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Investigation into the Internal Flow and Temperature Characteristics for Greenhouse Ventilation Patterns using Computational Analysis

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ABSTRACT
Proper ventilation of the greenhouse inhibits the excessive fluctuation of temperature and humidity, which enhances the quality and productivity of agriculture. Air flow and temperature distribution are very important. In the presentation research, thermal-fluid analysis was performed to analyze the significant factors affecting ventilation such as ventilation parameter and external wind speed. For this, model for the analysis is consistence of the greenhouse with 13 multi-coopers, and conducted to transient thermal fluid dynamics analysis. The analysis result show that the initial cooling speed was lower for forced ventilation than for the natural convection because of the air curtain phenomenon. but forced convection proved to be effective for temperature uniform distribution, which caused subsequent temperature decrease in the greenhouse after certain time. The standard deviation was introduced and applied as an evaluation criterion for temperature uniformity, and the visual effect and standard deviation method tended to agree with each other. Therefore, it is recommended that ventilation of the greenhouse is more effective when the natural ventilation is followed by forced circulation using fan after a certain time. Temperature distribution is quantitatively evaluated by applying the standard deviation method which is regarded as more efficient method.
Keywords: Fluid Dynamics, Thermal-Fluid Flow, Greenhouse, Ventilation Effects

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I. INTRODUCTION

Greenhouse enables temperature and humidity to be controlled properly, minimizing the effects of the elements on the growth of (cash) crop and produce. Enclosed environment of the greenhouse requires frequent ventilation to maintain proper growth condition to optimize biological factors affecting metabolism of the produce and crops. Natural convection is caused by opening either skylight windows or side windows, circulating air environment inside out and vice versa. On the other hand, ventilation fan installed in the greenhouse is used to force air circulation through the window openings. Domestic Korean farmers prefer natural ventilation for additional financial burden for installation of ventilation fans[1]. However, such natural ventilation caused non-uniform temperature contour in the greenhouse, causing a climate change of another kind and ensuing reduction of crop harvest and degradation of its quality as well as longer growth time. In view of this, homogeneous environment in terms of time and space in the greenhouse has become a primary concern[2]. Natural ventilation via ventilation windows showed inherent temperature gradient caused by fixed installation position of the windows, limits on the full opening areas of the windows. To counter such technical barriers, ventilation fans and perforated plastic tubes are installed to improve air circulation in the greenhouse, the former method being more economically feasible and more effective for air circulation and heat distribution[3]. Literature survey shows various research results on evaluation of greenhouse ventilation characteristics. Mistriotis et al claimed that temperature distribution in the greenhouse was affected by laminar air flow in view of the ventilation characteristics as affected by the outside wind velocity[4]. Campen and Bot also showed that the greenhouse ventilation efficiency depended on the outside wind direction, In their ventilation efficiency studies[5], Bartzanas et al noted that average flow velocity in the greenhouse was affected by the arrangement of the ventilation facilities such as window openings[6]. Hong et al performed similar studies on ventilation efficiency of the isothermal greenhouses, where greenhouse structure was correlated with natural elements such as outside wind direction[7]. Finally, Lee et al investigated into the effect of the natural ventilation air quantity on the necessary ventilation via correlating natural ventilation air quantity chart with number of ventilation outlets, outside wind velocity, wind direction and ventilation methods[8]. The previous researchers used analysis method for ventilation efficiency to evaluate greenhouse air ventilation characteristics, which was mainly applied as a basis to evaluate air quantity for greenhouse ventilation via calculating exchange rate between the internal and external air of the greenhouse. However, such approach was not sufficiently comprehensive in evaluation of the greenhouse air temperature variation with ventilation time and corresponding greenhouse air temperature distribution during ventilation. For more reliable evaluation of ventilation efficiency, it is necessary to measure the time to reach appropriate uniform temperature in the greenhouse during ventilation and temperature uniformity caused by ventilation. For this, numerical modeling method was applied for thermal-fluid analysis on the indoor temperature of the greenhouse. Greenhouse temperature variation and temperature uniformity were observed during ventilation duration using the thermal-fluid analysis results. Effective ventilation method was thus suggested by significant parameters such as effects of ventilation fan operation, opening of the skylight and side windows, and external wind velocity.

II. NUMERICAL ANALYSIS

2.1 Model description of greenhouse

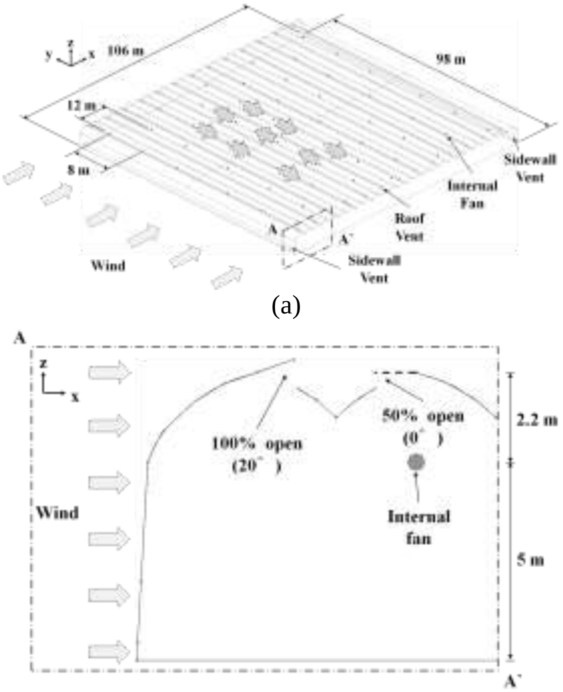
In the present paper, vinyl greenhouse with the multi-cooper roofs was selected as a model for computational analysis, and as a study subject, the shape and specification of the greenhouse are shown in Figure 1. As shown in Fig. 1 (a), schematically shows 13 cooper roofs comprising a vinyl greenhouse, and one cooper consists of two small round-type roofs. In this analysis model, there are 26 roofs and skylight windows, with the latter installed on each roof. There are two side windows with face to face each other. A fixed ventilation fan is also installed inside the greenhouse, 5m from the ground level. The blowing directions of the fans are adjusted as shown in Fig. 1 (a) thermal flow in the individual cooper is opposite to that in the adjacent cooper. The skylight window can be opened as shown in Fig. 1 (b), where two skylight windows per single cooper open in opposite direction from 0(-20°) to 100%(+20°).

2.2 Computational methods

The governing equations for the numerical analysis of the constructed model are as follows. The mass conservation equations, the momentum equations, and the energy conservation equations are calculated for the thermal-flow analysis in the present greenhouse model written in equations (1), (2), and (3).

- Mass conservation equations:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho U_i)}{\partial x_i} = S_m \tag{1}$$



(b)

Figure 1. Schematic diagram for greenhouse; (a) overview, (b) roof top vent.

- Momentum conservation equations:

$$\frac{\partial(\rho U_i)}{\partial t} + \frac{\partial(\rho U_i U_j)}{\partial x_i} = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_i}\left(\mu\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right) - \rho u_i u_j\right) + S_{U_i} \tag{2}$$

- Energy conservation equations:

$$\frac{\partial\left[\rho\left(e + \frac{1}{2}U^2\right)\right]}{\partial t} + \frac{\partial\left(\rho U_i\left(e + \frac{1}{2}U^2\right)\right)}{\partial x_i} = -\frac{\partial q_i}{\partial x_i} - \frac{\partial P U_i}{\partial x_i} - \frac{\partial}{\partial x_i}\left(U_i \mu\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right)\right) + q' \tag{3}$$

, where, U_i and u_i are the average speed and the variation speed of the respective x_i, P is the pressure, ρ and μ represent the density and the viscosity of each fluid. $-\rho u_i u_j$ is the Reynolds stress tensor, S_m and S_{U_i} are the source terms of the mass conservation and momentum equations, respectively. e and U are the internal energy and velocity magnitudes, q_i is the heat flux in the direction x_i. q' represents the generation or absorption of heat per unit volume.

The second and fourth terms in Eq. (3) can be alternatively expressed as Eq. (4).

$$\frac{\partial\left(\rho U_i\left(e+\frac{1}{2}U^2\right)\right)}{\partial x_i}+\frac{\partial PU_i}{\partial x_i} = \frac{\partial}{\partial x_i}\left(\rho U_i\left(e+\frac{1}{2}U^2+\frac{P}{\rho}\right)\right) \quad (4)$$

Using the definition of total enthalpy(h_0) and equation (5), the equation (3), can finally lead to equation (6)

$$h_0 = h+\frac{1}{2}U^2 = e+\frac{P}{\rho}+\frac{1}{2}U^2 \quad (5)$$

$$\frac{\partial(\rho h_0)}{\partial t}+\frac{\partial(\rho U_j h_0)}{\partial x_j} = \frac{\partial P}{\partial t}+\frac{\partial q_j}{\partial x_j}-\frac{\partial}{\partial x_j}\left(U_i\mu\left(\frac{\partial U_i}{\partial x_j}+\frac{\partial U_j}{\partial x_i}\right)\right)+S_h \quad (6)$$

, where, h is the enthalpy of the fluid, and S_h is the energy source term.

The inside and outside fluid in the greenhouse is air, and the vinyl of the greenhouse is made of polyolefin film. The physical properties of the relevant substances for analytical modeling are listed in Table 1. As for, the boundary conditions of the finite element modeling, the external wind speed was assumed to be 1 or 3 m/s for natural and forced ventilations. In case of forced ventilation, the boundary condition is taken by using the static pressure curve of the fan installed inside the greenhouse. For modeling convection phenomenon of the air caused by temperature variation and buoyancy condition, gravitational acceleration of 9.81 m/s^2 was used. According the literature, the mean value of inside temperature after closure of ventilation windows was 51.7 °C. The initial inside and outside air temperatures of the greenhouse are taken as at 60 and 35 °C, respectively[9]. The modeling parameters affecting ventilation characteristics were composed of fan operation, opening of the side window, opening of the skylight windows, and the external wind speed. The combinations matrix for modeling are shown Table 2. A reference modeling condition was selected as a basis for comparison among the various modeling results and the ensuing interpretations: natural ventilation with closed side windows, 50 % opening of the skylight windows and the external wind speed of 1 m/s. In order to compare the effects of external wind speed, Case 2 was selected with external wind speed was changed by 3 m/s from the condition of Case 1. Case 3 was similarly selected to investigate into the effect of the opening angle and 100 % opening was taken as in the reference model. For comparison of the effects of the one and two skylight windows' opening, Case 4 was again devised in which the skylight windows were fully opened regardless of the outside wind direction. The effect of the side windows opening, was also taken into account via Case 5, which controls the area of the ventilation window, simultaneously opening the inlet and outlet of the two side windows installed as shown in figure 1 (b). Finally, role of the internal flow is analyzed via Case which modeled operation of the fan installed inside the greenhouse.

Table 1. Physical properties of air and polyolefin film.

Description		Symbol	Value
Air	Density [kg/m³]	ρ_{air}	1.207
	Viscosity [kg/m-s]	μ_{air}	1.85x10⁻⁵
	Thermal conductivity [W/m-K]	k_{air}	0.026
	Specific heat [J/kg-K]	$C_{p,air}$	1,007
Polyolefin Film	Density [kg/m³]	ρ_{poly}	900
	Thermal conductivity [W/m-K]	k_{poly}	0.410
	Specific heat [J/kg-K]	$C_{p,poly}$	2,200

Table 2. Numerical analysis models according to types of ventilation.

Case #	Vent Type[a]	Side Wall Vent[b]	Roof Vent Angle[c]	Wind Velocity[d] [m/s]
1	Natural (Fan x)	Closed	Single (50 %)	1
2				3
3			Single (100 %)	1
4			Both (50 %)	1
5		Opened	Single (50 %)	1
6	Forced (Fan o)	Closed	Single (50 %)	1

a. Fan operation status
b. Open perpendicular to the wind direction
c. Single : Lean against wind direction
Both: Lean against wind and head wind direction
0% = -20° (closed), 50% = 0° (half opened), 100% = 20° (full opened)

d. Wind speed outside the greenhouse

III. RESULTS AND DISCUSSION

3.1 Predicted temperature distribution of greenhouse

Effects of skylight and side window openings and ventilation fan on the temperature variation in the greenhouse were modeling in the previous sections. For Case 1, modeling results are shown in Fig. 2 for 50 % skylight window opening and constant external wind velocity of 1 m/s. Initially greenhouse temperature was 60 ℃ but temperature changed with injection of 35 ℃ external air.

Temperature contour of the entire greenhouse at t = 100 s is shown in Fig. 2 (a) to examine temperature variation characteristics. Fig. 2 (a) shows that lower and higher temperature profiles were obtained upwind and downwind, respectively.

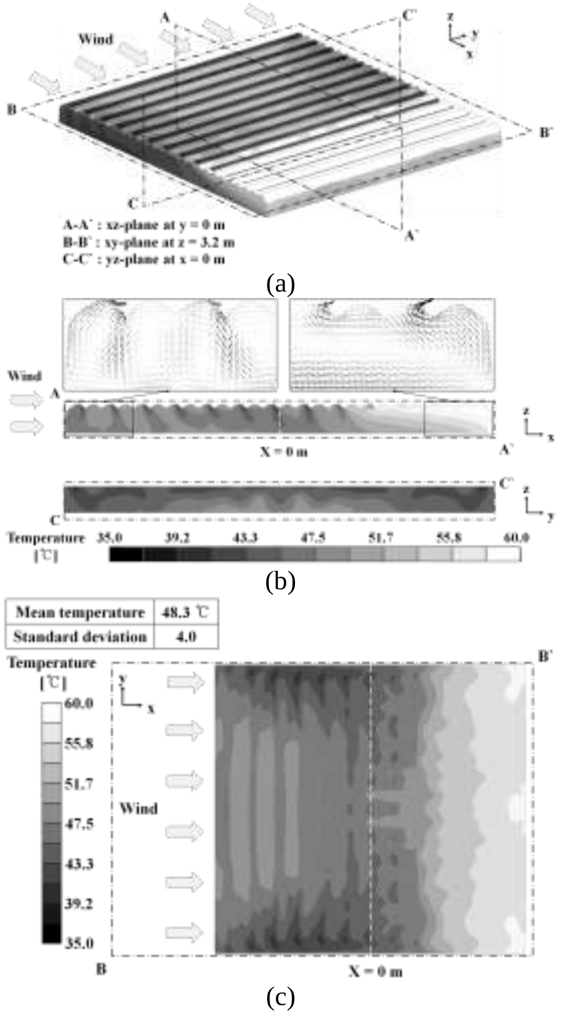


Figure 2. Temperature distribution of natural vent at 100 sec (Case 1: Natural vent, Side wall close, Roof 50 % single open, wind speed 1 m/sec); (a) temperature overview, (b) temperature distribution and air flow vector at center line (section view of A-A` and C-C`), (c) temperature distribution at 3.2 m height (section view of B-B`)

This is caused by forced external air flow in the skylight window openings, with concomitant pressure variation with wind direction, causing some skylight windows openings to act as air inlets or air outlets, depending on the wind pressure variation. Such air inlet and outlet areas show lower and higher air temperatures, respectively, and this is explained by cooler external air intake and longer residence time and the resultant hotter air formed by the inside air of the greenhouse. Fig. 2 (b) schematically depicts greenhouse air temperature distribution in XZ (parallel to the wind direction) and YZ (perpendicular to wind direction) planes.

In view of the temperature distribution along the XZ plane, the air inlet ventilation window area is cooler than the air outlet ventilation window area. The YZ plane is formed by vertically intersecting the external wind flow from the center of the greenhouse and the YZ plane's temperature contour is symmetrical with respect to the centerline of the greenhouse as shown in Figure 2 (c) On the other hand, temperature distribution on the XY plane (Z = 3.2 m) shows rather non-uniform and irregular nature with eccentric accumulation caused by variation of wind direction, as shown in Figure 2 (c). This is attributed to ventilation efficiency variation with external wind direction and temperature change. Average temperature on the XY plane and its standard deviation were 48.3 ℃ and 4.0, respectively, slightly higher temperature difference position-wise.

Modeling result for Case 5 is schematically shown in Fig. 3 for 1 m/s of external wind velocity with one skylight window 50 % opened and two side windows fully opened. Overall average temperature in the greenhouse shows similar distribution to that of Case 1, as depicted in Fig. 3 (a). This is attributed to the same effect by the wind direction. However, Case 5 was modeled for more voluminous air intake through the side windows and this caused lower temperature distribution in more extensive areas.

Fig. 3 (b) shows cross-sectional temperature contour thus modeled. The temperature profile in the XZ plane confirmed improved ventilation efficiency for the same duration of ventilation, which is attributed to the increased intake of the external air through the fully opened side windows. Furthermore, temperature profile in the YZ plane showed that fully opened side windows effectively improved ventilation effects, thus generating more homogeneous temperature profile. The Case 1 was modeled exclusively for fully opened skylight windows and the ensuing natural convective air flow caused by the temperature gradient in the greenhouse. On the other hand, the Case 5 considered fully opened side windows, thus directly affecting internal air flow in the greenhouse via external air intake.

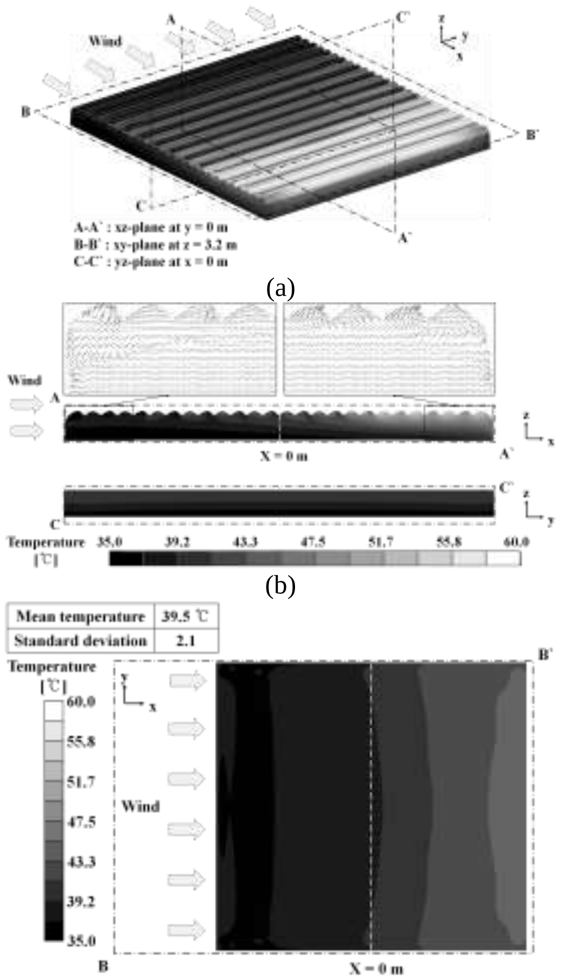


Figure 3. Temperature distribution of the side vent and natural at 100 sec (Case 5: Natural vent, Side wall open, Roof 50 % single open, wind speed 1 m/sec); (a) temperature overview, (b) temperature distribution and air flow vector at center line (section view of A-A` and C-C`), (c) temperature distribution at 3.2 m height plane (section view of B-B`)

The massive air intake through the fully opened side windows mainly caused the parallel temperature distribution in the XY plane of the greenhouse as shown in Fig. 3 (c), where average temperature and lower position-wise standard deviation of 39.5 ℃ and 2.1 are obtained, respectively. Ventilation fan was installed to alleviate the eccentric temperature distribution in the greenhouse and the Case 6 is modeled based on the external air velocity of 1 m/s and 50 % opening of the skylight windows with ventilation fan operating.

The Fig. 4 (a) shows temperature distribution in the same direction as the external air flow but the peculiar phenomenon of eccentric temperature distribution observed for the Case 1 is significantly alleviated. This is attributed to improved agitation of the greenhouse air via ventilation fan.

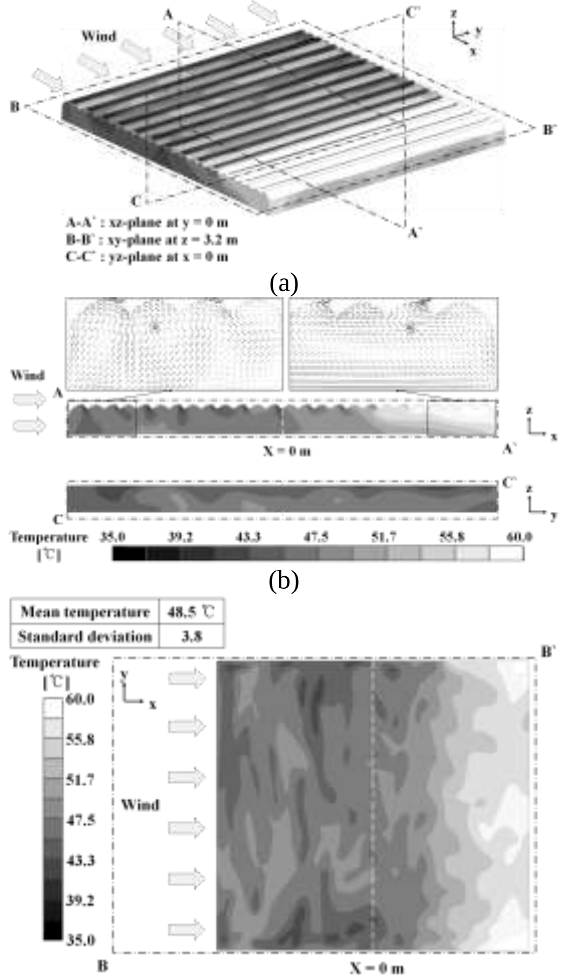


Figure 4. Temperature distribution of forced vent at 100 sec (Case 6: Forced vent, Side wall close, Roof 50 % single open, wind speed 1m/sec); (a) temperature overview, (b) temperature distribution and air flow vector at center line (section view of A-A`, C-C`); (c) temperature distribution at 3.2 m height plane (section view of B-B`)

Fig. 4 (b) shows temperature distribution in the XY cross-section parallel to the external air flow direction. The temperature profile of Fig. 4 (b) shows cooler portion around the ventilation window where vigorous intake of the external air is observed. However, hotter temperature around the ventilation window area was similar to the Case 1, where the internal air was exiting through the ventilation window. The effect of ventilation fan is rather suitably explained by the temperature distribution along the YZ cross-section for the external air flows. This is further substantiated by the temperature distribution for the XY-cross-section of the greenhouse, as depicted in Fig. 4 (c). The ventilation fan vigorously agitated the internal air flow, which further improved position-wise temperature deviation over the Case 1. In this case, average temperature and its standard deviation on the plane were 48.5 ℃ and 3.8, respectively, thus showing improved position-wise temperature deviation with increased average temperature compared with that of Case 1. This phenomenon is explained by the ventilation fan's air curtain effect of screening the natural convective flow caused by the temperature gradient in the greenhouse, thus causing stagnant air stratum in the lower part of the greenhouse.

3.2 Effects of the geometrical and operating parameters

In order to evaluate the ventilation effect of the greenhouse caused by the side windows and the ventilation fan, the temperature and temperature variation at specific locations were evaluated with ventilation time. The temperature variation in the greenhouse with the Y position (-50 ~ 50 m) at X = 0.0 and Z = 3.2 m are shown in Fig. 5. For Case 6, the air temperature inside the greenhouse is uniformly distributed in contrast to the Case 1 and this is attributed to the ventilation fan installed for Case 6.

After 100 seconds of ventilation, the predicted average temperatures were 44.7 and 45.9 ℃ for the Case 1 and Case 6 with the corresponding standard deviations of 1.3 and 1.1 respectively. This is attributed to the improved temperature bias phenomenon contributed by the ventilation fan.

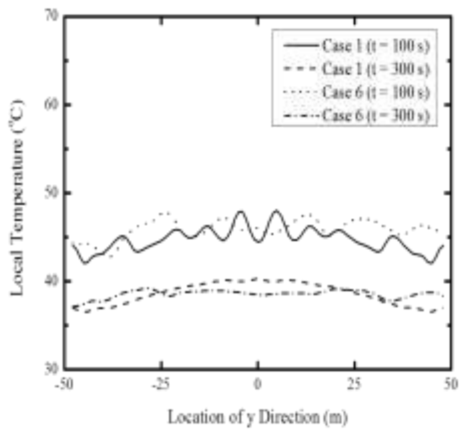


Figure 5. Comparison of temperature distribution effect between natural and forced ventilation at 3.2 m height, 0m longitudinal line (YZ-plane) (Case 1: **Natural vent**, Side wall close, Roof 50 % single open, wind speed 1 m/sec and Case 6: **Forced vent**, other conditions same to Case 1) ; Case 1 (100 s) mean temperature : 44.7 ℃, standard deviation : 1.3 ; Case 1 (300 s) mean temperature : 38.6℃, standard deviation : 1.3 ; Case 6 (100 s) mean temperature : 45.9 ℃, standard deviation : 1.1 ; Case 6 (300 s) mean temperature : 38.6 ℃, standard deviation : 0.5

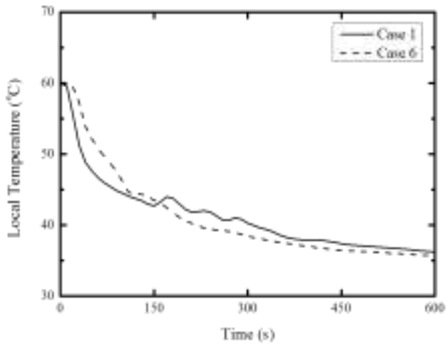


Figure 6. Comparison of temperature distribution effect between natural and forced ventilation center point (at x=0, y=0, z=3.2 m) (Case 1: **Natural vent**, Side wall close, Roof 50 % single open, wind speed 1 m/sec and Case 6: **Forced vent**, other conditions same to Case 1)

After 300 seconds ventilation the predicted average temperatures were 38.6 °C for both of the Case 1 and Case 6. However, smaller standard deviation of 0.5 was predicted for the Case 6, compared to 1.3 for the Case 1, indicating that temperature bias for the Case 1 was greatly improved.

Parameters affecting the fan performance with time were studied via the temperature curves for the Case 1 and the case 6 at the center of the greenhouse (X = 0.0 m, Y = 0.0 m, Z = 3.2 m), which are shown in Fig. 6. The heat transfer occurs via natural convection for the Case 1 and the fluctuating temperature curve arose. However, relatively smooth temperature decreasing predicted for the Case 6 was attributed to the operating fan.

To explain the difference in temperature distribution with cooling time observed for the natural convection and the forced convection, there the XY plane (Z = 3.2 m) of the greenhouse was selected to model the mean temperature and its standard deviation and the results are shown in Fig. 7. The mean temperatures with cooling time predicted for the natural and the forced convection were similar, albeit with smaller standard deviation for the Case 6 with ventilation fan. The air curtain phenomenon caused by the ventilation fan obstructed the inflow of external air, thereby reducing the cooling effect of the greenhouse.

The effects of external wind velocity is shown in Fig. 8, where modeling was performed for the external wind velocity of 1 m / s (Case 1) and 3 m / s (Case 2) with one side of the skylight window was open by 50 % in both cases. As the outside wind velocity increases, cold air quickly flows into the greenhouse, rapidly cooling the greenhouse.

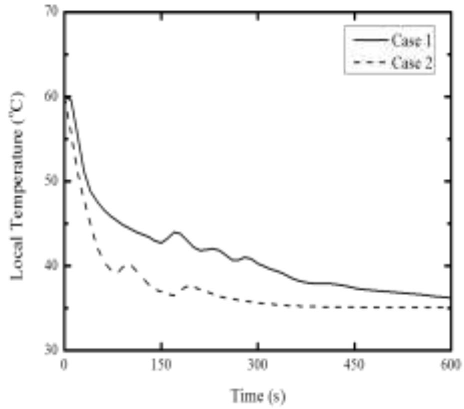


Figure 7. Comparison of temperature distribution effect between natural and forced ventilation at 3.2 m height, XY-plane (Case 1: **Natural vent**, Side wall close, Roof 50 % single open, wind speed 1m/sec and Case 6: **Forced vent**, other conditions same to Case 1)

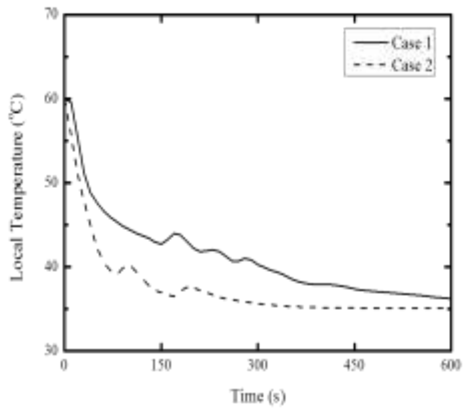


Figure 8. Comparison of temperature distribution effect for the external wind velocity at center point (x=0, y=0, z=3.2 m) (Case 1: Natural vent, Side wall close, Roof 50 % single open, **wind speed 1 m/sec** and Case 2: **wind speed 3 m/sec**, other conditions same to Case 1)

The effect of skylight window opening was modeled as Case 5 by varying the angle of the skylight windows and the number of open windows. The analysis results for the Case 1 is also shown for comparison with the Case 5 in Fig. 9. When the skylight windows were fully open, the convective heat flow in the greenhouse became more vigorous because the direction of the external air inflow was opposite. However, the effect of changing the opening angle of the skylight windows was not significant compared to that of fully opening the two side windows.

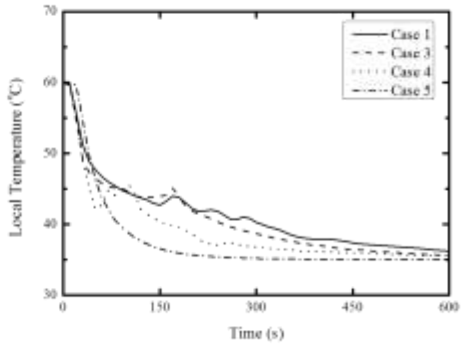


Figure 9. Comparison of temperature distribution effect for the ventilation types at center point (x=0, y=0, z=3.2 m) (Case 1: Natural vent, Side wall close, **Roof 50 % single open**, wind speed 1 m/sec and Case 3: **Roof 100 % single open** and Case 4: **Roof 100 % both open** and Case 5: **Side wall open**, other conditions same to Case 1)

It can be safely argued that the effect of fully opening the side windows caused massive influx of outside air which is directly influenced by the outside wind. When the side window is fully open, the outside air is introduced through the lower position than the sash and the hotter air is discharged through the sash via natural convection. When the side windows opened, external air is taken into the lower position than the skylight windows location and the hotter air is discharged through the skylight windows via natural convection. Therefore, comparable temperature rise to that predicted by the Case 1 was not observed.

IV. CONCLUSION

In this study, it was investigated the temperature change mechanism due to the ventilation structure and the velocity of the external wind of the greenhouse that used to control the growth environment by thermal-fluid analysis. In the greenhouse ventilation structure, it was performed the thermal- fluid analysis for the opening of the skylight and the side window, the forced ventilation of blower, and the result was as follows.

Forced ventilation of the blower is lower than the temperature decreasing effect of the natural convection at the initial stage of ventilation, because of the air curtain phenomenon of the flow by the blower. On the other hand, it found that the ability to uniformize the temperature inside the greenhouse improved. In addition, the effect of temperature uniformity is shown to be accompanied the effect of increasing the temperature deceasing efficiency after a certain period.

It confirmed that the contribution to the temperature deceasing effect due to the ventilation was in the order of the speed of the outside air, the side window, the sky window, and the forced ventilation of blower. We presented a method of evaluating the uniformity of a standard deviation, and this method will be used the useful method as quantitative expression.

The characteristics of ventilation for the skylight window were confirmed the characteristic to be exhausted at the top of the window and inhaled at the bottom. In addition, the ventilation results of the degree of skylight window opening founded that the temperature deceasing effect, for the opening area of more than 50 % at external wind speed 1 m/sec, did not have a great influence.

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