공학석사 학위논문

Analysis of Natural Ventilation Rate of Multi-span Greenhouses built on Reclaimed lands using CFD

전산유체역학을 이용한 간척지 내 자연환기식 연동 온실의 환기량 평가

2016 년 2 월

서울대학교 대학원

생태조경 · 지역시스템공학부 지역시스템공학전공

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지도교수 이 인 복

이 논문을 공학석사 학위논문으로 제출함
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이상연의 공학석사 학위논문을 인준함
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Abstract

Greenhouse area has increased continuously making possible for intensive cultivation, high quality agricultural product in South Korea. However, there is no enough space for installing large-scale greenhouse complex in South Korea, because the land area that account for 70% of South Korea's territory consist of mountain area. Reclaimed lands which are newly developed have great worth as agricultural lands because reclaimed lands can be used deliberately regardless of near terrain. Recently, Korea government made a public announced about the development plan of large-scale greenhouse complex in representative reclaimed lands. However, wind environments of reclaimed land are entirely different from those of inland. Natural ventilation studies for greenhouses built on reclaimed land should be conducted with proper wind profiles of the reclaimed land. Meanwhile, many standard documents for ventilation design did not describe quantitative design standard of natural ventilation which is commonly used. Therefore, natural ventilation rates were computed and analyzed to suggest standard for ventilation design of multi-span greenhouse built on reclaimed lands.

In this study, natural ventilation rate of multi-span greenhouse was computed and analyzed according to greenhouse type (Venlo, Wide-span, 1-2W), number of spans (two, five, eight), wind speed (1.0, 2.5, 5.5 $m \cdot s^{-1}$), wind direction (90, 45, 0°), and vent opening (side vent, side-roof vent, roof vent). Computational Fluid Dynamics (CFD) simulation was used for the purpose of overcoming the limitation of field experiments, such as laborious and cost consuming, requirement of equipment for multipoint measurement, vulnerability to unstable weather condition, and so on. An analysis of the wind environment was performed to design the wind profiles of reclaimed lands in South Korea. CFD simulation models for multi-span greenhouses were designed based on a design method for a CFD simulation model, which was validated by Ha (2015). The designed wind profiles of the reclaimed lands were applied to the CFD simulation models. Two methods, mass flow rate (MFR)

and tracer gas decay (TGD), were used to calculate the natural ventilation rates of multi-span greenhouses. The natural ventilation rates computed by these two methods were evaluated by comparing them with the ventilation requirements.

As the result of comparing the natural ventilation rates computed by the two methods, it was judged that the tracer gas decay method evaluated the actual natural ventilation more closely than the mass flow rate method. In analyzing the overall ventilation rates, the results also showed that the natural ventilation rates were influenced considerably by wind speed and wind direction. The natural ventilation rates increased linearly as wind speed increased. As the number of spans increased, the natural ventilation rates generally decreased. It was observed that the effect of ventilation through the roof ventilators of the 1-2W type greenhouse was higher than in the Venlo and wide-span greenhouses. As a result of analyzing the homogeneity of the local ventilation rates, it was found that the homogeneity was mainly influenced by wind direction and the configuration of the ventilators except for wind direction.

The results of analyzing the overall ventilation rates will be used as basic data to establish design standards for multi-span greenhouses built on reclaimed lands. Additionally, the results of analyzing the local ventilation rates are expected to be utilized for controlling the microclimate in large-scale greenhouses uniformly. The charts for expecting the natural ventilation rates will be used for designing the ventilation of greenhouses and the guidance of maintenance control.

The natural ventilation rates were computed and evaluated according to various conditions as basic research to create design standards for natural ventilation. A study evaluating the effects of crops and buoyancy on natural ventilation is still required. When crops exist in a greenhouse, the air flow patterns and natural ventilation rates are completely changed according to the arrangement of the crops, variety of the crops, crop height, etcetera. Also, when wind speed is low, buoyancy-driven ventilation is more important. With additional research, it will be possible to suggest quantitative standards for designing the ventilation of greenhouses that will be practical for the managers and designers of greenhouses.

Keyword : Computational Fluid Dynamics (CFD), Multi-span Greenhouse, Natural Ventilation Rate, Reclaimed Land, Ventilation Requirement,

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1. Introduction

Greenhouse area in South Korea has increased steadily since 1970 due to the advantages of easy environmental control, intensive cultivation, stable year-round production, and high-quality agricultural products (see Fig. 1). Greenhouse area increased from about 700 ha in 1970 to 51,058 ha in 2013. The ratio of the crop yield from greenhouses to the total crop yield increased from about 5% in 1970 to about 30% in 2013 (Ministry of Agriculture, Food and Rural Affairs, 2014a). Although the area of single-span greenhouses currently accounts for around 73% of the total greenhouse area in South Korea, horticultural facilities have been automated and enlarged following the growth of vegetable consumption per capita and consistent reductions in the ratio of the farming population.

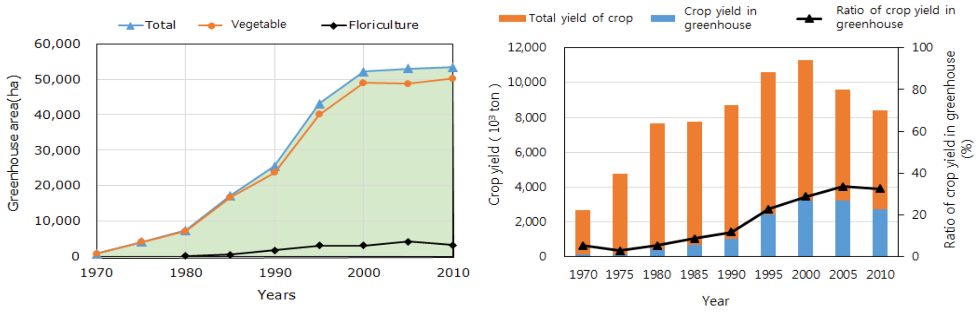


Fig. 1 The tendency of increasing greenhouse area (left) and crop yield from greenhouse (right) in South Korea

However, there are constraints on the amount of space for installing large-scale greenhouses in South Korea, because the land that accounts for 70% of South Korea's territory consists of mountainous areas (Ministry of Agriculture, Food and Rural Affairs, 2014a). Newly developed reclaimed lands have great worth as agricultural lands, because reclaimed lands can be used deliberately by planner regardless of the terrain nearby. Recently, the Korean government announced a new development plan for establishing large-scale greenhouse complexes at 12 representative reclaimed lands in South Korea. These planned areas total about 53,125 ha (Ministry of Food, Agriculture, Forestry and Fisheries, 2010).

To control environmental factors (temperature, humidity, CO2 concentration, etc.) properly, many methods are used in greenhouses, such as heating, cooling, ventilation, carbon dioxide application, and so on. Natural ventilation is one of the main methods used to maintain proper environments for growing crops. Natural ventilation is an effective and economical method for improving indoor air quality, decreasing air temperature in the summer, preventing excess humidity and controlling the concentration of CO_2. Most greenhouses in South Korea have been operated by using natural ventilation systems, not forced ventilation system, because of economic reasons (Kwon et al., 2011). However, the natural ventilation of a greenhouse is greatly influenced by the external wind environment. Wind environment characteristics, such as wind velocity, turbulence intensity, and gust frequency, in reclaimed lands are completely different from those of inland areas, due to the effects of low topographical obstacles and the oceanic climate (Korean Meteorological Administration, 2014). Therefore, ventilation studies of greenhouses on reclaimed land should be conducted with the reclaimed land’s proper wind profiles.

Many researchers have studied the natural ventilation of greenhouses according to various environmental conditions such as external wind speed (Sase et al., 1984; Mistriotis et al., 1997), external wind direction (Campen and Bot, 2003; Hong et al., 2008; Bartzanas et al., 2004), ventilator configurations (Kittas et al., 1996; Bartzanas et al., 2004; Lee and Short, 2000) and greenhouse type (Boulard et al., 1997; Bourlard and Fatnassi, 2005; Hong et al., 2008). Although the performance of natural ventilation under various environmental conditions has been analyzed by several previous studies, no research has been done about the ventilation of greenhouses taking the external wind environment of reclaimed land into consideration.

Previous studies have been conducted on air flow pattern and ventilation efficiency of greenhouses using field experiments (Sase, 1989; Kittas et al., 1995;

Kittas et al., 1996; Boulard et al., 1996; Fatnassi et al. 2002; Perez parra et al., 2004; Teitel et al., 2008; Fatnassi et al. 2009). However, analyzing the ventilation performance is difficult to be conducted through field experiments due to various limitations. A field experiment needs a large amount of equipment for simultaneous multipoint measurements. Unstable weather conditions and requiring a longer experimental period are another limitation when performing field experiments. Alternative solutions have been identified to overcome the mentioned limitations. Computational fluid dynamics (CFD) and wind tunnel experiments, among various other study approaches, are efficient measurement techniques for analyzing the characteristics of air movement because these methods can control the environmental conditions. Wind tunnel experiments have been widely used for the fluid analysis of greenhouses (Sase et al., 1984; Okushima et al., 1998; Okushima et al., 2000; Lee et al., 2003a) because it is easy to control the wind environment in wind tunnel test, leading to high reliability. However, a wind tunnel test is laborious and cost consuming. Research in agriculture using CFD with various applications has increased globally year after year up to the present day. CFD deals with complex physical phenomena with a few limited factors and can record massive data under various environmental conditions (Lee et al., 2003b). For this reason, CFD simulation has been actively used to estimate the air flow patterns and ventilation efficiency of greenhouses (Okushima et al., 1989; Bartzanas et al., 2004; Kacira et al., 2004a; Boulard et al 1997; Lee and Short, 2000; Lee and Short, 2001; Hong et al., 2008).

Meanwhile, several standards books for designing greenhouse ventilation described the heating systems and ventilation requirement for controlling the temperature in the summer (Korea Rural Community Corporation, 1997; American Society of Agricultural Engineers, 2003; Natural Resource Agriculture, and Engineering Service, 1994; Hellickson and Walker, 1983; Lindley and Whitaker, 1996). However, these standard books did not include quantitative standards for designing natural ventilation, which is mostly used to the control internal climate in a greenhouse. The natural ventilation of greenhouses varies considerably due to external wind and thermal conditions, greenhouse type, ventilator configuration, and so on. Therefore, natural ventilation rates should be quantitatively evaluated to design the natural ventilation of greenhouses.

The primary objective of this study was to evaluate the natural ventilation rates of multi-span greenhouses and suggest charts for expecting natural ventilation rates. For the purpose of overcoming the limitations of field experiments, CFD simulation models were designed according to greenhouse types, number of spans, vent openings, and the wind environments of reclaimed land. Mass flow rate and tracer gas decay methods were used to calculate natural ventilation rates. Natural ventilation rates computed by these two methods were analyze and compared according to the environmental conditions. Additionally, natural ventilation rates were compared with the ventilation requirements for controlling temperature in greenhouses. Finally, charts which can be used for computing the natural ventilation rates considering the wind environment of the reclaimed land in South Korea were created. The charts are expected to be used for establishing standards for ventilation design.

2. Literature Review

2.1. Studies on Greenhouse Ventilation

Ventilation is the fundamental method used to control the factors of a greenhouse's internal environment, such as temperature, humidity, CO_2 concentration, and so on. Many researchers have analyzed natural ventilation rates according to ventilator configuration, the external wind environment, the greenhouse type, and so on.

Many studies on the natural ventilation of greenhouses have been performed with field experiments. Sase (1989) measured internal air velocity according to plant arrangement using a hot-wire anemometer. A comparative analysis was performed using velocity coefficients that were defined as the ratio of internal air velocity to external wind velocity. Kittas et al. (1995) observed the air exchange rate in a greenhouse with roof ventilators using the tracer gas decay method with N_2O as the tracer gas. A model that estimates the ventilation flux was derived as a function of the temperature difference between the inside and outside air, the wind velocity and the ventilator's area. Kittas et al. (1996) carried out field experiments that analyzed the influence of wind speed on the ventilation rates in a greenhouse with a lateral ventilator opening using the tracer gas decay method with N_2O as the tracer gas. Boulard et al. (1996) evaluated the ventilation rates in a greenhouse with a side ventilator opening using tracer gas or a heat and water balance technique. Fatnassi et al. (2002) measured the ventilation rates of a large Canarian type greenhouse with insect-proof and observed the increase of the ventilation rates as the wind velocity and ventilator size was increased. Additionally, it was found that insect-proofing induced a strong pressure drop through the opening. Perez-parra et al. (2004) measured the ventilation rates of the parral greenhouse according to ventilator configuration using a tracer gas decay method with N_2O. Teitel et al. (2008) carried out field experiments in a naturally ventilated mono-span greenhouse with screened side ventilators to determine characteristics of the internal environment, such as ventilation rate, humidity, temperature, and so on.

Field experiments have been performed steadily because of their advantages in measuring real field data. However, a field experiment is vulnerable to the external weather conditions and limited by the experiment's equipment, labor and cost. For the purpose of overcoming the limitations of field experiments, CFD simulation has been used to analyze the natural ventilation of greenhouses, because CFD simulation has the advantages of procuring massive data under various environmental conditions and controlling the environmental conditions. Boulard et al. (1997) investigated air flow in a twin-span greenhouse with the wind blowing parallel to the greenhouse ridge through CFD simulation and a field experiment. Lee and Short (2000) analyzed the distribution of airflow in four and one-half greenhouses according to wind direction, wind speed, vent opening size, and the presence of plants using CFD simulation. Bartzanas et al. (2004) and Kacira et al. (2004b) carried out CFD simulation to evaluate the effects of ventilator configuration on ventilation rates and airflow patterns. The CFD simulation models were validated by comparing their data with field experiment data. Hong et al. (2008) compared the natural ventilation efficiencies of the multi-span greenhouse typically used in Korea. A tracer gas decay method was applied to the CFD simulation and used to analyze the natural ventilation efficiencies quantitatively. Molina-Aiz et al. (2010) compared the efficiency of the finite element method and the finite volume method as CFD solvers for analyzing natural ventilation in greenhouse. Teitel and Wenger (2014) computed and compared the air exchange of mono-span greenhouse with side openings using three methods; experiments, CFD simulation and a model that related air exchange through pressure drop.

2.2. Standards for Greenhouse Ventilation Design

”*Design Standards for Greenhouse Environment*” issued by the Korea Rural Community Corporation (1997) presented calculation formulas for the ventilation requirements for controlling temperature, humidity and CO_2 concentration. Additionally, standards for forced and natural ventilation systems were suggested. However, the qualitative standards were only suggested, except for the greenhouse type, external wind and thermal conditions, and so on. The ”*ASAE Standard: Heating, Ventilating and Cooling Greenhouse*” issued by the American Society of Agricultural Engineers (2003) was suggested as the standard for designing the natural and forced ventilation of greenhouses. This standard book suggested ventilation requirements for controlling the temperature based on the energy balance model. In case of design standard for a forced ventilation system, this standard book described the capacity of the exhaust fan, the installed location of exhaust fan, pad cooling system, fog cooling system, and winter ventilation. Qualitative standards for natural ventilation were described for the size and angle of the roof vent opening. “*Greenhouse Engineering*” issued by Natural Resource, Agriculture, and Engineering Service (1994) did not describe a detailed design standard for ventilation. This standard book just suggested a graph that presents the relationship between the ventilation rates and the difference in internal and external temperatures with two shading conditions. The “*Ventilation of agricultural structure*” issued by Hellickson and Walker (1983) recommended 0.75~1 of air exchange per minute for controlling the proper temperature in the summer and briefly explained forced and natural ventilation systems. “*Agricultural Building and Structure*” issued by Lindley and Whitaker (1996) presented graph for explaining the level of rising temperatures according to ventilation rates. This standard book briefly explained a standard for the equipment used in natural and forced ventilation systems. The standards for a forced ventilation system focused on the area of the inlet vent, the capacity of the exhaust fan, the design ventilation rate in winter, and so on. “*Handbook of Horticultural Facilities*” issued by Japanese Horticultural Facilities Association

(2011) suggested ventilation requirements according to solar radiation conditions. This standard book describe the design factors of a forced ventilation system's configuration of the exhaust fan and inlet vent, the air flow of the exhaust fan, and so on. The configuration of the vent opening was suggested according to greenhouse type. Ventilation rates and airflow patterns were explained according to external wind conditions and not according to greenhouse type.

The above-mentioned standard books only defined qualitative standards for designing natural ventilation except quantitative design standards. Besides, these standard books did not explain natural ventilation rates according to external wind environments, greenhouse type, and ventilator configuration. Natural ventilation is performed differently according to external wind and thermal conditions, greenhouse type, ventilator configuration, and so on. Therefore, natural ventilation rates should be studied quantitatively, taking various environmental conditions into consideration to suggest design standards for the natural ventilation of greenhouses.

2.3. Studies on Greenhouses Built on Reclaimed Lands

The characteristics of the wind environment are completely different from the characteristics of inland areas, due to the effects of low topographical obstacles and oceanic climate. Additionally, the ground of reclaimed land can be weaker than that of inland areas and can contain more salinity. Some research has studied greenhouses taking the environment of reclaimed land into consideration.

The research on greenhouses built on reclaimed land has mainly focused on the structural safety of the greenhouses due to the environmental characteristics of reclaimed land, such as frequent strong wind and gusts, weak ground, etcetera. Yun et al. (2013) analyzed the design wind speed and snow cover depth according to the return period using the weather data of 72 weather stations located near reclaimed land in South Korea. Yu et al. (2014) analyzed the problems that can occur when a greenhouse is built on reclaimed land using wooden pile. Kim et al. (2014) evaluated the wind pressure coefficient of an Even-span type greenhouse considering the wind environment of reclaimed land according to roof slope. Choi et al. (2015) measured the settlement of a foundation using wooden pile at a 1-2W greenhouse built on Gyehwa reclaimed land. Lee et al. (2015) tried to establish a technique for designing the foundation of a greenhouse built inside a greenhouse.

Another researcher studied the light environment and the growth characteristics of cultivated crops in greenhouses built on reclaimed land. Lee et al. (2014) analyzed the characteristics of the light environment in a greenhouse considering the weather of reclaimed land, such as frequent sea fog due to high humidity. Additionally, a 3D model was developed to predict the distribution of the light environment and changes in the luminous intensity in greenhouses. Um et al. (2013) carried out a comparative analysis of the growth characteristics and yield between a greenhouse built on reclaimed land and at a common farm.

Previous research has focused on structural stability, the light environment, and the growth characteristics of crops considering the environmental conditions of reclaimed land. However, no studies have been done on the ventilation of greenhouses considering the environment of reclaimed land. To design the ventilation systems of greenhouses considering the wind environment of reclaimed land, natural ventilation rates should be analyzed quantitatively under various environmental conditions.

3. Materials and Methods

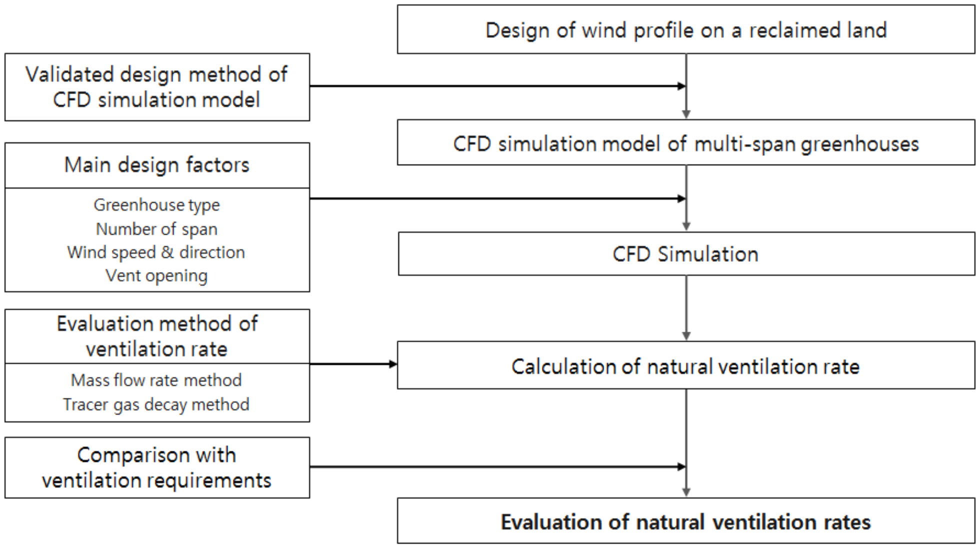
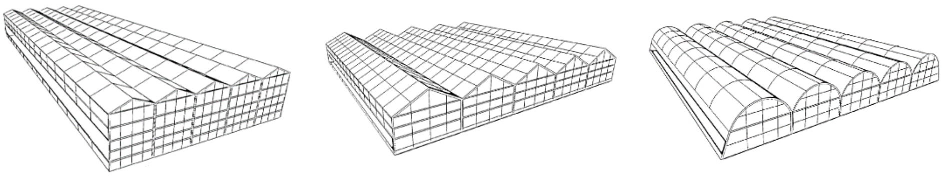


Fig. 2 Flow chart of this study to evaluate natural ventilation rates of multi-span greenhouses built on reclaimed lands

The flowchart in Fig. 2 describes the procedure for evaluating the natural ventilation rates of multi-span greenhouses built on reclaimed lands. First, an analysis of the wind environment was performed to design the wind profiles of reclaimed lands in South Korea. CFD simulation models for multi-span greenhouses were designed based on a design method for a CFD simulation model, which was validated by Ha (2015). The designed wind profiles of the reclaimed lands were applied to the CFD simulation models. Two methods, mass flow rate (MFR) and tracer gas decay (TGD), were used to calculate the natural ventilation rates of multi-span greenhouses according to greenhouse type, number of spans, wind speed, wind direction, and vent opening. The natural ventilation rates computed by these two methods were evaluated by comparing them with the ventilation requirements. Finally, charts for expecting natural ventilation rates were created according to multi-span greenhouse types.

3.1. Target Greenhouses

Three types of multi-span greenhouses that are typically used in South Korea were selected as target greenhouses: Venlo, Wide-span, and 1-2W type greenhouses. The specifications of the greenhouse types were determined by following the specification and design standards for horticultural facilities (Ministry of Agriculture, Food, and Rural Affairs, 2014b) and the standard design of Korean glass greenhouses (Ministry of Land, Transport and Maritime Affairs, 1997). Fig. 3 and Table 1 show the schematic information and specifications of multi-span greenhouses according to greenhouse type. The side ventilators of Venlo and Wide-span type greenhouses operated as a sliding system. In the 1-2W type greenhouse, the side ventilators operate as a roll-up system. The roof ventilators of the Venlo type greenhouse open in a zigzag pattern. The windward and leeward roof ventilators of the Wide-span and 1-2W types of greenhouses open simultaneously.



(a) Venlo (b) Wide-span (c) 1-2W

Fig. 3 Schematic information of multi-span greenhouses according to greenhouse type

Table 1 Specification of multi-span greenhouses according to greenhouse type

	Venlo	Wide-span	1-2W
Width (per span)	3.2 m	9.0 m	7.0 m
Ridge height	4.95 m	6.5 m	4.7 m
Eave height	4.3 m	4.3 m	2.8 m
Length	45.0 m	45.0 m	45.0 m
Side ventilator height	1.45 m	1.45 m	1.3 m
Roof ventilator height	1.1 m	1.4 m	1.2 m
Floor area (per span)	144 m^2	405.0 m^2	315.0 m^2
Volume (per span)	666.0 m^3	2187.0 m^3	1263.0 m^3

3.2. Target Reclaimed Lands and Weather Data

The target areas were seven representative reclaimed lands in South Korea (Hwaong, Sihwa, Seokmoon, Iweon, Goheung, Yeongsan River, and Saemangeum) where the Korean government announced plans to develop a large greenhouse complex. Weather data from the past 20 years (January 1, 1983 to December 31, 2012) of nine weather stations (Incheon, Woojung, Seosan, Gunsan, Buan, Mokpo, Jindo, Haenam, and Goheung) located near the seven representative reclaimed lands were collected from the Korea Meteorological Administration (KMA) and analyzed. The locations of the seven target reclaimed lands and nine weather observation stations are shown in Fig. 4.

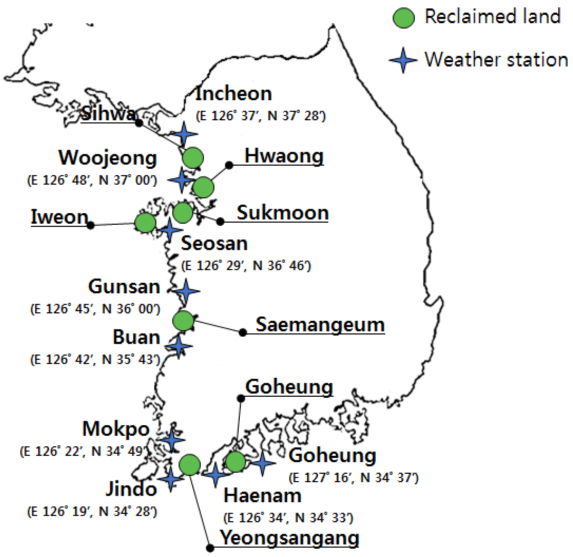


Fig. 4 Target reclaimed lands and weather stations located at near reclaimed lands

3.3. Computational Fluid Dynamics (CFD)

CFD simulation is a numerical method for solving the Navier-Stokes equation using discretization methods: finite difference method (FDM), finite element method (FEM), finite volume method (FVM), etcetera. Fluid flow and energy were analyzed by solving the mass conservative equation (1), momentum conservative equation (2), and energy conservative equation (3) (ANSYS Fluent User's Guide, 2013). CFD simulation has also been actively applied and used in the field of agricultural engineering. In this study, the commercial software GAMBIT (ver. 2.4, Fluent Co., New Hampshire, USA) and ANSYS FLUENT (ver. 15.0, ANSYS Inc., PA, USA) were used. GAMBIT was used to design a three-dimensional grid and numerical calculation domain. FLUENT was used to compute the governing equation of air flow. Because of the thickness of the cover material, the frame of the greenhouse scarcely affected the air flow, so the CFD simulation models were simplified without regard to the thickness of the cover material or the frame of the greenhouse.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = S_m \tag{1}$$

$$\frac{\partial}{\partial t}(\rho \vec{v}) + \nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla \mathrm{P} + \nabla \tau + \rho \vec{g} + \vec{F} \tag{2}$$

$$\frac{\partial}{\partial t}(\rho E) + \nabla \cdot \left(\vec{v}(\rho E + P)\right) = \nabla \left(k_{eff} \nabla \mathrm{T} - \sum_j h_j \vec{J}_i + (\bar{\tau} \vec{v}) \right) + S_h \tag{3}$$

Where,

E	: Total energy (J)
ρ	: Density ($kg \cdot m^{-3}$)
$\vec{v}$	: Velocity ($m \cdot s^{-1}$)
P	: Constant pressure (Pa)
$\bar{\tau}$	: Stress tensor (Pa)
$\vec{g}$	: Gravitational acceleration ($m \cdot s^{-2}$)
$\vec{F}$	: External force vector ($N \cdot m^{-3}$)
S_m	: Mass source ($kg \cdot m^{-3}$)
k_{eff}	: Heat transmission coefficient
$\vec{J}_i$	: Component of diffusion flux
S_h	: Total entropy ($J \cdot K^{-1}$)

3.4. Evaluation Methods of Ventilation Rates

3.4.1. Ventilation Requirements

The ventilation requirement was defined as the ventilation rate required to control the optimum environment for the growth of crops, such as temperature, humidity, CO_2, etcetera. In summer, excessive temperature rise has a negative effect on the growth of crops as a high temperature injury. The ventilation requirements for temperature control (Korea Rural Community Corporation, 1997) in a greenhouse were determined from the following equation (4). When the inside air temperature of a greenhouse is decreased close to the outside temperature, a higher ventilation rate is required. Ventilation requirements consider specific factors, such as the difference between the design temperature inside the greenhouse and the outside temperature, as well as optional crop coefficients, radiation, and the transmissivity of the covering material, excluding the wind conditions.

$$\text{Air Exchange}_{VR} = \frac{1}{C_v} \times \left\{ \frac{\alpha \tau S(1-f)A_f}{\Delta T} - kA_c \right\} \times \frac{1}{V} \tag{4}$$

Where,

Air Exchange$_{VR}$	: Air exchange of ventilation requirements ($AE \cdot s^{-1}$)
C_v	: Volumetric specific heat of air ($kcal \cdot m^{-3} \cdot ℃^{-1}$)
α	: Correction rate of heat area
τ	: Solar transmissivity of greenhouse cover
S	: Solar radiation ($kcal \cdot m^{-2} \cdot min^{-1}$)
f	: Evapotranspiration coefficient
ΔT	: Difference between design temperature inside greenhouse and outside temperature (℃)
k	: Overall heat transfer coefficient ($kcal \cdot m^{-2} \cdot min^{-1} \cdot ℃^{-1}$)
A_f	: Floor area of greenhouse (m^2)
A_c	: Cover area of greenhouse (m^2)
V	: Volume of greenhouse (m^3).

3.4.2. Natural Ventilation Rates

To evaluate the natural ventilation rate under the environmental conditions of reclaimed lands, mass flow rate and tracer gas decay methods were used. The mass flow rate (MFR), which has been used worldwide, was represented by the number of air exchanges with the assumption that air flowing in from the outside was used to completely replace the internal air. The mass flow rate was expressed as follows:

$$\text{Air Exchange}_{MFR} = G \times \frac{1}{\rho_{air,gh}} \times \frac{1}{V} \tag{5}$$

$$\mathrm{G} = v_x \times \rho_{air,vent} \times A_{vent} \tag{6}$$

Where,

Air Exchange$_{MFR}$	: Air exchange of mass flow rate (AE·min^{-1})
G	: Mass flow at vent (kg·s^{-1})
V	: Volume of greenhouse (m^3)
A_{vent}	: Vent area of greenhouse (m^2)
v_x	: Wind speed of x-axis at vent (m·s^{-1})
$\rho_{air,gh}$	: Air density in greenhouse (kg·m^{-3})
$\rho_{air,vent}$	: Air density at vent (kg·m^{-3})

The mass flow rate method has the advantage of calculating the overall ventilation rate simply. But the mass flow rate method also has some limitations. When the mass flow rate method was applied in field experiments, the possibility of error increased while measuring the wind velocity at the greenhouse's ventilator. Unstable weather conditions and limited measuring points caused errors. Increasing the measuring points at ventilators could disturb the air flow pattern. Also, the mass flow rate does not consider ventilator configurations and the internal air flow patterns of a greenhouse.

The ventilation rates based on the tracer gas decay method were calculated by quantitatively analyzing the concentration decay curve of the tracer gas. After filling the inside of the greenhouse uniformly with the tracer gas concentration, ventilation was started. As the ventilation progressed, the concentration of the tracer gas in the greenhouse was measured. The ventilation rate based on the tracer gas decay method was described as follows:

$$\text{Air Exchange}_{TGD} = \frac{\ln\left(\frac{C_0}{C_t}\right)}{(t - t_0)} \tag{7}$$

Where,

Air Exchange_{TGD} : Air exchange of tracer gas decay ($AE \cdot min^{-1}$)

C_0, C_t : Concentration of tracer gas (ppm) at t_0, t time (sec)

t : Ventilation time (sec).

The tracer gas decay method considers internal air flow patterns, structural characteristics, the greenhouse's ventilator configuration, and the external wind conditions. Local ventilation rates in the greenhouse can be estimated using the tracer gas decay method. In field experiments, an error can occur due to limited multipoint measurements, irregular environmental conditions, and uncertain gas control, so it is hard to do a quantitative assessment. However, that kind of problem can be supplemented using CFD simulation; the CFD simulation can control various factors artificially.

Fig. 5 shows two cases that were the same except for ventilator configuration. When the mass flow rate method was used to compute the ventilation rate in these cases, the ventilation rates were the same because the air flow at the inlet and outlet was the same. However, the ventilation rates based on the tracer gas decay method were different because the air flow patterns were different according to the location of the outlet. When the mass flow rate method was used, the ventilation in the case on the right was overestimated, because the inflow air was not used to exchange the internal air entirely.

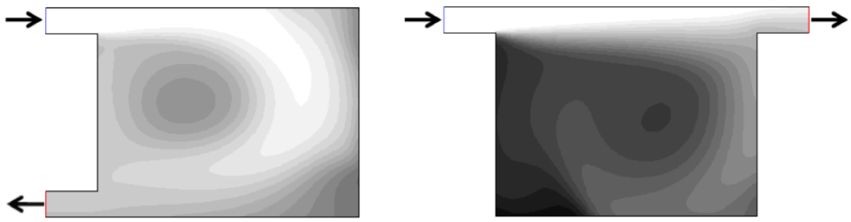


Fig. 5 Air flow at inlet outlet was the same at these cases but ventilator configurations were different

3.5. Analysis Procedures

3.5.1. Design of the CFD Simulation Model

The accuracy and reliability of CFD simulation models are very important in the field of CFD simulation study. Ha (2015) performed the particle image velocimetry (PIV) test in a wind tunnel to visualize the air flow pattern and analyze the distribution of the air flow qualitatively and quantitatively. Ha (2015) also performed the grid independence test and turbulence model test according to grid size (0.1, 0.2, 0.4, 0.6, 0.8, 1.0 m) inside a greenhouse model and a turbulence model (Standard $k-\varepsilon$, Realizable $k-\varepsilon$, RNG $k-\varepsilon$, Standard $k-\omega$, SST $k-\omega$). Ha (2015) compared the measured PIV results and the CFD simulated results according to grid size and turbulence model to validate the accuracy of the CFD simulation model. As a result of the grid independence test, the CFD computed results of the grid size of 0.1 m and 0.2 m show good agreement with the results of the PIV measurements. However, the proper grid size inside the greenhouse model was determined as 0.2 m when the calculation time and accuracy of the calculation results were taken into account. As a result of the turbulence model test, the RNG $k-\varepsilon$ turbulence model was determined to be the most accurate model for the analysis of the internal air flow pattern in a greenhouse. Because the preceding research on the natural ventilation of a greenhouse suggests the use of the RNG $k-\varepsilon$ turbulence model (Lee, 2005; Lee, 2007, Hong, 2008), Ha's (2015) results were concluded to be reasonable results. In this study, a grid size of 0.2 m and the RNG $k-\varepsilon$

turbulence model were used based on Ha's (2015) validation results to design the CFD simulation model for analyzing greenhouse ventilation.

The external wind environment is very important in analyzing natural ventilation. Accordingly, designing the proper external domains is required. If the external domain is small, it is impossible to analyze the air flow accurately. Contrarily, if the external domain is too big, the calculation takes too long. Based on the preceding research (Franke et al., 2004; Bournet et al., 2007; Bournet and Boulard, 2010), the boundary domain in this study was designed as 15H (H: ridge height of the greenhouse) windward, 15H leeward, and 10H from the ground. The designed boundary domain is shown in Fig. 6. The grids near and inside the greenhouse were designed densely to analyze the air flow pattern near and inside the greenhouse more accurately.

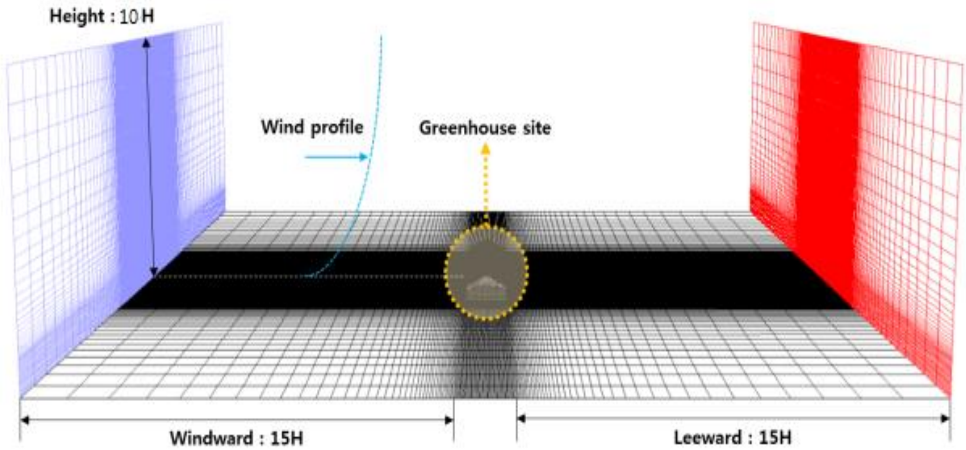


Fig. 6 Design of external domain for analyzing the natural ventilation of greenhouse

The CFD simulation models were designed according to greenhouse types and number of spans. Also, the CFD simulation models were designed so that these models could consider all vent openings as changing the boundary conditions. The amount of mesh according to greenhouse type and number of spans is shown in Table 2. The amount of mesh in the Wide-span type greenhouse was the highest with the same condition of span numbers because the volume of the Wide-span type greenhouse is the biggest of the target greenhouse types. The amount of mesh in the Venlo type greenhouse was the lowest because the volume of the Venlo type greenhouse is the smallest of the target greenhouse types.

Table 2 The number of mesh of CFD simulation model according to greenhouse type and number of spans

	2-span	5-span	8-span
Venlo	1,667,930	2,411,625	3,164,760
Wide-span	3,281,285	6,038,355	8,776,545
1-2W	2,512,515	4,317,915	6,088,800

The mesh quality is an important factor for accuracy in the CFD simulation results and convergence during the computing process. Hexahedral mesh, which is generally known as the best mesh quality, was used in this study. Equiangle skewness (Q_{EAS}) was used to evaluate the mesh quality quantitatively and was expressed as:

$$Q_{EAS} = max\left[\frac{\theta_{max} - \theta_{eq}}{180 - \theta_{eq}}, \frac{\theta_{eq} - \theta_{min}}{\theta_{eq}}\right] \tag{8}$$

Where,

θ_{max} : Maximum angle in cell

θ_{min} : Minimum angle in cell

θ_{eq} : Angle for equiangular cell

(e.g., θ_{eq}=60°: triangle, θ_{eq}=90°: square)

The range of equiangle skewness is 0` to 1. Highly skewed cells can decrease accuracy and destabilize the solution. A general rule is that the maximum equiangle skewness should be kept below 0.95. A maximum value above 0.95 may lead to convergence difficulties (ANSYS Fluent meshing user's guide manual, 2013). The maximum values of equiangle skewness were calculated to evaluate the mesh quality of the designed CFD simulation model in this study and are shown in Table 3. As a result of evaluating the mesh quality of the CFD simulation models, all of the CFD models were determined to have proper mesh quality.

Table 3 maximum values of equiangle skewness of CFD simulation models

	2-span	5-span	8-span
Venlo	0.509	0.509	0.509
Wide-span	0.467	0.467	0.467
1-2W	0.752	0.752	0.752

To design the wind environments of reclaimed land, which are different from inland wind environments, an ESDU code (Engineering Sciences Data Unit, 84011 and 84030, IHS, UK) was used to consider changes in the surface roughness near the target reclaimed lands. Wind speed and turbulence profiles designed by ESDU codes were adopted for the CFD simulation. Designed wind speed and turbulence profiles were applied to the CFD simulation based on log law (Richards, 1989; Richardson and Blackmore, 1995; Hoxey and Richards, 1997) using the user-defined function (UDF) of ANSYS FLUENT. The wind and turbulence profiles based on log law were designed using equations (9), (10), and (11). The values of the parameters are shown in Table 4 and the wind speeds at the reference height were selected through the wind frequency analysis (Kim, 2015).

$$U(\mathrm{z}) = \frac{u^*}{k} \ln \frac{z + z_0}{z_0} \tag{9}$$

$$\mathrm{k}(\mathrm{z}) = \frac{u^{*2}}{\sqrt{C_\mu}} \tag{10}$$

$$\epsilon(\mathrm{z}) = \frac{u^{*3}}{k(z + z_0)} \tag{11}$$

Table 4 Specification of parameters for vertical wind speed and turbulence profiles

Factor	Value
Karman constant (k)	0.42
Roughness length (z_0)	0.03 m
Friction velocity (u^*)	0.53 m·s^{-1}
Empirical constant (C_μ)	0.09
Reference height (z_R)	10 m

To estimate the local ventilation rates in a greenhouse, the CFD simulation model was compartmentalized as shown in Fig. 7. Three sections according to height to floor (0~1m, 1~2m, upper section) and eleven sections according to lengthwise equal interval comprised one span; in the case of an eight-span greenhouse, the greenhouse model was divided into 264 sections total. The local ventilation rate of each section was calculated by the tracer gas decay method. The local ventilation rates were evaluated by comparing the results under various conditions. Furthermore, the homogeneity of the local ventilation rates was evaluated using the coefficients of variations.

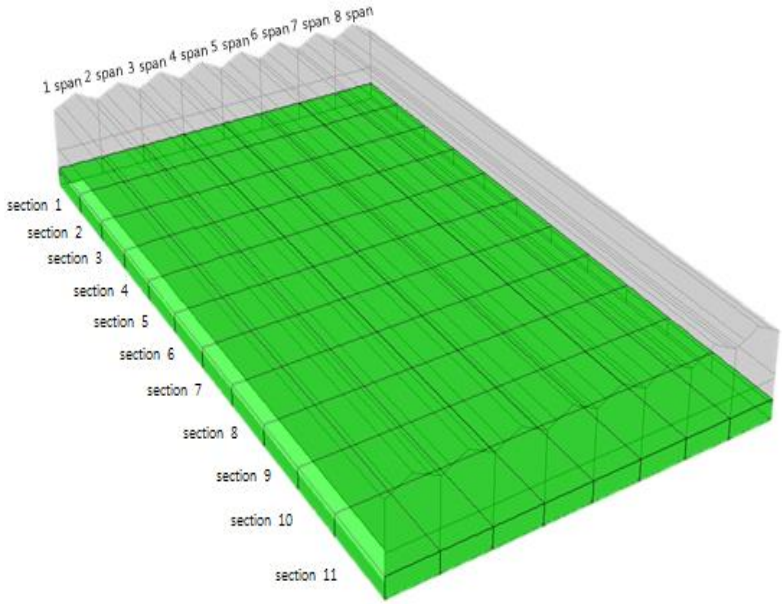


Fig. 7 Compartmentalization of 8-span Venlo type greenhouse model for analysis of local ventilation rates

The experimental variables for analyzing the ventilation rates of a multi-span greenhouse were determined to be the three types of greenhouses (Venlo, Wide-span, 1-2W), the three conditions of the number of spans (two, five, eight), the three conditions of wind speed (1.0, 2.5, 5.5 $m \cdot s^{-1}$), the three conditions of wind direction (90, 45, 0°), and the three types of vent openings (side vent, side-roof vent, roof vent) (as shown in Table 5). Greenhouses with two, five, or eight spans were selected to analyze the tendency of ventilation rates to increase as the number of spans increase. The wind speeds were determined by a wind frequency analysis of the wind environment from the target reclaimed lands. When the wind direction was perpendicular to the side ventilator, the wind direction was defined as 90°. When only the side ventilator was open, or only the side and roof ventilator were open, or only the roof ventilator was open, the types of vent openings were called “side vent,” “side-roof vent,” and “roof vent.”

Table 5 Experimental variables for estimating natural ventilation rates

	Case
Greenhouse type	Venlo, Wide-span, 1-2W
Number of span	2, 5, 8 spans
Wind speed	1.0, 2.5, 5.5 $m \cdot s^{-1}$
Wind direction	90, 45, 0°
Vent opening	Side vent, side-roof vent, roof vent

3.5.2. Analysis Method of the Ventilation Rate Using CFD

The ventilation requirements should be calculated and considered to design the ventilation of a greenhouse. When solar radiation was 800, 600, 400, or 200 $W \cdot m^{-2}$ (11.4, 8.6, 5.7, 2.9 $kcal \cdot m^{-2} \cdot min^{-1}$) and the range of the temperature difference between the internal air temperature and the external air temperature was 0 to 10℃, the ventilation requirements according to greenhouse types were calculated to be usable at installed greenhouses in various regions. It was assumed that crops did not exist in these greenhouses. The ventilation requirements were calculated using the suggested factors from the greenhouse standards used in Korea (Korea Rural Community Corporation, 1997). The values of parameters for computing ventilation requirements were shown in Table 6.

Table 6 The value of parameters for computing ventilation requirements

Factor	Value	
Volumetric specific heat of air (C_v)	0.3 kcal·m^{-3}·℃$^{-1}$	
Correction rate of heated area (α)	1.2	
Solar transmissivity of greenhouse cover (τ)	0.7	
Solar radiation (S)	11.4, 8.6, 5.7, 2.9 kcal·m^{-2}·min^{-1}	
Evapotranspiration coefficient (f)	0 (No plants)	
Floor area of greenhouse (A_f)	venlo	1,152 m^2
	Wide-span	3,240 m^2
	1-2W	2,574 m^2
Area of greenhouse cover (A_c)	venlo	1,867 m^2
	Wide-span	4,771 m^2
	1-2W	4,317 m^2
Volume of greenhouse (V)	venlo	5,328 m^3
	Wide-span	17,496 m^3
	1-2W	10,104 m^3
Overall heat transfer coefficient (k)	0.08 kcal·m^{-2}·min^{-1}·℃$^{-1}$	

To compute the mass flow rate, the mass flow at all cells of the vent area was computed by CFD simulation. Inflow and outflow were separated with a distinction of the directionality of the mass flow at each cell on the surface of the vent area. Total mass flow was calculated through a surface weighted average as seen in equation (12).

$$\frac{1}{A}\int \Phi dA = \frac{1}{A}\sum_{i=1}^{n} v_{cell_i}|A_i| \tag{12}$$

A	: Vent area (m^2)
A_i	: Area of i-th cell (m^2)
v_{cell_i}	: Wind speed at i-th cell ($m{\cdot}s^{-1}$)
n	: The number of cell at vent.

The ventilation rate based on the tracer gas decay method was calculated by analyzing the decay curve of the tracer gas concentration. In this study, CO_2 was used as the tracer gas. The initial concentration of the tracer gas was set at 2000 ppm. The CFD simulation was performed until the concentration of the tracer gas decreased to 1% of the initial concentration (Ha, 2015). The concentration of tracer gas was applied through a conversed value of the mass fraction for the purpose of the correct calculation in the CFD simulation model. The mass fraction was defined as follows:

$$Mass\ fraction_{tracer\ gas} = \frac{C_{tracer\ gas} \times \rho_{tracer\ gas}}{(C_{air} \times \rho_{air}) + (C_{tracer\ gas} \times \rho_{tracer\ gas})} \tag{13}$$

Where,

C_{air}	: Concentration of air (ppm)
$C_{tracer\ gas}$	: Concentration of tracer gas (ppm)
ρ_{air}	: Density of air ($kg{\cdot}m^{-3}$)
$\rho_{tracer\ gas}$	: Density of tracer gas ($kg{\cdot}m^{-3}$)

4. Results and Discussion

4.1. Wind Environment

The frequency of the wind speed was analyzed to determine the wind speed at the reference height using weather data from the weather station located near the target reclaimed lands. The ranges of the prevailing wind speed and frequency are shown in Table 7. The wind speed at the reference height was determined as 1.0, 2.5, and 5.5 $m \cdot s^{-1}$ so that the natural ventilation rate during low and high wind conditions could be evaluated. The wind and turbulence intensity profiles were designed using the determined wind speed at the reference height and applied to the CFD simulation.

Table 7 Analysis of wind speed frequency at weather stations located near target reclaimed lands

Weather station	Prevailing wind speed ($m \cdot s^{-1}$)	Frequency (%)
Buan	1.5~3.5	35.9
Goheung	1.5~3.5	36.8
Gunsan	1.5~3.5	39.4
Haenam	1.5~3.5	34.8
Incheon	1.5~3.5	46.9
Jindo	3.5~7.5	55.7
Mokpo	3.5~7.5	36.0
Seosan	1.5~3.5	34.2
Woojung	0.5~1.5	34.4

Fig. 8 shows the results of analyzing the wind direction of each weather station. At the weather stations located along the west coast (Buan, Gunsan, Haenam, Mokpo, Jindo), the prevailing wind directions are northwest and southeast. The reason for this prevailing wind direction is the effect of the temperature difference between sea and land during the day and at night. At the weather station located on the south coast (Goheung), the prevailing wind direction is north. However, the prevailing wind directions at the weather stations located near reclaimed lands were not considered in this study because the effect of the wind environment was different depending on the direction of the installed greenhouse. Instead, various wind directions at the greenhouses were selected as 90, 45, or 0° considering the symmetry of each greenhouse's shape.

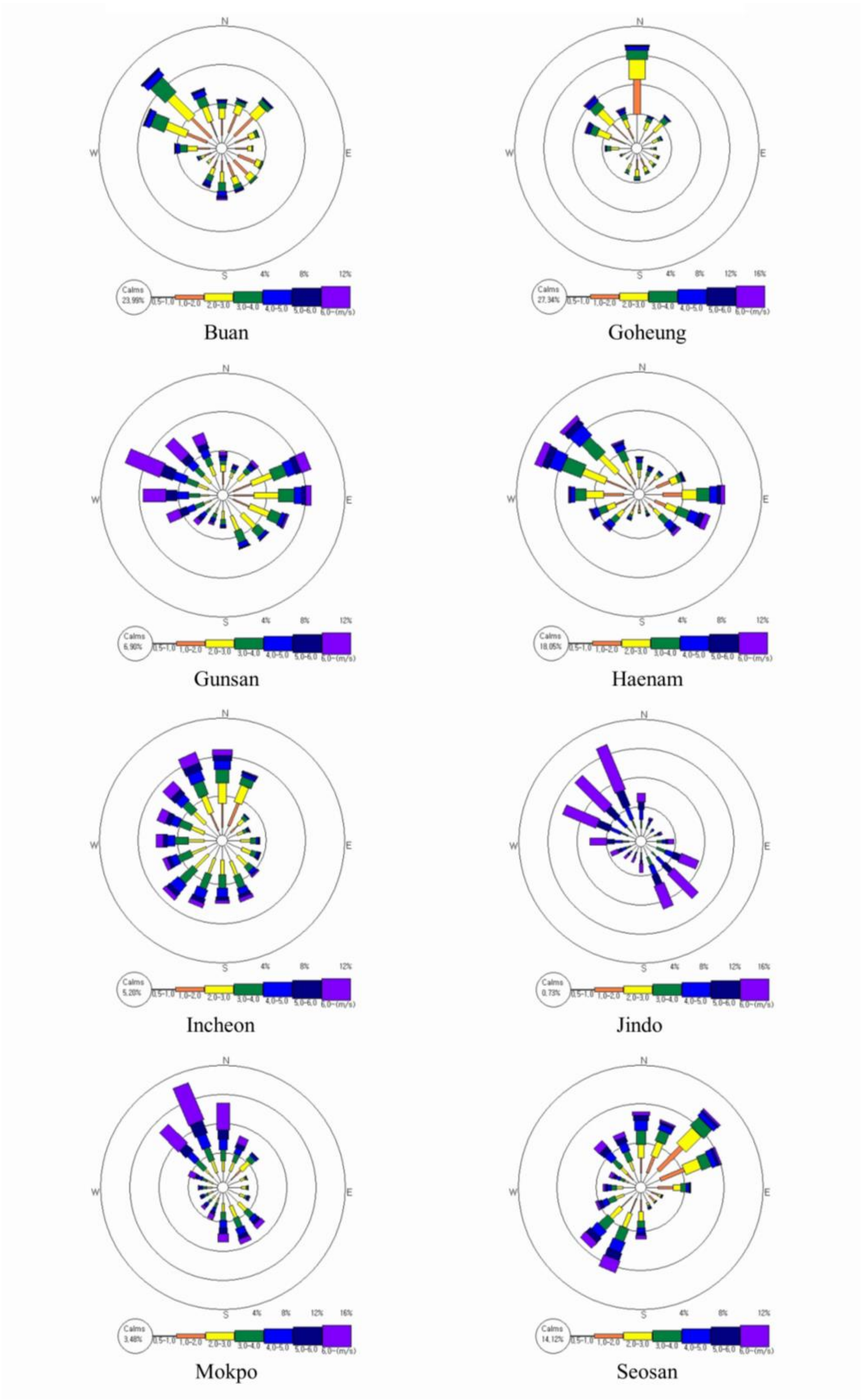


Fig. 8 wind rose at weather station located near target reclaimed lands

4.2. Ventilation Requirement

In this study, the ventilation requirements were estimated according to the level of solar radiation and greenhouse type and are shown in Figs. 9-11. Because the ventilation requirements were calculated as the number of air exchanges per minute, the ventilation requirements were the same under equal environmental conditions, independent of the number of spans. As a result of analyzing the ventilation requirements, the ventilation requirements were increased following an increase in the solar radiation with equal environmental conditions. This tendency was reasonable results, as the ventilation requirements were computed by the energy balance equation. For example, when the outside air temperature was 30℃ and the solar radiation was 800 W·m2, the ventilation requirements of Venlo, Wide-span, and 1-2W type greenhouses for maintaining the air temperature at 33℃ in the greenhouse were 2.2, 1.9, and 2.6 AE·min^{-1}, respectively. With the same environmental conditions, the ventilation requirements of the 1-2W type greenhouse were the highest and the Venlo type greenhouse were the lowest. Using Figs. 9-11, the ventilation requirements could be calculated according to the weather conditions in the region where the greenhouse was installed. Therefore, the ventilation requirements were expected to be used for designing the ventilation of each greenhouse. When designing the ventilation of a greenhouse, solar radiation should be selected according to the Technical Advisory Committee (TAC), which has provided a ratio for risk level. Generally, TAC's level of 2.5% or 5.5% has been used as the standard to design agricultural facilities (Rural Research Institute, 1997; ASHRAE Handbook, 1993).

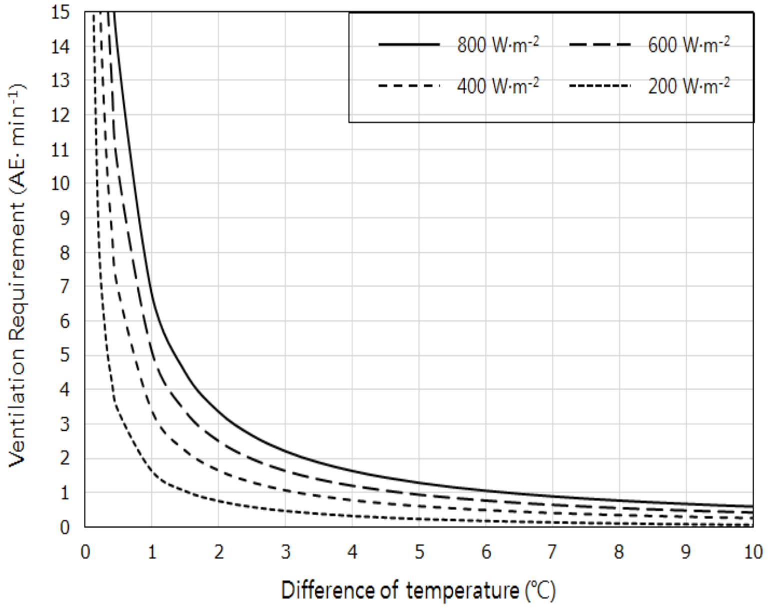


Fig. 9 Ventilation requirements of Venlo type greenhouse according to conditions of solar radiation

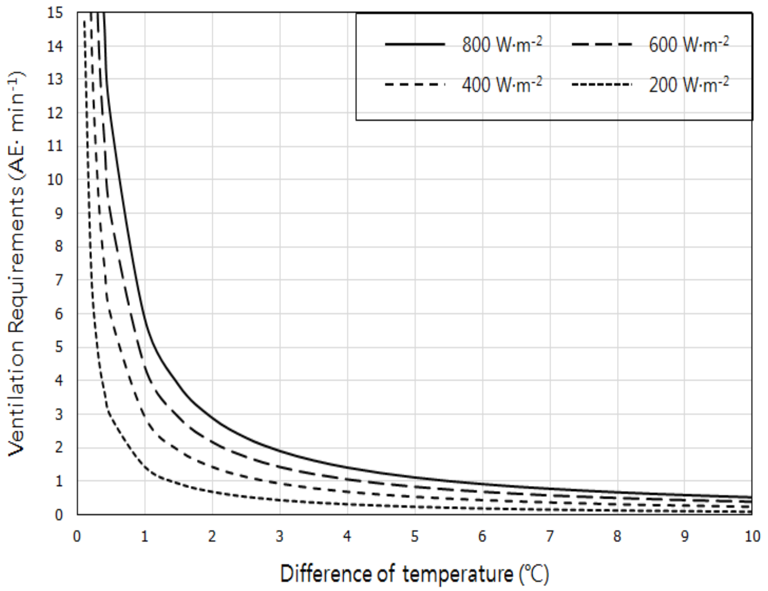


Fig. 10 Ventilation requirements of Wide-span type greenhouse according to conditions of solar radiation

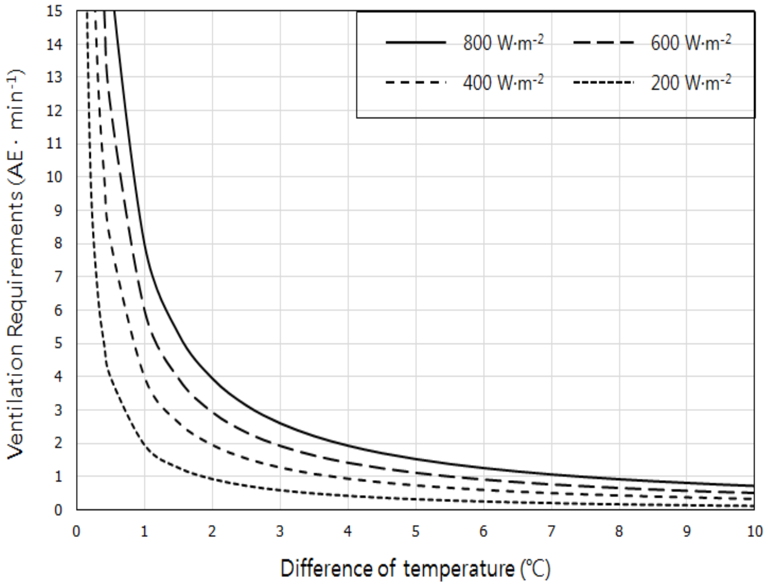


Fig. 11 Ventilation requirements of 1-2W type greenhouse according to conditions of solar radiation

4.3. Analysis of Natural Ventilation Rates

4.3.1. Overall Ventilation Rates of Greenhouses

The natural ventilation rates were calculated by the mass flow rate and tracer gas decay methods using CFD simulation according to greenhouse type, number of spans, the external wind environment (wind speed, wind direction), and vent openings. The results of computing the natural ventilation rates are shown in Tables 8-13 according to the calculation method and greenhouse type. The natural ventilation rates were diverse according to the environmental conditions.

When the wind direction was 90°, wind speed was 5.5 $m \cdot s^{-1}$, and the vent opening was the side-roof vent, the natural ventilation rate of the two-span Venlo type greenhouse calculated by the mass flow rate method was the highest at 10.00 $AE \cdot min^{-1}$. When the wind direction was 0°, wind speed was 1.0 $m \cdot s^{-1}$, and the vent opening was the roof vent, the natural ventilation rate of the eight-span Venlo type greenhouse calculated by the mass flow rate method was the lowest at 0.08 $AE \cdot min^{-1}$. When the wind direction was 90°, wind velocity was 5.5 $m \cdot s^{-1}$, and the vent opening was the side-roof vent, the natural ventilation rate of the two-span Venlo type greenhouse calculated by the tracer gas decay method was the highest at 10.67 AE·min^{-1}. When the wind direction was 0°, wind speed was 1.0 m·s^{-1}, and the vent opening was the roof vent, the natural ventilation rate of the eight-span Venlo type greenhouse calculated by the tracer gas decay method was the lowest at 0.09 AE·min^{-1}.

When the wind direction was 90°, wind speed was 5.5 m·s^{-1}, and the vent opening was the side-roof vent, the natural ventilation rate of the two-span Wide-span type greenhouse calculated by the mass flow rate method was the highest at 5.52 AE·min^{-1}. When the wind direction was 0°, wind speed was 1.0 m·s^{-1}, and the vent opening was the side vent, the natural ventilation rate of the eight-span Wide-span type greenhouse calculated by the mass flow rate method was the lowest at 0.04 AE·min^{-1}. When the wind direction was 90°, wind speed was 5.5 m·s^{-1}, and the vent opening was the side-roof vent, the natural ventilation rate of the two-span Wide-span type greenhouse calculated by the tracer gas decay method was the highest at 7.64 AE·min^{-1}. When the wind direction was 0°, wind speed was 1.0 m·s^{-1}, and the vent opening was the side vent, the natural ventilation rate of the eight-span Wide-span type greenhouse calculated by the tracer gas decay method was the lowest at 0.02 AE·min^{-1}.

When the wind direction was 90°, wind speed was 5.5 m·s^{-1}, and the vent opening was the side-roof vent, the natural ventilation rate of the two-span 1-2W type greenhouse calculated by the mass flow rate method was the highest at 2.6 AE·min^{-1}. When the wind direction was 0°, wind speed was 1.0 m·s^{-1}, and the vent opening was the roof vent, the natural ventilation rate of the eight-span 1-2W type greenhouse calculated by the mass flow rate method was the lowest at 0.03 AE·min^{-1}. When the wind direction was 90°, wind speed was 5.5 m·s^{-1}, and the vent opening was the side-roof vent, the natural ventilation rate of the two-span 1-2W type greenhouse calculated by the tracer gas decay method was the highest at 3.29 AE·min^{-1}. When the wind direction was 0°, wind speed was 1.0 m·s^{-1}, and the vent opening was the roof vent, the natural ventilation rate of the eight-span 1-2W type greenhouse calculated by the tracer gas decay method was the lowest at 0.05 AE$\cdot$min^{-1}.

In comparing the natural ventilation rates according to greenhouse type, the natural ventilation rates were high to low in this order: Venlo, Wide-span, and 1-2W. The natural ventilation varied depending on the calculation methods. In the case of the Venlo type greenhouse, the difference in the natural ventilation rate according to the calculation methods was about 20%. In the Wide-span type greenhouse, the difference in the natural ventilation rate according to the calculation methods was about 40%. In the 1-2W type greenhouse, the difference in the natural ventilation rate according to the calculation methods was about 30%.

The difference in the natural ventilation rates resulted from the characteristics of the calculation methods. For example, if the tracer gas flowed out at a constant concentration, the ventilation rates calculated by the mass flow rate and tracer gas decay methods were equal. However, because the distribution of the tracer gas was not uniform, the ventilation rates calculated by the mass flow rate and tracer gas decay methods were different. When the concentration of the tracer gas that flowed out was higher than the average concentration of tracer gas, the ventilation rate calculated by the tracer gas decay methods was higher than the ventilation rate calculated by the mass flow rate. Contrarily, when the concentration of the tracer gas that flowed out was lower than the average concentration of tracer gas, the ventilation rate calculated by the tracer gas decay methods was lower than the ventilation rate calculated by the mass flow rate (Hong et al., 2008). In the mass flow rate method, the internal air flow pattern of the greenhouse was not considered, because the ventilation rate was calculated by using only the mass flow at the vent area and the volume of the greenhouse. On the other hand, the tracer gas decay method did consider the air flow pattern inside the greenhouse to calculate the ventilation rate because the ventilation rates were calculated by analyzing the concentration reduction of the tracer gas at various points inside the greenhouse.

Therefore, it was judged that the tracer gas decay method evaluated actual natural ventilation more closely than the mass flow rate method did.

Table 8 Computed natural ventilation rates of Venlo type greenhouse using mass flow rate method (Unit: AE·min^{-1})

Vent opening	Wind speed (m·s^{-1})	2-span			5-span			8-span		
		Wind direction								
		90°	45°	0°	90°	45°	0°	90°	45°	0°
Side vent	1.0	0.73	0.65	0.19	0.46	0.36	0.15	0.27	0.23	0.11
	2.5	1.87	1.66	0.37	1.10	0.96	0.35	0.67	0.51	0.28
	5.5	6.97	3.84	1.65	2.42	2.08	0.84	1.47	1.17	0.64
Side-roof vent	1.0	2.49	1.40	0.37	0.80	0.70	0.23	0.59	0.48	0.20
	2.5	4.32	3.73	0.93	1.96	1.70	0.76	1.45	1.21	0.49
	5.5	10.00	8.33	1.97	4.28	3.72	1.35	3.18	2.70	1.10
Roof vent	1.0	0.30	0.25	0.12	0.19	0.21	0.09	0.17	0.20	0.08
	2.5	0.72	0.72	0.32	0.45	0.57	0.28	0.39	0.46	0.27
	5.5	1.58	1.65	0.72	0.99	1.10	0.67	0.79	1.09	0.62

Table 9 Computed natural ventilation rates of Wide-span type greenhouse using mass flow rate method (Unit: AE·min^{-1})

Vent opening	Wind speed ($m \cdot s^{-1}$)	2-span			5-span			8-span		
		Wind direction								
		90°	45°	0°	90°	45°	0°	90°	45°	0°
Side vent	1.0	0.32	0.28	0.13	0.23	0.11	0.05	0.11	0.07	0.04
	2.5	0.81	0.71	0.33	0.30	0.27	0.12	0.19	0.16	0.09
	5.5	1.89	1.57	0.75	0.67	0.58	0.30	0.38	0.35	0.17
Side-roof vent	1.0	0.83	0.66	0.20	0.29	0.30	0.18	0.28	0.32	0.17
	2.5	2.48	1.66	0.49	0.78	0.73	0.44	0.79	0.70	0.41
	5.5	5.52	3.65	1.18	1.70	1.61	0.89	1.73	1.61	0.88
Roof vent	1.0	0.44	0.38	0.21	0.42	0.23	0.12	0.29	0.21	0.10
	2.5	1.11	0.99	0.33	0.74	0.47	0.33	0.55	0.37	0.25
	5.5	2.35	2.17	0.70	1.63	1.12	0.68	1.29	0.74	0.46

Table 10 Computed natural ventilation rates of 1-2W type greenhouse using mass flow rate method (Unit: AE·min^{-1})

Vent opening	Wind speed (m·s^{-1})	2-span			5-span			8-span		
		Wind direction								
		90°	45°	0°	90°	45°	0°	90°	45°	0°
Side vent	1.0	0.37	0.33	0.14	0.14	0.13	0.05	0.12	0.10	0.03
	2.5	0.93	0.77	0.36	0.34	0.31	0.17	0.26	0.19	0.09
	5.5	2.05	1.82	0.83	0.81	0.67	0.34	0.48	0.44	0.21
Side-roof vent	1.0	0.48	0.46	0.20	0.40	0.33	0.21	0.38	0.31	0.20
	2.5	1.16	1.08	0.53	1.03	0.82	0.54	0.98	0.77	0.53
	5.5	2.60	2.53	1.43	2.25	2.12	1.13	2.14	1.97	1.22
Roof vent	1.0	0.13	0.12	0.06	0.25	0.23	0.14	0.25	0.25	0.15
	2.5	0.30	0.25	0.14	0.59	0.56	0.34	0.67	0.62	0.41
	5.5	0.69	0.59	0.33	1.26	1.13	0.84	1.49	1.44	0.84

Table 11 Computed natural ventilation rates of Venlo type greenhouse using tracer gas decay method (Unit: AE·min^{-1})

Vent opening	Wind speed ($m \cdot s^{-1}$)	2-span			5-span			8-span		
		Wind direction								
		90°	45°	0°	90°	45°	0°	90°	45°	0°
Side vent	1.0	0.72	0.71	0.20	0.30	0.26	0.09	0.23	0.26	0.09
	2.5	0.97	0.71	0.51	0.75	0.37	0.32	0.48	0.35	0.24
	5.5	3.68	3.53	1.12	1.57	1.74	0.61	1.09	1.74	0.55
Side-roof vent	1.0	2.79	1.96	0.23	0.87	0.66	0.16	0.81	0.48	0.11
	2.5	5.22	3.43	0.57	2.08	1.54	0.43	1.88	1.11	0.29
	5.5	10.67	7.00	1.22	4.45	3.01	0.78	4.26	3.07	0.63
Roof vent	1.0	0.24	0.26	0.11	0.12	0.13	0.10	0.11	0.13	0.09
	2.5	0.59	0.62	0.37	0.34	0.35	0.28	0.28	0.34	0.27
	5.5	1.26	1.23	0.81	0.75	0.78	0.72	0.58	0.72	0.62

Table 12 Computed natural ventilation rates of Wide-span type greenhouse using tracer gas decay method (Unit: AE·min^{-1})

Vent opening	Wind speed (m·s^{-1})	2-span			5-span			8-span		
		Wind direction								
		90°	45°	0°	90°	45°	0°	90°	45°	0°
Side vent	1.0	0.42	0.21	0.13	0.38	0.13	0.03	0.17	0.11	0.02
	2.5	0.98	0.44	0.27	0.44	0.32	0.20	0.33	0.27	0.08
	5.5	1.92	1.04	0.65	0.65	0.79	0.38	0.60	0.55	0.12
Side-roof vent	1.0	2.21	0.49	0.17	0.86	0.23	0.12	0.72	0.17	0.11
	2.5	3.34	1.23	0.42	1.95	0.56	0.40	1.63	0.45	0.18
	5.5	7.64	2.47	0.94	3.87	1.20	0.76	3.32	0.64	0.45
Roof vent	1.0	0.18	0.15	0.09	0.10	0.10	0.06	0.07	0.07	0.04
	2.5	0.50	0.43	0.26	0.45	0.20	0.18	0.19	0.18	0.15
	5.5	0.94	0.87	0.69	0.61	0.55	0.41	0.55	0.44	0.38

Table 13 Computed natural ventilation rates of 1-2W type greenhouse using tracer gas decay method (Unit: AE·min^{-1})

Vent opening	Wind speed ($m \cdot s^{-1}$)	2-span			5-span			8-span		
		Wind direction								
		90°	45°	0°	90°	45°	0°	90°	45°	0°
Side vent	1.0	0.54	0.24	0.12	0.46	0.17	0.06	0.20	0.13	0.05
	2.5	1.14	0.72	0.32	0.66	0.39	0.19	0.51	0.32	0.07
	5.5	2.47	1.41	0.70	1.40	1.13	0.35	1.12	0.83	0.20
Side-roof vent	1.0	0.59	0.39	0.20	0.39	0.34	0.17	0.39	0.31	0.16
	2.5	1.49	1.00	0.44	0.98	0.89	0.40	0.86	0.66	0.39
	5.5	3.29	2.06	0.95	2.61	1.96	0.93	2.52	1.50	0.92
Roof vent	1.0	0.12	0.11	0.08	0.19	0.15	0.09	0.25	0.16	0.14
	2.5	0.28	0.25	0.22	0.53	0.42	0.23	0.62	0.49	0.26
	5.5	0.70	0.66	0.41	1.06	0.81	0.62	1.43	1.01	0.66

To analyze the effect of the number of spans on the natural ventilation rate, the natural ventilation rates of the two-, five-, and eight-span greenhouses were calculated and evaluated according to greenhouse type. To analyze the decrease in the natural ventilation rates following an increase in the number of spans, the ratios of the natural ventilation rate of the five- and eight-span greenhouses to the natural ventilation rate of the two-span greenhouse were computed and are shown in Tables 14-16 according to greenhouse type.

In the Venlo type greenhouse, when the vent opening was the side vent and the wind directions were 90 and 45°, the natural ventilation rates of the five-span greenhouse compared to those of the two-span greenhouse decreased about 50% and the natural ventilation rates of the eight-span greenhouse compared to those of the two-span greenhouse decreased about 35%. When the vent opening was the side-roof vent and the wind directions were 90 and 45°, the natural ventilation rates of the five-span greenhouse compared to those of the two-span greenhouse decreased about 40% and the natural ventilation rates of the eight-span greenhouse compared to those of the two-span greenhouse decreased about 35%. The reason why the natural ventilation rates decreased following an increase in the number of spans was that the ratio of the increasing volume of the greenhouse following the increase of the number of spans was high for the amount of inflow air. The ratio of the decreasing natural ventilation rates at the roof vent was lower than at the side vent. Although the area of the side ventilator following the increasing number of spans did not change, the area of the roof ventilators increased following the increasing number of spans. In the Wide-span type greenhouse, the tendency was similar with the Venlo type greenhouse. The natural ventilation rate of the Wide-span greenhouse decreased following an increase in the number of spans. When the vent opening was the side vent, the tendency of the 1-2W greenhouse was similar to the Venlo and the Wide-span type greenhouses. However, when the vent opening was the roof vent, the ratio of the decreasing ventilation rates of the 1-2W type greenhouse following an increase in the number of spans was lower. When the vent opening was the roof vent, the natural ventilation rates of the 1-2W type greenhouse increased following the increase in the number of spans. The reason why this tendency was different by greenhouse type was that the effect of the roof ventilation of the 1-2W type greenhouse was higher than the Venlo and Wide-span type greenhouses. In the Venlo and Wide-span type greenhouses, the effect of the increasing volume was higher than the effect of the increasing amount of inflow air following an increase in the number of spans. Contrarily, in the 1-2W type greenhouse, the effect of the increasing amount of inflow air was higher than the effect of the increasing volume following the increase in the number of spans. These differences resulted from structural differences in the greenhouse shapes.

Table 14 Ratio of ventilation rates according to number of spans (Venlo type greenhouse)

Vent openings	Method	Wind direction 90°			Wind direction 45°			Wind direction 0°		
		2 span	5 span	8 span	2 span	5 span	8 span	2 span	5 span	8 span
Side vent	MFR	100%	52%	31%	100%	56%	32%	100%	75%	57%
	TGD	100%	54%	37%	100%	46%	45%	100%	54%	47%
Side-roof vent	MFR	100%	40%	30%	100%	47%	33%	100%	71%	54%
	TGD	100%	38%	35%	100%	41%	34%	100%	70%	50%
Roof vent	MFR	100%	63%	54%	100%	77%	70%	100%	85%	79%
	TGD	100%	56%	46%	100%	57%	54%	100%	85%	77%

Table 15 Ratio of ventilation rates according to number of spans (Wide-span type greenhouse)

Vent openings	Method	Wind direction 90°			Wind direction 45°			Wind direction 0°		
		2 span	5 span	8 span	2 span	5 span	8 span	2 span	5 span	8 span
Side vent	MFR	100%	48%	26%	100%	38%	23%	100%	38%	27%
	TGD	100%	56%	35%	100%	70%	55%	100%	54%	21%
Side-roof vent	MFR	100%	32%	32%	100%	45%	45%	100%	85%	81%
	TGD	100%	49%	42%	100%	47%	33%	100%	81%	53%
Roof vent	MFR	100%	77%	57%	100%	53%	42%	100%	85%	63%
	TGD	100%	69%	45%	100%	58%	46%	100%	67%	53%

Table 16 Ratio of ventilation rates according to number of spans (1-2W type greenhouse)

Vent openings	Method	Wind direction 90°			Wind direction 45°			Wind direction 0°		
		2 span	5 span	8 span	2 span	5 span	8 span	2 span	5 span	8 span
Side vent	MFR	100%	38%	28%	100%	39%	26%	100%	41%	24%
	TGD	100%	67%	43%	100%	68%	53%	100%	53%	31%
Side-roof vent	MFR	100%	86%	82%	100%	77%	72%	100%	95%	95%
	TGD	100%	71%	67%	100%	90%	72%	100%	92%	89%
Roof vent	MFR	100%	191%	210%	100%	202%	233%	100%	244%	264%
	TGD	100%	167%	212%	100%	142%	161%	100%	123%	150%

When the vent opening was the roof vent, the tendency of the increasing natural ventilation of the 1-2W type greenhouse was observed to be unlike the other greenhouse types. The external air flow patterns of the Wide-span and 1-2W greenhouses are shown in Fig. 12 to explain the opposite tendency. Because the roof ventilators of the Venlo and Wide-span type greenhouses were open to the upside, the windward roof ventilator disturbed the inflowing air through the leeward roof ventilators. For this reason, although the roof ventilators' area increased following the increase in the number of spans, the inflowing air through the roof ventilators was not enough. Contrarily, because the roof ventilators of the 1-2W did not disturb the inflowing air through the roof ventilators, the air could sufficiently inflow through the windward and leeward roof ventilators. Therefore, the natural ventilation rates of the 1-2W greenhouse under the condition of the roof vent increased following the increase in the number of spans. In other words, the effect of the ventilation through the roof ventilators in the 1-2W type greenhouse was higher than the effect of the ventilation through the roof ventilators in the Venlo and Wide-span greenhouses.

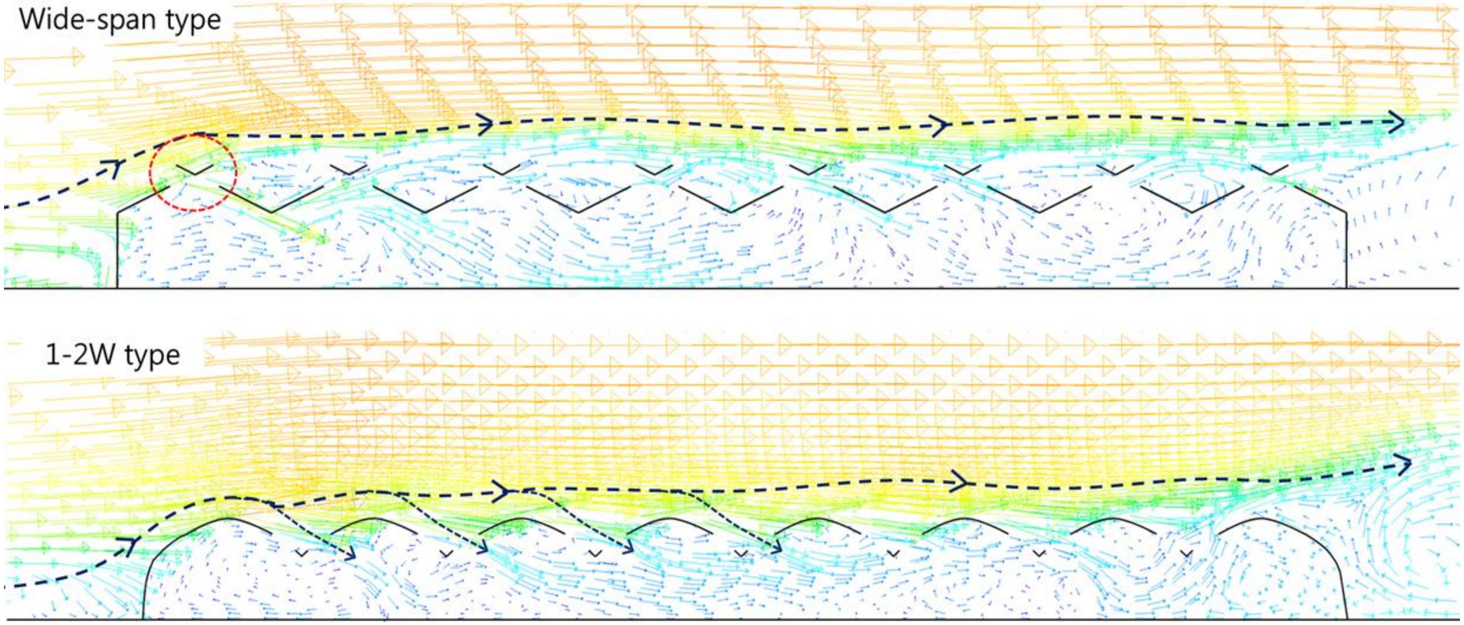


Fig. 12 Difference of external airflow pattern according to structural difference of greenhouse types

To evaluate the effect of the wind environment on natural ventilation, the natural ventilation rates were calculated and analyzed according to wind speed (1.0, 2.5, 5.5 $m \cdot s^{-1}$) and wind direction (90, 45, 0°). When the vent opening was the side vent, the natural ventilation rates were calculated by two methods as shown in Figs. 13-14. As a result of analyzing the natural ventilation rates of the Venlo type greenhouse according to wind speed, the natural ventilation rates computed by both the mass flow rate and tracer gas decay methods increased linearly by 2.5 and 5.5 times as the wind speed increased to 2.5 $m \cdot s^{-1}$ and 5.5 $m \cdot s^{-1}$ from 1.0 $m \cdot s^{-1}$. However, when the wind direction was 90°, the natural ventilation rates computed by the mass flow rate increased by about 2.6 and 9.5 times as the wind speed increased from 1.0 $m \cdot s^{-1}$ to 2.5 $m \cdot s^{-1}$ and 5.5 $m \cdot s^{-1}$, respectively. When the wind directions were 90° and 45°, the natural ventilation rates were similar at 1.0 and 2.5 $m \cdot s^{-1}$ of wind speed. The results of analyzing the natural ventilation rates according to wind direction were that the natural ventilation rates of all the greenhouse types computed by the two methods were highest to lowest in the order of 90, 45, and 0° under the same environmental conditions except for wind direction. The differences in the natural ventilation rates between the wind directions of 90° and 0° were especially enormous. The reason for this was that the amount of inflowing air at 90° of wind direction was more than the amount of inflowing air at 0°.

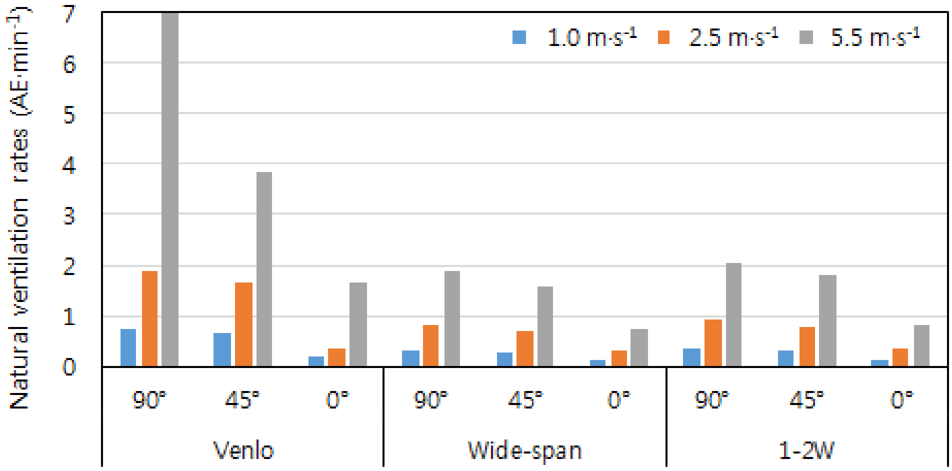


Fig. 13 Natural ventilation rates computed by MFR according to wind conditions and greenhouse type when number of span is two and side ventilators were only open

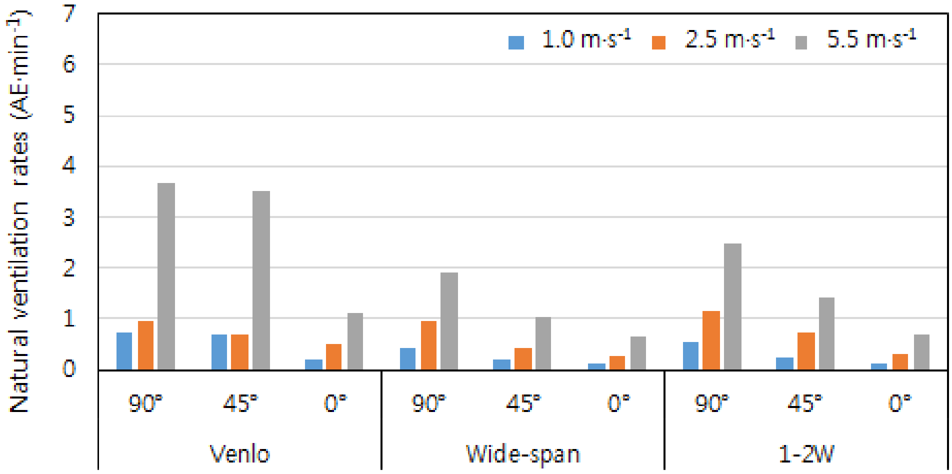


Fig. 14 Natural ventilation rates computed by TGD according to wind conditions and greenhouse type when number of span is two and side ventilators were only open

To evaluate the effects of vent openings on natural ventilation, the natural ventilation rates were calculated and analyzed according to vent opening (side vent, side-roof vent, roof vent). When the wind direction was 90°, the natural ventilation rates of the two-span greenhouse were calculated by the two methods according to greenhouse type and are shown in Figs. 15-16. As a result of analyzing the natural ventilation rates of the Venlo type greenhouse according to vent opening, the natural ventilation rates under the condition of the side-roof vent computed by both the mass flow rate and tracer gas decay methods were higher than with other vent openings. In the Venlo and Wide-span type greenhouses, when the tracer gas decay method was used, the natural ventilation rates at the side-roof vent were higher than the natural ventilation rates at the side vent by a large difference. When the mass flow rate method was used, the natural ventilation rates of the Wide-span greenhouse under the condition of the roof vent were higher than with the side vent. However, when the tracer gas decay method was used, the natural ventilation rates of the Wide-span greenhouse under the condition of the side vent were higher than with the roof vent. The reason why the difference in this tendency was observed depending on the evaluation methods of the natural ventilation rates was that the natural ventilation rates computed by the mass flow rate method were overestimated. Because the windward and leeward roof ventilators were opened simultaneously in the Wide-span greenhouse, the fresh air that flowed into the windward roof ventilators did not ventilate the inside of the greenhouse sufficiently and it flowed out directly through the leeward roof window. In the 1-2W type greenhouse, the natural ventilation rates computed by both the mass flow rate and tracer gas decay methods were similar under the conditions of the side vent and side-roof vent.

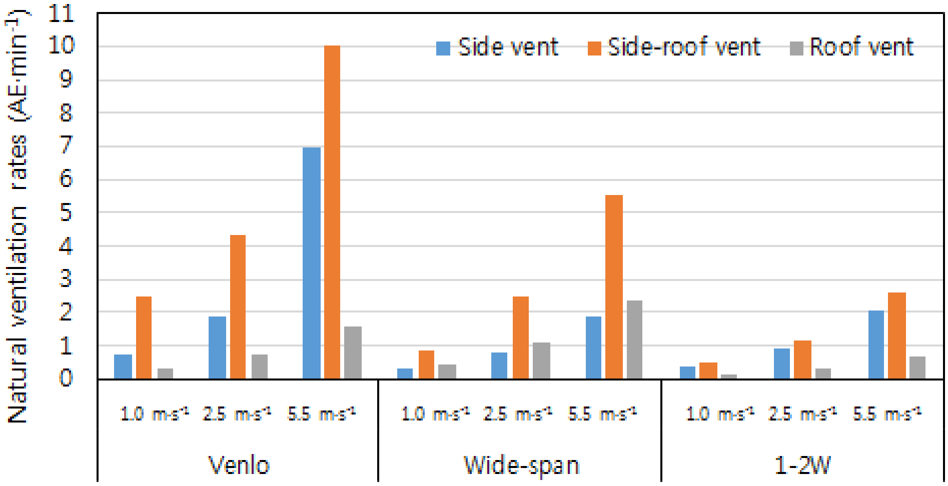


Fig. 15 Natural ventilation rates computed by MFR according to vent openings when number of span was two and wind direction was 90°

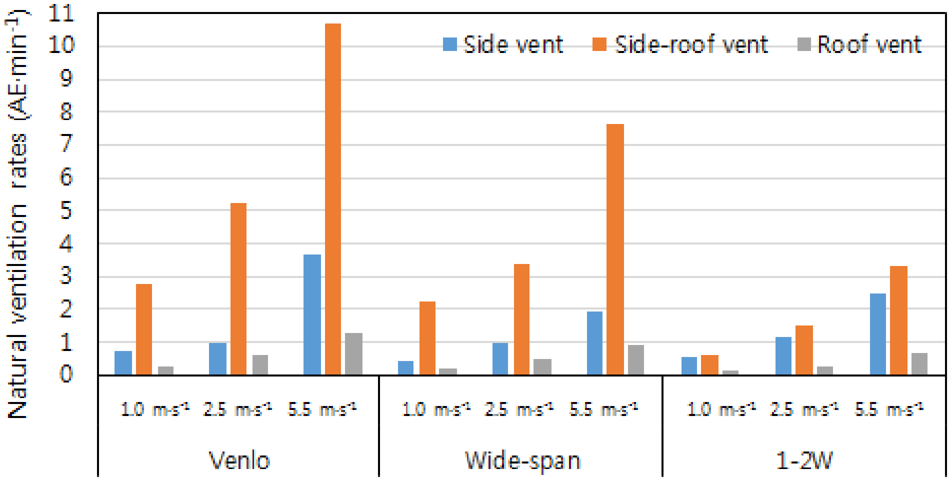


Fig. 16 Natural ventilation rates computed by TGD according to vent openings when number of span was two and wind direction was 90°

4.3.2. Local Ventilation Rates of Greenhouses

To analyze the distribution of the natural ventilation rates at 0~1 m height, representative cases were selected and analyzed. After the analysis of the representative cases, all the cases were evaluated on the basis of the analysis method. Fig. 17 shows the distribution of the local ventilation rates of the eight-span Venlo type greenhouse at 0~1 m height according to wind direction when the vent opening was the side vent and the wind speed was 1.0 $m \cdot s^{-1}$. When the wind direction was 90°, the local ventilation rates of both side walls on the windward side were relatively higher than those of the center on the leeward side. When the wind direction was 45°, the end wall of the windward side had a relatively low ventilation rate. When the wind direction was 0°, the natural ventilation rate was low overall and the local ventilation rates were especially low at the end wall of the windward side. When the wind direction was 0°, stagnant areas were observed at the end wall of the windward side. The difference in the tendency of the local ventilation rates at 0~1 m height was derived according to wind direction. Fig. 18 shows the vector field and air flow pattern of the eight-span Venlo type greenhouse at 1 m height according to wind direction when the vent opening was the side vent and the wind speed was 1.0 $m \cdot s^{-1}$. The distribution of the local ventilation rates was confirmed as shown in Fig. 16. When the wind direction was 90°, the inflowing air streamed from the windward side ventilators to the leeward side ventilators and the wind speed of the inflowing air decreased in the center of the leeward side. When the wind direction was 45°, external air from the side ventilators flowed into the greenhouse obliquely and an eddy occurred in the center of the greenhouse. When the wind direction was 0°, the external air flowed into the greenhouse from both leeward side ventilators and the internal air flowed out of the greenhouse from both windward side ventilators. As the wind velocity from the windward side was very low, a stagnant area was observed.

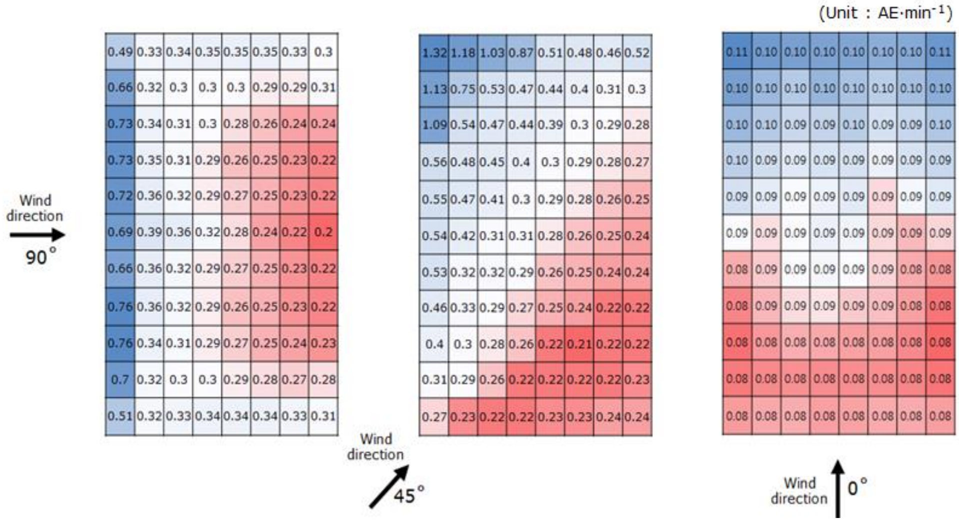


Fig. 17 Distribution of ventilation rate at 0~1m height of Venlo type greenhouse according to wind direction when wind speed is 1.0 m·s^{-1}, the number of spans is eight and vent openings is side vent (blue color: maximum ventilation rate, red color: minimum ventilation rate)

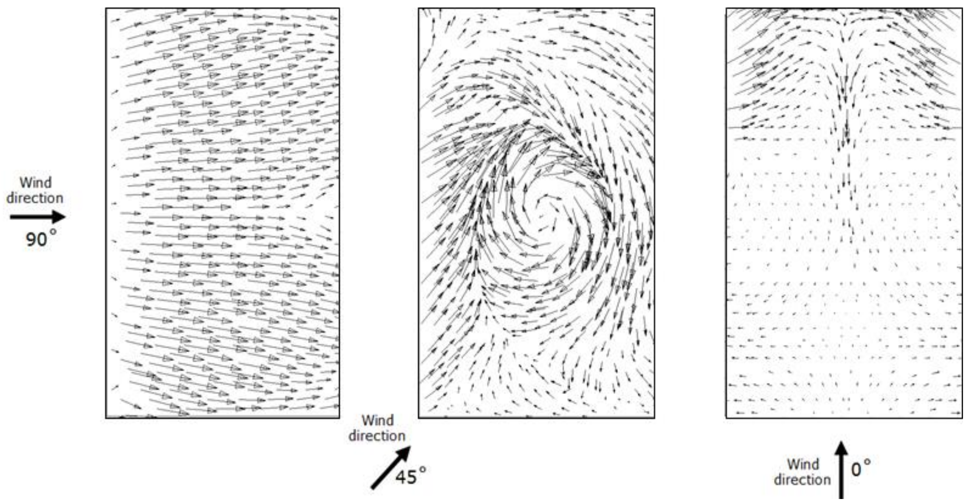


Fig. 18 Air flow pattern at 1m height of venlo type greenhouse according to wind direction when wind speed is 1.0 m·s^{-1}, the number of spans is eight and vent openings is side vent

To analyze the homogeneity of the local ventilation rates according to wind direction, the average ventilation rate at 0~1 m height, standard deviations, coefficients of variation, and the ratio of the maximum ventilation rate to the minimum ventilation rate were calculated when the greenhouse type was an eight-span Venlo type greenhouse, the vent opening was the side vent, and wind speed was 1.0 $m \cdot s^{-1}$ (see Table 17). The standard deviations were computed as 0.14 $AE \cdot min^{-1}$, 0.23 $AE \cdot min^{-1}$, and 0.01 $AE \cdot min^{-1}$ at 90, 45, and 0° of wind direction, respectively. The coefficients of variations were computed as 0.41, 0.60, and 0.07 at 90, 45, and 0° of wind direction, respectively. The ratios of the maximum ventilation rate to the minimum ventilation rate were computed as 3.80, 6.29, and 1.38 at 90, 45, and 0° of wind direction, respectively. Therefore, the homogeneity of the local ventilation rate was best at 0° of wind direction and was worst at 45° of wind direction, because the standard deviation, coefficient of variation, and ratio of maximum ventilation rate to minimum ventilation rate were highest at 45° of wind direction and lowest at 45° of wind direction.

Table 17 Homogeneity of ventilation rate at 0~1m height according to wind direction when wind speed was 1.0 $m \cdot s^{-1}$, the number of spans is eight and vent openings is side vent

Index	Wind direction		
	90°	45°	0°
Average ventilation rate at 0~1m height ($AE \cdot min^{-1}$)	0.34	0.38	0.09
Standard deviation ($AE \cdot min^{-1}$)	0.14	0.23	0.01
Coefficient of variation	0.41	0.60	0.07
Maximum ventilation rate /Minimum ventilation rate	3.80	6.29	1.38

Generally, the standard deviation increased following the increase in the average of the data. It is difficult to compare with the homogeneity of data that have different averages, using the standard deviation. Therefore, in this study, the coefficient of variation was calculated and used to compare the homogeneity of the local ventilation rates that had different averages. The smaller the coefficient of variation was, the higher the homogeneity was. The coefficients of variation of the local ventilation rates at 0~1 m height were calculated for all cases and are shown in Tables 18-20 according to greenhouse type. The distinct tendency of homogeneity at 0~1 m height was not observed depending on greenhouse type. The homogeneity of the 1-2W type greenhouse was favorable overall because the coefficient of variation of the 1-2W type greenhouse was smaller overall than the other greenhouse types. Contrarily, the homogeneity of the Wide-span type greenhouse was relatively low as the coefficient of variation of the Wide-span type greenhouse was relatively higher than the other greenhouse types. As a result of analyzing the homogeneity of the local ventilation rate at 0`~1 m height according to wind direction, homogeneity was favorable at 0° of wind direction because the coefficient of variation at 0° of wind direction was lower than at other wind directions. It was judged that the homogeneity of the local ventilation rates at 0~1 m height was unrelated to wind speed as no tendency was observed according to wind speed. As a result of analyzing the homogeneity of the local ventilation rate at 0~1 m height according to vent opening, the homogeneity of the roof vent was favorable as the coefficient of variation at the roof vent was smaller than at other vent openings. However, homogeneity was favorable at 0° of wind direction and the roof vent, because the natural ventilation rates were low. Although homogeneity was good, ventilation was not performed properly. Therefore, the ventilation rate and homogeneity were considered simultaneously to evaluate the adequacy of ventilation performance.

Table 18 Coefficient of variation of local ventilation rates at 0~1m height in Venlo type greenhouse according to number of span, wind speed, wind direction and vent opening.

Vent opening	Wind speed ($m \cdot s^{-1}$)	2-span			5-span			8-span		
		Wind direction								
		90°	45°	0°	90°	45°	0°	90°	45°	0°
Side vent	1.0	0.33	0.39	0.07	0.41	0.40	0.16	0.41	0.60	0.08
	2.5	0.30	0.39	0.07	0.42	0.50	0.10	0.48	0.49	0.08
	5.5	0.27	0.40	0.06	0.43	0.33	0.12	0.48	0.56	0.09
Side-roof vent	1.0	0.17	0.21	0.05	0.31	0.54	0.06	0.37	0.67	0.16
	2.5	0.17	0.23	0.07	0.30	0.51	0.07	0.36	0.68	0.21
	5.5	0.20	0.28	0.06	0.28	0.45	0.08	0.36	0.53	0.18
Roof vent	1.0	0.06	0.15	0.09	0.13	0.16	0.16	0.09	0.14	0.21
	2.5	0.04	0.07	0.06	0.08	0.08	0.13	0.05	0.12	0.13
	5.5	0.04	0.08	0.06	0.09	0.13	0.07	0.06	0.08	0.12

Table 19 Coefficient of variation of local ventilation rates at 0~1m height in Wide-span type greenhouse according to number of span, wind speed, wind direction and vent opening.

Vent opening	Wind speed ($m \cdot s^{-1}$)	2-span			5-span			8-span		
		Wind direction								
		90°	45°	0°	90°	45°	0°	90°	45°	0°
Side vent	1.0	0.56	0.33	0.08	0.78	0.75	0.06	1.07	0.89	0.26
	2.5	0.20	0.41	0.09	0.55	0.74	0.23	0.55	0.68	0.10
	5.5	0.14	0.42	0.08	0.21	0.69	0.08	0.26	0.74	0.07
Side-roof vent	1.0	0.15	0.47	0.05	0.38	0.98	0.12	0.37	1.20	0.16
	2.5	0.23	0.44	0.07	0.38	0.97	0.14	0.46	1.20	0.16
	5.5	0.22	0.45	0.06	0.39	0.98	0.12	0.43	1.20	0.12
Roof vent	1.0	0.09	0.19	0.08	0.08	0.13	0.09	0.20	0.09	0.38
	2.5	0.08	0.19	0.09	0.13	0.29	0.10	0.11	0.08	0.18
	5.5	0.06	0.17	0.08	0.12	0.12	0.10	0.12	0.09	0.19

Table 20 Coefficient of variation of local ventilation rates at 0~1m height in 1-2W type greenhouse according to number of span, wind speed, wind direction and vent opening.

Vent opening	Wind speed ($m \cdot s^{-1}$)	2-span			5-span			8-span		
		Wind direction								
		90°	45°	0°	90°	45°	0°	90°	45°	0°
Side vent	1.0	0.19	0.33	0.10	0.15	0.62	0.16	0.43	0.81	0.10
	2.5	0.23	0.26	0.10	0.15	0.60	0.08	0.60	0.76	0.07
	5.5	0.14	0.24	0.10	0.31	0.50	0.22	0.33	0.56	0.17
Side-roof vent	1.0	0.07	0.24	0.09	0.11	0.44	0.11	0.15	0.49	0.25
	2.5	0.27	0.31	0.09	0.11	0.43	0.12	0.15	0.54	0.13
	5.5	0.14	0.26	0.09	0.17	0.46	0.10	0.17	0.52	0.15
Roof vent	1.0	0.06	0.10	0.07	0.25	0.20	0.14	0.32	0.11	0.13
	2.5	0.11	0.14	0.06	0.21	0.14	0.11	0.21	0.12	0.11
	5.5	0.22	0.17	0.07	0.20	0.18	0.11	0.17	0.14	0.09

To evaluate the distribution of the local ventilation rates according to sections of the height (0~1 m, 1~2 m, and the upper section of the greenhouse), representative cases were selected and analyzed before the analysis of all cases. Fig. 19 shows the distribution of the local ventilation rates of the eight-span Venlo type greenhouse at the section of height according to the vent opening when the wind direction was 90° and the wind speed was 1.0 m·s^{-1}. When the vent opening was the side vent, the ventilation rate was high in the windward lower section of the greenhouse and low in the windward upper section of the greenhouse. When the vent opening was the side-roof vent, the tendency of the ventilation rate was similar in side vent. However, the local ventilation rates in the upper section of the greenhouse improved as the roof vents were opened. When the vent opening was the roof vent, the local ventilation rates were lower overall than with other vent openings. The local ventilation rates were relatively high in the leeward upper section of the greenhouse and relatively low in the windward lower section of the greenhouse.

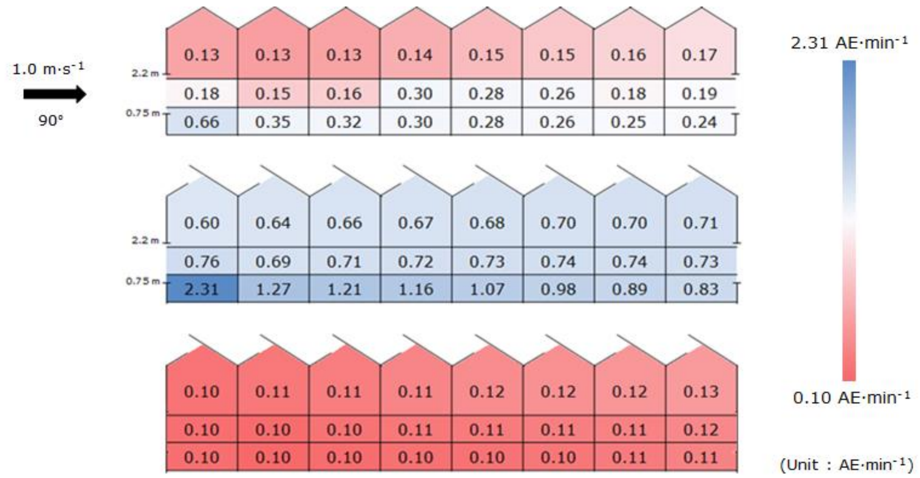


Fig. 19 Internal ventilation rate according to vent openings when wind speed was 1.0 m·s^{-1}. the number of spans is eight and wind direction is 90°

To analyze the homogeneity of the local ventilation rates at sections of the height (0~1 m, 1~2 m, and the upper section of the greenhouse) according to vent openings, the standard deviation, coefficient of variation, and ratio of maximum ventilation rate to minimum ventilation rate were calculated when the greenhouse type was the eight-span Venlo type greenhouse, the wind direction was 90°, and the wind speed was 1.0 m·s^{-1} (see Table 21). The standard deviations were 0.11 and 0.36 AE·min^{-1} at the side vent and side-roof vent, respectively. The coefficients of variation were 0.50 and 0.41 at the side vent and side-roof vent, respectively. The standard deviation at the side-roof vent was higher than at the side vent. However, the coefficient of variation at the side-roof vent was lower than at the side vent. Using the coefficient of variation is more appropriate than using the standard deviation as criteria for evaluating homogeneity because the averages of the ventilation rates were different. The ratios of the maximum ventilation rate to minimum ventilation rate were 5.08, 3.85, and 1.30 at the side vent, side-roof vent, and roof vent, respectively. Therefore, the homogeneity of the side vent was worse than with other vent openings because the coefficient of variation and the ratio of maximum ventilation rate to minimum ventilation rate were the highest at the side vent.

Table 21 Homogeneity of internal ventilation rate according to vent openings when wind speed was 1.0 m·s^{-1} and wind direction is 90°

Index	Vent opening		
	Side vent	Side-roof vent	Roof vent
Total ventilation rate of greenhouse (AE·min^{-1})	0.23	0.81	0.11
Standard deviation (AE·min^{-1})	0.11	0.36	0.01
Coefficient of variation	0.50	0.41	0.07
Maximum ventilation rate /Minimum ventilation rate	5.08	3.85	1.30

To evaluate the homogeneity of the local ventilation rates according to sections of the height (0~1 m, 1~2 m, and the upper section of the greenhouse), the coefficients of variation of the local ventilation rates were calculated for all cases and are shown in Tables 22-24 according to greenhouse type. From the results of comparing homogeneity according to greenhouse type, the homogeneity of the 1-2W type greenhouse was favorable as the coefficients of variation were low overall. Contrarily, the homogeneity of the Venlo type greenhouse was lower than the other greenhouse types as the coefficients of variation were higher overall than the other greenhouse types. When the wind direction was 0° and the vent opening was the roof vent, high homogeneity was observed in all greenhouse types. Because the distinct tendency of homogeneity was not observed according to wind speed, the effect of wind speed on the homogeneity of the local ventilation rates according to sections of height was slight.

Table 22 Coefficient of variation of local ventilation rates at section of height in Venlo type greenhouse according to number of span, wind speed, wind direction and vent opening.

Vent opening	Wind speed ($m \cdot s^{-1}$)	2-span			5-span			8-span		
		Wind direction								
		90°	45°	0°	90°	45°	0°	90°	45°	0°
Side vent	1.0	0.91	0.47	0.01	0.57	0.12	0.05	0.50	0.13	0.02
	2.5	0.74	0.15	0.01	0.54	0.17	0.03	0.58	0.13	0.02
	5.5	0.84	0.21	0.01	0.58	0.16	0.04	0.56	0.17	0.02
Side-roof vent	1.0	0.06	0.08	0.03	0.46	0.22	0.03	0.41	0.07	0.12
	2.5	0.24	0.24	0.02	0.46	0.26	0.01	0.42	0.16	0.16
	5.5	0.23	0.17	0.03	0.46	0.14	0.04	0.39	0.16	0.13
Roof vent	1.0	0.03	0.12	0.12	0.07	0.06	0.05	0.07	0.05	0.15
	2.5	0.03	0.03	0.04	0.07	0.01	0.07	0.05	0.08	0.07
	5.5	0.03	0.03	0.03	0.08	0.03	0.05	0.05	0.03	0.05

Table 23 Coefficient of variation of local ventilation rates at section of height in Wide-span type greenhouse according to number of span, wind speed, wind direction and vent opening.

Vent opening	Wind speed ($m \cdot s^{-1}$)	2-span			5-span			8-span		
		Wind direction								
		90°	45°	0°	90°	45°	0°	90°	45°	0°
Side vent	1.0	0.39	0.14	0.01	0.58	0.26	0.02	0.36	0.24	0.06
	2.5	0.32	0.10	0.03	0.21	0.32	0.08	0.21	0.16	0.06
	5.5	0.33	0.17	0.02	0.22	0.23	0.06	0.17	0.19	0.04
Side-roof vent	1.0	0.31	0.17	0.01	0.32	0.12	0.04	0.46	0.11	0.13
	2.5	0.20	0.17	0.05	0.39	0.11	0.07	0.43	0.11	0.13
	5.5	0.14	0.18	0.03	0.41	0.11	0.05	0.38	0.11	0.06
Roof vent	1.0	0.06	0.06	0.01	0.07	0.03	0.04	0.09	0.06	0.11
	2.5	0.04	0.02	0.01	0.06	0.17	0.01	0.09	0.06	0.15
	5.5	0.04	0.04	0.02	0.06	0.05	0.05	0.09	0.07	0.17

Table 24 Coefficient of variation of local ventilation rates at section of height in 1-2W type greenhouse according to number of span, wind speed, wind direction and vent opening.

Vent opening	Wind speed ($m \cdot s^{-1}$)	2-span			5-span			8-span		
		Wind direction								
		90°	45°	0°	90°	45°	0°	90°	45°	0°
Side vent	1.0	0.18	0.15	0.05	0.14	0.21	0.07	0.16	0.39	0.05
	2.5	0.15	0.09	0.02	0.11	0.12	0.02	0.38	0.17	0.04
	5.5	0.22	0.11	0.02	0.16	0.27	0.16	0.11	0.34	0.12
Side-roof vent	1.0	0.19	0.11	0.03	0.14	0.18	0.05	0.12	0.12	0.11
	2.5	0.15	0.11	0.07	0.13	0.21	0.07	0.11	0.28	0.04
	5.5	0.18	0.08	0.02	0.14	0.14	0.06	0.11	0.28	0.04
Roof vent	1.0	0.05	0.03	0.01	0.21	0.08	0.14	0.31	0.05	0.07
	2.5	0.04	0.04	0.01	0.16	0.06	0.05	0.13	0.06	0.06
	5.5	0.05	0.04	0.01	0.14	0.07	0.04	0.16	0.05	0.08

4.4. Suggested Charts for Expecting Natural Ventilation Rates and Comparison of the Ventilation Requirements and Natural Ventilation Rates

Finally, charts for expecting natural ventilation rates were compiled based on the natural ventilation rates calculated under the various environmental conditions. The compiled charts are shown in Figs. 18-20 according to greenhouse type. Because it was judged that the tracer gas decay method evaluated the actual natural ventilation more closely than the mass flow rate method, charts for expecting natural ventilation rates were compiled using the natural ventilation rates computed by the tracer gas decay method. The ventilation requirements for maintaining 2, 4, and 6℃ of temperature difference at 800 W·m-2 of solar radiation were also expressed in the charts to evaluate the natural ventilation rates by comparing them with the ventilation requirements.

The natural ventilation rates of the Venlo type greenhouse were evaluated through comparative analysis with the ventilation requirements. When the wind direction was 90° or 45° and wind speed was 5.5 $m \cdot s^{-1}$, most of the natural ventilation rates satisfied the ventilation requirements for maintaining 6℃ difference with the outside temperature (1.1 $AE \cdot min^{-1}$). However, when the wind direction was 0°, all of the natural ventilation rates did not satisfy the ventilation requirements for maintaining 6℃ difference with the outside temperature (1.1 $AE \cdot min^{-1}$). Besides, when the vent opening was the roof vent, most of the natural ventilation rates did not satisfy the ventilation requirements for maintaining 6℃ difference with the outside temperature (1.1 $AE \cdot min^{-1}$). From the results of the Wide-span type greenhouse, when the wind direction was 0°, all of the natural ventilation rates did not satisfy the ventilation requirements for maintaining 6℃ difference with the outside temperature (0.9 $AE \cdot min^{-1}$). When the vent opening was the roof vent, all of the natural ventilation rates did not satisfy the ventilation requirements for maintaining 6℃ difference with the outside temperature (0.9 $AE \cdot min^{-1}$). From the results of the

1-2W type greenhouse, when the wind direction was 0° and the vent opening was the roof vent, all of the natural ventilation rates did not satisfy the ventilation requirements for maintaining 6℃ difference with the outside temperature (1.3 $AE \cdot min^{-1}$).

When the natural ventilation of a greenhouse is designed, the structural characteristics of the greenhouse, the wind environment, and the thermal conditions of the region where the greenhouse will be installed should be analyzed and considered. After the natural ventilation rates were computed, it was evaluated whether the natural ventilation rates satisfied the ventilation requirements or not. The charts suggested in this study are expected to be used for establishing standards of ventilation design.

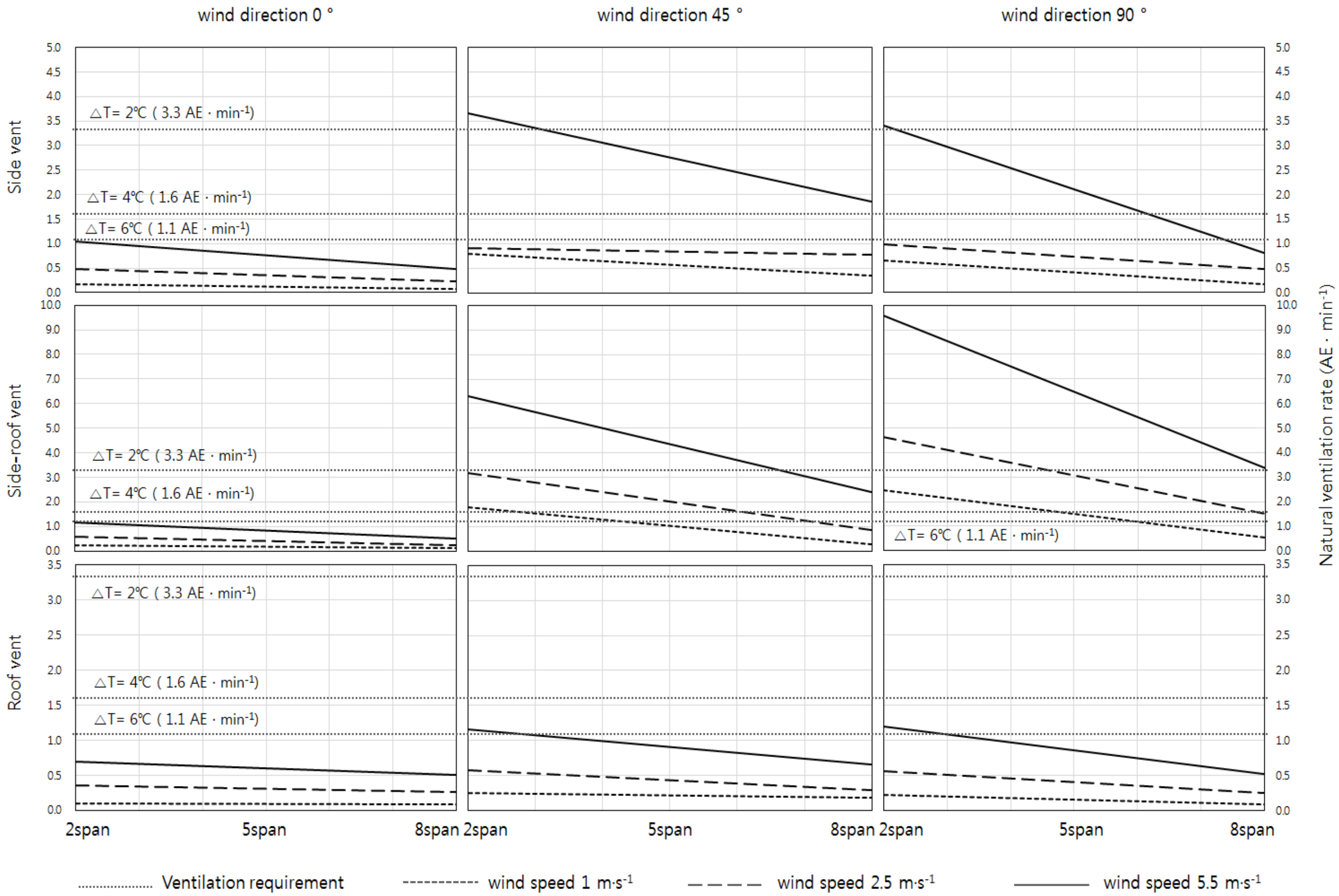


Fig. 20 Chart for expecting natural ventilation rate of Venlo type greenhouse

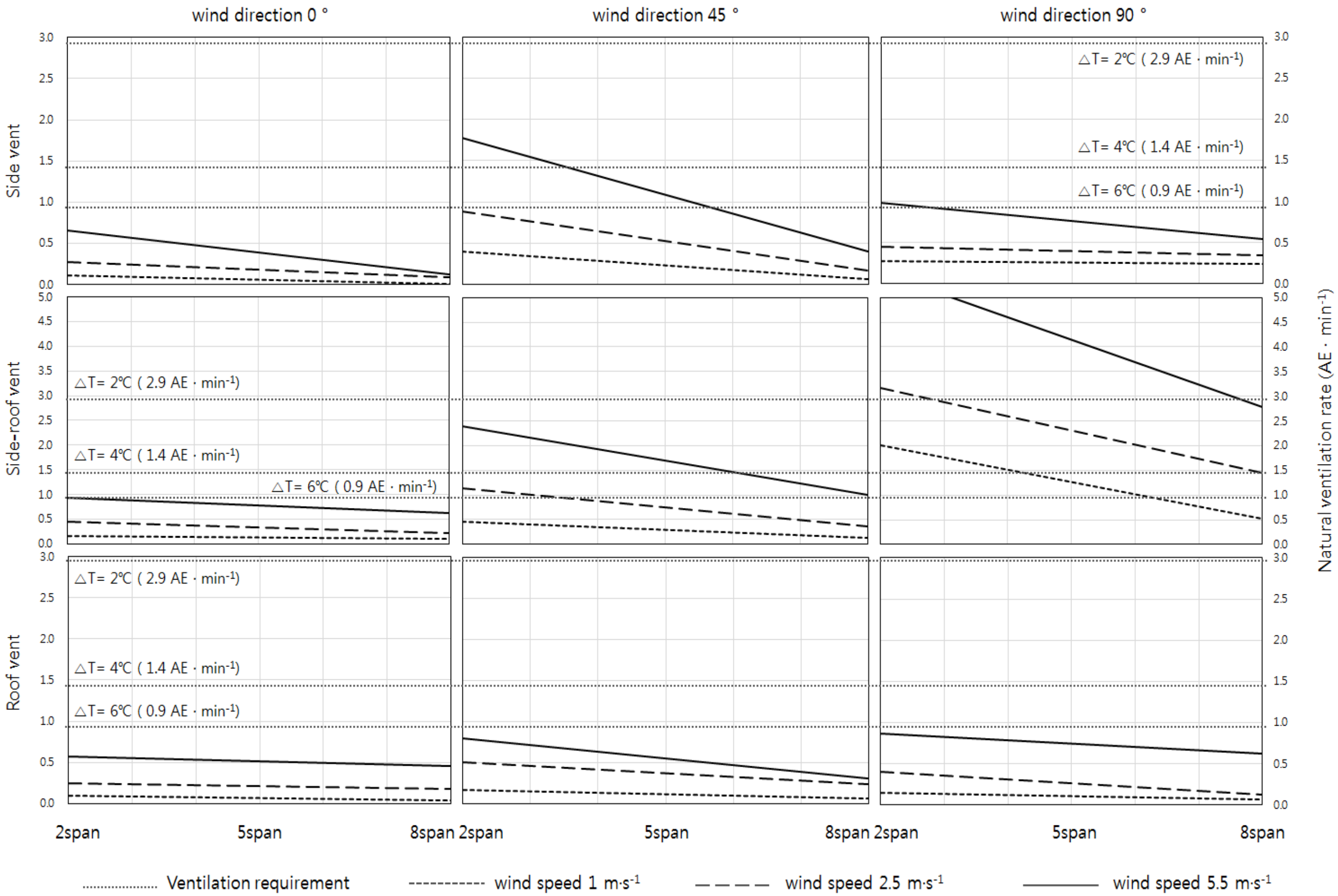


Fig. 21 Chart for expecting natural ventilation rate of Wide-span type greenhouse

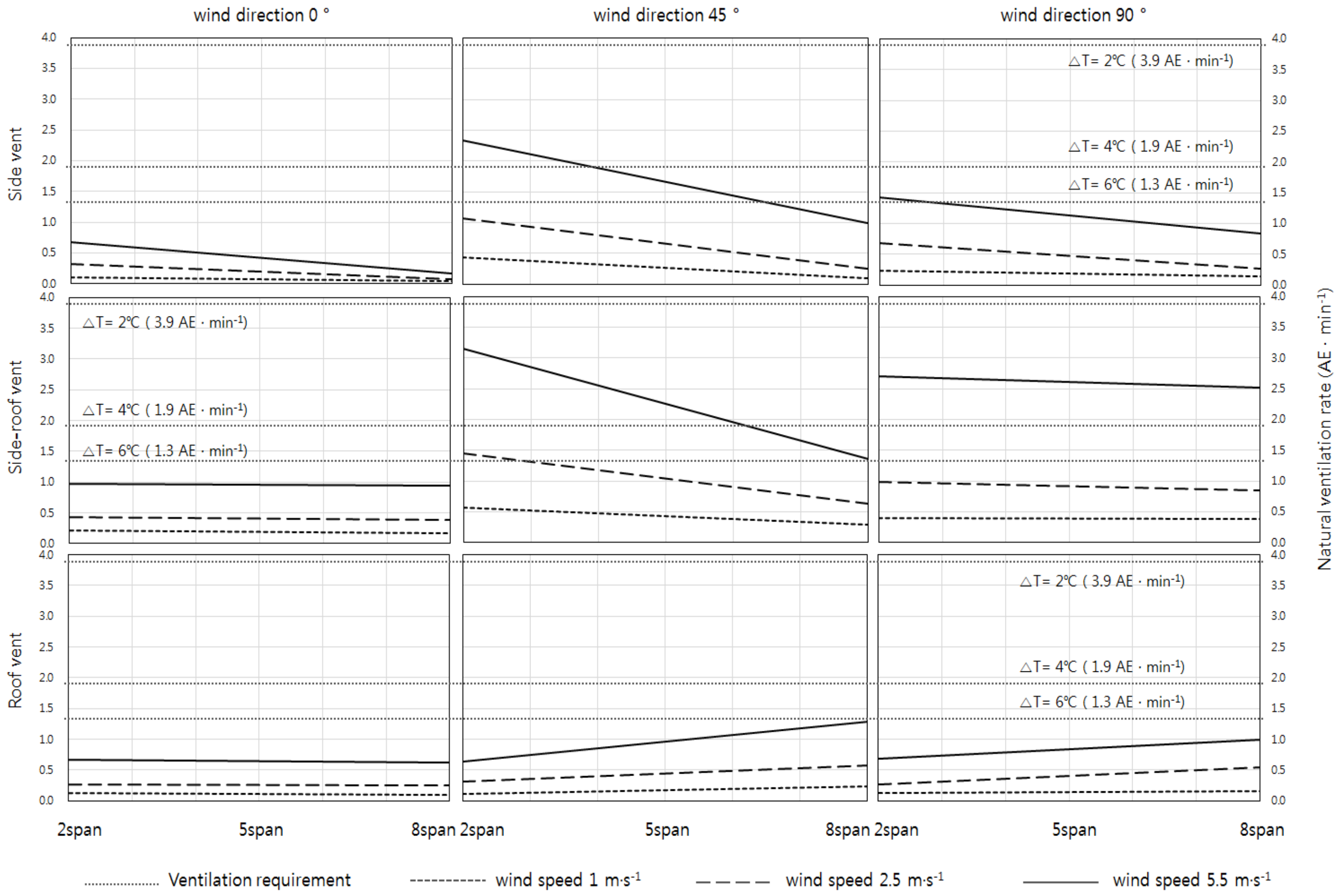


Fig. 22 Chart for expecting natural ventilation rate of 1-2W type greenhouse

5. Conclusion

Large-scale greenhouses built on reclaimed lands have great worth and have been developed in South Korea because the reclaimed land can be used regardless of topographical obstacles. However, published standards have not described quantitative standards for designing natural ventilation systems, which are used the most to control the internal climate of greenhouses.

In this study, the natural ventilation rates of multi-span greenhouses were evaluated with the consideration of the wind environments of reclaimed lands to serve as basic research for establishing standards for the design of ventilation for multi-span greenhouses built on reclaimed lands. The natural ventilation rates were calculated by the mass flow rate and tracer gas decay methods according to greenhouse type, number of spans, wind speed, wind direction, and vent openings. The computed natural ventilation rates were compared according to environmental conditions. Additionally, natural ventilation rates were evaluated by comparing them with the ventilation requirements for controlling the temperature in the summer.

As the result of comparing the natural ventilation rates computed by the two methods, it was judged that the tracer gas decay method evaluated the actual natural ventilation more closely than the mass flow rate method. In analyzing the overall ventilation rates, the results also showed that the natural ventilation rates were influenced considerably by wind speed and wind direction. The natural ventilation rates increased linearly as wind speed increased. As the number of spans increased, the natural ventilation rates generally decreased. When the vent opening was the roof vent, the tendency of the increasing natural ventilation of the 1-2W type greenhouse was observed to be unlike the other greenhouse types. It was concluded that the effect of ventilation through the roof ventilators of the 1-2W type greenhouse was higher than in the Venlo and Wide-span greenhouses. Additionally, it was observed that the natural ventilation rates were decreased as the increase of the number of spans. The natural ventilation rate was high in order of the wind direction 90, 45, 0°. The results of analyzing the overall ventilation rates will be used as basic data to establish design standards for multi-span greenhouses built on reclaimed lands.

As a result of analyzing the homogeneity of the local ventilation rates, it was found that the homogeneity was mainly influenced by wind direction and the configuration of the ventilators except for wind direction. The results of analyzing the local ventilation rates are expected to be utilized for controlling the microclimate in large-scale greenhouses uniformly. The charts for expecting the natural ventilation rates will be used for designing the ventilation of greenhouses and the guidance of maintenance control.

The natural ventilation rates were computed and evaluated according to various conditions as basic research to create design standards for natural ventilation. A study evaluating the effects of crops and buoyancy on natural ventilation is still required. When crops exist in a greenhouse, the air flow patterns and natural ventilation rates are completely changed according to the arrangement of the crops, variety of the crops, crop height, etcetera. Also, when wind speed is low, buoyancy-driven ventilation is more important. With additional research, it will be possible to suggest quantitative standards for designing the ventilation of greenhouses that will be practical for the managers and designers of greenhouses.

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국문 초록

전산유체역학을 이용한 간척지 내 자연환기식 연동 온실의 환기량 평가

이상연

생태조경 · 지역시스템공학부 지역시스템공학 전공

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우리나라의 온실 면적은 고품질의 농산물 생산, 수확 시기의 조절, 고소득 창출 등의 장점으로 1970년대부터 꾸준히 증가하여 2013년에는 약 53,732 ha로 증가하였다. 단동형 온실은 우리나라의 온실 중 약 73%로 대부분을 차지하지만, 농산물 수요의 증가와 농업인구의 감소에 따라 시설의 자동화와 대형화가 추진되고 있다. 하지만 우리나라 국토의 70%는 산지로 구성되어 있으며 지속적인 산업화와 도시화로 농경지가 감소하고 있어 대형 시설을 조성하기에 공간적 제약이 존재한다. 간척지는 새롭게 생겨나는 토지로써 주변 지형에 구애받지 않고 넓은 면적의 토지를 계획적으로 이용할 수 있다는 장점이 있다. 이에 맞춰 정부는 국내 간척지 12지구에 고품질 농산물의 연중 안정된 대량 생산을 목적으로 약 5,185ha 면적의 대규모 시설 농업 단지 조성 계획이 추진되고 있다. 온실의 자연환기는 설비비나 운용비 등의 경제적 이점 때문에 작물의 적정 생육 환경을 조성하기 위해 가장 일반적으로 활용되는 방법 중 하나이다. 자연환기는 외부 풍환경에 직접적인 영향을 받기 때문에 자연환기 해석 시 외부 풍환경의 고려는 필수적이다. 하지만 간척지의 경우 내륙에 비해서 상대적으로 주변 장애물이 없어 풍향이 일정하고 풍속이 크며 해안에서 발생하는 대류 순환으로 인한

난류의 영향을 강하게 받는 기상 특성을 가진다. 따라서 간척지 설치 온실에서 외부 풍환경에 크게 영향을 받는 자연환기 시 이를 고려한 환기 분석이 요구된다. 한편 기존의 국내·외 환기설계 기준서들은 온실의 열평형 방정식을 이용한 난방과 냉방 시스템의 설계, 냉방을 위한 필요환기량 산정 등에 대해 주로 서술하고 있을 뿐, 자연환기 설계에 대한 정량적인 기준을 제시하고 있지 않다. 따라서 본 연구에서는 간척지 입지 연동 온실의 자연환기 설계 기준 제시를 위한 기초자료를 확보하고자 다양한 환경 조건 (연동수, 풍속, 풍향, 환기 구조)에서 국내 대표 연동 온실 (벤로형, 와이드스판형, 1-2W형)의 자연환기량을 산정하고 평가하였다.

본 연구에서 실험 장비의 제한, 많은 노동력과 비용의 소모, 실험적 오차 발생 등의 현장 실험의 한계를 극복하고 연동 온실의 환기를 평가하고자 CFD 시뮬레이션을 이용하였다. 간척지의 기상 분석을 통해 간척지 풍환경을 설계하였으며 이를 CFD 시뮬레이션에 적용하였다. CFD 시뮬레이션 모델은 Ha (2015)에 의해 온실의 환기해석에 적합하다고 검증된 모델 설계 방법에 따라 온실 내부 격자사이즈는 0.2 m로 설계하였으며 RNG $k-\varepsilon$ 난류 모델을 사용하였다. 온실의 자연환기량 평가를 위해 질량교체환기량 산정법과 추적가스 농도감쇠법을 CFD 시뮬레이션에 적용하여 이용하였으며 두가지 방법을 통해 온실 전체 체적에 대한 환기량을 평가하였다. 또한 추적가스 농도감쇠법을 통해 온실 내부의 구역별 환기량을 평가하고 이를 바탕으로 변동계수를 산정하여 온실 내부의 환기 균일성을 분석하였다. 추가적으로 온도 조절을 위한 필요환기량과 비교하여 자연환기량을 평가하였다.

두가지 산정법으로 산정된 자연환기량을 통해 두가지 방법 특징을 비교한 결과 질량교체환기량보다 추적가스 농도감쇠법을 통해 산정된 자연환기량이 보다 온실의 실제 환기량에 가깝게 평가된다고 판단된다. 온실의 전체 환기량의 비교 분석 결과, 온실의 자연환기량은 풍속과 풍향에 따라 다양하게 산정되었다. 3가지 형태 온실에서 모두 온실의

연동수가 증가함에 따라 온실의 자연환기량 또한 감소하는 경향이 도출되었다. 하지만 1-2W형 온실에서 천창으로만 환기할 경우, 다른 형태의 온실과 달리 연동수가 증가함에 따라 온실의 자연환기량이 증가하는 경향이 도출되었다. 이는 1-2W형 온실의 천창 구조에 의한 차이로 다른 형태의 온실보다 1-2W형 온실의 천창 환기의 효과가 큰 것으로 판단된다. 또한 풍속이 증가함에 따라 온실의 자연환기량을 선형적으로 증가하는 경향이 도출되었으며 풍향이 90, 45, 0° 인 순서로 환기량이 크게 나타나는 경향을 보였다.

온실의 내부 구역별 환기 균일성 평가 결과, 풍속은 온실 내부 환기 균일성에 큰 영향을 미치지 않으며 풍향과 환기구조에 영향을 받는 것으로 분석되었다. 또한, 전체적으로 풍향이 0° 인 경우와 천창환기 방식의 경우 환기의 균일성이 높게 평가되었다. 하지만 풍향이 0° 이거나, 천창환기 방식의 경우 온실 내부의 환기량이 전체적으로 낮기 때문에 환기가 적절히 이루어진다고 판단될 수 없다, 따라서 온실의 환기 적절성을 판단할 때 온실의 전체적인 환기량과 온실 내부 구역별 환기량의 균일성을 동시에 고려해야 될 것으로 판단된다.

연동 온실의 전체 환기량 평가 결과는 온실의 환기 설계 기준을 제시하기 위한 기초자료로 활용될 수 있으며, 내부 구역별 환기량 평가 결과의 경우 대형화 온실의 내부 미기상 환경 조절을 위해 활용될 수 있을 것으로 사료된다. 최종적으로 제시한 자연환기량 산정 선도를 통해 주어진 환경 조건에서 용이하게 자연환기량을 산정하고 필요환기량과 비교할 수 있을 것으로 판단된다. 앞으로 본 연구에 추가적으로 작물을 고려하여 자연환기를 평가와, 외부 풍속이 약한 경우 부력에 의한 중력 환기에 대한 평가가 요구된다. 본 연구에서 축적한 연동 온실의 자연환기량 자료와 더불어 추가적인 연구를 통해 간척지 입지 온실의 자연환기량 설계를 위한 정량적 기준 제시가 가능할 것으로 기대된다.

주 요 어 : 전산유체역학, 연동 온실, 자연환기량, 간척지, 필요환기량

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