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Simulation of thermal environment in a three-layer vinyl greenhouse by natural ventilation control

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Abstract. A high energy, efficient, harmonious, ecological greenhouse has been highlighted by advanced future agricultural technology recently. This greenhouse is essential for expanding the production cycle toward growth conditions through combined thermal environmental control. However, it has a negative effect on farming income via huge energy supply expenses. Because not only production income, but operating costs related to thermal load for thermal environment control is important in farming income, it needs studies such as a harmonious ecological greenhouse using natural ventilation control. This study is simulated for energy consumption and thermal environmental conditions in a three-layered greenhouse by natural ventilation using window opening. A virtual 3D model of a three-layered greenhouse was designed based on the real one in the Gangneung area. This 3D model was used to calculate a thermal environment state such as indoor temperature, relative humidity, and thermal load in the case of a window opening rate from 0 to 100%. There was also a heat exchange operated for heating or cooling controlled by various setting temperatures. The results show that the cooling load can be reduced by natural ventilation control in the summer season, and the heat exchange capacity for heating can also be simulated for growth conditions in the winter season.

1 Introduction

As the proportion of farmers using greenhouses has increased recently, studies on the farm household income of domestic and foreign greenhouses have been actively carried out. Through the analysis of the thermal environment of various greenhouse models, diverse greenhouse models are actually applied [1] and attempts to increase productivity through an automation system have been made. In Korea, as in other countries, combined thermal environment control technology for the greenhouse to increase the productivity of cultivated crops through the smart farm is necessary in order to improve the profitability of farm households. There is also a growing need for research and development on the total

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service platform that is associated with the operation of smart farms, such as energy and agriculture management.

Although heating the facilities is necessary in winter and cooling is required to avoid high temperatures and humidity in summer, enormous energy costs are required in order to control the thermal environment according to the growth conditions and it is a factor that hurts the profits of farm households, so it is necessary to establish various energy saving measures for the facilities. Recently, in order to reduce the energy cost, renewable energy resources using solar heat and geothermal heat are being employed [2, 3]. However, a disadvantage of renewable energy sources is that they may not be able to supply energy in a timely manner due to the volatility of the output. This problem may lead to a shortage of supply energy as well as failure to supply necessary energy in a timely manner.

In this study, the thermal environment in a greenhouse through natural ventilation was simulated before controlling the thermal environment through various energy sources. Through the 3D modeling and analysis of the three-layer vinyl greenhouse, the annual energy load is calculated and the energy load reduction and the combined control of temperature and humidity are confirmed through the opening and closing control function of the windows. Using TRNSYS, a three-layer vinyl greenhouse for strawberry cultivation located in Sangcheon-myeon, Gangneung-si, Gangwon Province was simulated. Through this simulation, the indoor temperature and indoor humidity in the enclosed greenhouse were confirmed, and a decrease of the cooling load depending on the change of the indoor temperature, indoor humidity, and natural ventilation through the on/off control of the side windows and skylights was also confirmed. Based on the calculation results, this study aimed to propose a method of operating an environmentally friendly greenhouse through natural ventilation as well as reducing the amount of required energy through thermal and environmental control.

2 3D modeling of the 3-layer greenhouse

2.1 3D modeling of the greenhouse

The 3D modeling of the real greenhouse, which was the analysis target of this study, was simulated through TRNBUILD of TRNSYS and TRNSYS3d of Sketch-up 2016, as shown in Fig. 1. In the case of TRNSYS, it has high accuracy and usability for energy loads of various general buildings as a technology for calculating the heat and energy flow of the building and the energy loads such as heating and cooling for the proper environmental control.

In addition, since it is possible to set the boundary conditions such as the ambient condition and solar radiation condition during the user's desired period, it is possible to supplement limitations of field experiments. Thus, recently, it is frequently used in modeling not only for general buildings but also for agricultural buildings [4].

In this study, the factors related to structures such as each frame and vinyl covering constituting the greenhouse were constructed through the TRNSYS3d of the Sketch-up, and the thermal properties of each material, boundary conditions, and on/off control of windows were constructed through TRNBUILD as shown in Table 1 and Fig. 2.

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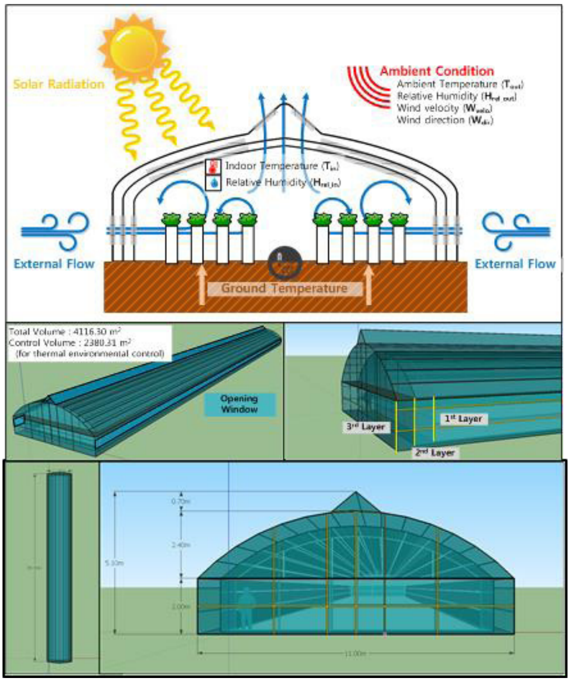

Fig. 1. 3D modeling of 3-layer greenhouse.

Table 1. Input design condition of the 3D modeling.

Weather DB	Calculation		Result
Solar Radiation Temperature Humidity Wind Atmospheric Pressure	Surface Info	Slope	Beam Radiation
		Azimuth	Diffuse Radiation
			Incidence Angle
	Atmospheric Condition	Ambient Temperature	Ambient Temperature
		Dewpoint Temperature	Sky Temperature
		Relative Humidity	
	Window Type	Wind Velocity , Direction	Mass Flow
		Atmoshperic Pressure	Window Open Signal

The ambient conditions of this study were determined using the weather data of the Korea Meteorological Administration for the northern part of Gangneung-si, which is the area nearest to the three-layer vinyl house for strawberry cultivation in Sangcheon-myeon, Gangneung-si. The weather data of the Korea Meteorological Administration were composed of the ambient temperature, indoor humidity, dew point temperature, solar radiation, wind velocity, wind direction and atmospheric pressure. The incoming solar radiation on each side of the greenhouse was calculated from solar radiation, the external ambient temperature and external relative humidity. The internal temperature was calculated using the external ambient temperature, the dew point temperature, calculated direct solar radiation and diffuse solar radiation. The internal thermal environment was simulated through incoming solar radiation on each side and the internal temperature. The wind speed, wind direction, and atmospheric pressure were used to calculate the amount of ventilation through each window.

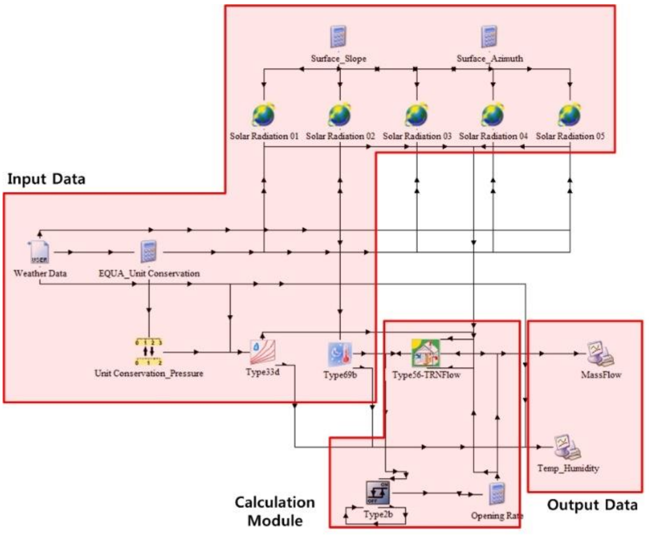

Fig. 2. TRNSYS input schematic diagram of 3-layer greenhouse.

2.2 Modeling of thermal and air nodes

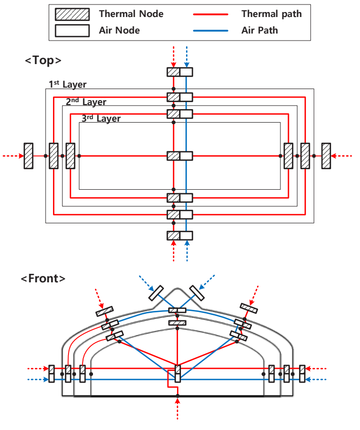

Fig. 3. Thermal and air node configuration.

For the greenhouse analysis for the thermal and environmental control, the analysis model is composed of the thermal-nodes and air-nodes by distinguishing between calculation for thermal heat balance and calculation for mass balance of air ventilation. The thermal-nodes consist of inner and outer walls, which are classified according to whether they are exposed to wind and solar radiation. The outer walls are influenced by the ambient conditions such as solar radiation, the ambient temperature, and the internal temperature. For the inner walls, the condition of the thermal environment is simulated and calculated taking into account the influences of conduction, convection and radiation energy through adjacent surfaces. Fig. 3 shows thermal and air node configuration.

In the study, boundary conditions were constructed by considering both the ground temperature and the internal temperature of the indoor air in contact with the ground in

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order to simulate the changes of the internal temperature depending on the floor surface, taking into account the effect of the ground temperature.

The air-node is for calculating the air flow rate according to the on/off control of the side windows. The window is opened from the bottom to the top. The width of the window and the height of the window (fully opened) were entered for each window located at each node, and the windows are controlled to be opened or closed according to the change of the indoor temperature.

3 Window opening model of the 3-layer greenhouse

3.1 Window opening model

The TRNFLOW module of TRNSYS was used to calculate the exit flow rate of air depending on the on/off control of the greenhouse windows. In TRNFLOW, the variables in Table 2 are used to calculate the mass flow rate according to the on/off control of the windows [5]. As shown in Fig. 3, the width of the window is constant, and the flow rate changes depending on the window opening rate which is increased by the on/off control of the windows. At this time, when the mass flow rate from Zone 1 to Zone 2 is $\dot{m}_{12}$ and the mass flow rate from Zone 2 to Zone 1 is $\dot{m}_{21}$, each mass flow rate is calculated by the following equation [6, 7].

Table 2. Main variables of window opening model.

Variable	Equation
Pressure	$\mathrm{p} = \frac{\rho}{2} \cdot C_p \cdot {v_o}^2$
Pressure difference	$\Delta\mathrm{p} = \frac{\rho}{2} \cdot \left(\frac{V}{C_d}\right)^2$
Mass flow rate	$\dot{m} = C_s \cdot (\Delta p)^n$
Real wind speed coefficient	$C_w = 0.08 \cdot \left(\frac{Gr}{Re^2}\right)^{-0.38}$

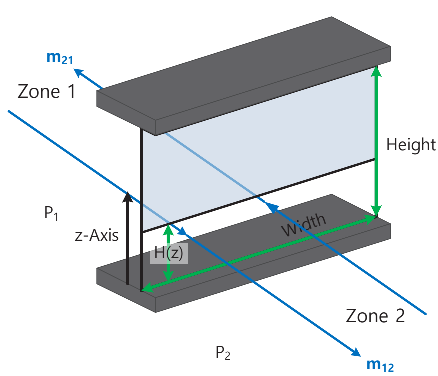

Fig. 4. Control window opening model.

$$\dot{m}_{12} = C_d \cdot \int_0^H \sqrt{2\rho(z) \cdot f_{12}(z)} \cdot H(z) \cdot dz \tag{1}$$

$$f_{12} = \begin{cases} \Delta p(z) & , if\ \Delta p(z) > 0 \\ 0 & , if\ \Delta p(z) < 0 \end{cases} \quad (2)$$

$$\dot{m}_{21} = C_d \cdot \int_0^H \sqrt{2\rho(z) \cdot f_{21}(z)} \cdot H(z) \cdot dz \quad (3)$$

$$f_{21} = \begin{cases} -\Delta p(z) & , if\ \Delta p(z) < 0 \\ 0 & , if\ \Delta p(z) > 0 \end{cases} \quad (4)$$

Thus, the air flow rate through ventilation influences the convection heat transfer and the internal temperature of the greenhouse changes. When the quantity of heat is $\dot{Q}_{vent}$, it can be calculated by the equation in (5) below.

$$\dot{Q}_{vent} = \dot{V} \cdot \rho \cdot C_p (T_{vent-air} - T_{indoor-air}) \quad (5)$$

Depending on the on/off control of the windows, $\dot{Q}_{vent}$ flows in or out of each node in Fig. 3, and consequently, the conditions of the thermal environment inside the greenhouse through natural ventilation are newly calculated [8].

4 Results of thermal environment analysis

4.1 Analysis of the thermal environment in the enclosed greenhouse

The calculation results of the thermal environment conditions such as the temperature and humidity inside the greenhouse through the 3D shape modeling are shown in Fig. 5.

For the internal temperatures of the enclosed 3-layer vinyl greenhouse without air-conditioning and heating facilities, the annual mean temperature is 17.7°C, the maximum temperature is 48.8°C, and the minimum temperature is -4.7°C. For seasonal temperatures, in winter (January to February and November to December), the mean temperature is 6.42°C, the maximum temperature is 23.5°C, and the minimum temperature is -4.7°C. In summer (July to August), the mean temperature is 31.5°C, the maximum temperature is 48.8°C, and the minimum temperature is 21.9°C. In spring and autumn (March to June and September to October), the mean temperature is 20.4°C, the maximum temperature is 44.8°C and the minimum temperature is 0.7°C.

In winter, since the temperature inside the greenhouse is low due to the influence of the low ambient temperature and the insignificant changes of the ground temperature, the heating load is expected to be large during winter months. In particular, it was also found that even though the ambient temperature is high, the indoor temperature is not significantly affected by it because of the influence of the ground temperature. In particular, it is predicted that the indoor temperature will be lowered due to the influence of the ground temperature at the time of sunrise or sunset, and as a result, freezing of the crops may occur. In summer, the indoor temperature is observed to be high because solar radiation is abundant, the angle of incidence is close to a vertical angle and the ground temperature is high. It can be seen that the humidity inside the greenhouse is well calculated according to the change of the internal temperature.

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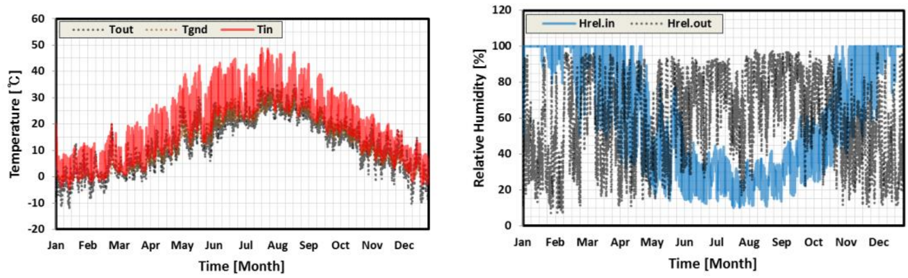
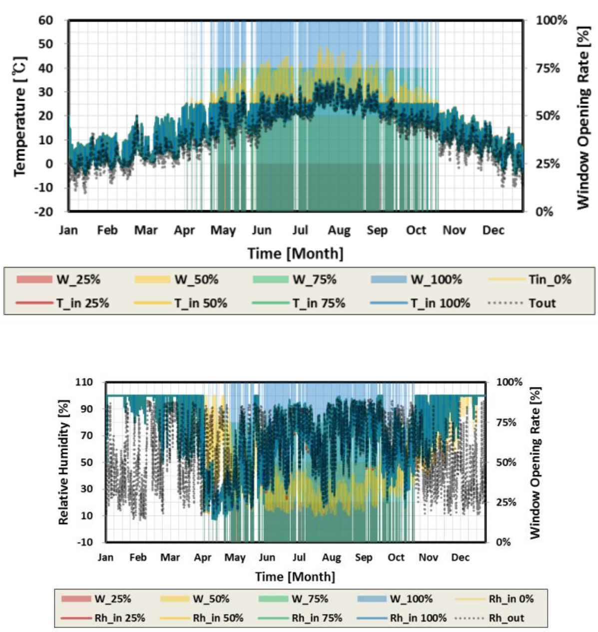


Fig. 5. Annually thermal environment conditions in closed greenhouse.

4.2 Analysis of the thermal environment by natural ventilation control

In order to control the indoor temperature inside the greenhouse in summer, a natural ventilation system that opens and closes side windows was modelled. The annual indoor temperature, humidity and mass flow rate according to the opening rate of the window are shown in Fig. 6. The setting temperature for the window on/off control was 25°C, the opening and closing time was differentiated by the time unit of 15 minutes, and the window opening rates were divided into 25%, 50%, 75%, and 100%. In the calculation results, the window on/off control is conducted from April to October of the year, and the operating time of the on/off control is different according to the opening rate during a total of 8760 hours. The opening rate is 25% for 1522 hours, 50% for 1495.5 hours, 75% for 1487.75 hours, and 100% for 1484.25 hours. The reason why the control time differs according to the opening rate can be confirmed by the mass flow rate graph. The mass flow rate changes according to the opening rate, so the amount of $\dot{Q}_{vent}$ varies accordingly. For this reason, the control operation time changes depending on the opening rate in order to match the setting temperature.



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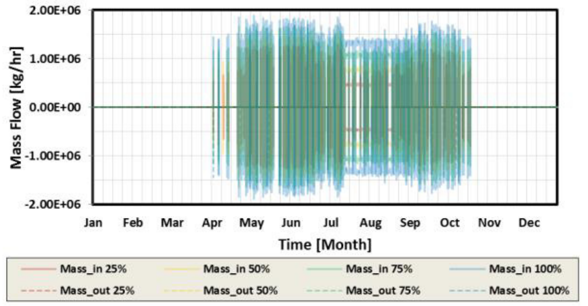

Fig. 6. Annually thermal environment conditions by natural ventilation control.

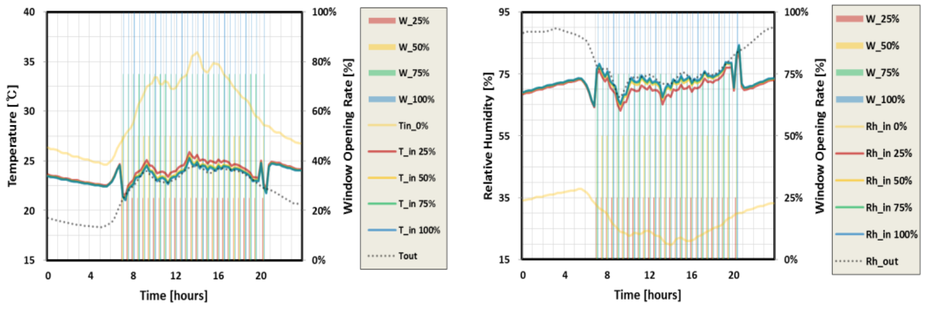

Fig. 7. Daily thermal environment conditions by natural ventilation control.

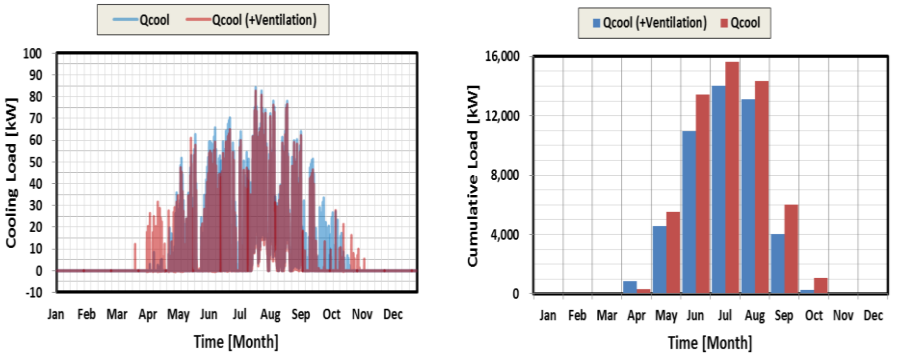

Fig. 8. Energy load comparison by only cooling and cooling with ventilation.

In order to examine daily thermal environment conditions, the calculation results according to the opening rate in July are presented in Fig. 7. Although it is controlled according to the on/off control of the windows, similarly to the ambient conditions, it can be seen that there is a slight difference according to the opening rate. Actually, temperature difference of about 1°C and humidity difference of about 5% were found between the opening rate of 25% and the opening rate of 100%.

4.3 Thermal load analysis for natural ventilation control

As described above, the differences in the thermal environment conditions of the greenhouse according to the opening rate were examined. At the same time, the cooling loads for the case of single cooling and for the case of cooling with natural ventilation control were calculated and compared with the cooling load of the enclosed greenhouse. The results of calculation of the total load are shown in Fig. 8 for the cases where single cooling was performed at 25°C and where cooling load was simulated with natural ventilation control. The cooling load of the enclosed greenhouse and the cooling load by natural ventilation control were found to be 56,386 kW and 47,859 kW, respectively, so it was confirmed that the cooling load can be reduced by approximately 17.82% (8,527 kW) when natural ventilation control is used.

5 Conclusions

In this study, 3D modeling of a 3-layer greenhouse was carried out, and the internal thermal environment conditions of the greenhouse according to the window on/off control were investigated. First, the thermal environment conditions in the enclosed greenhouse were examined, and the thermal environment conditions inside the greenhouse were compared by adjusting the window opening rate to 25%, 50%, 75%, and 100%. In particular, when the windows were controlled by setting the window opening rate to be 50% at the indoor temperature of 18°C and 100% at 23°C, it was confirmed that the cooling load of about 17.82% (8,527 kW) can be reduced in the case of cooling with natural ventilation control through the window on/off control compared to the cooling load of the enclosed greenhouse. These results show that it is possible to maintain not only the thermal environment conditions that meet the growth conditions, but also reduce the cooling load through natural ventilation.

Based on the above results, it is predicted that it will be possible to maintain the energy environment that meets the growth conditions of the crop through the surrounding ecological environment, and simulate a more effective thermal environment when the method is used together with renewable energy resources. In the future, we plan to conduct further research on the ways to reduce the heating load through natural ventilation during heating by adding heat exchanger control for heating during winter months.

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