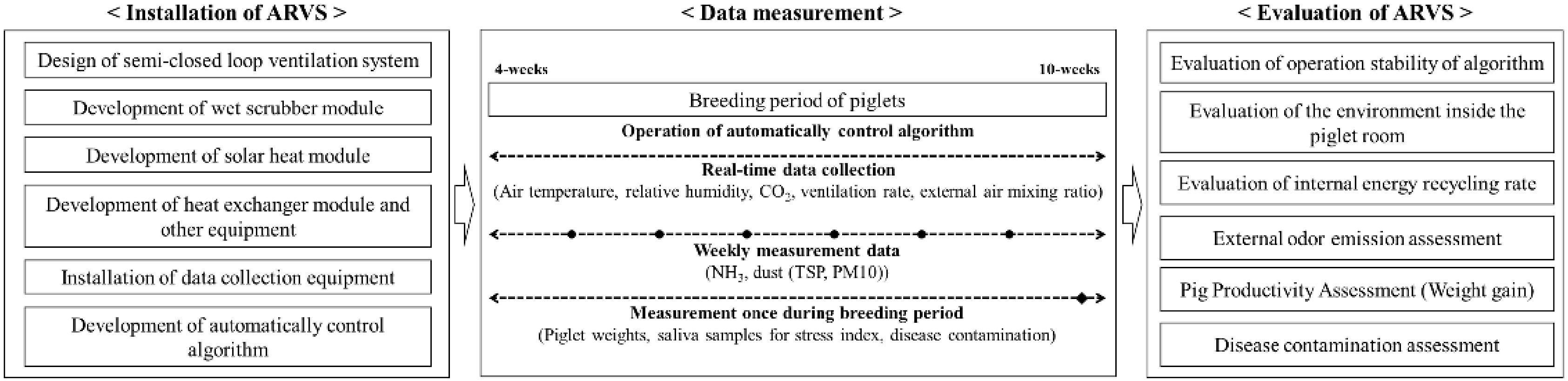


Figure 5-4 Overall experimental method and procedure for developing and evaluating the ARVS.

5.2.2.1. Design of semi-closed loop ventilation system

In mechanically ventilation system, the principle of ventilation is that air flows according to the pressure difference between inside and outside of facility. It is the exhaust fan that creates the static pressure difference inside and outside of the facility. The negative pressure ventilation method uses an exhaust fan to maintain the internal static pressure lower than the outside. Accordingly, ventilation is operated so that air can inflow through the inlet and the infiltration area, and the internal air can be exhausted through the fan.

In the case of ARVS, the exhausted air inside the piglet room can be flow into the inside again (Figure 5-5). Therefore, a simple pressure difference cannot occur because several exhaust fans were used at the same time. It was s semi-closed loop ventilation that cannot control the static pressure of the piglet room in general method because the pressure inside the piglet room can be affected by several fans. In addition, friction loss of air should be considered since all airflow passages were made of ducts. Therefore, the semi-closed loop ventilation system was designed to control the required ventilation rate and EAMR considering the pressure difference and friction loss. Park et al., (2022) analyzed the operating conditions of exhaust fan and friction loss to control the ventilation rate and EAMR for a semi-closed loop ventilation system. Based on the previous research, in order to quantitatively control the ventilation rate of this semi-closed loop, differential pressure sensors were installed in the outlet duct, the external air exhaust duct, and the inlet duct to measure the actual pressure loss. The correction factor calculated by comparing the target control value, the actual ventilation fan control value, and the actual airflow rate of the exhaust fan was applied to the automatically control algorithm.

(a) Outlet of piglet room and exhaust duct

(b) Wet scrubber module connected by duct

(c) External air mixing module after cleaning

Figure 5-5 The procedure of the ARVS semi-closed loop duct ventilation system. (a) Air can be exhausted through the exhaust duct from inside the piglet room. (b) The internal air passing through the duct cleaned in the wet scrubber. (c) The calculated amount of air can be discharged to the outside, and then same amount of external air can be mixed and the mixed air flows into the piglet room.

5.2.2.2. Wet scrubber module of ARVS

One of the most important modules of the ARVS is the wet scrubber module. In order to use the air inside the piglet room again, it was necessary to remove harmful gas, dust, and odors inside of the livestock house as much as possible. A typical harmful gas inside the pig house is ammonia. Also, complaints about odor are a big obstacle to farm operation. Therefore, the wet scrubber module was essential in the ARVS, and it was important to maximize the removal efficiency of the ammonia gas and complex odor. The wet scrubber showed different cleaning characteristics according to various physical and chemical factors. According to the results of previous studies, by optimizing the physical characteristics, the number of nozzles and types of fillers maximize the contact time between circulating water and air. The nozzle was set to 2×3, and the fillers were used in the form of a packed bed. The parallel flow that can minimize pressure loss was adopted as the scrubbing type among cross flow, counter flow, and parallel flow (Lim et al., 2011). Gas removal efficiency depends on the ratio of scrubber liquid flow rate to the exhaust airflow rate. In this study, the optimal liquid-to-gas ratio (L/G ratio) was selected about 2.7, and the water pump with the necessary capacity to maintain the L/G ratio was installed. Empty bed retention time (EBRT) is the time that air is in contact with the scrubbing liquid. EBRT can be calculated by dividing the volume of the scrubber (m^3) by the airflow rate ($m^3 \cdot s^{-1}$), which is the time dimension. The EBRT was an important factor in determining the size of an actual wet scrubber. In particular, in determining the EBRT, the size of the space that can be installed on the pig house and the ventilation rate should be considered. In this study, in order to maximize the removal efficiency of gas by physical characteristics, the EBRT was set to 5.25 (s) and the size of the scrubber was determined to be 7 m^3. Next, the circulating water of the wet scrubber should be chemically treated to remove gas and complex odors. In order to remove ammonia gas inside the piglet room, the pH of the circulating water should be acidic. On the other hand, in order to remove complex odors, a subacid solution and odor removal components were required. Therefore, in this study, the wet scrubber was designed in two stages, and the ammonia removal solution and the complex odor removal solution were used separately (Figure 5-6).


(a) Wet scrubber module with the recirculation pump (b) Washing nozzles inside the wet scrubber module

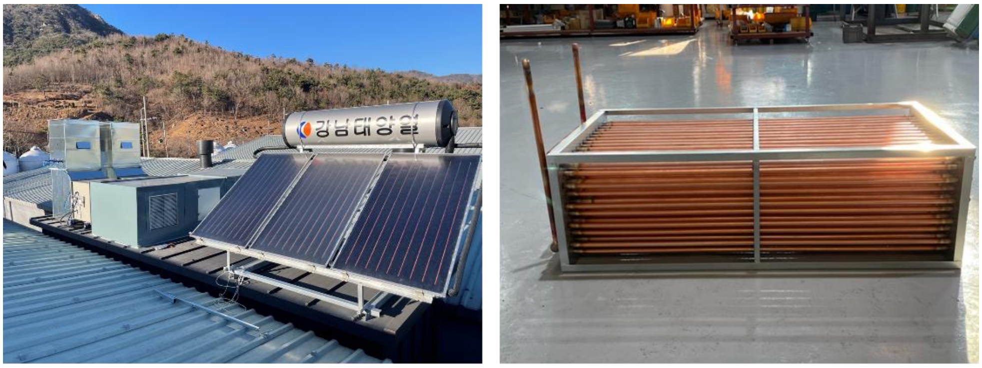
Figure 5-6 (a) Main body structure of the wet scrubber module and recirculation pump with pipe, (b) inside the wet scrubber with fillers and nozzle installed.

5.2.2.3. Solar heat module of ARVS

One of the advantages of the ARVS was that it can operate the high ventilation rate in winter season by reusing the thermal energy inside the piglet room. Harmful gases, dust, and complex odor inside the piglet room can be sufficiently removed by the wet scrubber, but if the ARVS is continuously used, humid air may accumulate excessively inside the piglet room. In particular, since carbon dioxide was difficult to remove using a wet scrubber, fresh air should be used even in winter. Because the external air was often required to control the carbon dioxide concentration, the solar heat module can be used to increase the inflow air temperature. It can also be used as an auxiliary heat source in extreme cold weather. Therefore, in this study, instead of directly using cold air, solar energy was used to increase ventilation rate and reduce energy costs.

The solar heat module was a method that used solar thermal energy as heating energy. The solar collector absorbs radiant energy from the sun. This thermal energy heats the water inside the heat storage tank and keeps the water at a high temperature. The stored hot water passed through pipes and coils in the heat exchanger module. The air passing through these heated coils gained thermal energy. It was important to select an appropriate capacity because the installation cost of a solar heating system increases rapidly as the scale increases.

In previous research, the heat transfer rate and thermal performance of the solar collector were evaluated. As a result of the module experiment and simulation analysis (in chapter 4), the solar heating system capacity suitable for the experimental piglet room was determined. Considering the size of the experimental piglet room, it was assumed that the internal temperature was 30°C, and when excluding the heat production of piglets, it was designed to cope with about 70% of the heating load. The size of the solar collector was 2010 × 3010 (mm), and the capacity of the heat storage tank was 400 L. The structure of the coil should be designed so that it does not resist airflow resistance. Therefore, it was designed so that the ratio of the resistance area to the cross-sectional area was 0.5 or less (Figure 5-7).



(a) Solar collector and solar water storage tank

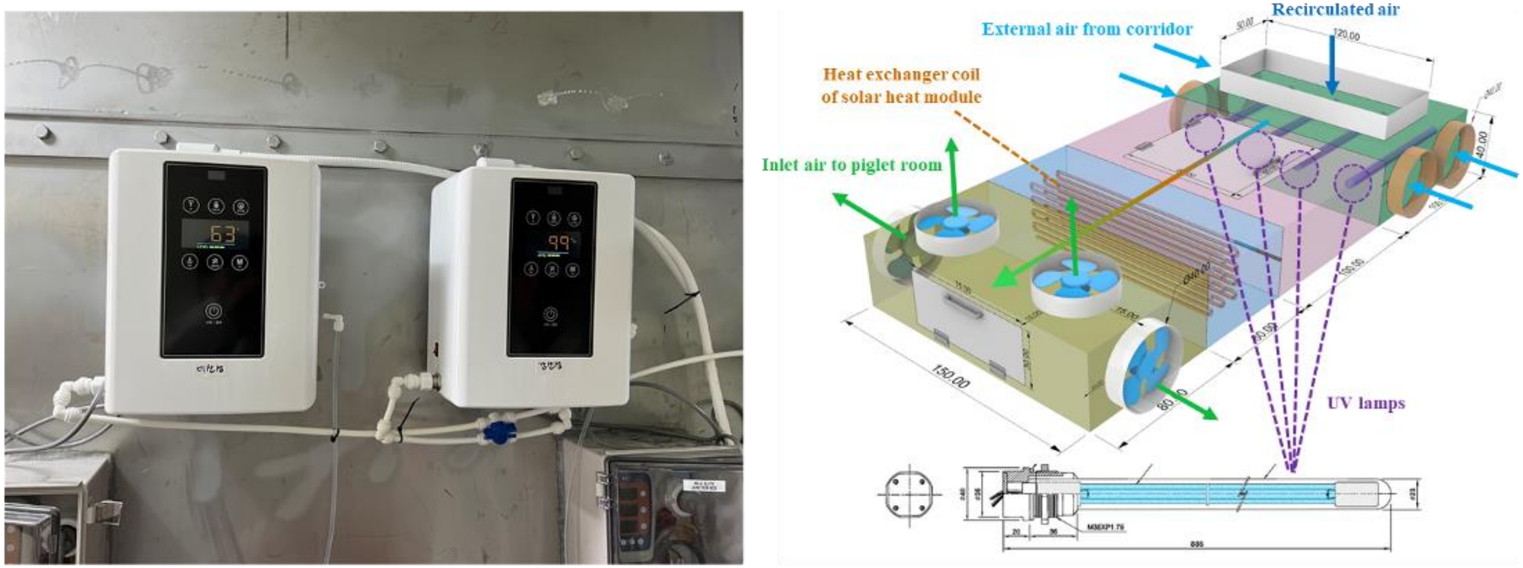
(b) Designed solar water coil for solar module

Figure 5-7(a) Solar collector and solar water storage tank of solar heat module installed on top of the wet scrubber container, (b) Solar coil of heat exchanger module designed considering the air resistance.

5.2.2.4. Other equipment of ARVS

Other equipment of the ARVS developed in this study included a circulating water treatment device of the wet scrubber module and the UV sterilization device (Figure 5-8). When designing the wet scrubber module, the physical removal method of harmful gas and odor was considered. However, it was necessary to effectively clean the air by changing a chemical removal method according to the type of target gas to be removed. In this study, ammonia gas and complex odor, which are representative harmful gases, were removed through the wet scrubber module. The pH concentration of the circulating water in the wet scrubber module should be maintained low to remove the ammonia gas. Melse and Ogink (2005) reported that the ammonia reduction efficiency of the acidic scrubbers was 69 to 99%, and the average odor reduction efficiency was 17 to 68% depending on the size, capacity, and scrubbing method of each scrubber. The removal efficiency of the wet scrubber module was about 40% when tap water was used, and the removal efficiency increased as the pH concentration decreased. It was able to sufficiently remove ammonia gas using acidic water. Moore Jr et al. (2018) used sodium bisulfate to acidify the solution, which was used as a scrubber solution to reduce ammonia. Therefore, in this study, a strongly acidic solution was used to remove ammonia as the first step. This solution was prepared by dissolving sodium bisulfate, and a pump and valve were installed to periodically inject the solution. In the second step, a solution for removing complex odors was used. Hansen et al. (2012) reported that reactive oxygen species were generated according the oxidation-reduction reaction of electrolyzed water, and organic acids and hydrogen sulfide, which were the causative substance of complex odors in pig house, can be removed. The acidic scrubber showed a high removal efficiency for ammonia because the ammonia gas has a high Henry constant with a low pH liquid. On the other hand, the odor removal efficiency using acidic scrubber was lower than ammonia removal efficiency because mainly odor contributed compounds such as fatty acids, H_2S, and VOCs are low solubility at low pH (Trabue et al., 2011). Therefore, in this study, slightly acidic electrolyzed water (SAEW) was used to remove complex odor in second step. A device for electrolyzing water and additives through an electrolyzer was installed and periodically supplied to the wet scrubber module.

A sterilizer was used to block and prevent livestock disease in the ARVS. The method of sterilizing ARVS piglet room was a total of three steps. First, the air was sterilized by an acidic solution and SAEW of circulating water. Next, UV lamps were installed in the circulating water tank for secondary sterilization. Finally, in the module where the cleaned air and external air were mixed, the air was sterilized just before entering the piglet room. When the wavelength is 253.7 nm, the DNA absorption rate is the highest, so the microbial sterilization effect is excellent (Kowalski, 2009). Song et al. (2009) sterilized the air with a filter, ozone, and photocatalyst to reduce the incidence of disease, dust, and odor in pig houses. Therefore, in this study, UV lamps with a wavelength of 254 nm were installed.



(a) Circulating water treatment device for injecting SAEW (b) UV sterilization and solar water heat exchange coil module

Figure 5-8 (a) SAEW device for circulating water in wet scrubber module, (b) Solar hot water coil and UV lamps in the heat exchanger module.

5.2.2.5. Real-time environmental data measurement and collection

The data measured in this study were divided into the data required for the operation algorithm of the ARVS and the data measured to analyze the internal environment and operation results. The most important factor in the operation of the ARVS was to properly maintain the rearing environment inside the piglet room. Therefore, the operation algorithm collected internal and external environmental data and used it for operation standards. Inside the piglet room, air temperature, relative humidity, carbon dioxide concentration, and ammonia concentration were measured in real time. The air temperature and relative humidity data outside the piglet room were collected and used as an operating algorithm together with the internal environmental data. In addition, the ventilation rate of the exhaust fan was measured to be used in algorithm. The pH of the circulating water was measured to check the circulating water and operate wet scrubber properly. Accordingly, the cycle of replacing the circulating water and the time of injecting the solutions were determined.

In this study, the validation experiment of winter season (Jan 6 to Feb 25, 2022) was conducted. The data analysis period was during the rearing period of ARVS piglet room. The sensors for collecting environmental data inside the piglet room were as follows (Figure 5-9). Six sensors (SH-VT260VS, Sohatech, South Korea) that measure internal air temperature, relative humidity, and carbon dioxide were installed uniformly at a height of 1.5 m inside the piglet room of ARVS as show in Figure 5-9. In addition, the same sensor was installed in the corridor, and the measured data was used as the operation algorithm data. A weather station (Watchdog 2900ET, Spectrum Technologies Inc., USA) was installed outside of the piglet room to measure external air temperature, relative humidity, rainfall, solar radiation, wind speed, and wind direction. In the case of CVS, the same sensors were installed in the center of the piglet room, and the data were collected during the same period. Because the ammonia sensor used a chemical contact node, the durability was not excellent inside the piglet room where the gas concentration, humidity, and dust concentration were high. Therefore, in this study, in order to measure the ammonia concentration, a complex gas meter (MultiRAE IR, RAE System, USA) was used to periodically measure the concentration inside and outside of piglet room. The airflow measuring probes (AFM-P series, AirflowTech, South Korea) were installed inside the inlet and outlet ducts to measure the ventilation rate of the ARVS. The total and static pressure were measured to calculated the airflow rate. The ventilation rates were calculated by converting the measured pressure into dynamic pressure through the differential pressure transmitters (DPT-R8, AirflowTech, South Korea). The data collected in real time was accumulated in the database through remote server. The data measured for 5 minutes was averaged and stored in the database, and this data could be checked on the web through the OneM2M server. OneM2M is an internet of things (IoT) service platform and was used for standardization in this study. The air temperature, relative humidity, carbon dioxide, and ammonia sensors were installed in the center of the CVS piglet room for relative comparison with ARVS piglet room.

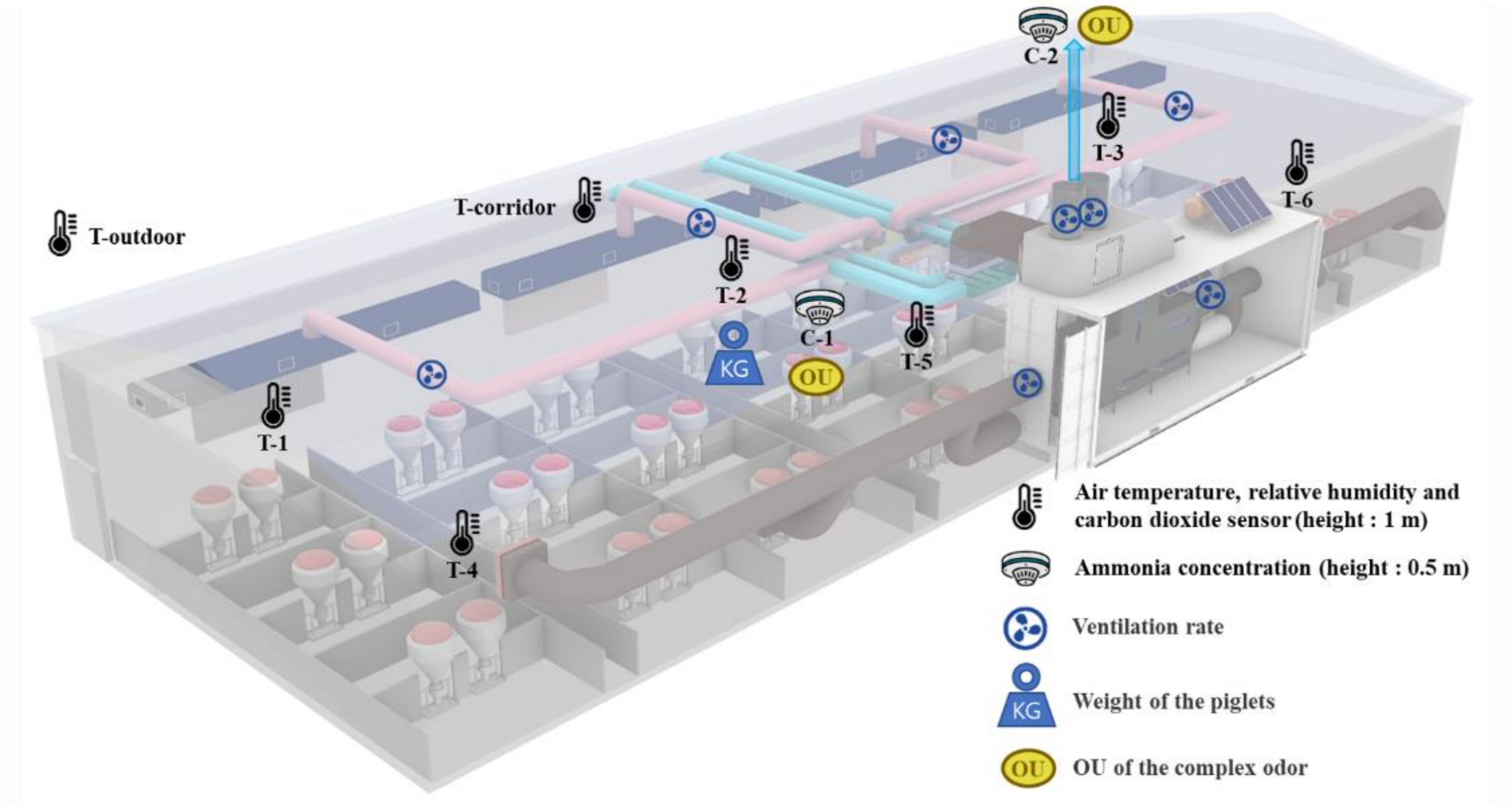


Figure 5-9 Sensor locations for measuring the internal environmental factors of piglet room applied ARVS.

5.2.2.6. Data collection through field experiment

In this study, data that could not be collected in real time was directly measured weekly. Factors directly collected through field experiments included complex odors from the inside and outside of the piglet room, the weight of pigs, and the concentration of dust. To evaluate the operating results of the ARVS, pig weight data were collected just before moving to the growing pig room. In addition, in relation to respiratory diseases of pigs and workers, the concentration of dust inside the piglet room was measured. Odor samples were collected and sensory evaluation was conducted to evaluate the effect of reducing odor emission from the piglet room.

The monitoring of the dust was measured individually by classification based on the aerodynamic diameter of the dust particles. The dust for measurement was total suspended particles (TSP) and particulate matter 10 (PM10) used in the atmospheric environment field. TSP refers to all particles suspended in the air, and PM10 refers to particles with an aerodynamic diameter of 10 μm or less (US EPA, 2001). Aerosol spectrometer (Aerosol spectrometer, GRIMM Aerosol Technik GmbH& Co., Germany) was used as equipment to measure the dust concentration. The concentration according to the particle diameter of the air was measured in real time through laser diffraction, and the measurement sensitivity was 0.001 mg. The dust concentration was measured in the center of the piglet room and 1.5 m in front of the outlet. As shown in the Figure 5-10 (a), dust was measured at the same time as when the odor was sampled. In the case of piglets' weight, it was measured after rearing was finished. When the piglets reached the age of 10 weeks, they moved to a growing pig room. Piglets were weighed on a portable scale while moving. Since there was a limit to measuring the weight of all piglets, the weight of the piglets was measured by repeating the weights of 3-4 piglets and averaging them (Figure 5-10 (b)).


(a) Aerosol spectrometer for measuring dust

(b) Portable weighing scales for piglets

Figure 5-10 (a) Aerosol spectrometer for measuring of dust (TSP, PM10) inside the piglet room, (b) weighing data collection using the portable scale installed in the corridor of piglet room.

Complex odor was evaluated through the air dilution olfactory method. In this study, for air dilution olfactory method, a portable odor sampling device (Odor collector, Odotech, South Korea) was used to collect the air inside the piglet room. Also, it was sampled from the outlet duct to evaluate the odor emission. Internal and external air can be sampled by installing the portable odor collector and making negative pressure inside the device. Samples for the evaluation of complex odors were prepared by collecting 10 L of air in the sampling bags. The concentration of the complex odor was evaluated according to the odor process test method (ES 09301) for samples. The air dilution olfactory experiments were conducted within 24 hours to maintain the state of raw materials. To use the diluted sample required for olfactory experiments, the odorless air samples that did not contain a livestock odor were made. Odorless air samples were made as shown in Figure 5-11 using an odorless air generator. The odorless air generator made the samples by removing moisture from the air using silica gel and removing odor components from the air using activated carbon. According to the dilution factor (10, 30, 100, 300 times) odor samples were provided to 5 panelists for evaluation. After the first evaluation, the panelists were given sufficient rest time, and then the next evaluation was conducted. For one odor sample, the geometric mean value of the remaining values excluding the maximum and minimum values among the data measured from each panel was calculated as the livestock odor concentration.

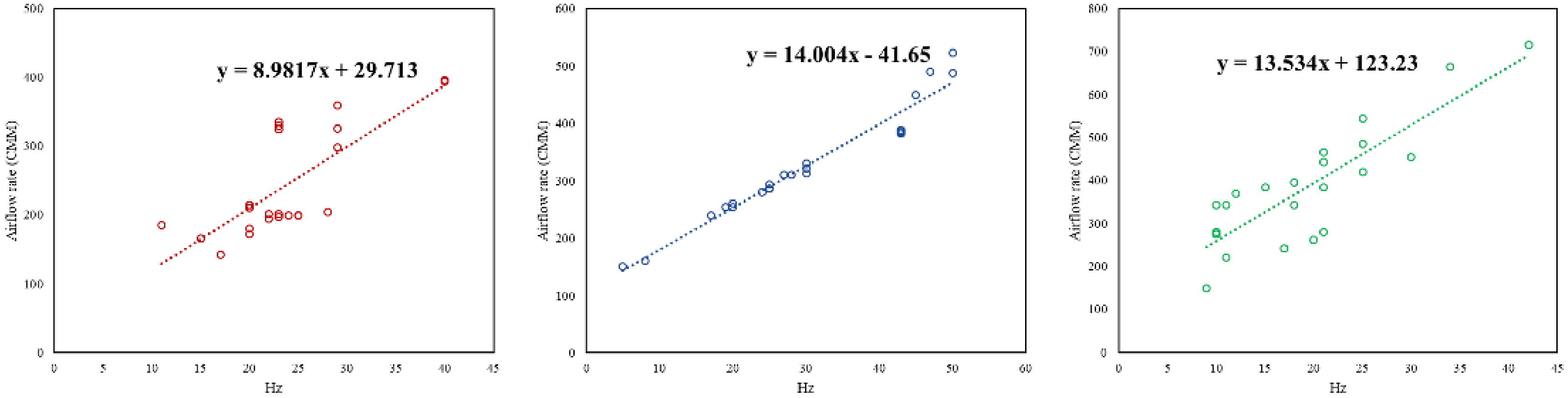
(a) Odorless air generator **(b) Odor samples for air dilution olfactory experiment**

Figure 5-11 (a) odorless air generator to make the sample of air dilution olfactory experiment, (b) odor samples according to the dilution rates.

5.2.2.7. Automatically control equipment and operation algorithm

In this study, for automatic control of ARVS, control equipment and algorithms were connected. The control standard of ARVS was the internal environment, and the control target was exhaust fans and EAMR. Therefore, the ventilation rate and the EAMR were quantitatively controlled according to the internal environmental conditions. The control devices for system control were exhaust fans of piglet room, external air mixing fans, and inlet fans. Each fan was controlled using the inverters, and if the control value of 0-60 Hz was determined in the algorithm, the electronic power was applied linearly to control the revolutions per minute (RPM) of the fans. However, since ARVS was a configuration of a semi-closed loop duct ventilation system, the control values should be corrected with the ventilation rates measured in the field experiment. The control reference frequency and the actual airflow rate were tested, and then the regression equations of the control value to be used in the algorithm were calculated (Figure 5-12).

The automatically control algorithm was developed based on the state machine. The state machine algorithm used the Java platform of OpenJDK (Oracle Co., USA), which is an open source software. Apache Tomcat (Tomcat 9, Apache Software Foundation), which provides a Java environment that can be connected to web server, was used to run the algorithm based on the data measured in real time through the server. The source code to run the algorithm was developed using STS (Spring Tools 4, VMware, Inc). The basic configuration of the state machine algorithm was shown in the Figure 5-13.



(a) Exhaust fan of piglet room (b) Inlet fan (c) External air mixing fan

Figure 5-12 Measurement results and regression results of inverter frequency for quantitative control of ARVS.

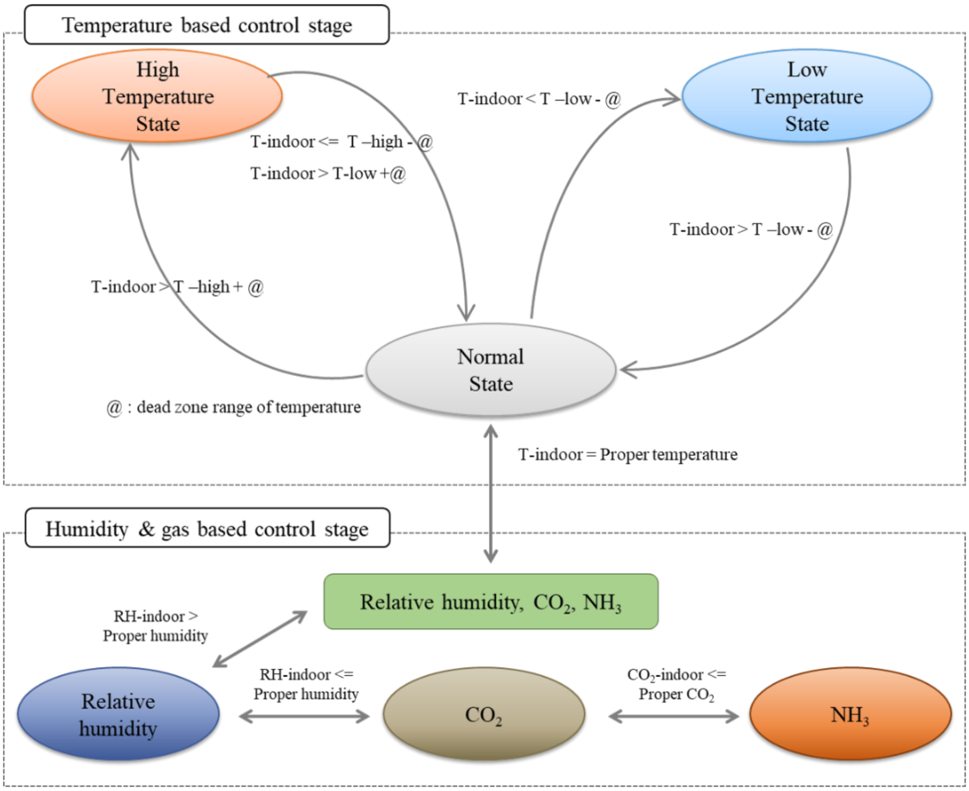


Figure 5-13 Schematic diagram and control sequence of state machine algorithm.

First, the state was determined so that the temperature, which was the most important environmental factor in the piglet room, was properly maintained. As the temperature rises or falls, the algorithm transitions from the normal state to another state. At this state, the algorithm can control the ventilation rate and the EAMR according to the external air temperature to control the proper temperature inside the piglet room. When the appropriate temperature is reached, algorithm can sequentially control to maintain the humidity and gas concentration properly. If the temperature changes significantly on the way, when the temperature state changes again, the ventilation rate and EAMR are controlled based on the temperature. If the temperature state does not change, control proceeds until all environmental conditions are satisfied. If the relative humidity and gas condition are not continuously changed to an appropriate level, all air can be exhausted to replace the internal air. After that, the state machine algorithm starts controlling again from the initial state. When all environmental conditions are maintained at an appropriate level, the control is set to a constant value.

The method for calculating the control value in the state machine algorithm was as shown in Equation 5-1 and 5-2. These equations were developed based on the measured data of internal environmental factors and ventilation rates in this study. When the external air temperature was higher than 15°C, the control value was determined according to the Equation 5-1. The value of a_1 was a coefficient for controlling the ventilation fan in consideration of the internal and external temperature deviation. For a_1, 50 for the inlet fan and exhaust fan of piglet room was used. 30 for the external air mixing fan were used. Here, the value of the constant a_1 was calculated based on the air flow value measured in the field. When the external air temperature was lower than 15°C, the control value of the fan was calculated according to the Equation 5-2. The value of a_2 and a_3 were coefficients considering the temperature deviation inside and outside the piglet room and the piglet's thermal demands. Also, a_4 was a correction coefficient for the internal and external temperature deviation. For all the fans, the a_2 value of 3.1 was applied equally. In the case of a_3, 45 was used for the inlet fan and exhaust fan of piglet room and 12 was used for the external air mixing fan. Since the a_1-a_4 can be changed according to the farm size, region of the pig farm, age of the pigs, and fan performance, coefficients should be recalculated using experimental data when applying to other system. It is possible to make the table using these equations for calculating the exact control values. In this study, using 20 × 20 table with the measured data set, the equations were calculated by calculating the linear regression equation.

$$CV = a_1 - (T_{in} - T_{out}) \qquad \text{Equation 5-1}$$

$$CV = \frac{(T_{in}-T_{out})^{a_3}}{(T_{low}-T_{out})^{a_2}} \times a_3 - (T_{in} - T_{out}) \times a_4 \qquad \text{Equation 5-2}$$

Where, *CV* is the control value of inverter (Hz), a_1-a_4 are coefficients of automatically control algorithm, T_{in} is the average air temperature inside the piglet room (°C), T_{out} is the external air temperature (°C), T_{low} is the low temperature standards according to the piglet age (°C). In this experimental farm, 4-weeks piglets were operated at 30°C and lowered by 1°C every week.

5.2.2.8. Evaluation of stress index of piglets and disease contamination

When the rearing environment of piglets were maintained at an appropriate level, it can be expected that the productivity of piglets was improved. Whether the piglet's rearing environment were properly maintained can be evaluated based on internal environmental data. However, based on these results, it was difficult to quantitatively judge that the piglets' condition improved. If the rearing environment of the piglets improves, the stress on the piglets can also be reduced. Therefore, in this study, the stress index was measured in order to quantitatively evaluate that the environment of piglets was improved (Figure 5-14 (a)). It was also evaluated how immune the piglets were from the livestock disease. To analyze the stress and immunity of piglets, saliva from piglets was sampled, and the relationship between the measured amount of endocrine secretion and stress was analyzed. Cortisol and Immunoglobulin A (IgA) were used to detect stress and immunity based on piglet saliva (Roque et al., 2018; Yonezawa et al., 2012). The amount of cortisol detected in saliva tends to increase as the stress of piglets increases. In the case of IgA, as an index for evaluating immunity, it was possible to evaluate the number of internal antibodies formed in piglets. After sampling the saliva of the piglets, the piglet's stress was measured through enzyme-linked immunosorbent assay (ELISA).

The saliva collection of piglets was conducted just before the piglets moved to the growing house. The equipment used is as follows. 96-well plate (Nalge Nunc International, NY, USA), 20x PBS and 20x PBS Tween-20 (HPBS-2010-74T, HANLAB, Cheongju, Korea), bovine serum albumin (BSA, Sigma Aldrich, St.Louis, USA), 3,3′,5,5′-Tetramethylbenzidine (TMB, Thermo Fisher Scientific, Massachusetts, USA), horseradish peroxidase (HRP) conjugation kit, goat anti-pig

IgA (Abcam, Cambridge, UK), ethanol 99.5% (Samchun chemicals, Seoul, Korea), goat anti-pig immunoglobulin A (IgA, BIO RAD, California, USA), purified pig IgA (Alpha Diagnostic international, Texas, USA), cortisol–BSA (Fitzgerald, Massachusetts, USA), cortisol-HRP (LSBio, Seattle, USA) was used for quantification of biomarkers in piglet saliva using enzyme-linked immunosorbent assay (ELISA). The ELISA plates were examined by a Tunable Microplate Reader (Versamax, Molecular devices, California, USA), and the absorbance value was determined at the wavelength of 450 nm. Cortisol in saliva was measured by competition enzyme-linked immunosorbent assay (ELISA) method and IgA in saliva was targeted by sandwich ELISA method. For the preparation of saliva sample, Saliva from around 20 piglets in 10 pens of ARVS and CVS piglet rooms were collected using hanging ropes for 1 hour. Collected saliva was centrifuged for 3 minutes at 13000 rpm. Upper solution was collected and stored at 4°C. To minimize side enzymatic reaction, all the saliva samples were measured within 12 hours after collection. The procedure of competition ELISA is as follows.

Step 1) BSA-cortisol was immobilized on the surface of microplate wells incubated for 1 hour at 24°C.

Step 2) Prepared saliva samples (20 μL) were mixed with HRP-anti-cortisol (1 $\mu g \cdot mL^{-1}$, 140 μL) solution and incubated for 1 hour at 24°C.

Step 3) After washing microplate five times with PBS, 50 μL of the saliva-antibody mixture were added to the BSA-cortisol coated microplate wells and incubated 1 hour at 24°C.

Step 4) TMB solution containing 0.02% H2O2 (50 μL) was added after final washing step (5X with PBS (0.01 M) and 5X with PBS-T (0.01 M)). After reaction for 3 minutes at room temperature, H2SO4 (3 M, 50 μL) solution was added as stopping reaction reagent.

To quantify concentrations of biomarkers in salivary sample, measured absorbance depends on the concentration of target materials were plotted. To get standard fitting curves of each biomarker, plotted values were fitted by using 4-parameter logistics equation (Equation. 5-3).

$$y = D + \frac{A-D}{1+(\frac{x}{C})^B} \qquad \text{Equation 5-3}$$

Where, x is concentration of the target sample and y is absorbance value. The minimum absorbance value that we can obtain is A. Maximum saturated value on the curve is D. C represent the point of halfway between A and D. And B is Hill's slope of the curve which related to the steepness of the curve at C.

Concentration of the biomarkers in unknown salivary sample can be inferred from measured absorbance value of the ELISA by using fitted curves. For cortisol concentration evaluation, 20 μL of varied concentrations of cortisol (0, 0.05, 0.1, 0.5, 1, 5, 10, 50 ng·mL^{-1}) were mixed with HRP-anti-cortisol (1 μg·mL^{-1}, 140 μL) (instead of step 2). Mixed solutions were incubated for 1 hour at 24°C. TMB solution containing 0.02% H2O2 (50 μL) was added after washing (5X with PBS (0.01 M) and 5X with PBS-T (0.01 M)). After incubation for 3 minutes at room temperature, H2SO4 (3 M, 50 μL) solution was added as stopping reaction reagent. The procedure of the Sandwich ELISA is as follows.

Step 1) Wells of 96 well-plates were coated with 50 μL of IgA capture antibody targeting each biomarker (1 μg·mL^{-1}, in 0.01 M PBS, pH 7.2) and incubated for 2 hours at 24°C.

Step 2) After washing three times with PBS and three times with PBS-T (0.05%

Tween 20 in 0.01 M PBS), 100 μL of blocking agent solution, 3% (w/v) bovine serum albumin (BSA) resolved in PBS was added and incubated for 1.5 hour to block non-specific binding sites. The wells were washed three times with PBS (0.01 M) and three times with PBS-T (0.01 M).

Step 3) Prepared saliva samples were 1000 times diluted and 50 μL of diluted saliva were added and incubated for 1.5 hour at 24°C.

Step 4) After washing wells with three times with PBS and three times with PBS-T, HRP-conjugated IgA detection antibody (1 $\mu g \cdot mL^{-1}$, in 0.01 M PBS, pH 7.2, 50 μL) were added and incubated for 1.5 hour at 24°C.

Step 5) After a final wash (five times with PBS and five times with PBS-T), TMB solution containing 0.02% H202 (50 μL) was added to each well. Following incubation for 3 minutes at room temperature, H2SO4 (3M, 50 μL) solution was added as stopping reaction reagent.

For IgA concentration evaluation, every process is same as Sandwich ELISA, except the step 3. Instead of adding saliva solution, 50 μL of varied concentrations of IgA (0, 1, 5, 10, 50, 100, 500, 1000, 5000, 10000 $ng \cdot mL^{-1}$) were added in each well. After incubating 1.5 hour at 24°C, experimental method follows the step 4 and 5. Every procedure was repeated 3 times to get the standard deviation of measurement.

Disease contamination analysis was conducted to evaluate whether disease was prevented (Figure 5-14 (b)). Therefore, porcine respiratory disease virus and microbiome analysis were conducted for evaluation of ARVS effect. A total of 4 important pathogens virus were diagnosed and tested. Porcine reproductive and respiratory syndrome virus (PRRSV), porcine circovirus type 2 (PCV-2), swine influenza virus (SIV), and porcine parvovirus (PPV) are major viruses that affect pigs. Porcine circovirus type 2 (PCV-2) infection inhibits the growth of pigs and causes post-weaning multi-systemic wasting syndrome. Swine influenza viruses (SIV) is caused by stress caused by weather conditions, infection by lungworms, transmission by humans, and birds. PPV is the causative agent of pig disease. Antigen polymerase chain reaction (PCR) tests for PPRSV, PCV-2, SIV, and PPV were conducted in the nasal samples of piglets. Nasal secretion samples from piglets were collected and used for testing. DNA and RNA were extracted from the samples using the Patho Gene-spinTM DNA/RNA Extraction Kit (iNtRON Biotechnology, South Korea). Next, cDNA was synthesized using the QuantiTect Reverse Transcription Kit (QIA GEN, Germany). DNA and cDNA were used as template strands, and PCR was conducted using AccuPower PCR PreMix (Bioneer, South Korea) using SimpliAmp Thermal Cycler (Applied Biosystems, USA).

Contamination of disease in piglet room was evaluated based on environmental samples, such as door, feeder, floor, wall, and corridor. PRRSV and PCV-2 of respiratory viruses were analyzed, and PCR tests were conducted for diarrhea-causing viruses porcine epidemic diarrhea virus (PEDV), transmissible gasoroenteritis virus (TGEV), and Rotavirus. The PCR test method was the same as the previous nasal sample analysis method.

Pig intestinal microbiome and nasal microbiome were tested and analyzed. For this purpose, feces and nasal samples from piglets were collected. The sample was extracted and PCR amplified using a Bacterial 16S rRNA gene V4 region (515F-806R) fusion primer. After PCR clean-up was conducted for about 12 minutes, concentrations were quantified and pooled. 20 µl of the library was loaded on the cartridge, the flow cell was combined, and then put into the sequencer. Indices such as alpha diversity and beta diversity were calculated for microbial community analysis (Table 5-1).


(a) Rope installed in the center of the piglet zone

(b) A piglet's nasal collection

Figure 5-14 (a) Saliva sampling method from ropes bitten by piglets, (b) nasal sampling for analysis of respiratory diseases in piglets.

Table 5-1 Meaning of alpha diversity index for intestinal microbiome analysis.

Alpha diversity	Mean
Chaol	Estimating the richness of a species based on the information of the discovered species, considering the possibility that undiscovered or unseen species remain in the sample
ACE	Estimating the richness of a species based on the information of the discovered species, considering the possibility that undiscovered or unseen species remain in the sample
Shannon	Estimates of the diversity of species present in the sample (the higher the value, the greater the diversity)
Simson	Concentration of species found in the sample (values from 0 to 1, the higher the value, the lower the diversity)

5.2.2.9. Energy recycling rate inside the piglet room

The piglet room with ARVS had the advantage of reusing the energy inside the piglet room. It was necessary to calculate the energy recycling rate (ERR) in order to quantitatively evaluate the temperature compensation effect of ARVS. The ERR can be calculated as the ratio of the thermal energy of the air flowing into the piglet room to the thermal energy of the air exhausted from the piglet room. Thermal energy can change depending on various factors such as heat loss in the duct, heat exchange with circulating water inside the wet scrubber, and the EAMR. Therefore, in this study, the ERR of the entire ARVS system was defined as the ratio between total amount of thermal energy exhausted and total amount of input energy. The equation for calculating the calorie and ERR were Equation 5-4 and 5-5.

$$Q = cm\Delta T \qquad \text{Equation 5-4}$$

$$\text{ERR (Energy Recycling Rate)} = \frac{Q_{in}}{Q_{out}} \times 100 \qquad \text{Equation 5-5}$$

Where, Q is the calorie of the air (cal), c is the specific heat of air (cal·kg^{-1}·°C^{-1}), m is the mass of air (kg), ΔT is difference of air temperature (°C). Here, the mass of air and difference of air temperature can be obtained from the ventilation rate and measure data of air temperature of the piglet room. Also, since the specific heat of air varies with the change in temperature, it was calculated considering the physical properties of air.

5.3. Results and discussions

5.3.1. Development of automatically control algorithm

5.3.1.1. Application of calibration equation of algorithm

In the initial algorithm, the method of controlling the ventilation rate and EAMR was applied as a constant value for each operating condition. It had to be corrected in consideration of the heat loss and fan airflow loss that occur during actual operation. Since it was initially applied as a constant as shown in the Figure 5-15, it was controlled to same values according to the temperature condition of the state machine algorithm. In the beginning, since the ventilation rate and the EAMR were controlled by a constant value, the same control standard was repeated as the state transition occurred according to the temperature change. Accordingly, the initial temperature was started at 27.8℃, and the internal temperature deviation was continuously occurred. When the temperature was lowered below the reference temperature, a command was input to reduce the ventilation rate and the EAMR. The internal air temperature increased as the ventilation rate decreased. When the temperature reached the proper state, the ventilation rate and the EAMR increased to predetermined value, and the temperature decreased again accordingly. When such control was repeated, the internal environment could be less stable. Accordingly, the revised algorithm was applied considering the correction factor in the algorithm. The algorithm was calibrated according to the temperature difference between the inside and outside, so that the ventilation rate and EAMR were controlled in real-time. After the algorithm improvement, the internal air temperature remained stable.

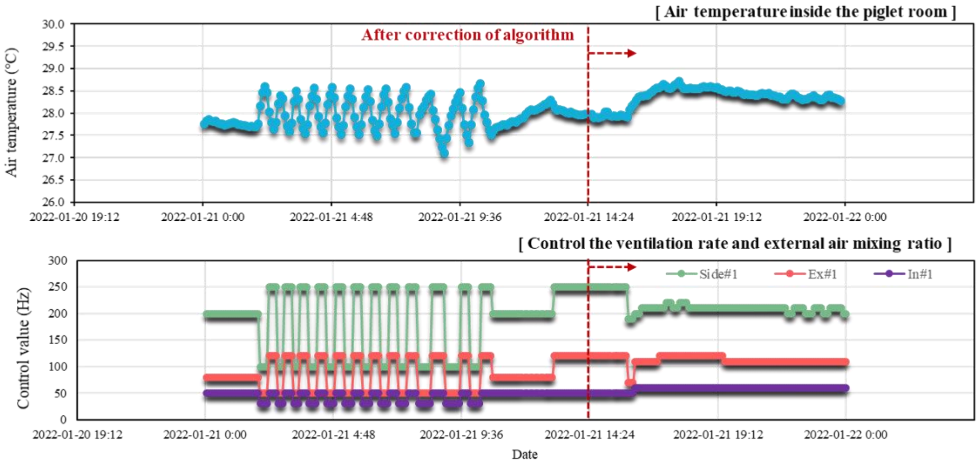
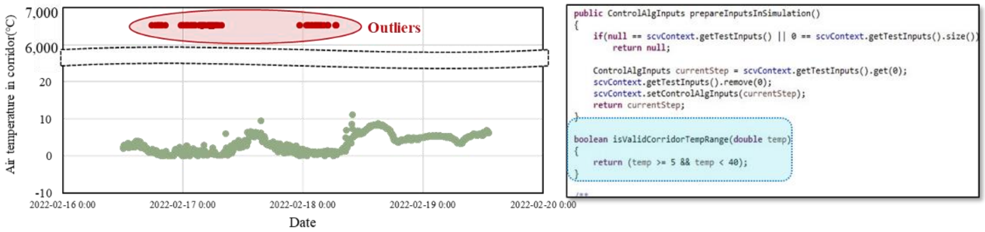


Figure 5-15 Result of air temperature controlled by constant value and calibrated algorithm.

5.3.1.2. Removal of outliers in measurement data for stable algorithm operation

The algorithm developed in this study was operated based on the internally environmental data. For the stability of the algorithm, it was essential to have the reliability of the measured values of the sensor. The environment inside the piglet room was not a general environment, but it could be a high temperature and high humidity. Also, because it could be constantly exposed to dust and harmful gases, the accuracy of the sensors can decrease. When an error occurred in the measured value of the sensor, the algorithm was erroneously controlled because the control standard can be deviated. In addition, since correction according to the data value was included, an inappropriate value may be set and a value that did not exist in the control range could be transmitted. In this case, accurate control became impossible and an error message occurred. In this study, outliers of measured data were filtered out and only values within the normal range were used in the algorithm. The filtered data were treated as null values and removed. Examples of removing outliers and data codes for removing outliers are shown in the Figure 5-16.



```
public ControlAlgInputs prepareInputsInSimulation()
{
    if(null == scvContext.getTestInputs() || 0 == scvContext.getTestInputs().size()
        return null;

    ControlAlgInputs currentStep = scvContext.getTestInputs().get(0);
    scvContext.getTestInputs().remove(0);
    scvContext.setControlAlgInputs(currentStep);
    return currentStep;
}

boolean isValidCorridorTempRange(double temp)
{
    return (temp >= 5 && temp < 40);
}

/**
```

Figure 5-16 Result of measurement data with the outliers and source code that removes outliers.

5.3.2. Results of measured ventilation rate

The results of the ventilation rate in ARVS piglet room and CVS piglet room during the whole period were shown in the Figure 5-17. During this time, the external air temperature was 5-10℃ during the day and sometimes dropped below −5℃ at night. Accordingly, the ventilation rate in the CVS piglet room was kept very low because the internal temperature could be lowered. Also, the ventilation rate was increased by 0.2 min^{-1} for about 3 days from Jan 25th. This was because the heat production of piglets was high and the temperature standard was 25℃. After leaving the CVS piglet room for about 5 days, 20-day-old piglets re-entered on Feb 4th. After that, it was continuously operated at a ventilation rate of 0.15 min^{-1}. The CVS was operated according to the settings of the farm workers. Therefore, constant ventilation rates were maintained regardless of the external temperature and the internal temperature. The operating ventilation rate was 0.12 min^{-1} on average and 0.2 min^{-1} on the maximum. A typical minimum ventilation rate of piglet was operated during the rearing period. On the other hand, in the ARVS system, the ventilation rate was changed in real time according to the internal and external environmental conditions. In particular, since the internal heat energy can be reused, the ventilation rate of ARVS could be operated higher than that of CVS. The ventilation rate of the ARVS piglet room was temporarily operated high. This was the farm's own operation to ventilate the piglet room before the piglets came in. As a result of the ARVS piglet room, the ventilation rate was maintained at 0.2-0.3 min^{-1} when there were young piglets (4-5 weeks). This was controlled by a constant value in algorithm, and the ventilation rates were set based on the values. After the algorithm was improved, it was controlled based on internal and external environmental data and temperature standards by week of age. Because the average ventilation rate was 0.4 min^{-1}, it was operated about 4 times higher than the minimum ventilation rate. The high ventilation rate was continuously maintained despite the winter season. The total ventilation rate of the ARVS piglet room was operated at more than 0.7 min^{-1}. Compare to the CVS piglet room, the ventilation rate of ARVS piglet room was operated 4.4 times on average, and the maximum difference was 13.4 times. These ventilation operations had a positive effect on the temperature, relative humidity, and gas conditions.

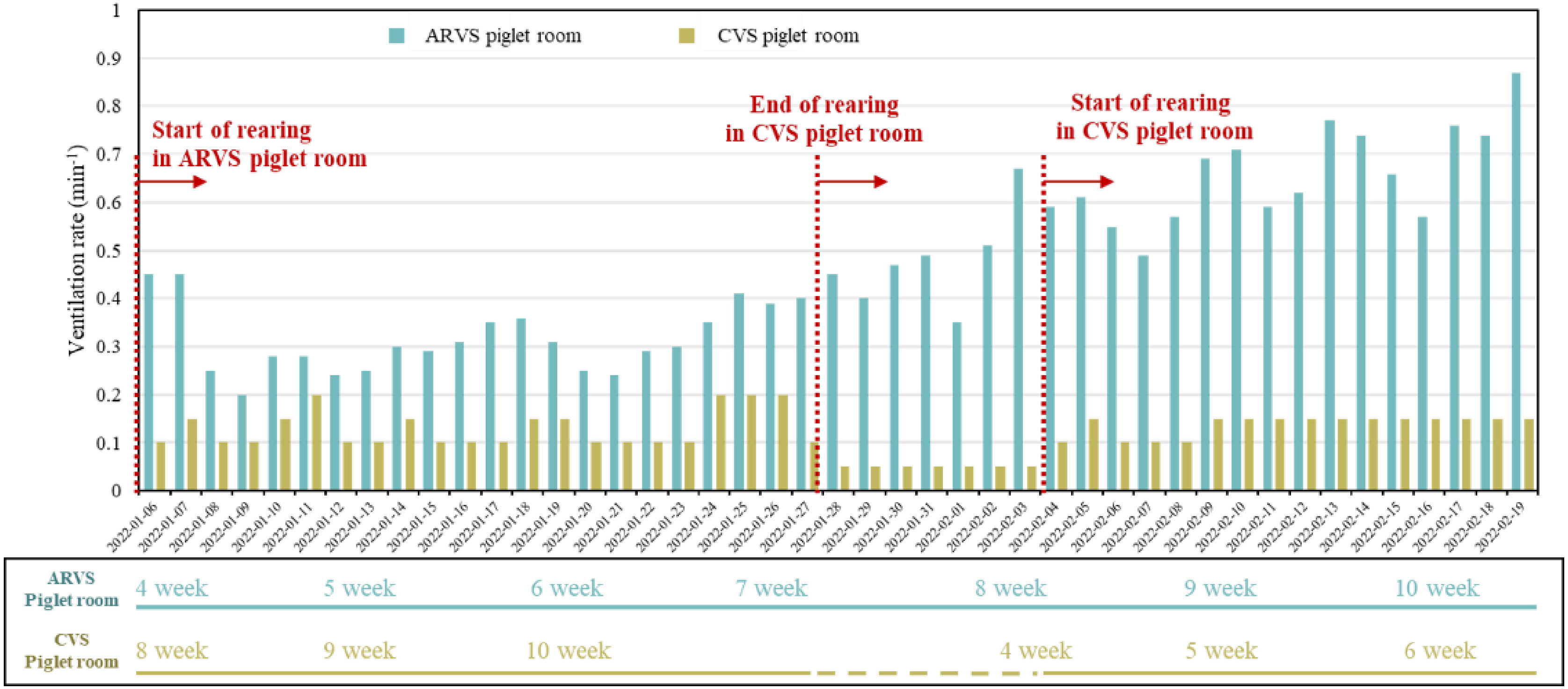


Figure 5-17 Results of the ventilation rate of the ARVS piglet room and CVS piglet room.

5.3.3. Results of measured air temperature and relative humidity of ARVS piglet room and CVS piglet room

The Figure 5-18 shows the internal air temperature and relative humidity in the ARVS piglet room and outdoor during the whole period. The internal air temperature control standard was initially started at 30°C and was lowered by 1°C every week. It was considered that operation according to the temperature standard was performed properly except when controlled by constant value. The temperature distribution was maintained within the range by setting it to 0.5°C as the deviation of the target temperature. As a result of correcting the control value and improving the algorithm using the correction coefficient, it was confirmed that the control was performed within the appropriate temperature range.

During the rearing period, the day and night temperature deviation of the external temperature was about 9°C, and the minimum temperature was measured to be −2°C. However, the temperature inside the pig house was maintained within an appropriate temperature range even under the continuous cold outside air condition. This was because it was possible to minimize the inflow of cold air from the outdoor while reusing the thermal energy inside piglet room. The relative humidity inside the piglet room was maintained at an appropriate level from about 50% at the beginning to about 70% at the end. After the piglets reached 7 weeks of age, water cleaning was conducted once a week. As a result, there were days when the relative humidity was temporarily high. On the other hand, the external relative humidity showed a very large scatter. This was because the target area was in the mountains, so the humid condition of outdoor frequently occurred. Also, relative humidity can be affected by temperature. Therefore, as the temperature rapidly decreased, the relative humidity was measured to be high. In spite of this humidity change, the internal relative humidity was maintained appropriately.

The internal air temperature and relative humidity was analyzed in consideration of the similar weather condition although not the same rearing conditions because the two experimental piglet room had a difference of about 20 days in age. The temperature and relative humidity of the CVS piglet room are shown in Figure 5-19. In the first week of January, the internal air temperature was measured at about 25°C, which was 2°C lower than the target temperature (27°C). When the piglets were actively gaining weight, the temperature could not be controlled and low temperature stress could occur. On the other hand, as the age of 10 weeks, the temperature should be lowered, but rather an increase of temperature was found. If the temperature is not controlled properly at this time, the piglets could face a sudden temperature change in the growing and finishing pig room. Therefore, at the age of 10 weeks of piglets, the temperature of 25°C should be well maintained. In addition, the relative humidity was maintained at about 75% despite the high temperature inside the piglet room. If the internal temperature was assumed to be the target temperature of 25°C, the relative humidity was calculated as about 100%. This was more than the optimum humidity condition. In the empty room without piglets, the air temperature was low and the relative humidity increased due to water cleaning. Around February 2, rearing of piglets started. The internal air temperature was measured at 27°C, and the temperature gradually decreased for a week. The radiator heating system was installed in the CVS piglet room. The radiator was operated during winter season, but the temperature inside the piglet room was very low. At this time, the outdoor air temperature was very cold, about 2°C. To prevent such low temperature stress, minimum ventilation rate (0.1 min^{-1}) was operated, but the temperature control failed. In addition, even with the increase of age, there was a difficulty in maintaining the target temperature of winter season in the CVS piglet room. Calculating the ratio of the time in ARVS piglet room and CVS piglet room when the air temperature exceeded the piglets' thermal demand was 1.13% and 74.19%, respectively. In particular, after 8 weeks of age, which was the most important period for piglets to gain weight, the air temperature inside the CVS piglet room was often exceeded the piglets' thermal demand.

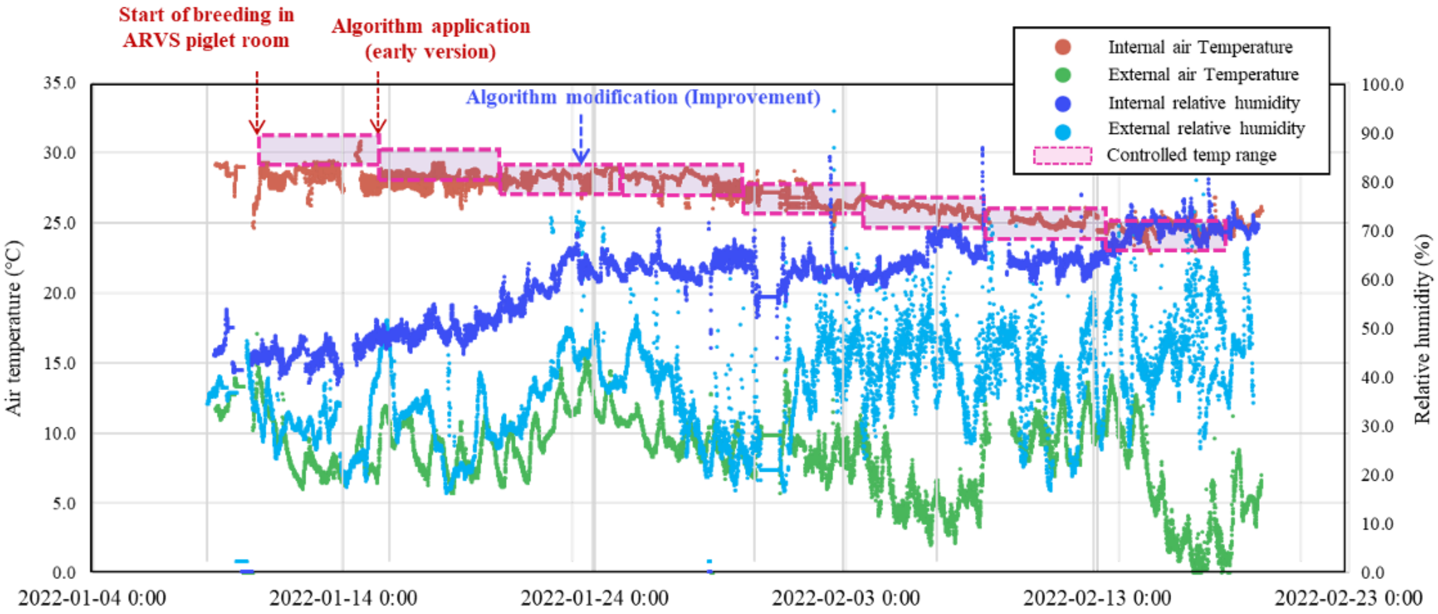


Figure 5-18 Results of the air temperature and relative humidity of the ARVS piglet room.

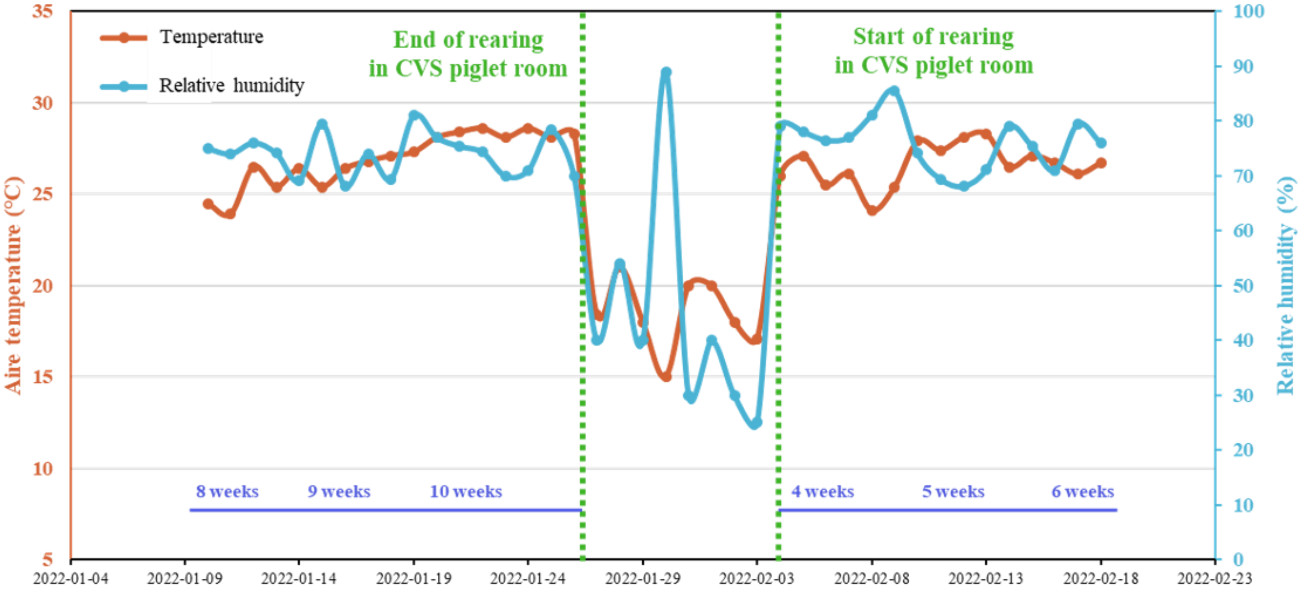


Figure 5-19 Results of the measured air temperature and relative humidity inside the CVS piglet room.

5.3.4. Calculation results of the internal energy recycling rate of the ARVS

In winter season, the ventilation rate of ARVS piglet room was high, and the internal air temperature was maintained properly compared to the CVS piglet room. The reason was that ARVS reused the thermal energy inside the piglet room. When the EAMR was high, the ERR was calculated to be low because a lot of heat energy inside the piglet room was exhausted. In the Figure 5-20, the ERR was calculated to be as low as about 20% when the EAMR was high. The reason for this was that the EAMR was increased by the algorithm when the internal air temperature increased during daytime and the relative humidity and gas was high. When the algorithm ordered to reduce the EAMR to maintain the proper temperature, the ERR increased again. The average ERR per a day was about 73%, indicating that the thermal energy reuse effect of ARVS was good. When the temperature was increased by solar radiation during the daytime, the ERR exceeded 100%. As a result of the operation of the algorithm, the EAMR did not change significantly because the temperature difference between the inside and outside of piglet room was not large during the daytime. At night time, the external air temperature was about 5°C. Accordingly, the algorithm frequently changed the EAMR to control the internal air temperature, resulting in ERR fluctuations as shown in Figure 5-20.

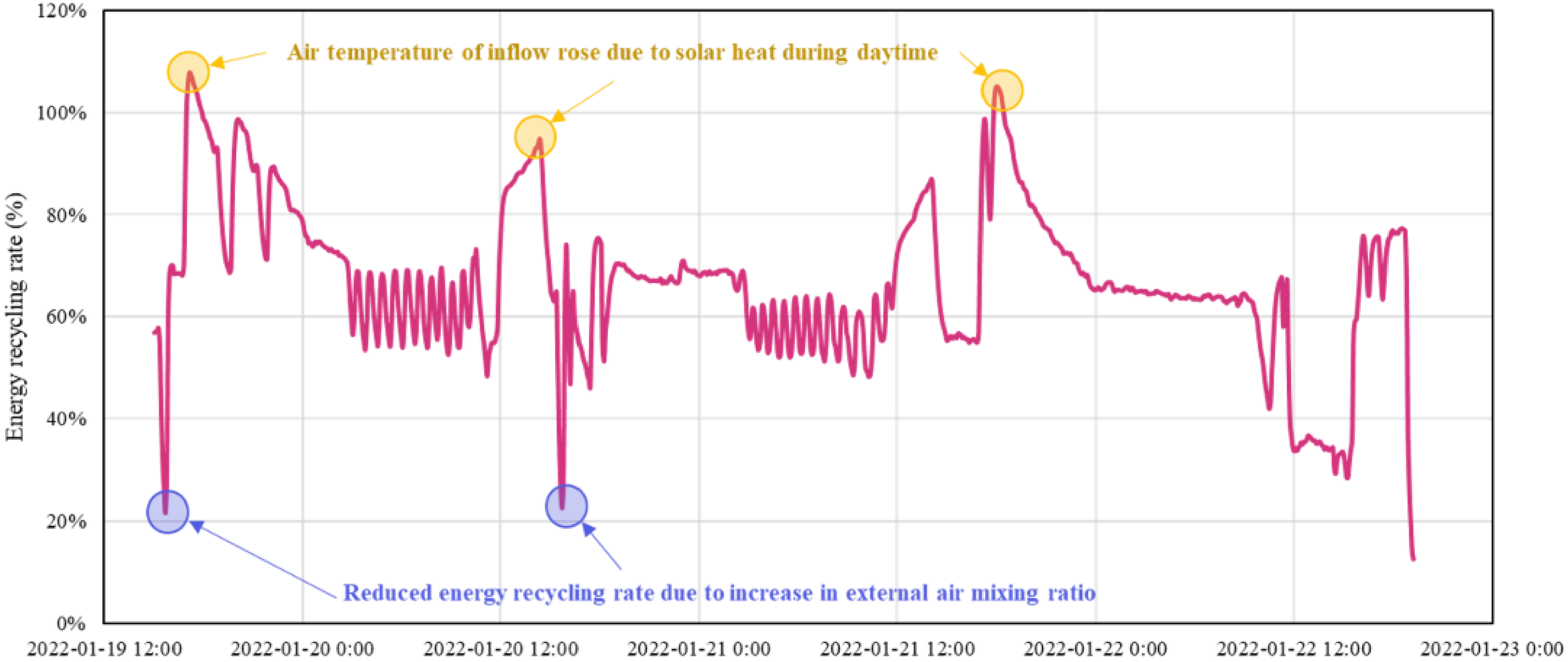


Figure 5-20 Results of energy recycling rate of ARVS.

5.3.5. Measurement results of ammonia concentration

The recommended ammonia gas concentration in piglet room was about 20 ppm. Therefore, ammonia measurement results in the ARVS piglet room and CVS piglet room were evaluated based on the concentration of 20 ppm. The Figure 5-21 was the measurement results of ammonia during the whole period. The results were daily measurement data. The measurement locations were the center of the ARVS piglet room, the center of CVS piglet room, and the duct at the end of the wet scrubber module.

The minimum ventilation rate in winter for CVS piglet room was about 0.1 min^{-1}, and the ventilation rate of ARVS piglet room was maintained at 0.4 min^{-1} to 0.7 min^{-1}. Accordingly, the ammonia concentration in the CVS piglet room was measured at 35 ppm, and increased to a maximum of 40 ppm. This was due to the low ventilation rate, which created a poor gas environment. The CVS had a limit in increasing the ventilation rate because the external air temperature was low in winter season. The concentration in the ARVS piglet room was continuously maintained within 20 ppm during the entire period. When the piglets were 4 weeks old, the piglets' thermal demand inside the ARVS piglet room was 31℃. Since the heat energy reuse rate was high, the amount of recirculated air was large. Therefore, the gas concentration was maintained at about 20 ppm. After that, the ventilation rate in ARVS piglet room increased. Accordingly, the internal ammonia concentration was kept as low as about 11 ppm.

The CVS piglet room failed to control the gas environment in winter season. A high ammonia concentration could cause a decrease in immunity to disease, loss of appetite, dizziness, and so on. Therefore, it can have a huge impact on farm productivity. In addition, high concentration of ammonia gas could adversely affect the health of workers in pig house (Donham et al., 1995). The risk of respiratory diseases in livestock is reported at 20-40 ppm. It also reported that stockman feel uncomfortable is possible at a 25-35 ppm (Busse, 1993). In the case of young piglets, for each increase in ammonia concentration to 50, 100, and 150 ppm, the growth retardation could occur by 12, 30, and 29% respectively (Drummond et al., 1980). In addition, it was reported that the amount of feeding increased in pig room with low ammonia concentration compared to those with high ammonia concentration (Jones et al., 1996). On the other hand, the ammonia concentration in ARVS piglet room was maintained appropriately. This improved the internal environment of the piglet room, also had a positive effect in reducing gas emission. In addition, the ammonia emission could be further reduced sine the air was exhausted to the outside through the wet scrubber. The average ammonia concentration at the outlet duct was measured to be 3.5 ppm. The removal efficiency was about 70% initially. After the increase in ventilation rate and EAMR, it was calculated up to 92%. This removal efficiency was higher than the target value when designing the wet scrubber module. Based on these results, it was evaluated that the ammonia concentration inside the ARVS piglet room was well controlled. In addition, the ventilation rate and EAMR to control the gas environment were well determined in the automatically control algorithm after maintaining the air temperature and relative humidity appropriately.

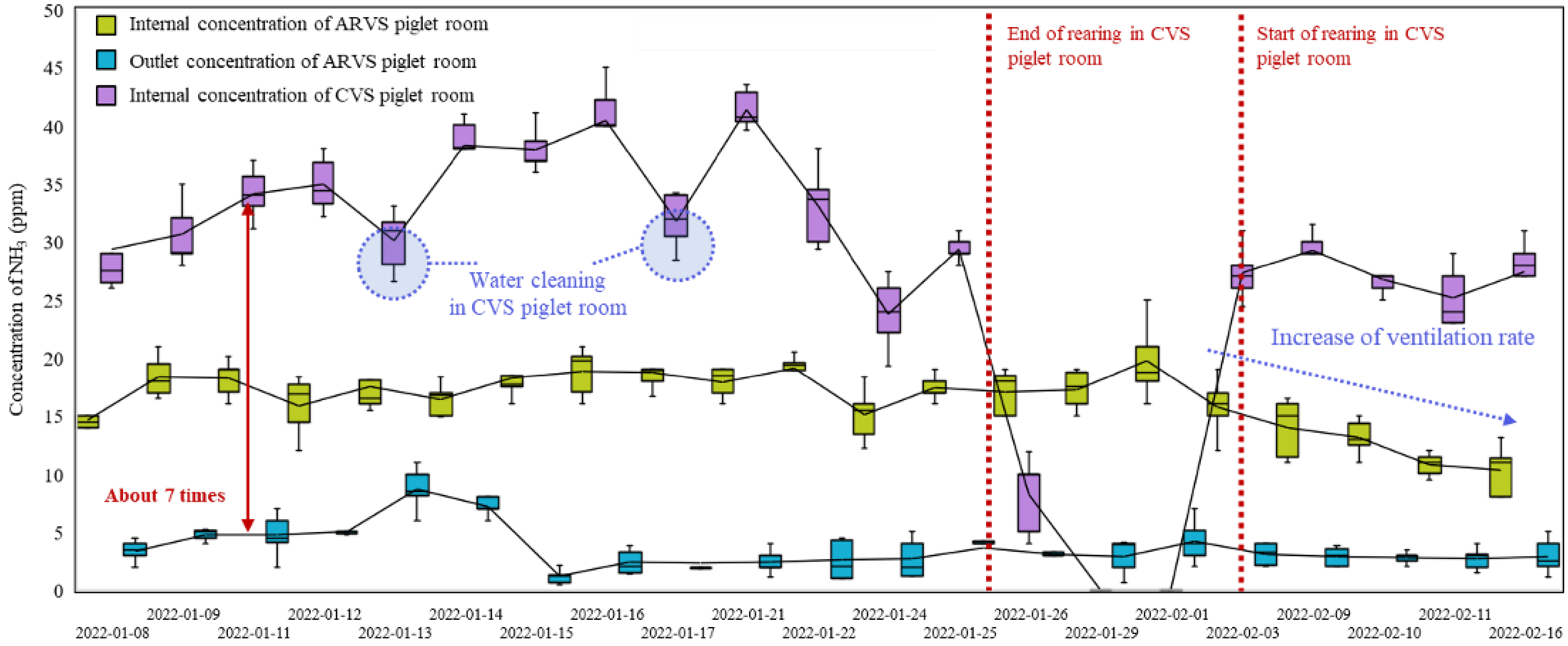


Figure 5-21 Results of ammonia concentration in piglet room (ARVS and CVS piglet room) and outlet duct.

5.3.6. Measurement results of complex odor and dust concentration (TSP & PM10)

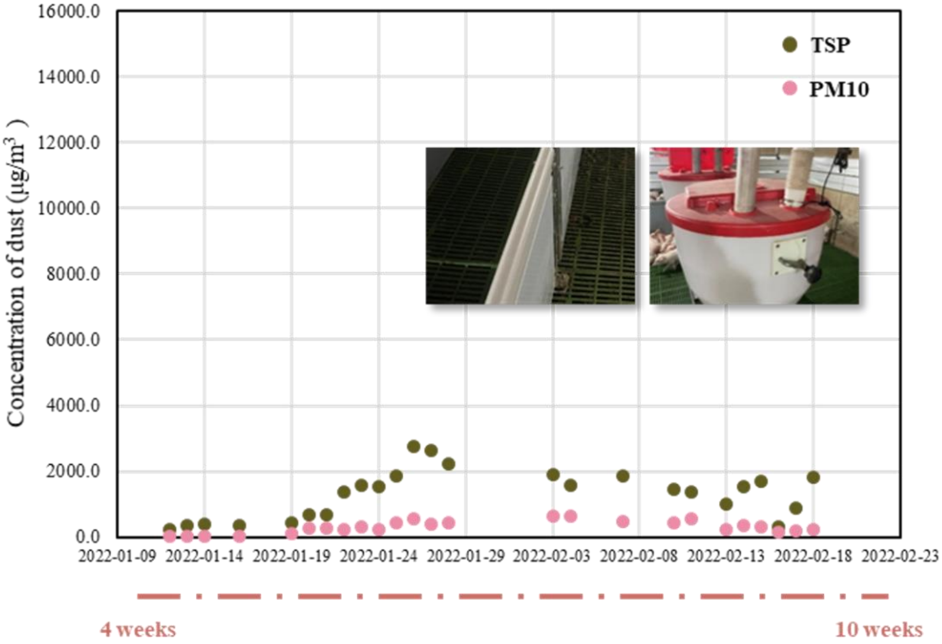
Since it was impossible to measure the complex odor in real time, the olfactory experiment was conducted using samples by week of age, and then the odor concentration was calculated. The results of calculating the concentration of complex odors and removal efficiency were shown in the Table 5-2.

The odor concentration in the ARVS piglet room with 4-week-old piglets was measured to be 1442 OU. This showed a similar trend to the ammonia gas concentration, because the amount of recirculated air was large. This was the same as the concentration of the CVS piglet room. The concentration of the outlet duct was 448 OU, and the removal efficiency was calculated to be about 68.9%. After that, as the ventilation rate increased, the complex odor concentration inside the ARVS piglet room was reduced by more than half. In addition, the concentration of the outlet duct decreased. The concentration inside the CVS piglet room was measured to be low, because it was measured at a high ventilation rate just before piglet transfer. After that, the odor concentration inside the CVS piglet room increased, and 1442 OU was measured at the end. The concentration of odor inside the CVS piglet room was equal to the concentration of odor emitted at the outlet of CVS piglet room. Therefore, it was confirmed that there was a difference of up to 10 times in the concentration of the emitted odor. On the other hand, the odor concentration in the ARVS piglet room gradually decreased. In the case of ARVS piglet room, a smaller amount of odor was emitted than the amount of the exhausted air because the amount of EAMR was exhausted to the outside. However, since the ventilation rate of CVS piglet room was low, it was possible to evaluate that odor concentration emitted was lower in ARVS piglet room, assuming that the amount of exhausted air was almost the same. Therefore, it was found that ARVS was effective in reducing the complex odor emission.

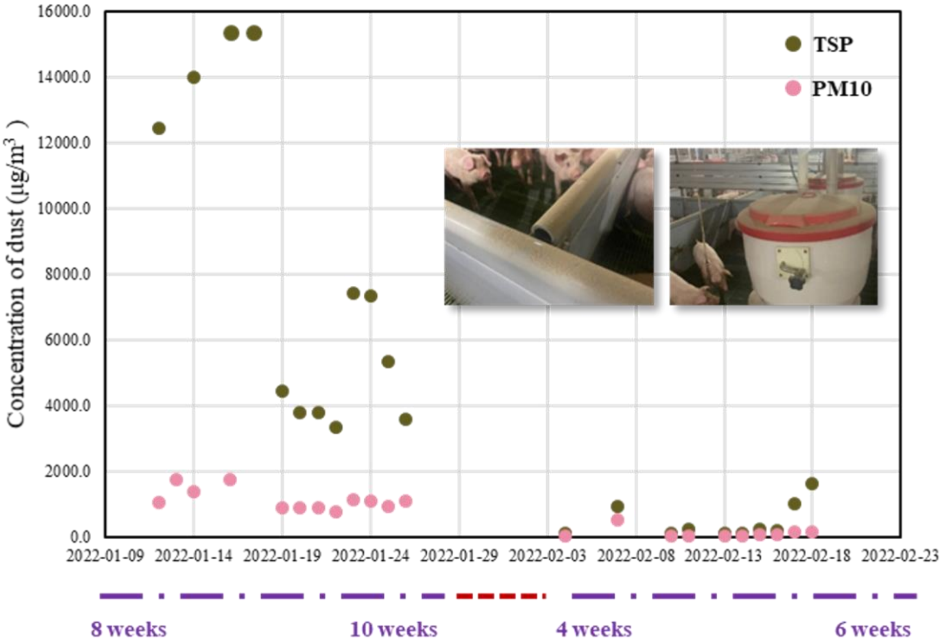
Table 5-2 Results of complex odor concentration based on the air dilution olfactory evaluation and removal efficiency.

Date	Inside of ARVS piglet room (OU)	Inside of CVS piglet room (OU)	Outlet duct (OU)	Removal efficiency (%)
Jan 19th	1442	1442	448	68.9
Jan 26th	669	144	208	68.9
Feb 9th	669	448	208	68.9
Feb 18th	448	1442	140	68.8

Dust concentration was measured and recorded periodically in the same way of ammonia gas or odor. The measurement result of dust concentration (TSP and PM10) is shown in the Figure 5-22. The dust concentration can be different depending on the rearing age, ventilation rate, and type of feed particles, but a clear difference occurred inside the ARVS piglet room and CVS piglet room. The average TSP concentration inside the ARVS piglet room was measured to be 1832.5 $\mu g\cdot m^{-3}$ and the maximum was 5691.1 $\mu g\cdot m^{-3}$, and the average PM10 was measured to be 299.7 $\mu g\cdot m^{-3}$ and the maximum was 654.0 $\mu g\cdot m^{-3}$. On the other hand, the average TSP inside the CVS piglet room was 4804.9 $\mu g\cdot m^{-3}$ and the maximum was 17681.5 $\mu g\cdot m^{-3}$, and the PM10 was measured to be 682.4 $\mu g\cdot m^{-3}$ and the maximum was 1758.5 $\mu g\cdot m^{-3}$. These of CVS piglet room were differences of about 3 times and up to 200 times on average concentration compared to the ARVS piglet room.



(a) Dust concentration inside the ARVS piglet room



(b) Dust concentration inside the CVS piglet room

Figure 5-22 Results of dust concentration (TSP & PM10) inside the ARVS piglet room and CVS piglet room.

5.3.7. Comparison of weight of piglets in ARVS piglet room and CVS piglet room

If the internal environment was improved by applying the ARVS, the biggest advantage was the increase in the growth of piglets. To evaluate these results, the weight of piglets was measured and compared. As a result of the measured weight, the average weight of piglets in ARVS piglet room was 33.4 kg and the average weight of piglets in CVS piglet room was 31.8 kg. The rearing period of the piglets was 50 days. Because the weight of weaning pigs was 20 kg, the weight gain per a day was 0.268 $kg\cdot day^{-1}$ and 0.236 $kg\cdot day^{-1}$, respectively. It means that the ARVS can make faster to slaughter weight. In addition, it was evaluated that the feed efficiency could be increased, which had a positive effect on pig productivity. The effect of improving the weight gain was about 7 days faster than the entire rearing period. Assuming that piglets are raised 365 days on this pig house, there is an advantage that piglets can be reared once a year than before. The accurate feed efficiency could be calculated by comparing actual feed intake, but there was a limitation in that in was not possible to measure individual feed intake in this experimental piglet room because of using entire feed silo.

Table 5-3 Results of weight of piglets (10 weeks) in ARVS piglet room and CVS piglet room.

	Total weight of 20 heads (kg)	Average weight (kg)
ARVS piglet room	667.3	33.4
CVS piglet room	635.5	31.8

5.3.8. Analysis of stress and disease of piglets

The cortisol concentration for evaluating the stress and the IgA concentration for antibody generation level for evaluating the immunity were shown in the Figure 5-23. The pink box was the range of cortisol concentration in piglets measured in animal welfare-type pig house. The piglets in ARVS piglet room had a relatively low concentration of cortisol. Since the ventilation rate of ARVS piglet room was high, the piglets felt comfortable in pleasant environment, so that the cortisol concentration was measured to be low. These results could also be confirmed through video data monitoring the state of piglets (Figure 5-24). Before the ARVS was installed, piglets were grouped on the sides of the pen to maintain each body temperature. However, after the ARVS was installed, it was confirmed that the piglets were resting comfortably in the entire pen. On the other hands, some pens with high concentration of cortisol up to 110 ng·mL^{-1} were found in CVS piglet room. From these results, the stress of piglets increased in CVS piglet room where the internal environment was poor. The cortisol concentration measured in pen #5, was very low because the piglets did not bite the saliva sampling rope and the amount of sampled saliva was small.

A high concentration of IgA means that the amount of antibody inside the piglets was increased. This was intended to be evaluated in relation to the presence or absence of disease. However, before saliva sampling, piglets were vaccinated. Accordingly, a large number of antibodies were formed inside the piglets because of vaccination. As shown in the Figure 5-23, the IgA concentration of piglets in the ARVS piglet room was higher than that of piglets in CVS piglet room. Antibodies inside the piglets in ARVS piglet room increased more actively, confirming that they were more immunizable from livestock disease.

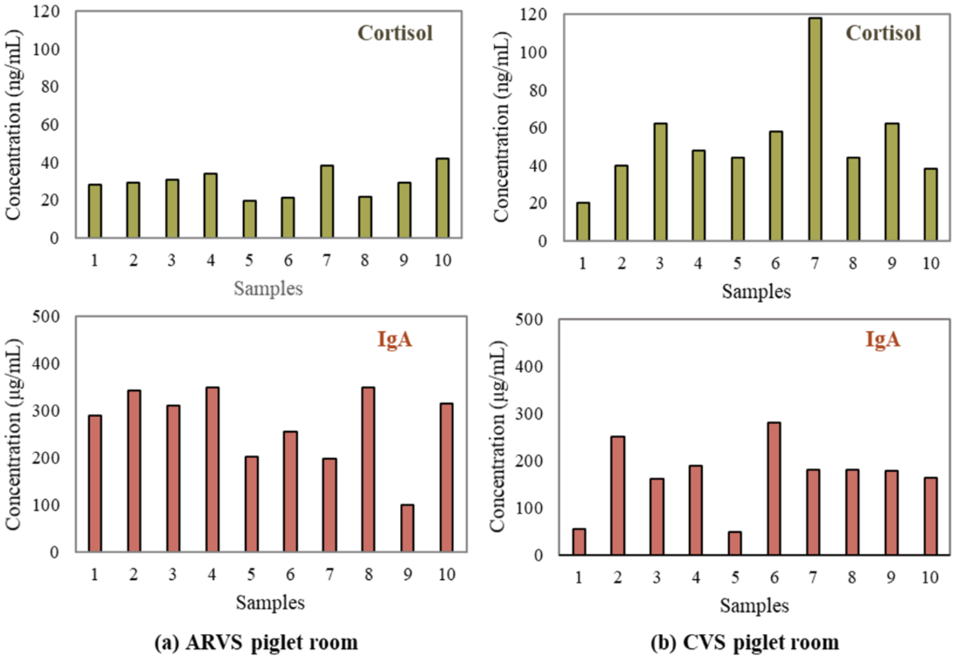


Figure 5-23 Results of cortisol concentration and IgA concentration for evaluating stress and immunity.

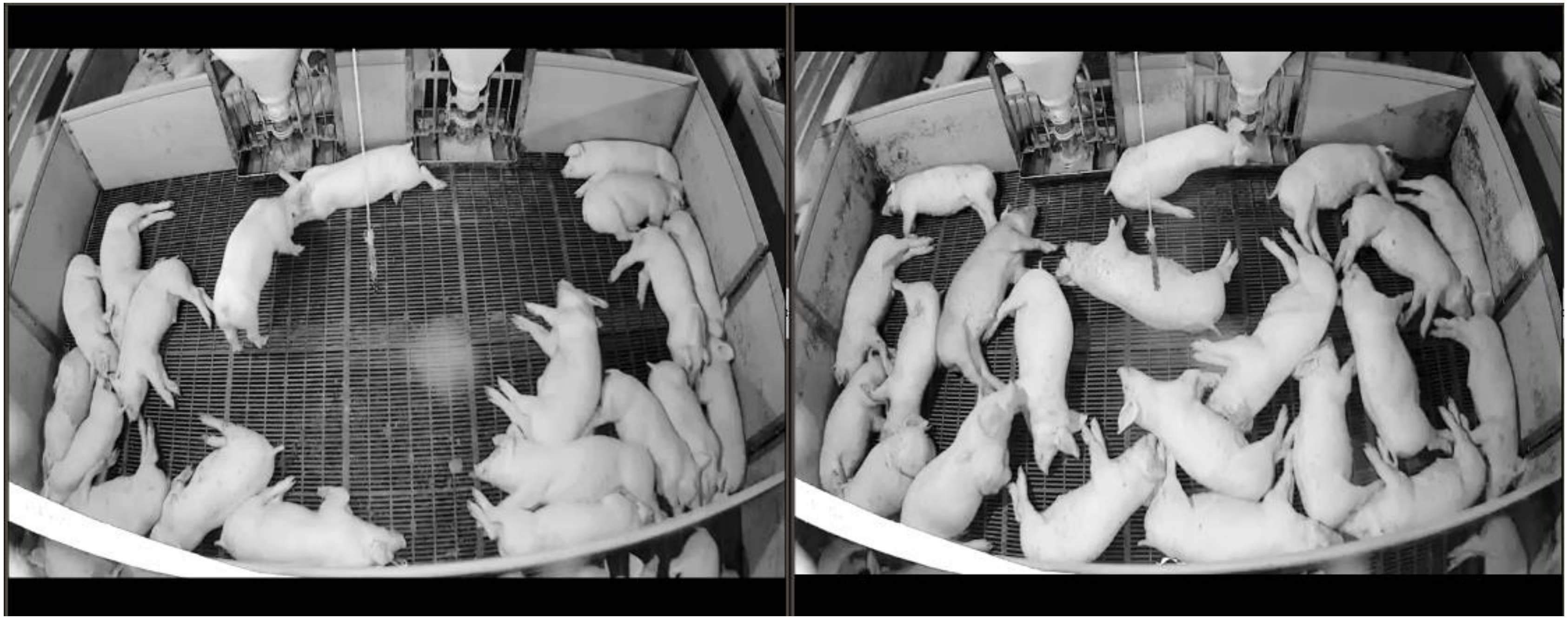


Figure 5-24 Piglets' behavior according to the difference of internal environment (before (left) and after (right) application of the ARVS).

The diagnostic analysis results of 4 types (PRRSV, PCV-2, SIV, and PPV) of swine respiratory viruses were as follows. The results of recording the number of positive piglets (10 heads of piglet in ARVS piglet room and CVS piglet room, respectively) were shown in the Figure 5-25. PCV-2, SIV, and PPV were negative in both piglet rooms, and one PRRSV was detected as positive in both piglet rooms. These results were obtained because swine respiratory viruses were well controlled in the experimental pig farm. Therefore, the degree of disease contamination in the ARVS piglet room and CVS piglet room was very low.

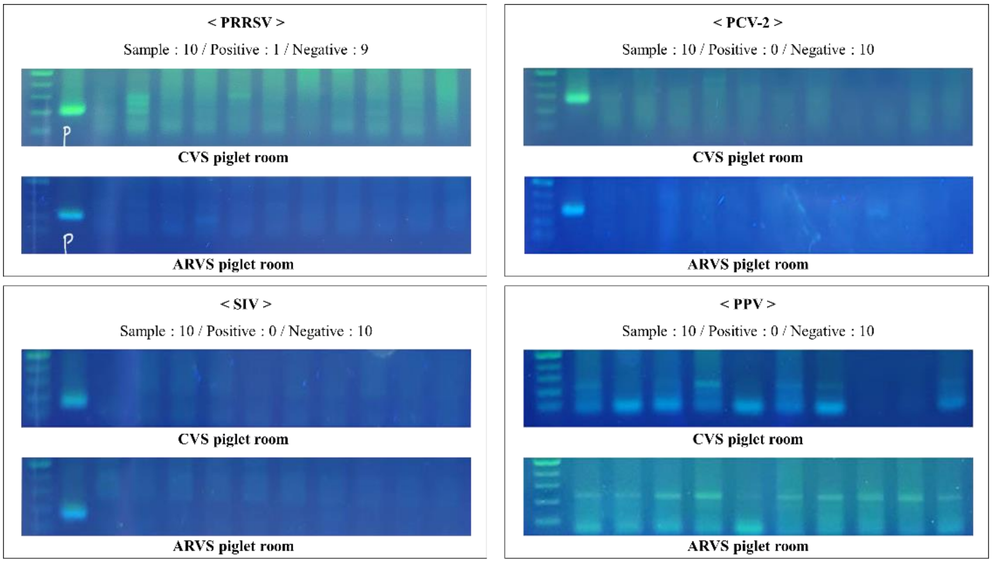


Figure 5-25 Detection results of swine respiratory disease viruses by PCR test in ARVS piglet room and CVS piglet room.

Also, in order to evaluate the cleanliness inside the piglet room, the environmental sample analysis was conducted. The number of positive detections by location inside the piglet room was shown in the Figure 5-26. PCV-2 and TGEV were negative in both piglet rooms. 8 and 10 positives of PRRSV were detected in

ARVS piglet room and CVS piglet room, respectively. Door, corridor, and indoor wall were locations where contact of piglets was difficult. On the other hands, feeder, floor and wall were very close to the piglets. It can be said that a large amount of PRRVS positive in these locations can increase the risk of disease in piglets. Positive responses at these locations were 1.75 times higher in the CVS piglet room than in the ARVS piglet room. One positive of PEDV was detected only in the feeder of the CVS piglet room. Positive responses of rotavirus were detected 2.3 times more in the CVS piglet room than in the ARVS piglet room, and 2.5 times more in the accessible area of piglets (Feeder, floor, and wall). As a result of comparing the positive responses of these environmental samples, it was confirmed that the internal environment of the ARVS piglet room was much cleaner than that of the CVS piglet room.

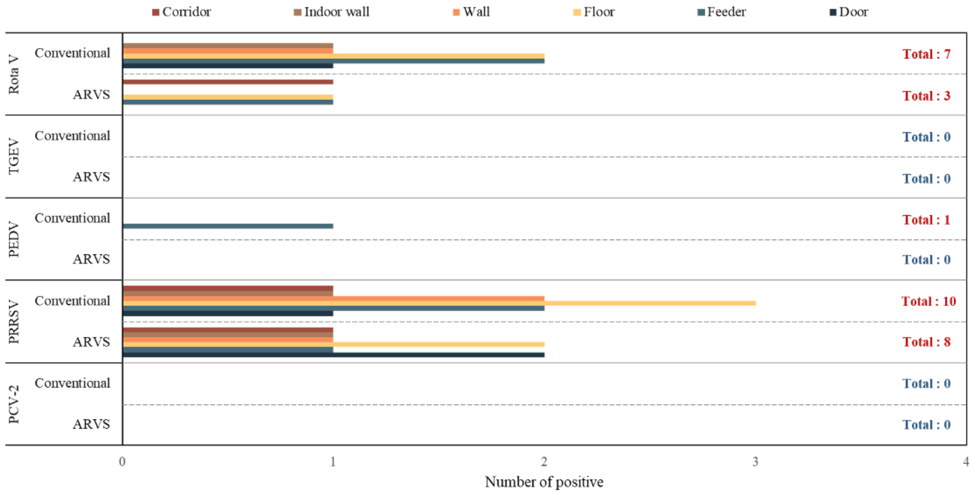
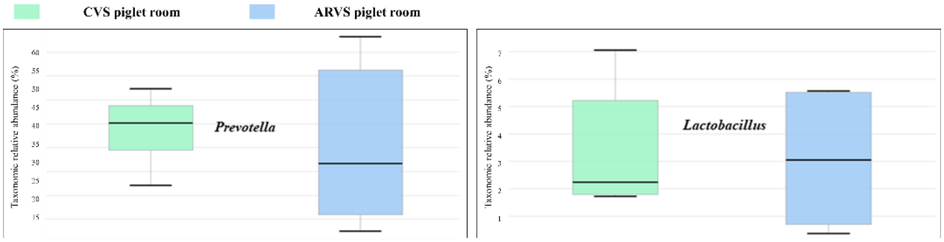
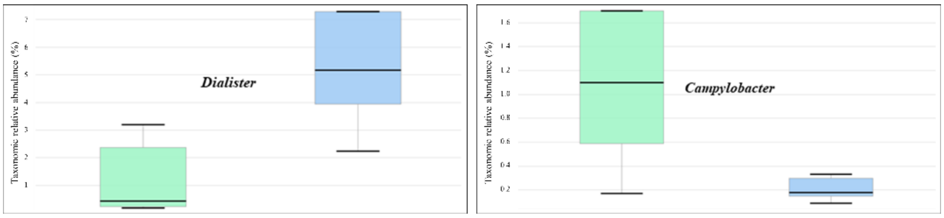


Figure 5-26 PCR detection results of environmental samples collected from various locations inside the ARVS piglet room and CVS piglet room.

The results of intestinal microbiome analysis were shown in the Figure 5-27. A slight increase in the beneficial bacteria such as Prevotella and Lactobacillus was found. However, the increased amount was small, and there was no statistical significance. Campylobacter is one of the causative bacteria of food poisoning that infects pigs and causes diarrhea as the main symptom. The route of transmission is excreted in the manure of pigs, through which it is transmitted to other pigs. Even, since Campylobacter is a zoonotic epidemic, cleanliness inside the farm is the most important factor. Campylobacter was significantly reduced in ARVS piglet room. These results could be seen as the effect of improving the internal environment of ARVS piglet room due to high ventilation rate. On the other hand, an increase of Dialister was observed. This bacterium was Dialister pneumosintes, which is a gram-negative, anaerobic, non-fermentative, and rod-shaped bacterium. Dialister pneumosintes are known as periodontal disease pathogens in humans. However, there were very few researches on pigs, so it was difficult to give meaning to them. The results of nasal microbiome analysis were shown in the Figure 5-28. Changes of Haemophilus, Prevotella, Moraxella, and Rothia were observed. In particular, a significant decrease in Rothia was found. Bacteria of Rothia are known to suppress immunity in humans, produce enterobactin, and cause intestinal dysplasia and bleeding, but whether it affects pigs is unknown.



(a) Beneficial intestinal bacteria



(b) Harmful intestinal bacteria

Figure 5-27 Changes in beneficial and harmful bacteria in the intestinal microbiome of piglets according to the ARVS application.

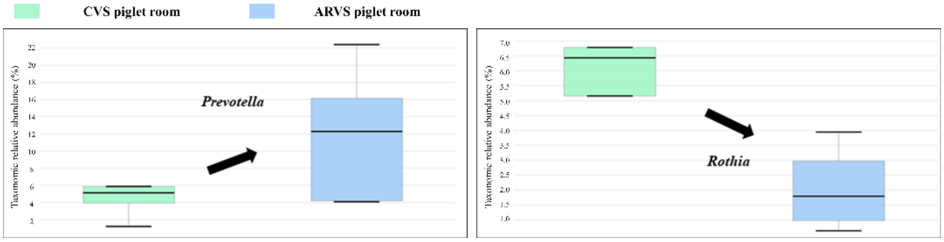


Figure 5-28 Changes in bacteria in the nasal microbiome of piglets according to the ARVS application.

5.4. Conclusions

In this study, the ARVS was designed and developed to apply on piglet room. The developed ARVS was applied to the actual pig house, and validation experiments were conducted during the winter season. For the design and combination of basic modules, the results of previous researches were used (chapter 3 and 4). When installing the modules, the semi-closed loop ventilation type was considered. In addition, automatic algorithm was developed and applied to all ARVS to enable real-time automatic control. For the validation experiment, a number of sensors inside the piglet room were installed to collect environmental data in real-time. In addition, in order to evaluated the pig productivity, data such as stress index, weight gain, livestock disease, and odor were collected.

During the winter season, while the automatic algorithm was operating normally, the ventilation rate and the EAMR were controlled in real time. When the external air was cold, the ventilation rate could be maintained 3.2 times higher on average in the ARVS piglet room than in the CVS piglet room. Nevertheless, the internal air temperature was kept properly in the ARVS piglet room. On the other hand, low temperature and humid environment were found in the CVS piglet room. The recommended concentration of ammonia was 20 ppm. The gas environment was improved in the ARVS piglet room, and the amount of ammonia emission was very low. On the other hand, the ammonia concentration inside the CVS piglet room exceeded the recommended concentration. The removal efficiency of the wet scrubber was 85.5% on average. It can be seen that the performance of the wet scrubber was very good. It was also effective in removing dust. It was possible to reduce the dust concentration due to the high ventilation rate. The dust concentration data showed a significant difference between the two piglet rooms. Additionally, as the internal air quality was cleaned, the durability of the internal measurement sensors can be improved, so that the lifetime of the sensors can be increased. Also, there may be advantages in that the accuracy of the measured data could be further increased.

Because these internal environments were improved, the rearing conditions of the piglets improved greatly. The piglets in the ARVS piglet room weighed 1.6 kg more than those in the CVS piglet room. The ARVS made faster to slaughter weight. The cortisol concentration of the ARVS piglet room was similar to that of animal welfare pig farm. It means that ARVS had significant effects in reducing stress of piglets. Disease contamination status was very good. In the ARVS piglet room, the beneficial bacteria were more than CVS piglet room, and the harmful pathogen was less than the CVS piglet room.

Chapter 6. Evaluation of pig productivity in spring and summer seasons including examination of cooling methods

6.1. Introduction

As the ambient temperature and the frequency of hot days increased due to climate change, heat stress of pig farm and economic impacts were of increasing concern (Beniston et al., 2017; Schauberger et al., 2019; Valiño et al., 2010). Pigs are particularly susceptible to heat stress because they lack functional sweat glands and have small lungs that reduce their ability to disseminate heat by panting (D'Allaire et al., 1996). Therefore, it is very important to manage the thermal environment inside the pig house in summer. In particular, heat accumulation can occur inside the pig room even if maximum ventilation was operated during summer. Heat stress results in a higher rate of secondary bacterial infections due to a compromised intestinal defense mechanism (Pearce et al., 2013). Meanwhile, in summer climate of South Korea, the humid environment was also a problem. In South Korea, the rainy season occurs every summer, and the weather conditions are hot and humid. When the humidity is high, the possibility of developing respiratory diseases of pigs may increase (Gordon, 1963), and if the temperature is high, the effect of humidity may be greater (Huynh et al., 2005). Therefore, the cooling methods were necessary to satisfy the pigs' thermal demand.

A cooling device was essential to prevent high temperature stress in summer season. A very important goal when cooling a facility is to prevent the flow of heat from the outdoors to the indoor (Firfiris et al., 2019). It is also important to efficiently dissipate the calories of pigs generated inside the pig house. In pig farms, evaporative cooling pads were generally used as a cooling method because of their economic advantages (Obando et al., 2020). However, since the performance of the evaporative cooling system largely depends on the external air conditions, there was a problem that the performance of the evaporative cooling system was lowered in South Korea where the temperature and humidity were high in summer (Yoo et al., 2015). In particular, if the humidity environment inside the pig house is not appropriate, it may adversely affect the growth. There is a method of adjusting the windchill temperature in order to simultaneously satisfy the temperature and humidity environment of pigs. Therefore, it was necessary to reduce the air temperature by windchill cooling method to prevent internal high temperature while satisfying the pigs' thermal demand.

In this study, the validation experiments were additionally conducted for spring and summer seasons. The results of experiment were evaluated in the same way as in the previous research (chapter 5). Meanwhile, unlike the winter season, cooling strategies were essential in summer season. Therefore, in this study, the evaluations of the cooling methods were conducted. 1) The capacity of the general cooling system required for temperature was calculated. 2) The water temperature and chiller capacity required for evaporative cooling were calculated using the wet scrubber. Finally, 3) as a windchill cooling method, the ventilation system was improved to increase the velocity near the piglet zone.

6.2. Materials and methods

6.2.1. Target facilities

The target facilities and ventilation structure experimented in this chapter were the same as in chapter 5.

6.2.2. Cooling methods of piglet room

6.2.2.1. Evaporative cooling method

In general, the method of lowering the air temperature inside the piglet room is to operate the maximum ventilation rate. The high ventilation rate can exhaust the internal heat. However, as much air is exhausted, a lot of external hot air can flow in. Therefore, it is necessary to lower the temperature of the incoming air. However, cooling the inlet temperature can consume a lot of energy because the temperature rises continuously due to the heat production of pigs. Therefore, for economical cooling method, most pig farms use the evaporative cooling method (Aarnink et al., 2006; Huynh et al., 2006). The most commonly used equipment in the pig facility with forced ventilation type is a cooling pad (Samer, 2015). In this study, all the air inside the piglet room passes through the wet scrubber module. The wet scrubber module was designed similarly to the principle of cooling tower mainly used in other industry. The cleaning water in the wet scrubber module was used to remove the complex odor, harmful gases, and dust, but also heat can exchange with the air from the piglet room. This was the same as the method of lowering the air temperature in the cooling pad. The principle of the change of air temperature can be divided into two ways. One is the method that sensible heat can be exchanged, the lower the temperature of the cleaning water, the more heat can be transferred from the air. The other method is the evaporative cooling effect of cleaning water. As the water temperature increases, the evaporation rate increases, reducing the time it takes to reach the critical relative humidity. The cooling efficiency can be increased accordingly. Therefore, in this study, the air temperature flowing into the piglet room after passing the wet scrubber was measured by controlling the temperature of cleaning water in the water tank (Figure 6-1). Then, the required water temperature was evaluated (Equation 6-1). In the chapter 4, the numerical model was developed to predict the thermal environment inside the piglet room. Since the ARVS required iterative calculations when predicting the thermal environment, the module of previous research was used in this study.

$$Q = cm\Delta T \qquad \text{Equation 6-1}$$

Where, Q is the calorie of the air (cal), c is the specific heat of air ($\mathrm{cal \cdot kg^{-1} \cdot {}^{\circ}C^{-1}}$), m is the mass of air (kg), ΔT is difference of air temperature (°C).


(a) Coiled tube for refrigerant flow (b) Water tank of wet scrubber with coiled tube installed (c) Refrigerant performance check (surface freezing)

Figure 6-1 Evaporative cooling method using low temperature of the cleaning water using chiller.

The data measurement methods and model calculation procedure were as follows to calculate the required calorie for cooling. In this experiment, it was important to confirm the change of the two states (Air temperature and cleaning water temperature). The air temperature could be evaluated by obtaining the air temperature difference between the exhausted air from the piglet room and reused air. The air velocity was measured inside the duct just before the wet scrubber because it was important to calculate the air flow rate. Therefore, the measured factors in the wet scrubber were air velocity in the outlet duct, cleaning water temperature, and air temperature before and after the wet scrubber. Based on the measured experimental results, the values of the air temperature change and the water temperature change were compared with the wet scrubber module of the numerical model in the previous research (chapter 4). Then, the cleaning water temperature according to the experimental conditions was calculated using the validated model, and the proper water temperature for the internal cooling capacity was selected considering the heat production of piglets. Finally, the capacity of the air conditions for controlling the water temperature was calculated using the converged water temperature after heat exchange. Based on these results, the required cooling capacity was evaluated. The measurement locations were shown in Figure 6-2.

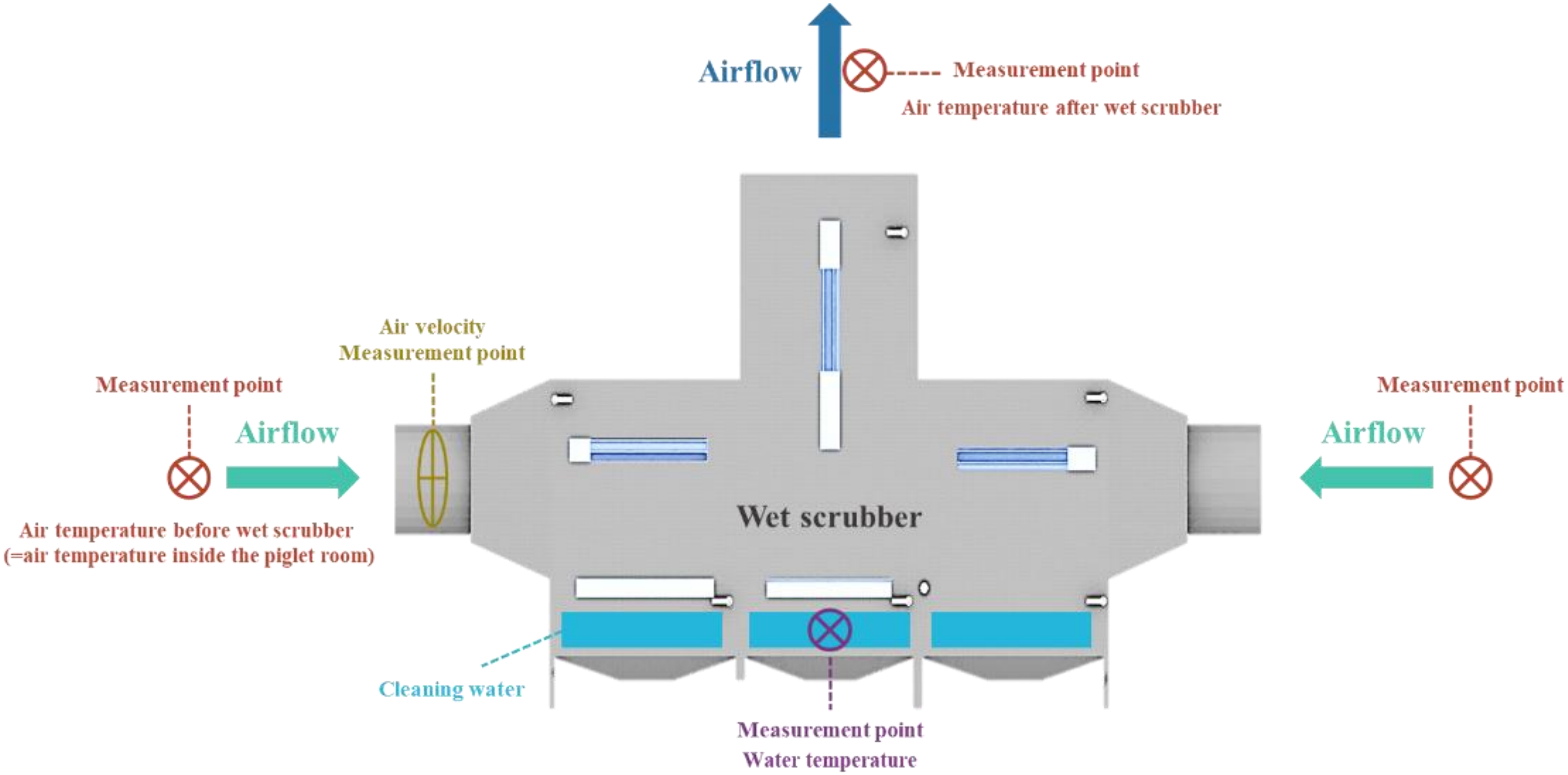
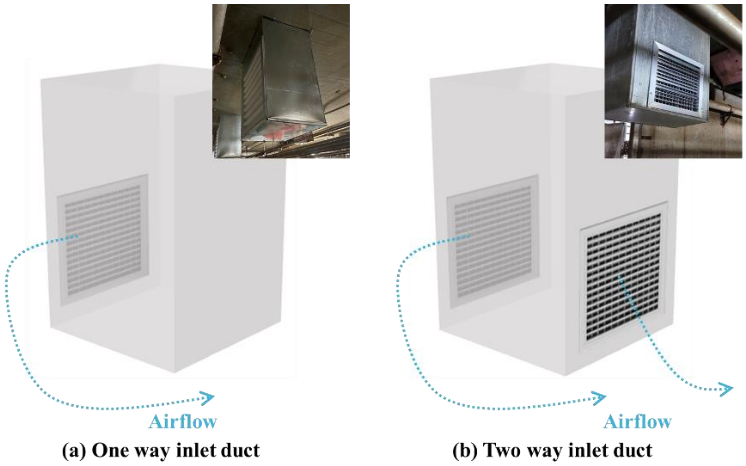


Figure 6-2 Measurement locations of wet scrubber to evaluate the cooling capacity of evaporative cooling method.

6.2.2.2. Convective cooling method

It was important to increase the air velocity near the piglets to enhance the windchill effect. Even if the air inside the piglet room is frequently replaced by operating the maximum ventilation rate, the air velocity near the piglets might not be proper depending on the location of inlet and outlet. Pexas et al. (2021) achieved the convective cooling with increased air velocity at pig lying area by adjusting the angle of the air inlets in the pig room from 75% open to 100% open. This was to reduce the load on the inlet area and made enough airflow (Park et al., 2018). Air velocity was increased at pig lying area from 0.15 $m \cdot s^{-1}$ under non-cooling, to approximately 1 $m \cdot s^{-1}$ (Pexas et al., 2021).

In this study, the internal distribution of air velocity with maximum ventilation rate was measured when the existing inlet ducts were used. Next, the existing inlet duct had one-way inlet type, but two-way inlet ducts were additionally developed and applied. These structures could increase the inlet area and form an airflow in the direction of the piglet zone (Figure 6-3). To measure the air velocity inside the piglet room, the portable hot wire anemometer (TSI-9565-A, TSI, USD) was used. The measurement locations were the piglet zones with a certain distance from the inlet to the outlet as shown in the Figure 6-4. The air velocity near the piglet zones was evaluated for two types (one-way inlet duct and two-way inlet duct) of inlet ducts under the condition of operating the maximum ventilation rate (0.8 min^{-1}).



(a) One way inlet duct

(b) Two way inlet duct

Figure 6-3 Overall schematic diagram of the experimental piglet room with ARVS installed.

Beckett (1965) suggested an effective temperature (ET) that could evaluate the effect on pigs considering air temperature, humidity and velocity. The ET equation can be expressed by considering each physical property of air independently, as shown in Equation 6-2.

$$ET = T + E_{hum} + E_{vel} \qquad \text{Equation 6-2}$$

Where, T is air temperature, E_{hum} and E_{vel} is the contribution of humidity and velocity to the ET, respectively, all expressed in °C. In this equation, the effect of humidity was assumed to be zero when the RH was 50%. Similarly, the effect of velocity was set to be zero when the air velocity was 0.2 $m \cdot s^{-1}$ (Bjerg et al., 2018). Bjerg et al. (2018) investigated how well the same data were reflected when using Equation 6-3 to calculated ET and considering the effects of humidity and velocity. This resulted in a coefficient of determination of 0.97 for the correlation between ET and the data presented by Tao and Xin (2003) who developed Temperature-

Humidity-Velocity Index (THVI).

$$ET = T + 0.0015(RH - 50)T + (-1.0(402 - T)(v^{0.66} - 0.2^{0.66}) \quad \text{Equation 6-3}$$

Where, *RH* is air relative humidity (%), and *v* is the air velocity ($m \cdot s^{-1}$).

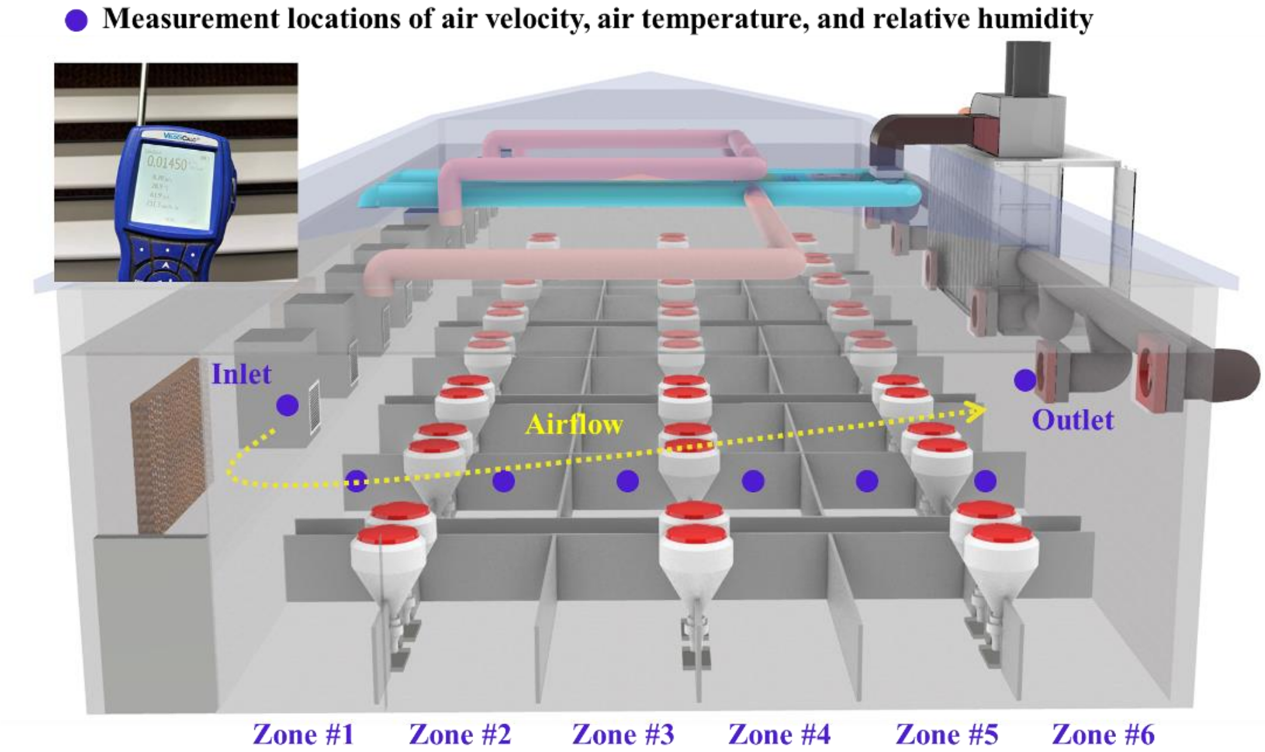


Figure 6-4 Measurement locations to evaluated the air velocity, air temperature, and relative humidity near the piglet zone when the maximum ventilation rate was operated.

6.2.3. Methods and procedure of validation experiment in spring and summer seasons

The validation experiment in spring and summer (in this chapter) was conducted in the same way as the experiment in winter (chapter 5). The experiment of the spring was conducted from April 28 to June 17 2022, and the experiment of summer was conducted from June 23 to August 12 2022. The experimental procedure was shown in Figure 6-5. There were two differences from the winter experiment. Since the automatically controlled algorithm developed in first experiment (chapter 5) was stabilized, the additional performance test was not conducted. Also, the internal energy recycling rate was not calculated in this study (in this chapter). Since the external air could be cold in winter, it was important to reuse the thermal energy inside the piglet room. However, the external air can be hot in summer, so reusing the internal thermal energy was useless. Because negative values of energy recycling rate were calculated in summer, it was excluded in this study.

Similar to the evaluation indices of validation experiment in winter (chapter 5), the validation experiments in spring and summer were conducted. The detailed experimental method was written in chapter 5. First, the real-time measurement data (ventilation rate, air temperature, relative humidity, carbon dioxide, and ammonia concentration) inside the piglet room were analyzed. The air temperature and relative humidity data outside the piglet room were collected and used as an operating algorithm together with the internal environmental data. The measured data was stored in the ICT-based server system in real time. The server data was extracted according to the period, and the rearing environment was analyzed.

Data that were difficult to measure in real time included odor sampling, dust measurement, and weight measurement. Odor and dust concentration were measured periodically to obtain data. Complex odor was evaluated through the air dilution olfactory method. For dust concentration, total suspended particles (TSP) and particulate matter 10 (PM10) were measured. The measurement locations were the same the location of odor sampling.

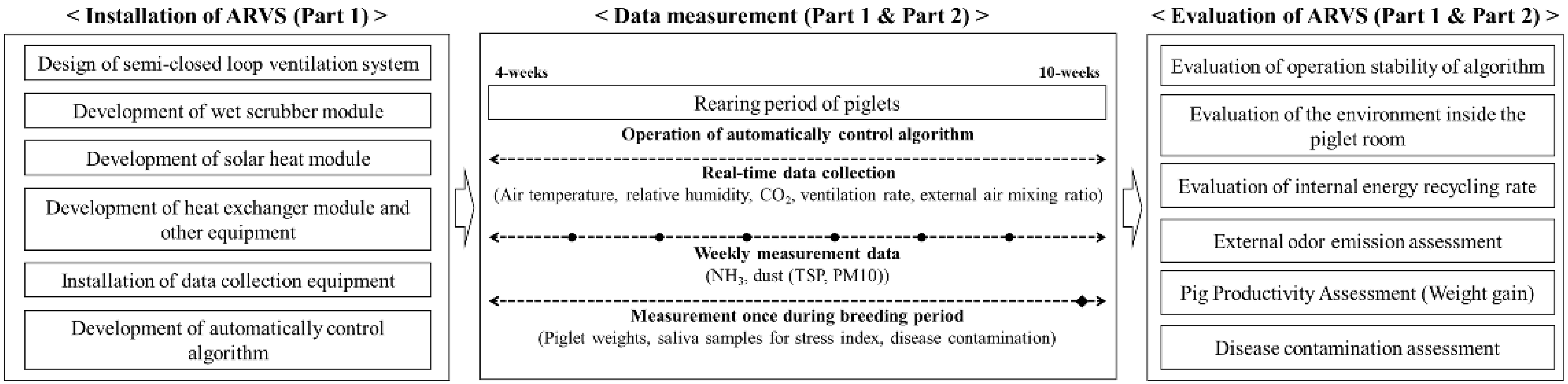


Figure 6-5 Overall experimental method and procedure for developing and evaluating the ARVS.

6.3. Results and discussions

6.3.1. Experimental results of cooling methods

6.3.1.1. Cooling effect and capacity calculation of wet scrubber module (evaporative cooling method)

In order to conduct the experiment according to the air velocity, internal air temperature, and cleaning water temperature were measured when the piglet room was empty. The measurement results were shown in Table 6-1. In the case of operating maximum ventilation rate, the average air velocity of one side section of wet scrubber was 8.6 $m \cdot s^{-1}$ (Table 6-1). When the experimental ventilation rate was 764 CMM (maximum ventilation rate of piglet in summer), the air velocity on both sides of the duct with a diameter of 550 mm was calculated to be about 8.9 $m \cdot s^{-1}$. Therefore, the experimental conditions for the air velocity were reasonable. In addition, when the ventilation rate was 460 CMM (required ventilation rate of piglet), the air velocity of 5.5 $m \cdot s^{-1}$ was measured, and these two air velocities were selected as the experimental conditions. Next, the experimental conditions of cleaning water temperature were 17.1, 20.2, and 23.0°C, respectively.

At this time, the incoming air temperature was controlled as a fixed variable to about 29°C. As the air passed through the wet scrubber, the air temperature was lowered by 6.6, 4.6, and 3.1°C, respectively, after contact with the cleaning water and heat exchange when the air velocity was 8.5 $m \cdot s^{-1}$. Dağtekin et al. (2009) mentioned that a 5.19°C decrease of the external air temperature after passing through the evaporative cooling pad. Choi et al. (1998) stated that cooling pads decreased the house inside temperature to 5.4°C in inlet site, 5.0°C in middle site, 2.8°C in outlet. Compared with the results of previous researches, the temperature reduction effect of the wet scrubber was significantly measured.

If it was assumed that the initial air temperature inside the piglet room was 29°C and the proper air temperature was 27°C, the cooling capacity inside the piglet room could be calculated as shown in the Table 6-2. It was necessary to find out the heat production of piglets inside the piglet room to calculate the proper water temperature and the capacity of the chiller. If it was assumed that 1000 piglets weighing 20 kg were reared when the ambient temperature was about 28°C, the calorific value inside the piglet room was calculated to be about 45041.64 $\mathrm{kcal \cdot hr^{-1}}$ (CIGR, 2002). The sum of the calorific value required to cool the air inside the piglet room and the heat production of piglets was 69059.7 $\mathrm{kcal \cdot hr^{-1}}$. Therefore, when maintaining the cleaning water temperature sufficiently low as in Case 1, it was possible to maintain the proper air temperature inside the ARVS piglet room. In addition, the water temperatures in Case 2 and 3 were not sufficient to cool the inside of piglet room. Therefore, in order to maintain the proper air temperature inside the ARVS piglet room, it was suitable to maintain the cleaning water temperature at 22.5°C or less.

Meanwhile, the time it took for the cleaning water temperature to reach the convergence temperature was very important. Since this wet scrubber was operated in ARVS, the air can be continuously recirculated. Therefore, if the piglets' heat is continuously generated inside the piglet room, it can be very difficult to lower the air temperature. The measured convergence times were 29, 24, and 23 minutes, respectively, depending on the cleaning water temperature. This was a very short time, and it was necessary to design the capacity of the chiller to continuously maintain the water temperature at a low temperature. When the air velocity was low (5.5 $\mathrm{m \cdot s^{-1}}$), the contact time between incoming air and cleaning water inside the wet scrubber can be long. As a result, the air temperature was lowered by 1.5 times. The cooling efficiency of the wet scrubber increased, but the convergence time of the cleaning water was shortened by about 60%. Therefore, it was necessary to calculated the target temperature of cleaning water and design the appropriate chiller capacity considering the piglet’s heat production and heat exchange by ventilation.

Table 6-1 Measurement results of temperature reduction effect of wet scrubber according to the cleaning water temperature and air velocity in the wet scrubber.

Case	Air velocity in wet scrubber ($m \cdot s^{-1}$)	Temperature of cleaning water (℃)	Air temperature (℃) before wet scrubber	Air temperature (℃) after wet scrubber	Temperature difference (℃)	Convergence time of cleaning water temperature (min)
1	8.5	17.1	29.1	22.5	-6.6	29
2	8.7	20.2	29.0	24.4	-4.6	24
3	8.6	23.0	29.1	26.0	-3.1	23
4	5.5	17.0	29.0	18.1	-10.9	16
5	5.4	20.1	29.0	22.1	-6.9	12
6	5.5	23.2	29.1	25.3	-3.8	10

Table 6-2 Calculation results of cooling capacity inside the ARVS piglet room considering heat exchange by ventilation and heat production of piglets (initial air temperature inside the ARVS piglet room : 29℃, target air temperature : 27℃, ventilation rate : 0.91 min^{-1}).

Factors		Values
Volume of ARVS piglet room (m^3)		835.0
Air density (kg·m^3)		1.09
Specific heat of air (kcal·kg^{-1}·℃$^{-1}$)		0.24
Cooling capacity inside the ARVS piglet room (kcal·hr^{-1})		24018.06
Heat production of piglets (1000 heads) (kcal·hr^{-1})		45041.64
Heat exchange by ventilation rate with wet scrubber cooling (kcal·hr^{-1})	Case 1	78058.69
	Case 2	55241.54
	Case 3	36027.09

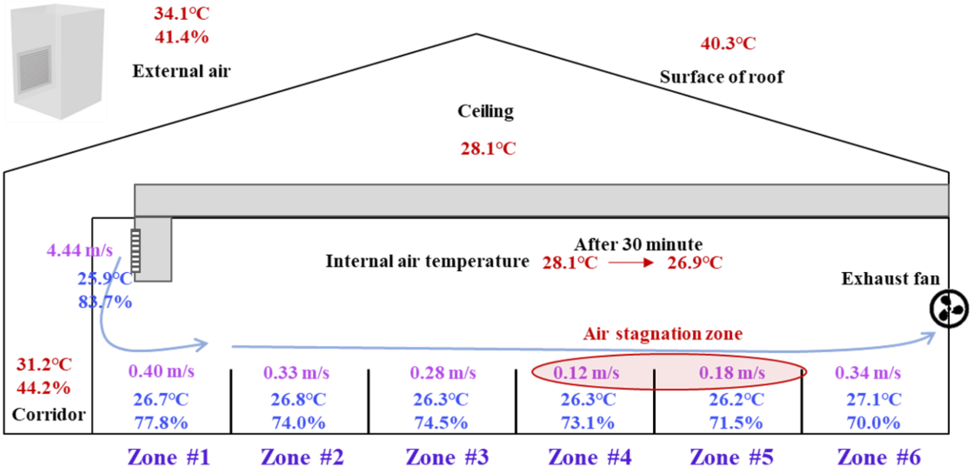
The cooling capacity required inside the piglet room was calculated based on the thermal balance equation. The calculation module used the numerical model developed in the Chapter 4. Through numerical calculation of the module, the internal air temperature considering the heat production of piglets was shown in the Table 6-3. In order to conduct iterative calculation using numerical model, the fixed values were set as follows. First, the heat production of 1000 heads of 8-weeks piglets was considered as an internal thermal environment. In addition, all heat exchange of the wall and structures were considered in the thermal environment module of the numerical model. The piglets' thermal demand of 8 weeks piglet was 27℃. The external weather conditions were the air temperature of 34.1℃ and the relative humidity of 41.4%. The ventilation rate was 764 CMM (0.91 min^{-1}) based on the maximum ventilation rate. The simulation experiments were conducted by changing the cleaning water temperature conditions starting with the initial temperature of 29℃ inside the piglet room. Compared with the actual measured data (Table 6-1), the differences of the air temperature after wet scrubber in the case 2, 3, and 5 (Table 6-3) were calculated to be 0.37, 0.36, and 0.37, respectively. Since the computed results of numerical model were reliable, the trends for each case were evaluated. It was case 7 and case 8 that the convergence temperature inside the piglet room was maintained properly. Although the air temperature could be lowered a lot after passing through the wet scrubber, more cooling was required to satisfy the piglets' thermal demand because of heat production of piglets. As a result, sufficient cooling was possible only when the cleaning water temperature was maintained below 13℃. The cleaning water temperature could increase with continuous use. When cooling was started using the cleaning water of 13℃ and 11℃, the convergence temperatures were 21.38℃ and 20.66℃, respectively. When calculating with the Eq. 1 considering the specific heat of water ($\mathrm{cal \cdot kg^{-1} \cdot {}^{\circ}C^{-1}}$), the volume of the water tank (0.5 m^3), and the density of water (1 $\mathrm{g \cdot ml^{-1}}$), the cooling capacity of the chiller was calculated at 8536.02 and 9839.85 $\mathrm{kcal \cdot hr^{-1}}$. Here, considering the convergence time of cleaning water temperature, the cooling time (operating flow rate of pump) was assumed to be 1 hour. When converting the units, the two values were calculated as 9.9 and 11.4 kW, respectively. These were about 4.5 times larger than the commonly used industrial chiller (1.5-3.5 kW), and a very large chiller should be installed. It was not economical because the size of the equipment was large compared to the size of the pig house and the initial installation cost was not reasonable. If the wet scrubber is used for cooling, there is a method of continuously changing the low temperature water so that the temperature of the circulating water does not decrease. However, the amount of water used may increase, and it may be difficult to control the pH of the cleaning water. The cooling method of a wet scrubber using chiller to lower the temperature of the cleaning water was not suitable economically and efficiently.

Table 6-3 Prediction results of thermal environment inside the ARVS piglet room using numerical model (Fixed values : ventilation rate (764 CMM), initial air temperature (29°C), and external air temperature (34.1°C)).

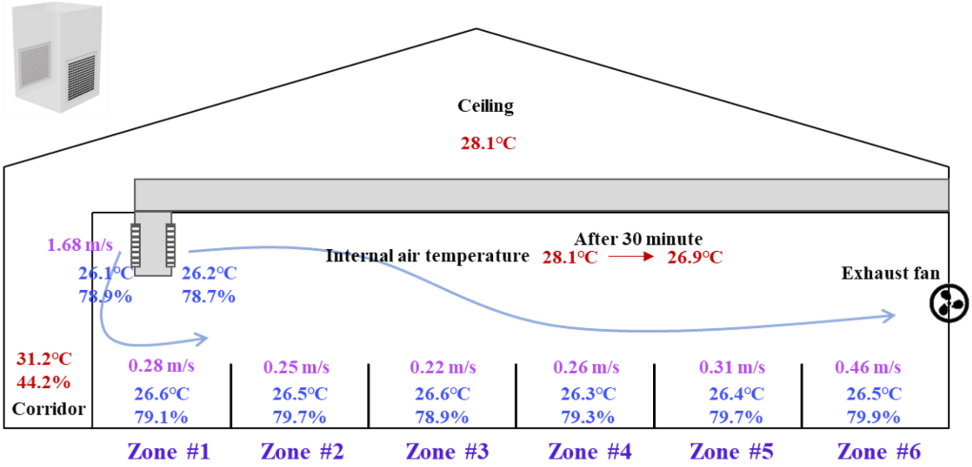
Case	Initial temperature of cleaning water (℃)	Convergence temperature of cleaning water (℃)	Initial air temperature inside the piglet room (℃)	Convergence air temperature inside the piglet room (℃)	Air temperature after wet scrubber (℃)
1	25	26.41	29	32.56	27.27
2	23	25.47	29	31.77	25.63
3	21	24.58	29	30.97	24.04
4	19	23.72	29	30.15	22.34
5	17	22.91	29	29.32	21.95
6	15	22.12	29	28.49	19.05
7	13	21.38	29	27.64	17.39
8	11	20.66	29	26.79	15.74

6.3.1.2. Measurement results of air velocity for convective cooling method

The results of measuring the internal air velocity according to the type of inlet were shown in Fig. 10. The fixed variables in this experiment were the ventilation rate (0.9 min^{-1}), the cleaning water temperature (25°C), and the initial air temperature inside the piglet room (28.1°C). In the case of using the one-way inlet duct, the air velocity in front of the duct was measured as high as 4.44 $\text{m}\cdot\text{s}^{-1}$. The temperature of the discharged air was 25.9°C, and the relative humidity was very high because the air passed through the wet scrubber module. The air flow was predicted as shown in Figure 6-6 (a). The maximum air velocity near the piglet zone was 0.4 $\text{m}\cdot\text{s}^{-1}$ and the average 0.275 $\text{m}\cdot\text{s}^{-1}$ was measured. In particular, the maximum air velocity was observed in zone #1 because the air velocity was high right in front of the inlet duct. According to the rearing standard of Korea (MAFRA, 2016), the air velocity near the piglets is recommended to be less than 0.5 $\text{m}\cdot\text{s}^{-1}$, Song et al. (2005) and Kim et al. (2022) measured the air velocity near the piglets of 0.2 to 0.3 $\text{m}\cdot\text{s}^{-1}$ in summer and 0.01 to 0.05 $\text{m}\cdot\text{s}^{-1}$ in winter. In the ARVS piglet room, the air velocity near the piglet zone were appropriately measured. Looking at the streamline of the air, the distance between the inlet and the outlet was about 10 m, and the direction of the inlet was opposite to the outlet. For this reason, the air stagnation zones were found in zone #4, and zone #5. In these zones, the air velocities of 0.12 $\text{m}\cdot\text{s}^{-1}$ and 0.18 $\text{m}\cdot\text{s}^{-1}$, which were less than half the velocity of zone #1, were measured. In order to solve such an air stagnation zone, a streamline where better air flow was formed inside the piglet room was predicted. The inlet ducts were modified so that the inlet and outlet directions faced each other (two-way inlet duct). As a result of the experiment under these conditions, the air velocity in front of inlet duct was reduced to 1.68 $m \cdot s^{-1}$. However, the average air velocity near the piglet zones increased slightly from 0.28 $m \cdot s^{-1}$ to 0.30 $m \cdot s^{-1}$. Meanwhile, the air stagnation was resolved (Figure 6-6 (b)). The standard deviation of the air velocity near the piglet zones decreased from 0.11 to 0.08. These air velocities were sufficient to lower the sensible temperature with a windchill factor.



(a) Results of measured data with one way inlet duct

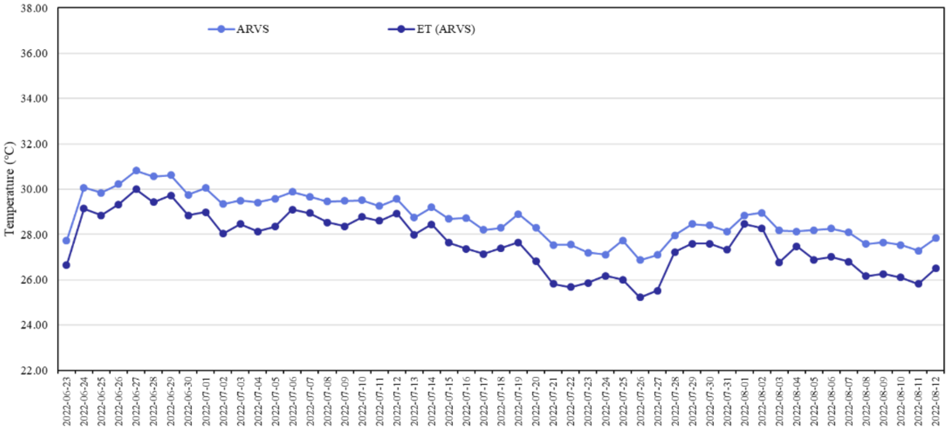


(b) Results of measured data with two way inlet duct

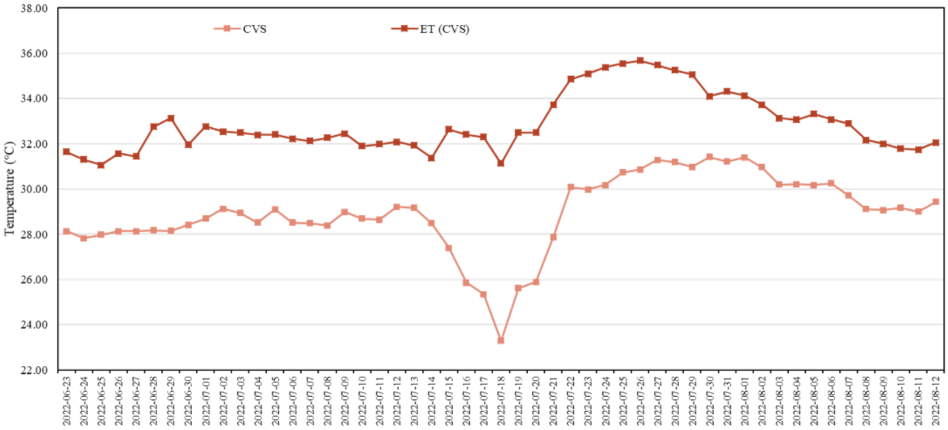
Figure 6-6 Measurement results of internal air temperature, relative humidity, and air velocity according to the inlet type (one way and two way). The operating ventilation rate was 0.9 min^{-1} and the cleaning water temperature was 20°C.

6.3.1.3. Results of calculated effective temperature (ET) of ARVS piglet room and CVS piglet room in summer season

Figure 6-7 shows the calculated ET inside the ARVS piglet room and CVS piglet room. The Figure 6-7 (a) shows the average daily temperature inside the ARVS piglet and calculated ET values during the summer season. During the rainy season (July 20-26), there was a large temperature difference between day and night, which temporarily lowered the average daily temperature. The internal average temperature over the entire period was 28.7℃, and the calculated ET considering relative humidity and air velocity near the piglet was lower than the measured internal temperature. The average ET was 27.6℃ and there was a difference of about −1.09℃ from the measured temperature inside the ARVS piglet room (Figure 6-7 (a)). Since the average air velocity inside the ARVS piglet room was maintained at 0.33 $m \cdot s^{-1}$, the ET could be lower than the measured air temperature during the summer season. On the other hand, the average air velocity near the piglet measured inside the CVS piglet room was 0.06 $m \cdot s^{-1}$. Low air velocity could increase the value of ET. From July 16th to 20th, the low temperature was measured because the piglets moved to the growing pig room and they were not in the piglet room. Therefore, the measured average air temperature and ET inside the CVS piglet room were 28.9℃ and 32.9℃, respectively, and the difference was 3.94℃ (Figure 6-7 (b)). That was the piglets inside the CVS piglet room could feel hotter than the actual measured temperature.



(a) Internal air temperature and ET inside the ARVS piglet room



(b) Internal air temperature and ET inside the CVS piglet room

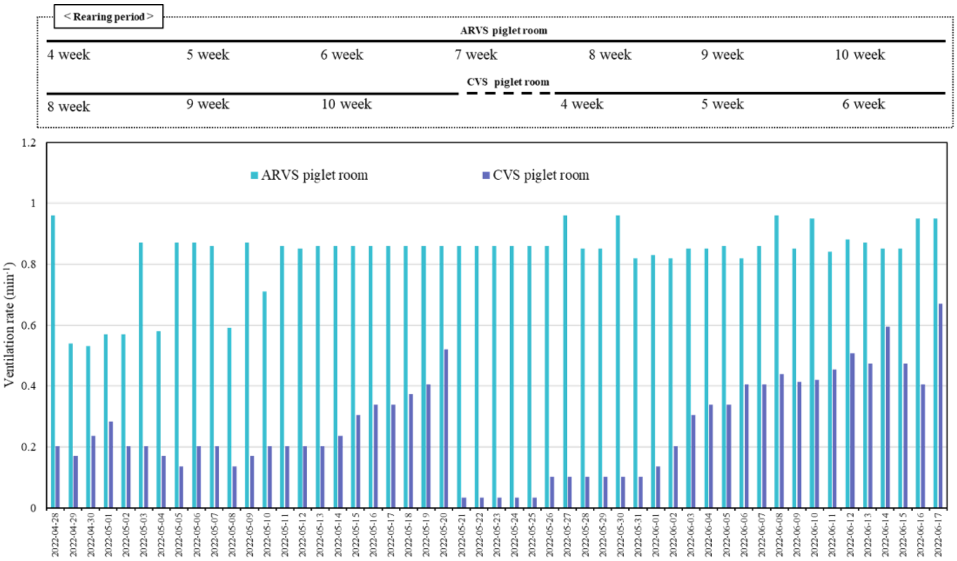
Figure 6-7 Results of measured air temperature and calculated ET inside the ARVS piglet room and CVS piglet room in summer season.

6.3.2. Results of measured ventilation rate of spring and summer seasons

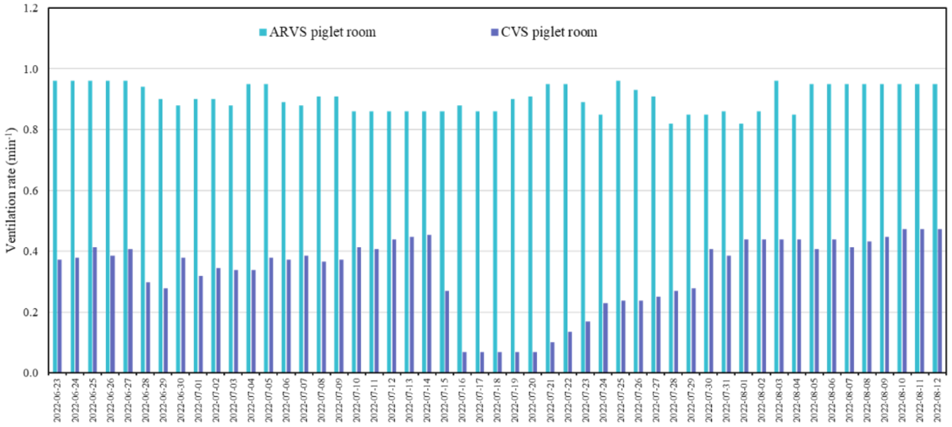
Figure 6-8 shows the measurement results of ventilation rates in spring and summer seasons. The ventilation rates of AVRS piglet room and CVS piglet room were plotted according to the rearing period. The ventilation rates of ARVS piglet room were operated 0.83 min^{-1} and 0.91 min^{-1} on average in spring and summer, respectively. Also, the ventilation rates of CVS piglet room were operated 0.26 min^{-1} and 0.33 min^{-1} on average in spring and summer.

In spring, at the initial period (4 weeks of age), because the external air temperature was low (average 14°C), the ventilation rate was operated at about 0.57 min^{-1}, and the ventilation rate controlled by the automatically algorithm according to the external air temperature was operated (Figure 6-8 (a)). On the other hand, in CVS piglet room, ventilation rate increased gradually from 8 to 10 weeks of age. Because the external air temperature was low (average 14°C), the ventilation rate decreased to 0.14 min^{-1} and increased to 0.52 min^{-1} just before moving to the growing pig room. After 5 days, from the start of rearing piglets (4 weeks age), the ventilation rate was operated 0.1 min^{-1}, and as the external air temperature increased, the ventilation rate was gradually increased.

In summer, the ventilation rate of ARVS piglet room was maintained very high with an average of 0.91 min^{-1} for all periods (Figure 6-8 (b)). The average external temperature was 25°C, but the temperature rose to a maximum of 33°C, resulting in a high temperature condition. Also, during the experimental period of summer season, the target area was the rainy season. Therefore, the automatically control algorithm increased the ventilation rate to control the air temperature and humidity inside the ARVS piglet room when it was hot and humid conditions. On the other hand, in CVS piglet room, the ventilation rate was operated at 0.45 min^{-1}, regardless of external weather conditions, until moving to the growing pig room. Similar to the results of spring season, starting with a low ventilation rate at the beginning of rearing piglets, the ventilation rate gradually increasing was measured.



(a) Ventilation rate of ARVS piglet room and CVS piglet room in spring



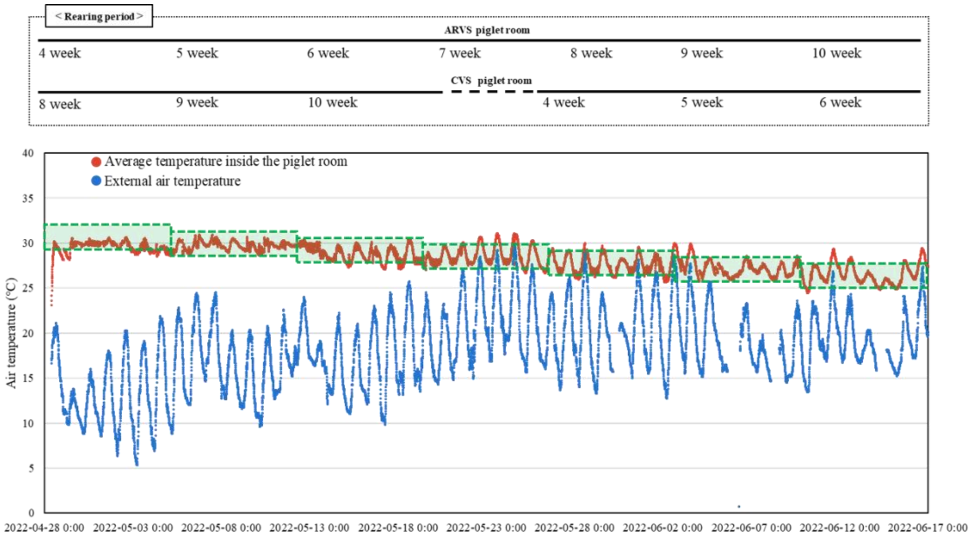
(b) Ventilation rate of ARVS piglet room and CVS piglet room in summer

Figure 6-8 Ventilation rate of ARVS piglet room and CVS piglet room in spring and summer seasons during the rearing period of piglets.

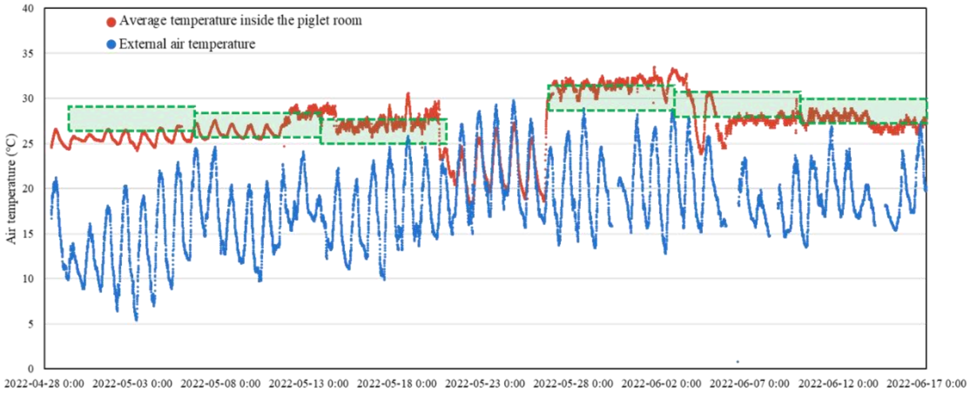
6.3.3. Results of measured air temperature inside the ARVS piglet room and the CVS piglet room in spring and summer

Figure 6-9 shows the internal and external air temperature data measured through the validation experiment in spring season. In spring, the temperature difference between day and night was large, with a maximum of about 15°C per day. If the temperature deviation is large, there is a very high possibility that temperature stress can occur in the piglet room. In particular, it was difficult to control the temperature inside the piglet room during spring season. In early May, the external air temperature dropped to a minimum of 5°C, and the temperature conditions were similar to those of winter. There were piglets of 8 weeks age inside the CVS piglet room, and the air temperature lower than the piglets' thermal demand (26-28°C) was measured (Figure 6-9 (b)). As the daytime temperature gradually increased, on May 8, when the external air temperature rose to 25°C, it was possible to satisfy the piglets' thermal demand. On May 12, the dust was wiped off the surface of the temperature sensor and the malfunctioning sensor was replaced at the CVS piglet room. The piglets of 10 weeks age inside the CVS piglet room had high heat production, and the internal temperature could be maintained at the appropriate level. Also, the piglets could move to the growing pig room while maintaining the 0.4 min^{-1} of ventilation rate because the external air temperature increased. When rearing of piglets (4 weeks age) was started, the radiator was operated to increase the air temperature inside the CVS piglet room. Due to the low ventilation rate and the operation of the radiator, the internal temperature was maintained higher than piglets' thermal demand (31°C). After June 3, the radiator inside the CVS piglet room was stopped as the external temperature rose during the daytime.

When the piglets (4 weeks age) began to be raised inside the ARVS piglet room, the external temperature was very low (5℃) (Figure 6-9 (a)). In order to satisfy the piglets' thermal demand (31℃), the automatic algorithm controlled the ventilation rate in real time. In particular, although there was a large deviation in the external air temperature, the operating algorithm of ARVS was able to maintain the appropriate internal temperature for the entire rearing period. However, since May 23, the daytime temperature has risen to about 30℃, and the air temperature inside the ARVS piglet room rose to 32℃. Also, the required temperature of piglets decreased as the piglets age, so the frequency of exceeding the control temperature level began to increase. Around June 7, the external temperature temporarily decreased due to rain. However, since the piglets inside the ARVS piglet room had high heat production due to increased body weight, the internal air temperature could be maintained at an appropriate level. As a result of rearing piglets using ARVS in the spring, it was successful in preventing temperature stress and satisfying the piglets' thermal demand. However, it was difficult to prevent high temperature stress during the period when the daytime temperature rose rapidly. Since higher temperature can occur in summer, it was attempted to control the rearing temperature of piglets based on the evaluation results of the cooling methods.



(a) Measured air temperature inside the ARVS piglet room in spring season

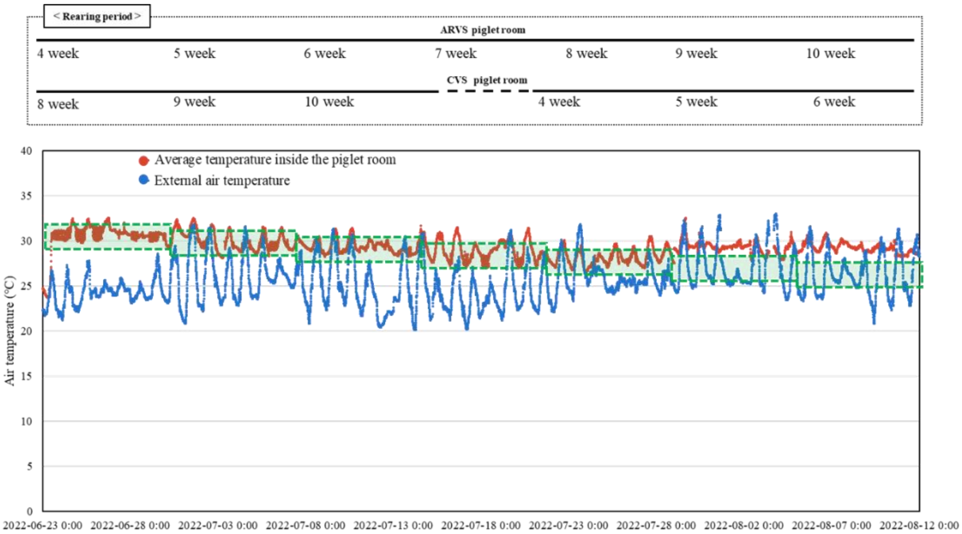


(b) Measured air temperature inside the CVS piglet room in spring season

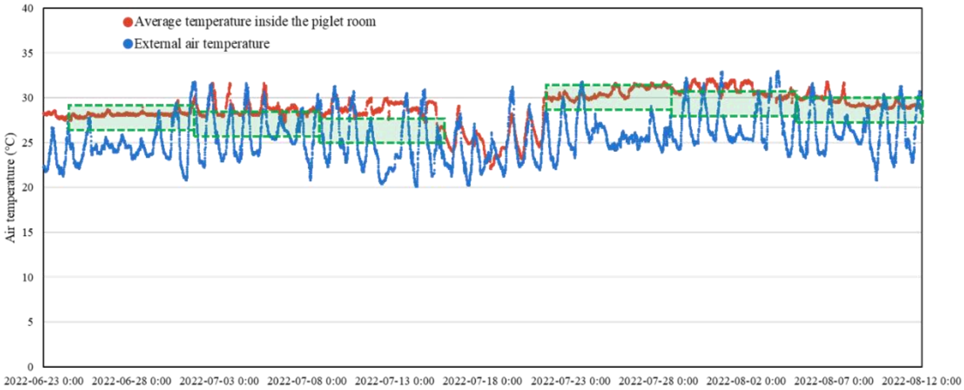
Figure 6-9 Internal air temperature and external air temperature of ARVS piglet room and CVS piglet room in spring season during the rearing period of piglets.

Figure 6-10 shows the air temperature data inside the ARVS piglet room and CVS piglet room in summer season. The frequency of occurrence of high temperature increased compared to spring season, with an average of 25.5℃ and a maximum of 33.0℃. When the piglets were young, the piglets' thermal demands were high, so the internal temperature of ARVS piglet room could be properly maintained (Figure 6-10 (a)). In preparation for the high temperature in summer, the external temperature was higher than the inside of the ARVS piglet room because the method to lower the sensible temperature of piglets was applied. Pigs feel different temperatures due to windchill effect. The average air velocity near the piglet zone inside the ARVS piglet room with two-way inlet duct was 0.3 $m \cdot s^{-1}$. When the ambient temperatures of piglets were 34, 32, 30, and 28°C, the sensible temperature felt by piglets were 31.1, 29.2, 26.6, and 24.7°C, respectively. Therefore, since the operating algorithm could control the maximum ventilation rate when the internal temperature was high, the sensible temperature lower than 2°C could be satisfied even in the hottest situation.

On the other hand, the internal temperature of CVS piglet room was measured differently from the general temperature distribution (Figure 6-10 (b)). The reason for this was the rain continued during the summer experimental period and the external humidity was very high. Accordingly, as the relative humidity inside the CVS piglet room increased, the heating device was operated to lower the relative humidity according to the judgement of the workers. In particular, around July 3, when the external temperature increased rapidly, the internal temperature, which exceeded the piglets' thermal demand (28°C), increased to 32°C. Then, high temperature stress occurred continuously for 5 days. In addition, the air temperature inside the CVS piglet room did not satisfy the piglets' thermal demand (26°C) before the piglets moved to the growing pig house.



(a) Measured air temperature inside the ARVS piglet room in summer season

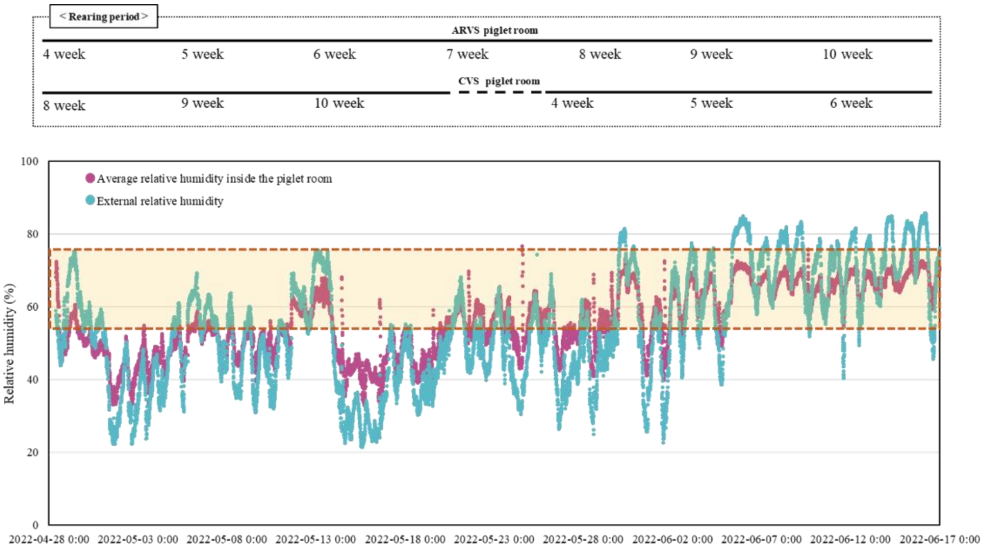


(b) Measured air temperature inside the CVS piglet room in summer season

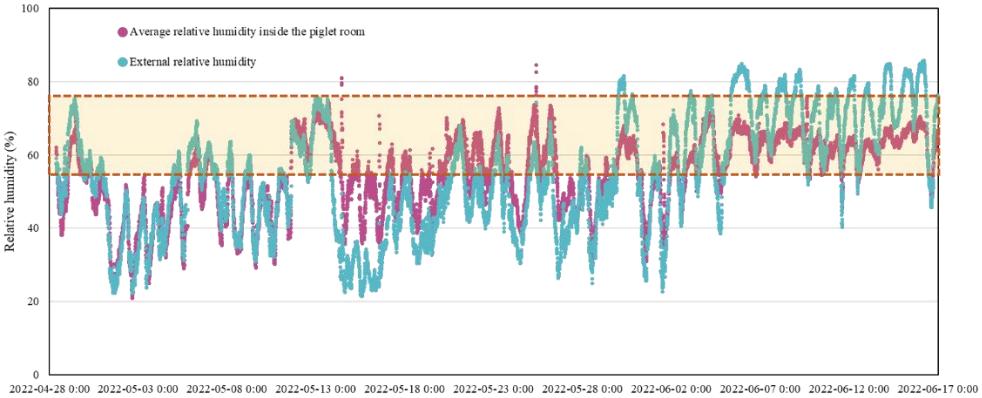
Figure 6-10 Internal air temperature and external air temperature of ARVS piglet room and CVS piglet room in summer season during the rearing period of piglets.

6.3.4. Results of measured relative humidity inside the ARVS piglet room and the CVS piglet room in spring and summer

Figure 6-11 shows the internal and external relative humidity data measured through the validation experiment in spring season. Since dry weather frequently occurred in spring, the relative humidity inside the piglet room was often low. The average relative humidity outside was 54.4%, and in the direst weather, the relative humidity was 21.4%. After June 1, rainfall occurred and the external relative humidity increased to a maximum of 85.7%. In the case of CVS piglet room (Figure 6-11 (b)), external air was used directly for ventilation, and the temperature inside the piglet room was increased by using the radiator. Accordingly, in the driest case, ARVS piglet room and CVS piglet room were measured to be 32.9% and 20.8%, respectively. The wet scrubber module in ARVS was able to increase the humidity of the air. However, as the humidified air after cleaning in the wet scrubber passed through the solar heat coil, the air temperature rose and the relative humidity could be lowered. In particular, because the external temperature was low during the experiment, the solar module was operated frequently. Although it rained, the relative humidity inside the CVS piglet room was measured within an appropriate range. The reason for this was that the relative humidity was low because the piglets inside the CVS piglet room were young, and the radiator was fully operated.



(a) Measured relative humidity inside the ARVS piglet room in spring season

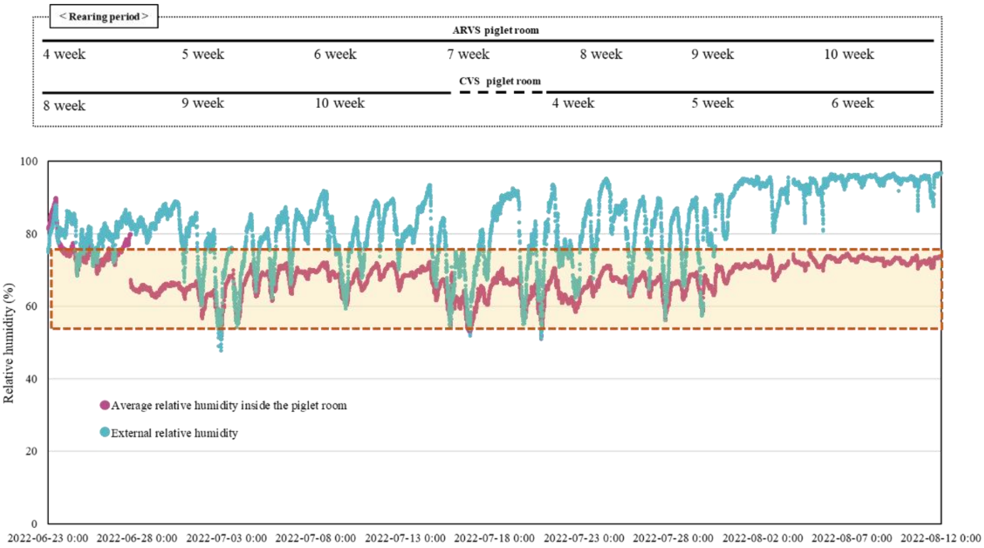


(b) Measured relative humidity inside the CVS piglet room in spring season

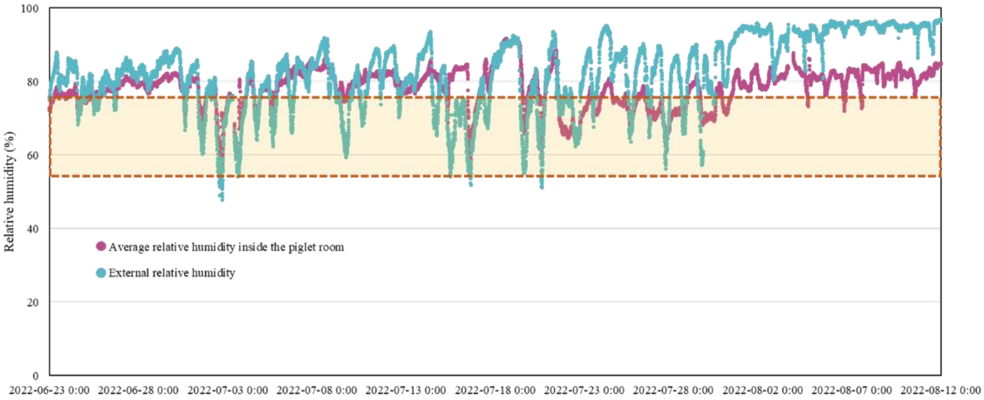
Figure 6-11 Internal and external relative humidity of ARVS piglet room and CVS piglet room in spring season during the rearing period of piglets.

Humidity problems can be most likely to occur during the summer rain season. During the summer experiment, continuous rainfall occurred and the average and maximum external relative humidity were 82.6% and 97.3%, respectively. However, the relative humidity inside the ARVS piglet room was maintained optimally during summer season (Figure 6-12 (a)). By the automatically controlled algorithm, the relative humidity could be appropriate by controlling the ventilation rate and the EAMR. Although the fluctuations occurred similarly to the trend of the external relative humidity, the internal relative humidity of ARVS piglet room was maintained within an appropriate range. The ARVS succeeded in properly maintaining the relative humidity inside the piglet room during the rainy season in summer.

On the other hand, the relative humidity inside the CVS piglet room was measured to be very high during the summer experiment. The average relative humidity inside the piglet room was 78.3%, and it rose to a maximum of 91.7%. Since the ventilation rate of CVS piglet room was operated 0.4 min^{-1} in summer, the relative humidity inside the piglet room was very similar to the trend of the external relative humidity. In particular, due to the heat inside the piglet room, the relative humidity was measured to be about 20% lower than the external relative humidity. At the beginning of piglet rearing (4 weeks age), the internal temperature was high and the relative humidity was within the appropriate range, but it rose again and the humidity exceeded 80% was measured (Figure 6-12 (b)). In conclusion, CVS failed to control internal humidity in hot and humid weather conditions in summer, and ARVS was evaluated to have excellent performance in humidity control.



(a) Measured relative humidity inside the ARVS piglet room in summer season



(b) Measured relative humidity inside the CVS piglet room in summer season

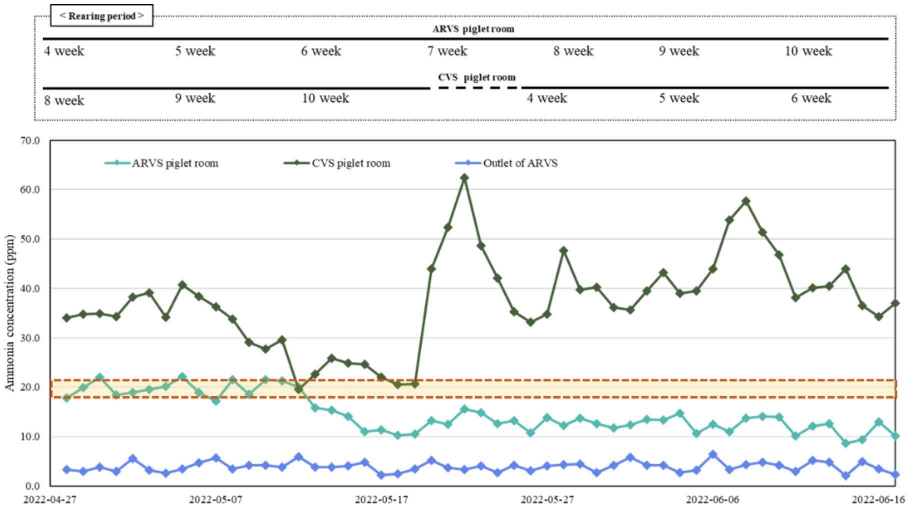
Figure 6-12 Internal and external relative humidity of ARVS piglet room and CVS piglet room in summer season during the rearing period of piglets.

6.3.5. Results of measured ammonia concentration inside the ARVS piglet room and the CVS piglet room in spring and summer

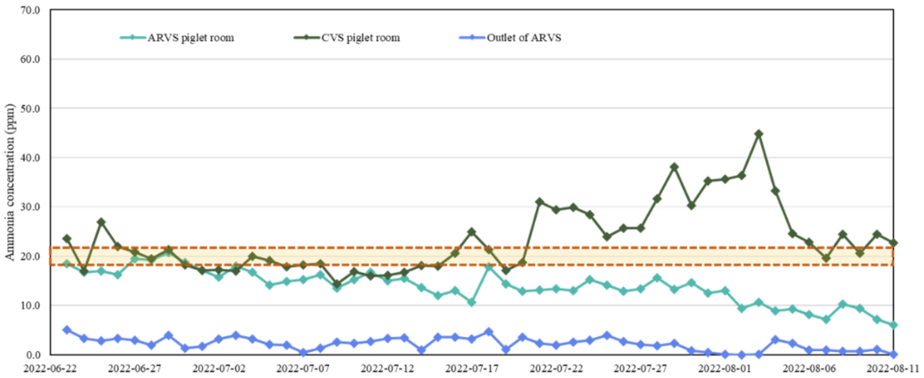
Figure 6-13 shows the ammonia concentration measured through the validation experiment in spring and summer seasons. The measurement locations were 1.5 m in front of the ventilation fan inside the ARVS piglet room and CVS piglet room. In ARVS, ammonia concentration was reduced by the wet scrubber module. Therefore, the concentration at the outlet of the external air mixing module in ARVS was measured and compared with the concentration of CVS piglet room. Through this, it was possible to simultaneously evaluate the gas environment inside the piglet room and the external ammonia gas emission.

The internal ammonia gas concentration of ARVS piglet room could be maintained below the appropriate concentration (20 ppm) in both spring and summer seasons. This was because the ventilation rate of ARVS was maintained high during the experiment period, and the internal gas could be sufficiently removed. In spring, the average, maximum, and minimum concentration of ammonia gas in ARVS piglet room were 14.7, 22.1, and 8.7 ppm, respectively (Figure 6-13 (a)). At the beginning of the rearing period, because the external air temperature deviation was large, the ventilation rate was controlled in real time. Therefore, it was maintained in the range of 20 ppm concentration, and as the ventilation rate gradually increased, the ammonia concentration was maintained within about 10 ppm. On the other hand, the ammonia concentration inside the CVS piglet room was measured to be very high in spring season, and the average, maximum, and minimum measured values were 37.3, 62.3, and 19.5 ppm, respectively. Just before moving to the growing pig room on May 17, as the ventilation rate of the CVS piglet room increased, the internal ammonia concentration decreased to 19.5 ppm. When there was no piglet in the CVS piglet room, the maximum concentration of ammonia gas was measured because the ventilation fan was not operated. It was confirmed that although the ventilation rate of CVS piglet room increased as the age of piglets increased, the ventilation rate was insufficient to reduce the ammonia concentration generated of the manure inside the CVS piglet room. The average, maximum, and minimum concentration at the outlet of ARVS piglet room were 3.9, 6.4, and 2.1 ppm, respectively. Ammonia concentration emitted from the CVS piglet room was on average 10.2 times higher than those of ARVS piglet room. In addition, the ammonia removal efficiency of the wet scrubber module was 72% on average, and the maximum removal efficiency was 87.5%.

The ammonia measurement results in summer were shown in Figure 6-13 (b). The average, maximum, and minimum ammonia concentrations in ARVS piglet room were measured to be 13.9, 20.7, and 6.1 ppm, respectively. Since the ventilation rate in spring and summer was operated similarly, the internal ammonia concentration of ARVS piglet room was maintained at an appropriate level. On the other hand, the average, maximum, and minimum ammonia concentrations inside the CVS piglet room were measured to be 23.4, 44.8, and 14.4 ppm, respectively. From 22 June to 15 July, the CVS piglet room was operated with high ventilation rate, and the internal ammonia concentration was measured within 20 ppm. Since it was raining at this time, all the windows and doors of the CVS piglet room were opened to control humidity. The intake of fresh air was increased, and the ammonia concentration could be lowered. When the young piglets (4 weeks age) were raised on July 21st, the ammonia concentration started to increase again due to low ventilation rate, and was measured to a maximum of 44.8 ppm. Ammonia emission concentration from ARVS piglet room in summer were very low. The concentration was measured as an average of 2 ppm, and the concentration emitted from CVS piglet room was measured to be 10.5 times higher than those emitted from ARVS piglet room. In conclusion, through ARVS in spring and summer, it was effective to lower the ammonia concentration inside the piglet room and reduce the ammonia concentration emitted to the outside.



(a) Ammonia concentration inside and outlet of ARVS piglet room and CVS piglet room in spring



(b) Ammonia concentration inside and outlet of ARVS piglet room and CVS piglet room in summer

Figure 6-13 Measured ammonia concentration of ARVS piglet room and CVS piglet room. The measurement locations were the inside of the ARVS and CVS piglet rooms and the outlet of the ARVS piglet room. Since the measured value of CVS was the same as the emitted value, it was compared with the concentration at the outlet of ARVS piglet room.

6.3.6. Measurement results of complex odor and dust concentration in spring and summer

The results of measuring the odor concentration in the spring and summer were shown in the Figure 6-14. The complex odors emitted from the ARVS piglet room and CVS piglet room were sampled, and odor concentrations were evaluated through the air dilution olfactory method. The average complex odor concentration emitted from ARVS piglet room and CVS piglet room were measured to be 141.4 and 672.6 OU, respectively. The trend of complex odor concentration was comparable with the ventilation rate. At the time of measurement, the ventilation rate of ARVS piglet room was maintained as high as 0.91 min^{-1} on average. As a result, the odor concentration emitted was very low overall, and on May 20, it was the highest at 448 OU. On the other hand, the concentration of emitted odor was high at CVS piglet room with low ventilation rate, and the highest 2080 OU was measured on May 20. On May 30, as the ventilation rate increased, the odor concentration decreased, and when the ventilation rate of 0.67 min^{-1} was operated, the lowest odor of 1000 OU was emitted. On July 15, the measured odor concentration was very low (96.5 OU) because the piglets in CVS piglet room moved to the growing pig room. After that, because young piglets (4 weeks age) were raised, the measured odor concentration was evaluated to be relatively low.

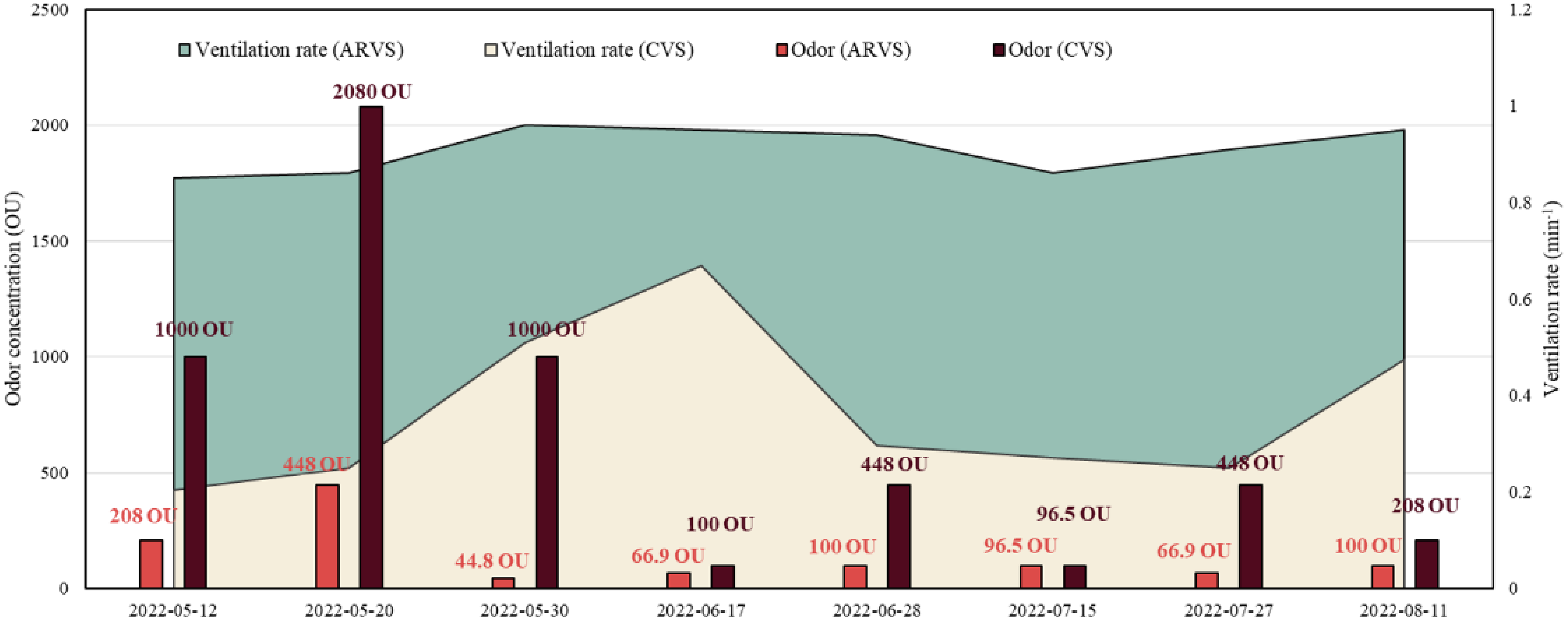
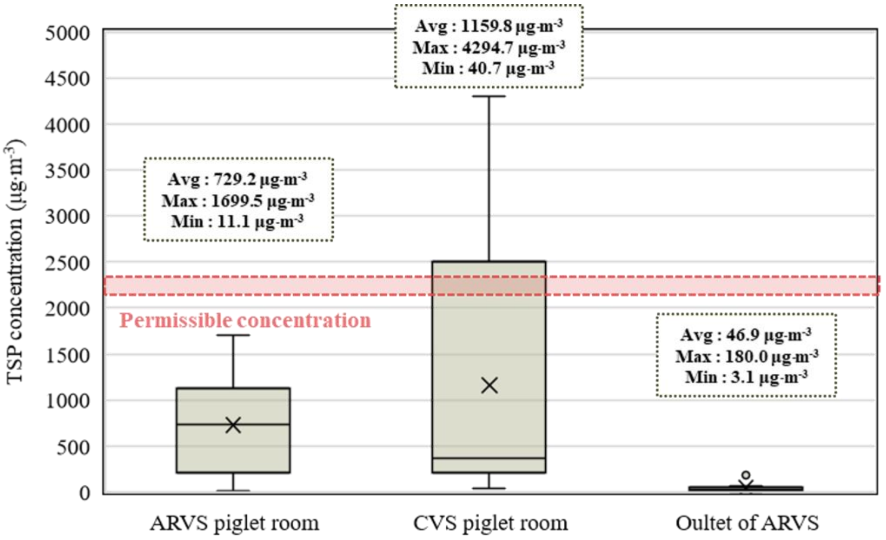
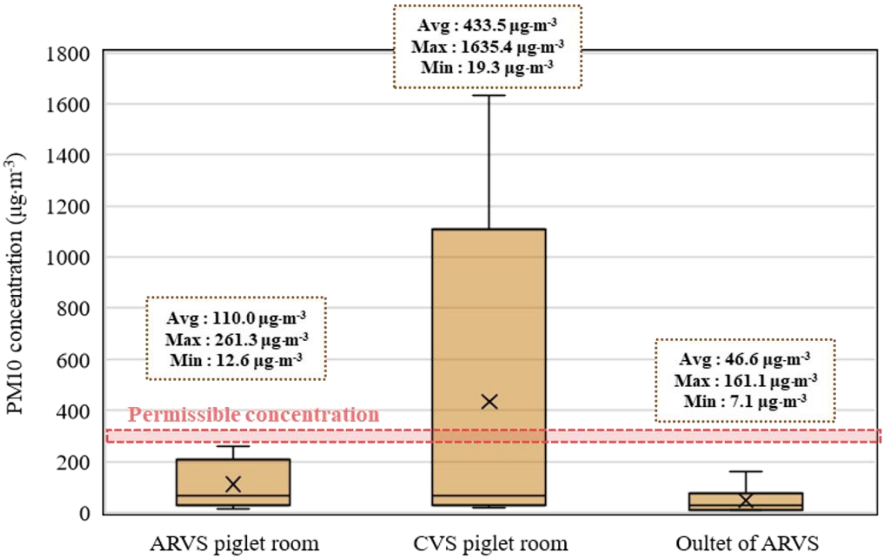


Figure 6-14 Results of complex odor concentration emitted from the ARVS piglet room and CVS piglet room and the measured ventilation rate data in spring and summer seasons.

Figure 6-15 shows the results of dust concentration (TSP and PM10) measurement during the experiment period of spring and summer seasons. The TSP concentration inside the ARVS piglet room was measured to be an average of 729.2 μg·m^{-3} and a maximum of 1699.5 μg·m^{-3}, which was 1.6 times and 2.5 times different from the measured values of 1159.8 μg·m^{-3} and 4294.7 μg·m^{-3} inside the CVS piglet room, respectively (Figure 6-15 (a)). In particular, in CVS piglet room, it was evaluated that there was a risk of respiratory diseases exceeding the permissible concentration level. The TSP concentration of outlet was measured to be very low as expected, with an average of 46.9 μg·m^{-3} and a maximum of 180 μg·m^{-3}. The TSP removal efficiency of the wet scrubber was evaluated to be very high with an average of 89%, which was similar to the winter validation experiments. The PM10 concentration inside the ARVS piglet room was measured within the permissible concentration level with an average of 110.0 μg·m^{-3} and a maximum of 261.3 μg·m^{-3} (Figure 6-15 (b)). However, in the case of CVS piglet room, the average of PM10 concentration was 433.5 μg·m^{-3} and the maximum was 1635.4 μg·m^{-3}, which greatly exceeded the permissible concentration. The reason that the concentration of PM10 was significantly higher than that of TSP inside the CVS piglet room was considered to be the effect of particle size and ventilation rate. TSP generally means all airborne dust with a particle size of 50 μm or less, and PM10 means dust with a particle size of 10 μm or less. Therefore, this was because the amount of suspended PM10 was larger than the amount that was removed inside the CSV piglet room with the low ventilation rate. The PM10 removal efficiency of the wet scrubber was 59% on average, which was similar to the experimental results in winter.



(a) TSP concentration



(b) PM10 concentration

Figure 6-15 Results of dust concentration (TSP and PM10) inside the ARVS and CVS piglet rooms and outlet of ARVS piglet room.

6.3.7. Comparison of weight of piglets in ARVS piglet room and CVS piglet room

The results of measuring the weight of 10-week-old piglets in the spring and summer seasons were shown in the Table 6-4. Piglets of ARVS piglet room weighed more than piglets of CVS piglet room in both seasons. During the spring, the average weight difference of piglets in the two piglet rooms was about 2.8 kg, and the weight gains in ARVS and CVS were 0.178 kg·day^{-1} and 0.122 kg·day^{-1}, respectively. It means that the ARVS can make faster to slaughter weight, similar to the results of winter season. Meanwhile, there was a 1 kg difference in the weight in summer season, and the weight gains were calculated as 0.214 kg·day^{-1} and 0.194 kg·day^{-1}, respectively. Therefore, it was confirmed that the weight gains of ARVS were improved than those of CVS regardless of the season.

Comparing the measured weights of all seasons, a significant difference was found in the weight gains of piglets according to the season. In winter season, the weight gains of ARVS and CVS were 0.267 kg·day^{-1} and 0.235 kg·day^{-1}, respectively (chapter 5). The weight gain in the winter season was the highest, and the that of spring was the lowest. When the ambient temperature of piglets is low in winter, the weight gain can be reduced by increasing metabolism for heat generation. In summer, the ambient temperature is high and the amount of drinking water increases, which may decrease the weight gain (Huynh et al., 2005). However, in winter, ARVS controlled the piglets' thermal demand well, resulting in high weight gain. In CVS piglet room, although the CVS did not satisfy the piglets' thermal demand, a relatively high weight gain was measured because the heater was operated as much as possible to prevent the low temperature stress when it was very cold. In summer, the external weather condition was rainy, so it did not have a significant effect on the drinking water of piglets. Therefore, it was considered that the weight gain was the least during the spring, when temperature deviations frequently occurred.

Table 6-4 Results of weight of piglets (10 weeks) in ARVS piglet room and CVS piglet room.

		Total weight of 20 heads (kg)	Average weight (kg)
Spring season	ARVS piglet room	578.2	28.9
	CVS piglet room	521.6	26.1
Summer season	ARVS piglet room	613.7	30.7
	CVS piglet room	594.0	29.7

6.4. Conclusions

In this study, the validation experiment was conducted by installing ARVS in a piglet house. The validation experiments for spring and summer season were conducted with the same procedure as for the experiments in winter. In order to prepare for the high temperature period in summer, the experiment about the cooling method was conducted.

As a result of evaluating the evaporative cooling effect, it was analyzed that the wet scrubber module in ARVS had a similar effect to the cooling tower. When the cooling effect according to the temperature of the cleaning water inside the wet scrubber module was compared, the target temperature of the cleaning water to reach the proper air temperature inside the piglet room was selected to be about 17 to 20℃. The sum of the calorific value required to cool the air inside the piglet room and the heat production of piglets was 69059.7 $\text{kcal}\cdot\text{h}^{-1}$. Therefore, when maintaining the cleaning water temperature sufficiently low as 17.1℃, it was possible to maintain the proper air temperature inside the ARVS piglet room. However, as a result of calculating the cleaning water temperature using the numerical model, sufficient cooling was possible only when the cleaning water temperature was maintained below 13℃. Here, the required cooling capacity was estimated to be 8536.02 $\text{kcal}\cdot\text{hr}^{-1}$, which was 4.5 times higher than that of a general chiller. It was not economical because the size of the equipment was large compared to the size of the pig house and the initial installation cost was not reasonable.

For the experiment of the convective cooling method, the effect of improving the air velocity near the piglet was evaluated. The inlet ducts were modified so that the inlet and outlet directions faced each other (two-way inlet duct). As a result of the experiment under these conditions, the air velocity in front of inlet duct was reduced to 1.68 $m\cdot s^{-1}$. However, the average air velocity near the piglet zones increased slightly from 0.28 $m\cdot s^{-1}$ to 0.30 $m\cdot s^{-1}$. As a result of evaluating the ET, there was a difference of about −1.09℃ from the measured temperature inside the ARVS piglet room. Also, the measured average air temperature and ET inside the CVS piglet room were 28.9℃ and 32.9℃, respectively, and the difference was 3.94℃.

In spring and summer, the ventilation rate of ARVS piglet room was generally high. Accordingly, the temperature inside the ARVS piglet room was properly controlled in the spring when the temperature difference was large. On the other hand, although it was in a high temperature state during summer, it was at the appropriate level considering ET. The humidity problem could occur due to the continuous rainfall in summer, but the humidity inside the ARVS piglet room was maintained optimally compared to the CVS piglet room. Ammonia emission concentration from ARVS piglet room in summer were very low. The concentration was measured as an average of 2 ppm, and the concentration emitted from CVS piglet room was measured to be 10.5 times higher than those emitted from ARVS piglet room. It was very effective in reducing not only ammonia but also complex odor. Similar to the results of the winter experiment (chapter 5), the piglets' weight of ARVS piglet room was greater than that of CVS piglet room, and a positive result was obtained for pig productivity.

Chapter 7. Conclusions

7.1. General conclusions

This thesis has great significance to improve the representative problems in pig farm, such as pig productivity (rearing environment & energy cost), livestock disease, and environment load (ammonia and complex odor emission). To overcome these problems, in this study, the ARVS was developed. The concept of ARVS was to reuse the air inside the pig room after it cleaned through the wet scrubber. It has the advantage of being able to reuse the thermal energy inside the pig room. Accordingly, it was possible to increase the ventilation rate of the pig room, then there was an effect of improving the rearing environment. In particular, since the thermal energy inside the pig room was reused, it was very effective in reducing heating energy cost in winter season. In addition, since the air was circulated and used, the inflow of external air was very small. Even in the ARVS, because there were three stage of sterilization, the prevention of airborne transmission of diseases was excellent. The amount of air discharged after cleaning with wet scrubber was less than that of conventional ventilation type. In particular, the removal efficiency was maintained high, and the concentration of harmful gas (ammonia) and complex odor was very low.

First, in chapter 3, field experiments were conducted to analyze problems and evaluate applicability to the target pig house. the main problems of the internal environment inside the pig house were identified through the field experiments and CFD simulation of the experimental piglet house. The accuracy and computational efficiency of the CFD model were validated based on the field measurement data, and case studies were conducted based on the validated CFD model. Based on the

CFD computed results, various aerodynamic analyses were conducted according to various conditions such as outdoor weather conditions, the ventilation rate, and inlet types. In addition, by applying the ARVS to the developed CFD model, the suitability of the ARVS was evaluated according to the ventilation rate, EAMR, and removal efficiency.

In chapter 4, an optimal numerical model for predicting the internal rearing environment of piglet house was developed to suggest a design and operation plan for the ARVS. This numerical model was designed based on various balance equations, and the environment inside the piglet room was calculated according to the heat, moisture, and gas generation mechanisms of the ARVS. Therefore, the developed numerical model could be used generally through farm information such as farm size, age, and weather condition. From these results, the operation plan of the ARVS can be suggested using this numerical model. Based on the optimal design of this study, scale-up experiment and application of the ARVS will be conducted.

In chapter 5, the ARVS was designed and developed to apply on piglet room. The developed ARVS was applied to the actual pig house, and validation experiments were conducted during the winter season. For the design and combination of basic modules, the results of previous researches were used (chapter 3 and 4). When installing the modules, the semi-closed loop ventilation type was considered. In addition, automatic algorithm was developed and applied to all ARVS to enable real-time automatic control. For the validation experiment, a number of sensors inside the piglet room were installed to collect environmental data in real-time. In addition, in order to evaluated the pig productivity, data such as stress index, weight gain, livestock disease, and odor were collected.

In chapter 6, the validation experiment was conducted by installing ARVS in a piglet house. The validation experiments for spring and summer season were conducted with the same procedure as for the experiments in winter. In order to prepare for the high temperature period in summer, the experiment about the cooling method was conducted.

In conclusion, after completing the design and development of ARVS, as a result of conducting validation experiment, the four representative problems were improved using this entire system. By applying ARVS and increasing the ventilation rate of the piglet room, the rearing environment inside the piglet room was maintained optimally regardless of the external weather conditions. Accordingly, the weight gain of piglets was improved, which had a positive effect on pig productivity. Meanwhile, since the internal thermal energy inside the piglet room was reused, even if the ventilation rate in winter could be increased, the air temperature could be properly maintained without operating the heating device. Through this, energy consumption was reduced, and the annual electricity consumption was calculated to be lower than that of CVS piglet room. The disease contamination rate was less than 1%, and the piglet room was maintained in a very clean state. Odor and ammonia emission were also significantly improved. Since the removal efficiency of the wet scrubber was excellent and the amount of discharged air was small, it was possible to be free from regulations and complaints of odor emission.

7.2. Future research

This study developed a technology to improve the four representative problems of pig house. As mentioned in chapter 3 and chapter 4, this study designed and developed the ARVS. If the ARVS are actually installed on other pig farms, there are many things to consider at the design stage. There are various variables such as number of pigs, environment conditions, and location of outlets for each pig farm. Accordingly, the capacity design of the modules in the ARVS may vary. With the design method and capacity determination method suggested in chapter 3 and chapter 4, it is possible to design individually considering these farm conditions. In the future, it is necessary to design and install the ARVS for pig farm under different conditions, and then conduct additional validation experiments.

In this study, the ARVS was used to control the internal temperature of piglet room without the heating device. Although it succeeded in reducing heating energy consumption through this, ARVS piglet room used more equipment than CVS piglet room. In other words, it is necessary to evaluate the total energy consumption including the total amount of electricity used annually.

Furthermore, disease contamination was evaluated during validation experiment in spring, summer, and winter. As a result of the disease contamination evaluation, it was evaluated that the inside of the piglet room was clean. However, the cleanliness for disease inside the ARVS piglet room and CVS piglet room was almost similar. In order for the results of the disease contamination of the two piglet rooms to differ more clearly, the disease should occur. It is not an appropriate method to infect piglets by causing disease for the experiment. In particular, since it is difficult to predict whether a disease will occur, experiments on the disease are extremely limited. Therefore, it is necessary to analyze through long-term disease monitoring in pig farms where the ARVS is installed and operated.

Finally, the entire system should be considered to be installed economically because farmers can use this system usefully. However, there might be limitation to design the size and type for each pig farm. It can be very expensive to install with huge system. In this study, the initial installation cost was about 100 million won. Therefore, it is necessary to optimize the size and type of system considering the actual user and pig farm.

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국문초록

국내 농업생산액은 꾸준히 증가하는 가운데, 육류소비량의 증가에 따른 대량생산이 요구됨에 따라, 농업생산액 중에 축산업의 생산액은 약 40% 가량을 차지하고 있다. 이중에서도 가장 많은 비중을 차지하고 있는 양돈 산업은 대량생산을 위하여, 양돈 사육시설의 대형화, 밀집사육, 자동화 등이 늘어나고 있는 추세이다. 이러한 양돈산업의 발전을 저해할 수 있는 현안들은 대표적으로 4가지가 있다. 1) 돈사 내부의 생육환경 조절의 어려움, 2) 에너지 문제, 3) 양돈 질병, 4) 악취 및 유해가스에 의한 환경부하가 있다.

먼저, 대형화된 시설에서 돼지를 사육하는 경우에는 내부 생육환경이 열악해지고 균일성과 안정성이 떨어질 수 있다. 특히, 돼지들은 온도, 습도, 가스 환경에 예민하며, 열악한 사육환경이 조성되는 경우에는 면역력이 약해지고 질병에 취약해질 수 있으며, 소화불량, 식욕저하 등에 따른 증체량 감소와 같은 문제를 야기할 수 있다. 이러한 양돈 시설 내부의 환경조절을 위해서는 주로 환기를 실시하여, 돈사 내부의 열, 수분, 가스 등을 배출하고 신선한 공기를 유입시킨다. 그러나 겨울철에는 외부 기온이 낮기 때문에, 돼지들의 호흡기 질병 발생을 예방하기 위하여, 환기를 거의 시키지 못하는 실정이다. 온도조절을 위하여 환기량을 매우 낮게 운영하게 되면, 돈사 내부의 습도, 이산화탄소, 암모니아, 분진 등이 축적되어 매우 열악한 환경이 조성된다. 또한 여름철에는 극심한 혹서기 및 장마철로 인하여 환기를 수행하여도 내부 열, 수분을 충분히 조절하지 못할 수 있다. 이러한 내부 환경을 조절하기 위하여, 냉난방기를 가동하는 방법이 있다. 그러나 우리나라는 사계절이 뚜렷하고 계절별 온도차, 환절기의 일교차가 크기 때문에, 냉난방 에너지가 많이 요구된다. 따라서, 냉난방 에너지를 과도하게 투입하게 되면, 오히려 전체 생산액에 큰 피해를 줄 수 있다. 양돈산업의 대표적인 피해 사례로는 질병 및 전염병에 따른 대량 살처분이 있다. 매년 겨울에 구제역과 같은 양돈 질병이 발생하여 피해 농가가 많은 실정이며, 최근에는 아프리카돼지열병과 같은 유행성 질병에 농가 피해가 증가하고 있는 추세이다. 이러한 전염병의 전파경로 중 공기중 전파는 우리나라와 같이 축산 농가가 밀집되어 있는 경우에는 질병 발생 위험이 매우 높다. 이러한 공기중 전파는 환기에 의하여 돈사 내부의 공기교체에 의하여 주로 발생할 수 있다. 한편, 축사 내부의 유해가스, 미세먼지, 악취 등은 환기를 통하여 배출된다. 최근에는 양돈시설 주변의 인근 주민,

관광객 등에 의하여 이러한 악취 민원이 급증하고 있는 추세이다. 이에 따라, 환경부에서는 유해가스 배출 기준을 제시하며, 규제가 강화되고 있으며, 이러한 양돈 시설 외부의 환경 부하의 문제도 해결해야할 현안 중 하나이다.

기존 양돈시설의 환기방식은 돈사 내부의 공기를 배출시키고 배출된 양만큼 입기구를 통하여 외부의 신선한 공기를 유입시키는 방식이다. 앞서 언급한 대표적인 4가지 양돈 현안은 이러한 기존 환기방식으로는 극복하기 어려울 수 있다. 따라서, 본 연구에서는 대표적인 양돈 현안을 모두 해결하기 위하여, 공기재순환 환기시스템을 개발 및 적용하고자 하였다. 공기재순환 환기시스템은 돈사 내부에서 배출되는 공기를 재사용하는 방식으로, 돈사 내부의 열에너지를 순환시켜, 겨울철 환기량을 증가시키고, 에너지 소비량을 절감하며, 돈사 내외부 공기교환을 최소화하여 대표적인 축산 현안을 해결할 수 있다.

본 연구는 총 6개의 챕터로 구분되어 있다. 챕터 1에서는 본 논문의 연구 배경 및 필요성을 기술하였다. 챕터 2는 본 연구의 타당성을 뒷받침하기 위한 다양한 선행연구에 대하여 정리하여 본 논문의 의의를 강조하였다.

본 연구에서는 양돈시설에 적용하기 위한 공기재순환 환기시스템을 설계 및 개발하여, 검증실험을 수행하였다. 챕터 3은 공기재순환 환기시스템이 설치될 실험 농장에서 사전 현장실험 결과를 제시하였다. 실험 돈사에서의 내부 환경, 환기량, 기상 등을 측정하여 기존 돈사의 문제점 및 공기재순환 환기시스템을 통하여 어떻게 개선될 수 있을지 적정성을 평가하였다. 실제 돼지가 사육되고 있는 돈사에서는 다양한 환경조건 및 변수를 바꿔가며 실험하는 것이 제한되었다. 따라서, 전산유체역학 시뮬레이션 (CFD) 모델을 활용하여 돈사 내부 환경의 공기역학적 분석을 수행하였다. 추가적으로, 개발된 모델에 공기재순환 환기시스템 모듈을 탑재하여, 대상 시설에 공기재순환 환기시스템의 적정성 평가가 이루어졌다. 먼저, 현장실험 결과, 여름철 고온스트레스, 겨울철 저온문제, 낮은 환기량, 높은 암모니아 농도 등이 측정되어, 계절에 따른 내부 적정 생육환경 조절이 어려운 것을 확인하였다. 전산유체역학 시뮬레이션 모델을 설계하고, 현장에서 측정한 데이터를 바탕으로 검증을 수행하였다. 검증은 경계조건에 대한 열환경, 가스환경 검증 및 난류모델 검증이 수행되었으며, 각각의 오차는 0.9%, 5%, 2%였으며, 연산효율성을 위한 격자독립성 테스트 결과, 최적의 격자개수는 약 690만개, skewness는 0.92, orthogonal quality는 최소 0.213으로 설계하였다. 시뮬레이션

결과를 바탕으로, 겨울철 난방기 사용 기준, 중천장 슬랏의 비대칭적 구조에 따른 문제점을 발견하였으며, 공기재순환 환기시스템 모듈을 적용한 결과, 환기량 및 외부 공기 혼합 비율에 따라 열환경, 가스환경을 모두 만족하는 경우를 확인하였다. 이에 따라, 대상 시설에서의 공기재순환 환기시스템의 적용은 충분히 효과를 기대할 수 있을 것으로 판단하였다.

챕터 4에서는 공기재순환 환기시스템의 구성 모듈에 대한 수치모델을 개발하여, 최적의 조합 및 운영 방안을 제시하고자 하였다. 먼저, 돈사 내부의 열환경, 수분환경, 가스환경을 모의하기 위하여, 각 물질의 Balance 방정식을 이용하여, 모듈의 순서에 따라 순차적으로 계산하도록 설계하였다. 반복연산을 수행해야하기 때문에, 모듈들의 조합에 따른 연산이 가능하도록 파이썬 언어를 이용하여 모델을 수치화하였다. 조합에 사용된 모듈은 공기세정장치 모듈, 열교환 모듈, 태양열 모듈, 외부 공기 혼합 모듈이었다. 각 순서도에 따른 시스템을 8개로 구분하여, 외부 환경 조건을 온도, 습도로 구분하고, 돈사 내부의 환기량, 외부 공기혼합 비율에 따라 총 10800의 시나리오를 연산하였다. 수치모델의 돈사는 모듈별 실험 및 검증을 수행한 서울대하교 평창캠퍼스 소재의 테스트베드 돈사를 기준으로 수행하였다. 실제 돼지가 있으면 다양한 조건에 따른 실험이 불가능하기 때문에, 가상의 인공 돈사에서 수행하였으며, 대상 시설에서는 실제 돼지가 사육하는 환경을 인공적으로 모의가 가능하였다. 수치모델의 검증은 대상 시설의 열환경 데이터를 바탕으로 수행되었으며, 침기 및 풍량손실을 검증 변수로 선정하여 수행되었다. 검증 결과, 환기팬 부하량에 따른 손실 20% 및 침기 1% 조건에서 MBE 및 RMSE가 각각 0.23%, 0.11로 도출되었다. 모듈 조합에 따른 최적 조건 분석 결과 태양열 모듈을 사용하며, 열교환 모듈이 공기세정장치 모듈 후단으로 배치하는 것이 유리한 것으로 도출되었다, 실제 양돈 시설에 설치될 때에는 최적 용량을 고려할 수 있도록 수치모델이 활용될 수 있을 것으로 기대된다.

챕터 5, 6에서는 공기재순환 환기시스템을 실제 양돈 농가에 설치한 뒤, 계절별 실험을 수행한 결과이다. 실험의 목적은 돼지의 생육환경이 개선되어 생산성에 미치는 효과, 공기재순환을 활용하였을 때, 에너지 재사용 및 난방에너지 절감을 통한 에너지 효율, 축산질병 오염도 평가, 악취 및 유해가스 배출 저감 효과를 평가하기 위함이었다. 먼저, 공기재순환 환기시스템의 개별 모듈을 앞서 챕터 3, 4에서 개발한 시뮬레이션 및 수치모델을 기반으로 설계하여 대상 시설에 설치하였다. 공기재순환 환기시스템이 내외부 환경

데이터를 실시간으로 수집하여 이를 자동으로 제어할 수 있도록, 상태머신 자동제어 알고리즘을 개발하였다. 개발된 알고리즘의 초기 조건을 상수로 입력하여 운영한 뒤, 실제 데이터가 축적된 후, 보정계수를 적용하여 정밀한 제어가 가능하도록 설정하였다. 실험 결과의 상대비교를 위하여, 데이터 수집 돈사는 기존 환기시스템을 유지하는 돈사와 공기재순환 환기시스템이 적용된 돈사이다. 실험 결과, 겨울철에는 기존 돈사에 비하여, 공기재순환 환기시스템의 환기량이 약 3.5배 가량 높게 운영되었음에도 불구하고, 돈사 내부의 온도는 적정 수준으로 유지하였다. 특히, 높은 환기량으로 인해 내부 가스환경은 적정 운영 기준인 20 ppm보다 낮게 유지되었다. 여름철 및 환절기에는 기존 돈사도 환기량이 높았지만, 공기재순환 환기시스템은 강우가 발생한 여름철과 낮밤 일교차가 큰 환절기에도 실시간으로 대응하여, 내부 적정 온도, 습도, 가스환경을 유지하는데 성공하였다. 내부 사육환경이 개선됨에 따라, 각 돈사의 출하시 무게가 계절별로, 동절기 1.6 kg, 환절기 2.8 kg, 하절기 1.0 kg이 증가하였다. 특히, 스트레스를 나타내는 돼지 Cortisol 물질을 샘플링하여 분석한 결과, 공기재순환 환기시스템의 돼지들의 스트레스 지수가 유의미하게 기존 돈사의 돼지들보다 낮게 나온 것을 확인하였다. 한편, 에너지 재활용율을 평가한 결과, 약 78%로 매우 높은 회수율을 보였으며, 겨울철 난방장치를 사용하지 않은 공기재순환 환기시스템 돈방과 기존 돈방의 에너지 사용량은 상당히 유의미하게 차이가 발생하였다. 두 돈방의 질병 오염도 평가 결과, 양돈의 대표 호흡기 질병 4개종을 샘플링하였으나, 검출율 1%대로 모두 매우 낮게 측정되었다. 한편, 돼지들의 장내 마이크로바이옴, 비강 마이크로바이옴 및 환경 시료 분석 결과, 공기재순환 환기시스템 돼지들의 유익균이 유의미하게 증가하였으며, 유해균이 유의미하게 줄어든 것을 확인할 수 있었다. 한편, 실험 돈사에서, 질병 오염도가 유의미하게 개선된 것을 확인할 수 있는 데이터는 부족하였으나, 실제 운영되고 있는 돈사에서 질병이 발생하는지 평가하는 것은 매우 위험하고 희박한 확률이기 때문에, 장기적인 모니터링이 필요할 것으로 사료된다. 두 실험 돈방에서 배출되는 악취 및 유해가스 (암모니아) 측정 결과, 암모니아 배출량은 최대 7배 낮게, 악취의 경우 최대 10배 낮게 배출되며, 공기재순환 환기시스템에서 배출되는 악취 및 유해가스 농도 기준은 국가에서 권고하는 배출기준보다 훨씬 낮은 값이 측정되었다.

본 연구에서는 양돈시설의 발전을 저해할 수 있는 대표적인 현안을 4가지 선정하여, 이를 개선 및 극복하기 위한 공기재순환 환기시스템 개발 및 검증을

수행하였으며, 이러한 4가지 문제에 대해서 모두 해결이 가능하였다. 그러나 본 연구에서의 한계점은 대상 돈사의 계절별 반복 실험의 부재, 구조적으로 다양한 양돈시설에 대한 실험의 부재, 전염병의 발생 여부 등에 따른 미흡한 점이 발견되었다. 또한 실제 에너지 사용량을 정량적으로 평가하기 위해서는 모든 시스템에 대한 에너지 평가도 이루어질 필요가 있다. 따라서, 향후에는 장기적인 반복실험을 통하여, 생산성, 에너지, 악취 오염 평가, 질병 평가 결과에 대한 데이터를 축적하여, 보다 개선된 공기재순환 환기시스템을 개발할 예정이다.

주요어: 공기재순환 환기시스템, 수치모델, 복합악취, 생육환경, 양돈시설, 에너지, 전산유체역학, 축산질병

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