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Comparative Study on Efficiencies of Naturally-Ventilated Multi-Span Greenhouses in Korea

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〈Abstract〉

This research analyzed the ventilation effect of the multi-span greenhouse based on the types of greenhouse structure, weather conditions, and locations inside the greenhouse. To compare and analyze the ventilation effects with different types of greenhouse, the uniform environmental conditions should be selected in advance. But these factors are not controlled and require tense many precision facilities and labor forces. Thus, the CFD simulation was used for the air stream to be analyzed qualitatively and quantitatively. In addition, for the ventilation effect analysis, the TGD (Tracer Gas Decay) was used to overcome the shortcomings of the current ventilation measurement method. The calculation error of ventilation rate using TGD was low (10.5%). Thus, the TGD is very effective in calculating the ventilation efficiency. The wind direction of 90 degrees showed the best ventilation effect. The ventilation rate also decreased along the air circulation path, and the rate was the lowest around the outlet. The computed fluid method (CFD) turned out to be a power tool for simulating flow behavior in greenhouse.

Keywords : Multi-span Greenhouse, Ventilation Effects, Computed Fluid Method

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1. Introduction

Horticultural crop production in Korea has taken 0.3 % of total agricultural output, and vegetables have taken 67% of horticultural crop production. In 2014, greenhouse cultivation has reached about 44% (91,487ha) in the total vegetable-growing area (206,148ha). Farm household economy has depended on greenhouse cultivation especially in fruits and vegetables which took 88% of total horticultural production. Thus, producing high quality and safe agricultural products is essential to protect farmers from agricultural imports as a result of free trade and to keep domestic prices stable with agricultural exports. Greenhouse has been spotlighted because it makes year-round production of agricultural products with high quality. For this reason, the greenhouses are enlarged to improve the productivity and automation. However, when the greenhouse becomes bigger, the air flow, temperature, and humidity distribution differ within it. This non-uniform distribution of climate debases the productivity and quality of the plants, causes the diseases and pest problems and inhibits the year-round production of high quality agricultural products. Thus, ventilation is essential part in greenhouse cultivation, so research on ventilation especially, during summer season is needed. In addition, research on multi-span greenhouses should be conducted for the economic perspective.

Most researchers working on naturally ventilated multi-span greenhouses have conducted field experiments and simulation for their study[1][2][3][4][6][7][8][9]. However, the experiments were limited to a specific greenhouse and did not produce further studies, so the structure of greenhouse with effective ventilation system has not developed yet. The simulation with computational fluid dynamics (CFD), which complements the shortcoming of field experiments, should be used for quantitative and systematical analysis. Computational fluid dynamics which enables the analysis of air flow can control the conditions including environment and greenhouse artificially and analyze the results qualitatively.

The simulation with CFD for estimating ventilation in a greenhouse represents real environmental conditions and characteristics of greenhouse structure artificially. It enables in-depth analysis of the turbulence of the air flow. In addition, the results can be calculated similar to the real situation by applying the characteristics of greenhouse structure (e.g. heat transfer), weather conditions (e.g. solar radiation and wind), and buoyancy effect. While conventional Energy balance model calculated only the average values of natural ventilation inside the greenhouse, CFD model using Tracer gas analyzed the micrometeological factors and air flow inside the greenhouse. This study employed a quantitative ventilation effect analysis method using the TGD (Tracer Gas Decay) method to overcome the shortcoming of the conventional ventilation measurement method. The method used the User Defined Function (UDF) tool for CFD simulation.[5][12][13]

The purpose of this study was to compare and analyze the efficiencies of naturally-ventilated multi-span greenhouses in Korea based on the types of greenhouse structure, weather conditions, and locations inside the greenhouse. In addition, the ventilation efficiencies were analyzed based on the calculation method.

2. Material and method

This study simulated the ventilation effects based on the wind in the wide-span type greenhouse using CFD. The ventilation was calculated using Tracer gas decay to compare based on the height and location inside the greenhouse[10][17][18].

2.1 CFD

This study used CFD which applies Reynolds theory of Navier-Stokes equation to calculate each cell inside the greenhouse. The calculated area should be divided into mesh with proper size and distribution using Gambit (Ver. 2.2, Fluent Co. New Hampsher, USA) to improve the accuracy of the results. Fluent (Ver.6.2, Fluent Co. New Hampsher, USA) was used as a main module for calculation using CFD[11][14].

Appropriate turbulence model was needed to increase the accuracy of the simulation. However, a single turbulence model which can be applied to every type of problems does not exist. Therefore, the turbulence model should be determined based on the physical characteristics of each model, types of problem, required degree of accuracy, and time spent for simulation. RNG k-ε model was used for CFD model.

$$\rho\frac{Dk}{Dt}=\frac{\partial}{\partial x_i}\left[\alpha_k\mu_{eff}\frac{\partial k}{\partial x_i}\right]+G_k+G_b-\rho\epsilon-Y_M \quad (1)$$

$$\rho\frac{D\epsilon}{Dt}=\frac{\partial}{\partial x_i}\left[\alpha_k\mu_{eff}\frac{\partial \epsilon}{\partial x_i}\right]+C_{1\epsilon}\frac{\epsilon}{k}(G_k+C_{3\epsilon}G_b)-C_{2\epsilon}\rho\frac{\epsilon^2}{k}-R \quad (2)$$

Where,

ρ : density (kg/m3)

G_k : dynamic turbulent energy generated in average flow field

G_b : dynamic turbulent energy generated by buoyancy

Y_M : Fluctuations Expansion in compressed turbulence

α_k, α_ϵ : Effectiveness of Prandtl number k, ε

μ_{eff} : Effective viscosity

$C_{1\epsilon}$, $C_{2\epsilon}$, $C_{3\epsilon}$: constant

R in Eq. (2) was produced by the following equation.

$$R=\frac{C_\mu\eta^3(1-\eta/\eta_0)}{1+\beta\eta^3}\frac{\epsilon^2}{k} \quad (3)$$

Where, $\eta=Sk/\epsilon$, $\eta_0=4.38$, $\beta=0.012$,

S: scalar value of deformation sensors caused by vortex

2.2 Calculating ventilation efficiency

This study employed the TGD (Tracer Gas Decay) method to overcome the shortcoming of the current ventilation measurement method. This method calculates ventilation rate by analyzing the changes of gas concentration in the greenhouse where certain gas concentration was maintained. With this method, ventilation rate of specific point as well as total ventilation rate can be calculated by analyzing gas concentration.

The equation for Tracer gas decay is as follows.

Volume of air enter into the greenhouse is defined as $G\Delta t$ for period of time (Δt) and concentration change as ΔC, then the same volume of air ($G\Delta t$) drain out, while the volume of air ($G\Delta t$) enter into the greenhouse. As a result, the volume in the greenhouse is maintained constantly. The gas drained out from the greenhouse was $\frac{G\Delta t}{V}$, and the change of gas concentration was:

$$C_{\neq w} = \frac{VC - VC \times \frac{G\Delta t}{V}}{V} \quad (4)$$

As $, \Delta C = C_{\neq w} - C$

$$\Delta C = -\frac{CG}{V}\Delta t \quad (5)$$

After reducing time interval (Δt), it can be changed to differential form.

$$C = C_0 \cdot e^{-AER(t-t_0)} \quad (6)$$

AER : Air exchange rate
G : ventilation rate
C : gas concentration (mass fraction)
Co : primarygasconcentration
V : greenhouse volume

Ventilation at the time of t can be calculated as in Eg. (7)

$$AER = \frac{\ln\left(\frac{C_0}{C}\right)}{(t-t_0)} \quad (7)$$

Gas concentration per hour or gas concentration of each node was produced from the simulation, and ventilation rate was calculated with Eq. (7).

Error cannot be seen because the gas concentration was integrated until it became 0. The results from field experiments were less accurate than the results from the simulation because in the field experiments, outside weather conditions influenced the results. In addition, the gas concentration should be maintained constantly and homogenously from the beginning, but it was not easy to keep the uniform gas concentration in the greenhouse due to the fan. Moreover, few measurements cannot represent the whole ventilation rates of the big greenhouse, so it could not guarantee the accuracy and reliability.

2.3 Methods

The wide-span type greenhouse was used to analyze the ventilation effect of the multi-span greenhouse. Table 1 shows the specifications of the greenhouse, and Figure 1 shows the sketch of it.

Table 1. Specification of wide-span type

Item	Specification
Model name	3-3 S
ridge height (m)	5.25
eaves height (m)	3.0
number of span	3
width of span (m)	9.0
width of greenhouse (m)	27.0
length of greenhouse (m)	33.0
surface area of greenhouse(m2)	891.0
type of side vent	Horizontal sliding

Direction of wind was set at 90˚, 45˚, and 0˚ on the side of the greenhouse, the speed of wind was set at 2 m/s on 10 m above the ground. The turbulence layer thickness was set as 20 m. In Korea, the data of wind direction and speed was not

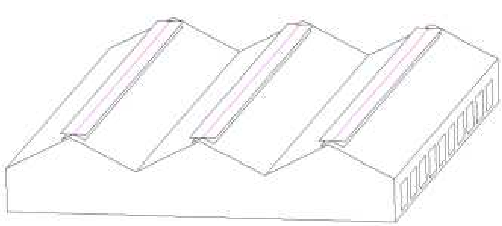


Fig.1. Sketches of multi-span greenhouse of wide-span type

found at the height of 20 m, instead data from 1 m and 10 m was measured. However, high quality boundary layer could not be designed with the data from those two heights. Therefore, this study used the equation from Silsoe Research Institute which formulated the flow boundary layer after measuring the air flow and turbulence at the rural areas in U.K[15].

$$\frac{\overline{V_z}}{\overline{V_{10}}} = \frac{\log(z/z_0)}{\log(10/z_0)} \tag{8}$$

Vz ; mean speed from the height of z (m/s)

V10 ; mean speed from the height of 10m (m/s)

Z ; height from the ground (m)

Zo ; 0.01m above the ground (m)

With Eq. (8) the speeds were calculated at each height, and the CFD model used those values. Speed of outside air flow field, kinetic-turbulent-energy and turbulent-dissipation-rate were calculated with Eq. (9) and (10).

$$k = \frac{1}{2}(u'^2 + \nu'^2 + w'^2) \tag{9}$$

$$\epsilon = \frac{C_\mu^{3/4} \times k^{3/2}}{l}, \quad l = \min(\kappa \times Z_n, \kappa \times \delta) \tag{10}$$

Where,

Cu : Empirical constant

Zm : height from the ground (m)

Δ : turbulence boundary layer

thickness (m)

K : Von Karman constant

Table 2 shows the boundary conditions of CFD model.

Table 2. Constant input values for the case file of CFD model

Contents	Value
Wind velocity (m/s)	2 at 10m height
Wind direction	90° to sidewall 45° to sidewall 0° to sidewall
Outside air temperature (K)	302.7
Outside ground temperature (K)	313.16
Inside floor temperature (K)	318.16
Greenhouse cover temperature (K)	313.16
Temperature of inlet air (K)	302.7
Density of inlet air (kg/m3)	1.225
Viscosity of inlet air (kg/m•s)	1.86E-05
Thermal conductivity of inlet air (W/m•K)	0.02647
Specific heat of inlet air (J/kg•K)	1006.43
Mass diffusivity of inlet air (m2/s)	2.262E-05
Molecular weight of air (g/mol)	28.966
Gravitational acceleration of inlet air (m/s2)	9.81
Atmospheric pressure (Pa)	101,325

Carbon dioxide (CO2)was used as Tracer gas. CO_2 has some merits compared to other gases in that it is cheap, safe, and accurate in measuring. But CO_2 needs to be replaced in the experiment with plants due to photosynthesis. Outside and inside CO2 concentrations were assumed as 400 ppm and 2,000 ppm, respectively. The unit of gas concentration input for the CFD Fluent was mass fraction. Eq. (11) and (12) used for unit conversion from ppm to mass fraction. The converted CO_2 concentration was 0.00061 (0.061% of air) and 0.00305 (0.305% of air).

$$MF_{air} = \frac{C_{air} \times \rho_{air}}{(C_{air} \times \rho_{air}) + (C_{co_2} \times \rho_{co_2})} \times 100 \quad (11)$$

$$MF_{co_2} = 100 - MF_{air} \quad (12)$$

MFair : mass fraction of air (%)

MFco2 : mass fraction of CO2 (%)

Cair,Cco2 : concentration of air and CO2 (ppm)

ρ_{air}, ρ_{CO_2} : density of air and CO2 (kg/m3)

CFD simulation was run as an unsteady simulation; the calculation was continued until average gas concentration in the greenhouse became close less than 2% to outside gas concentration 0.00061. Computational domain was initialized in order to drive Time dependent. After flow fields in the domain maintained as the condition of inlet air flow, CO_2 was added. At time dependent simulation, flow field at t=0 in the domain has constant flow behavior. One second after the simulation, the air entered from the side window which caused a

Table 3. Comparison of calculated ventilation rates using TGD method and mass flow method at 60 sec
(unit : ventilation rate , min-1)

Type \ Wind angle	0˚		45˚		90˚	
	TGD	Mass flow	TGD	Mass flow	TGD	Mass flow
Widespan	0.427	0.410	0.658	0.847	1.122	0.954

change in the flow field, but the air showed constant flow over time. Gas dilution in the greenhouse was influenced by the unstable flow field, so the air flow was more irregular and bigger than real, which caused large ventilation efficiency. To complement this, computational domain should be initialized first and then calculated in a steady state. By stabilizing the changed flow field, the simulation was performed more similar to the real situation. The CO_2 concentration was kept uniformly as 0.00305, and the ventilation was started at the same time with outside air entering.

Total average ventilation rate and average ventilation rate at each height were calculated using average gas concentration changes of CFD. The ventilation efficiency was analyzed using gas concentration changes from the height of 1 m. Ventilation rate produced by Tracer gas decay was compared with the one calculated by conventional method which used air flow from each vent.

3. Results and Discussion

3.1 Comparison of calculating method

The ventilation rate was calculated with the simulation result to the wind direction of 0^o, 45^o, 90^o by Tracer gas decay (TGD) method and conventional mass flow method. Table 3 shows the ventilation rates using TGD method and mass flow method at 60 seconds from the ventilation. The ventilation rate by mass flow represented the inlet air from outside and drained out air from the greenhouse, while the one by TGD represented the drained out CO2 from the greenhouse. The ventilation rate from TGD was greater than the one from mass flow when the volume of residual gas was larger than entered air. On the contrary, the ventilation rate from mass flow was greater than the one from TGD when the volume of left gas was smaller than entered air. Therefore, the large value of mass flow did not mean significant ventilation effect, and the mass flow method did not show the real ventilation.

3.2 Results

Table 4 shows the ventilation rates based on the wind directions, and Figure 2 shows the air flow and the change of CO2 concentration from the height of 1 m.

Table 4. Average ventilation rates based on wind directions

Wind angle		Result
0°	for 60sec	0.43
	for 120sec	0.46
	by 2%	0.45
	duration time (sec)	560
45°	for 60sec	0.66
	for 120sec	0.69
	by 2%	0.63
	duration time (sec)	418
90°	for 60sec	1.12
	for 120sec	1.21
	by 2%	1.26
	duration time (sec)	164

The ventilation rate changed with the time, and the CO_2 concentration showed different types of contour based on the wind direction. Thus, the comparison of ventilation rate at the time which had same effect was more reasonable than the one at a specific time. The wind direction of 90° showed the best ventilation effect with the ventilation effect of 2%. The ventilation rate at the wind direction of 0° decreased by 36%, 57%, 37%, and 79% when compared to the ones at the wind direction of 90°. The one at the wind direction of 45oalso decreased by 50%, 95%, 52%, and 91%. When the wind direction changed from 0° to 90° , the ventilation effect was improved significantly.

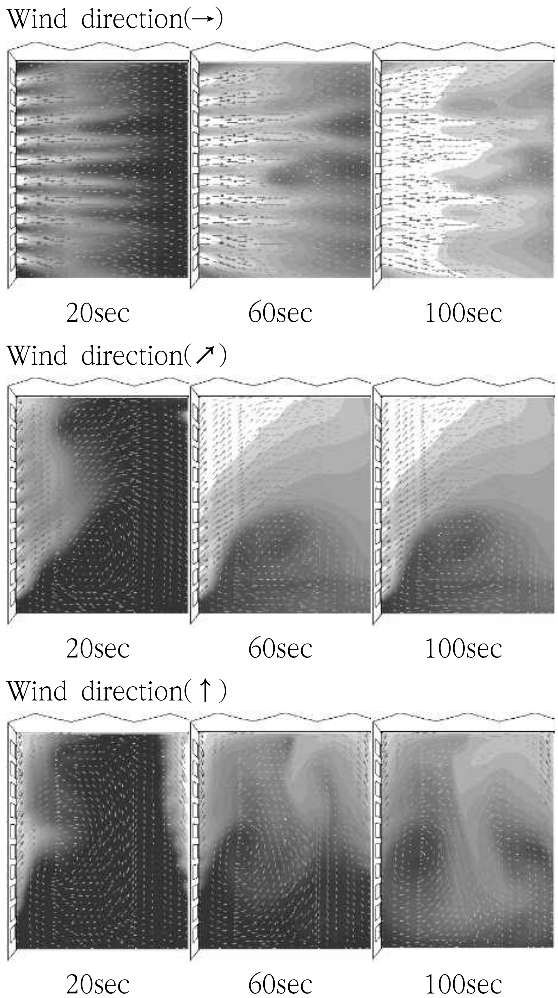
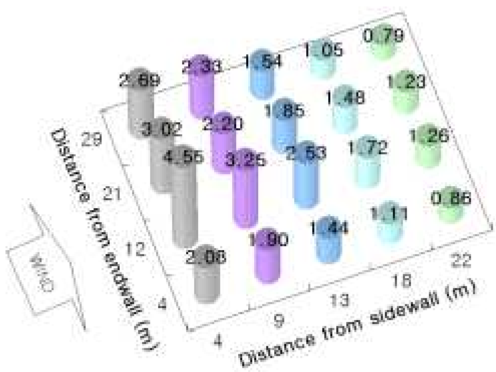
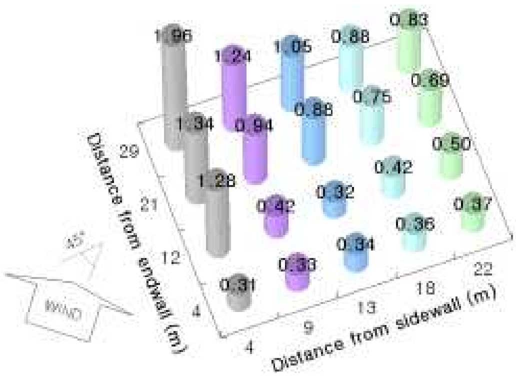


Fig. 2. CO2 concentration contours with the air flow in widespan greenhouse at 1m height (CO2 concentration color map : 0.00061 0.00305)

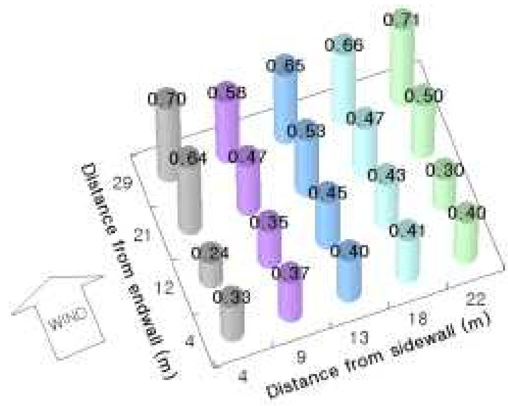
Large volumes of air entered through the inlet in the simulation of the wind direction of 90°. However, when the wind direction was changed, the volume of air decreased. And the air flow inside the greenhouse circulated along the wall. In the wind direction of 0°, entered air below the side vent and drained out air above the side vent exchanged simultaneously. Figure 3 shows the distribution of ventilation rates. Wind direction of 90° showed the best ventilation rate in the middle of side vent, and the rate decreased below the side vent. Wind direction of 45° showed the best ventilation rate below the side vent, and the rate decreased as counter-clockwise and reached lowest above the side vent. Wind direction of 0o showed the best ventilation rate above the side vent and lowest rate below the side vent, and the overall rate was low compared to other types of wind directions.



(a) 90°



(b) 45°



(c) 0°

Fig. 3. The distribution of ventilation rates for the wind directions of (a)90°, (b)45°, (c)0° from the height of 1m

The ventilation rate around the floor was higher by 20% when it compared with the total rate as shown in Figure 4. The reason is that entered air drained out at the side vent and dormer passing through the floor of the greenhouse which caused the air exchange around the floor[16]. However, the air entered from the dormer drained out through the dormer next to it. For this

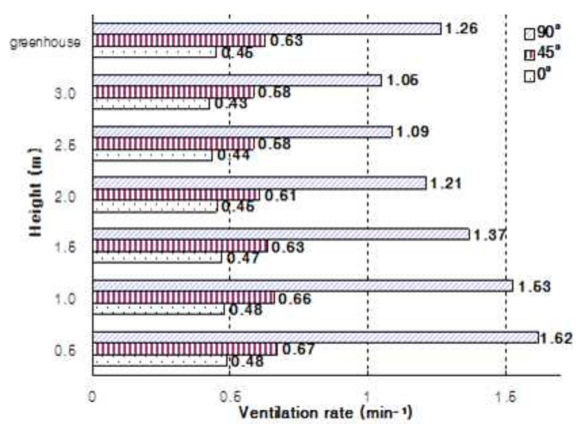


Fig. 4. Ventilation rates based on heights and wind directions

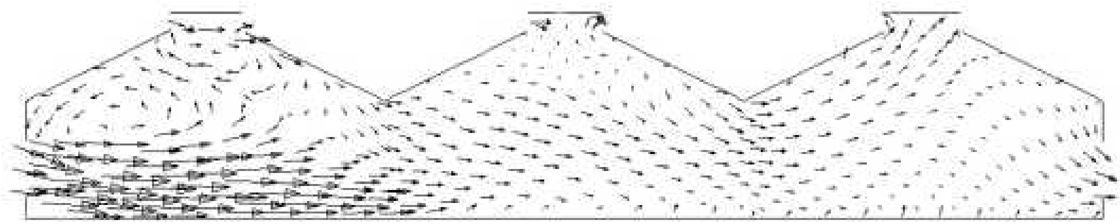


Fig. 5. Air flow pattern on vertical section with wind speed of 2m/s and height of 10m (wind direction(→))

* The large arrows indicates large magnitude of the velocity.
* There is a little difference between the interval of vectors and the space of the designed meshes caused by using a skip tool.

reason, the ventilation rate around dormer was relatively low. The ventilation rate with the wind direction of 0° decreased by 50% compared to the one with 90°, and the rate based on the height decreased with similar pattern.

4. Conclusion

This research analyzed the ventilation effect of the multi-span greenhouse. The average error between ventilation rate of TGD and the one of mass flow was 10.5%, and the TGD was appropriate to calculate the ventilation rate to consider ventilation efficiency. The ventilation rate at the wind direction of 0° decreased by 36%, 57%, 37%, and 79% when compared to the one at the wind direction of 90o. The one at the wind direction of 45° also decreased by 50%, 95%, 52%, and 91%. For efficient ventilation, the ventilation rate at the height of 1 m should be highest, and the side vent was influenced significantly by the ventilation height. The ventilation rate was highest around the side vent and decreased along with the air circulation path, and the rate was the lowest around the outlet.

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