Development of Semi-basement Type Greenhouse Model for Energy Saving

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Abstract

Purpose: The heat culture areas of greenhouses have been continuously increasing. In the face of international oil price fluctuations, development of energy saving technologies is becoming essential. To save energy, auxiliary heat source and thermal insulation technologies are being developed, but they lack cost-efficiency. The present study was conducted to save energy by developing a conceptually new semi-basement type greenhouse. **Methods:** A semi-basement type greenhouse, was designed and constructed in the form of a three quarter greenhouse as a basic structure, which is an advantageous structure to inflow sunlight. To evaluate the performance of the developed greenhouse, a similar structured general greenhouse was installed as a control plot, and heating tests were conducted under the same crop growth conditions. **Results:** Although shadows appeared during the winter in the semi-basement type greenhouse due to the underground drop, the results of crop growth tests indicated that there were no differences in crop growth and development between the semi-basement type greenhouse and the control greenhouse, indicating that the shadows did not affect the crop up to the height of the crop growing point. The amount of fuel used for heating from January to March was almost the same between the two greenhouses for tests. The heating load coefficients of the experimental greenhouses were calculated as 3.1 kcal/m$^2 \cdot$ °C $\cdot$ h for the semi-basement type greenhouse and 2.9 kcal/m$^2 \cdot$ °C $\cdot$ h for the control greenhouse. Since the value is lower than the double layer PE (polyethylene) film greenhouse value of 3.5 kcal/m$^2 \cdot$ °C $\cdot$ h from a previous study, Tthe semi-basement type greenhouse seemed to have energy saving effects. **Conclusions:** The semi-basement type greenhouse could be operated with the same fuel consumption as general greenhouses, even though its underground portion resulted in a larger volume, indicating positive effects on energy saving and space utilization. It was identified that the heat losses could be reduced by installing a thermal curtain of multi-layered materials for heat insulation inside the greenhouse for the cultivation of horticultural products by installing thermal curtain of multi-layered materials for heat insulation inside the greenhouse, it was identified that the heat losses could be reduced.

Keywords: Greenhouse, Heating load coefficient, Semi-basement type, Thermal curtain, Three-quarter

Introduction

The total facilities area for vegetable cultivation in South Korea was 51,787 ha, of which the heat culture areas accounted for 14,882 ha, as of 2014. This was approximately 1.5 times the cultivation area of in 2004, which was 9,652 ha. The ratio of oil to fuel used for heating greenhouses decreased from approximately 95% in 2004 to 85% in 2014, but the heat areas using oils as fuels increased from 9,157 ha in 2004 to 12,702 ha in 2014. The ratio of oil use is still higher than that of other fuels. In addition, although agricultural tax exemption oilis supplied for greenhouse heating, it is estimated that the heating cost accounts for 30 to 40% of the horticulture farm management costs, which is more than twice the management cost in advanced countries. Further, owing to fluctuations in international oil prices resulting from limited oil resource supply as well as recent global warming, new and renewable energy sources have emerged as alternatives to fossil fuels. Currently, new and

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renewable energy resources that can be used for greenhouses include natural energy such as sunlight, terrestrial heat, and water heat. Greenhouse heating methods using natural energy, latent heat storage systems using solar heat, and methods using heat pumps have been proposed (Song et al., 1994). As a part of the Agricultural Energy Utilization Efficiency Improvement Project, the Ministry of Agriculture, Food and Rural Affairs currently supports the installation of geothermal heating and cooling facilities by funding central government or local government subsidies. It is true that geothermal heat pumps are very helpful for heating energy saving of protected cultivation farms. However, geothermal heat pumps for cooling and heating greenhouses require studies to address high installation costs and improve the cooling and warming efficiency (Kang et al., 2005).

According to the results of an analysis of surplus solar heat generated by greenhouses in various regions in South Korea, yearly surplus solar heat reached approximately 53-225% of the required heating energy, indicating that surplus solar heat is sufficiently useful as a heating source (Suh et al., 2011). In China, surplus solar heat is stored at the north-side wall during the day, and is utilized as a heat source during the night (Ko, 2003). Some studies have been conducted to store solar heat in gravel as a heat storage material during the day and use the stored heat during the night (Lee et al., 2001; Ro et al., 2001; Jeon et al., 2015).

To reduce energy input costs in protected horticulture, it is necessary to develop a technology to maximize the surplus solar heat in greenhouses, or to develop a greenhouse model that can minimize heat loss.

In this study, the development of a greenhouse model using new concepts for energy saving was attempted. The heat loss of the greenhouse is 60 to 100%, where the heat is transferred to the outside through the surface of the covering material (JGHA, 2015). Therefore, a semi-basement type greenhouse model that can minimize heat losses by reducing the surface area of greenhouses was designed as a measure to reduce winter heating costs.

Materials and Methods

Greenhouse design

A conceptually new greenhouse model was designed based on the single-span greenhouse-10-8 type that can be found in the protected horticulture & herbal facilities disaster resistant types designs and specifications (Ministry of Agriculture, Food and Rural Affairs' notification, 2014). The structure was a three quarter vinyl greenhouse that allowed the inflow of sunlight. As shown in Figure 1, one semi-basement type greenhouse

(a) Semi-basement type greenhouse (Experimental)

(b) Conventional type greenhouse (Control)

Figure 1. Greenhouses for tests.

Table 1. Specifications of the greenhouses for tests		
	Semi-basement type	Control
Type	3/4 type single-span	3/4 type single-span
Orientation	East-West	East-West
Width (m)	7.5	7.5
Edge height (m)	3.6	3.6
Front side height (m)	1.6	1.6
Reverse side height (m)	3.0	3.0
Length (m)	30.0	30.0
Depth of basement (m)	0.6	-
Floor area (m^2)	185	185
Surface area (m^2)	399	399

* Location : 128.4°east longitude / 35.3°north latitude (Haman-Gun, Korea)

(a) Semi-basement type greenhouse (Experimental) (b) Conventional type greenhouse (Control)
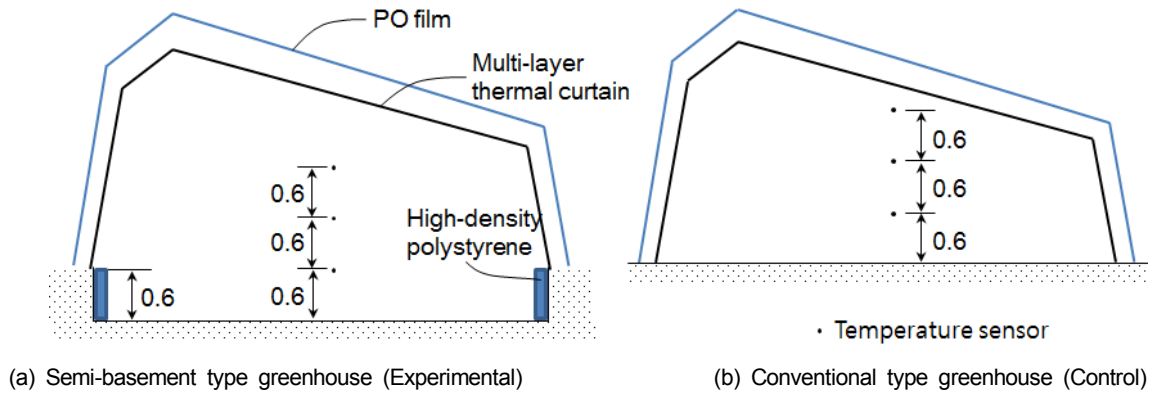
Figure 2. Structure of greenhouses and placement of the temperature sensors.

and one general greenhouse were installed for tests. As shown in Table 1, the greenhouses for the tests were 7.5 m wide, 30 m long, and 3.6 m high. The height of a bed for the high-established cultivation of strawberries was installed more than 1 m above ground. Fruit and vegetable crops cultivated by stem training do not experience growth limitations due to the shadows in the underground drop as their growing point is as high as 1 m in short growth period. Therefore, the semi-basement type greenhouse was installed after digging 60 m deep into the ground. To prevent thermal conduction through the 60 cm high soil walls formed inside the greenhouse, the soil walls were insulated with a 100 mm-thick high density styrofoam. The outside of the greenhouse was covered in PO (Polyolefin) films, and a thermal curtain of multi-layered materials was used for heat conservation.

Each greenhouse was heated by a 20,000 kcal/h capacity heater installed at the entrance of the greenhouse. The heater operating temperature was set to 16°C and the usage during the test period was recorded every day. As for the cultivated crop, tomatoes (variety:Dotaerang) were planted in soil on December 30, 2015. In the heating test, the data from December 31, 2015 (after the crop planting) to March 31, 2016 were analyzed.

The greenhouse environments were measured using temperature sensors (K type thermocouple), a recorder (YOKOGAWA, MV1000), hygrometers (MadgeTech, Temp RetrieverRH Data Logger), and insolation sensors (Apogee, SP-212). For temperature measurement inside the greenhouse, temperature sensors were placed vertically at 1.8 m, 1.2 m, and 0.6 m above a furrow at a point at 1/3 the length of the greenhouse from the front end, the center of the greenhouse, and a point at 1/3 the length of the greenhouse from the rear end, as shown in Figure 2. In addition, one temperature

sensor was placed outside the greenhouse to measure outdoor air temperature. A hygrometer was placed at a height of 1.8 m from the furrow at the same position as a temperature sensor at a point at 1/3 the length of the greenhouse from the front end, and a hygrometer was placed outside the greenhouse. An insolation sensor was placed in the vicinity of the crop growing point. All of the temperatures, humidity, and the amount of insolation were measured and recorded at intervals of 10 min.

In the case of the semi-basement type greenhouse, since the crop grows on the bottom surface, 0.6 m below the ground surface, shadows were formed on the underground portion. The shadow sizes formed due to drops are determined by the altitudes and azimuths of the sun by season. Therefore, the shadow sizes were investigated at the autumnal equinox and at the winter solstice when the meridian transit altitude of the son is the lowest. The altitudes and azimuths of the sun were determined from data provided by the astronomy and space information system (http://astro.kasi.re.kr).

Heating load analysis method

The heating load coefficient was considered to determine the heating load characteristics of the developed semi-basement greenhouse and the control greenhouse under the same conditions.

The heating load of a greenhouse is related to the calories supplied by the heater according to the indoor setting temperature. The heating load is calculated from the fuel consumption of the hot air heater used in the greenhouses for tests and Eq. (1) (Kim et al., 2000; Nam et al., 2008). The heating load coefficient (U) value was obtained from reverse calculations of the relationship between the heating load for one day and Eq. (2) (Kim et al., 2000; Nam et al., 2008).

$$Q_d = \eta \cdot \beta \cdot V_f \tag{1}$$

(a) Air temperature
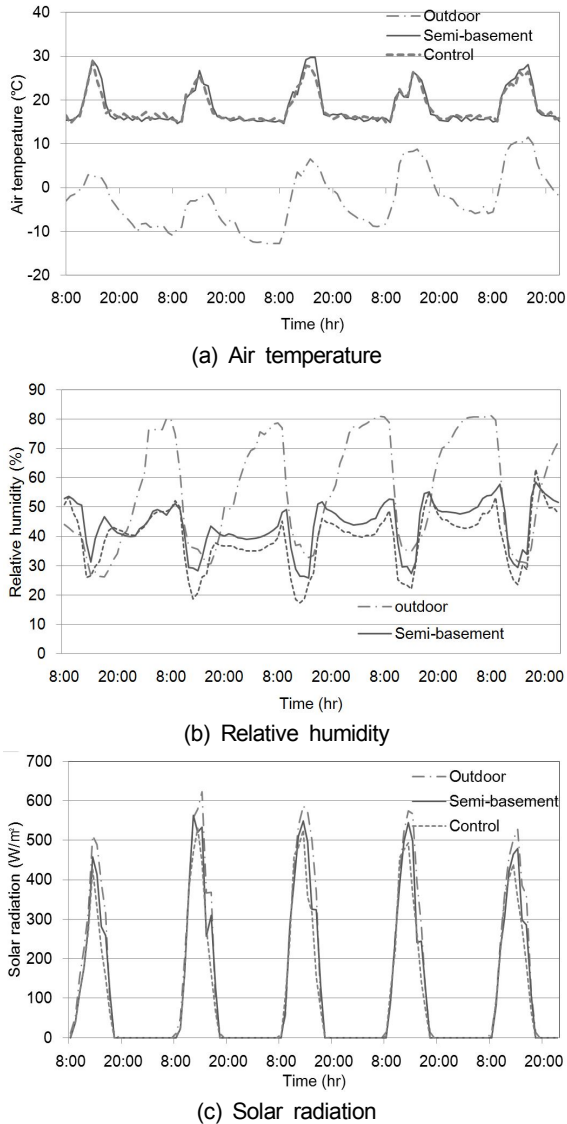

(b) Relative humidity

(c) Solar radiation

Figure 3. Comparison with meteorological environments of the greenhouses for tests (2016. 1.23.~ 1.27.).

where,

Q_d : Heating load during the period (kcal)

η : Thermal efficiency (0.8)

β : Caloric value (9,050 kcal/L)

V_f : Daily fuel consumption (L)

$$Q_d = A_g \cdot U \cdot \int (T_\in - T_{out})dt \qquad (2)$$

where,

Q_d : Heating load during the period(kcal)

A_g : Greenhouse covering area (m²)

U : Heating load coefficient (kcal/m²·℃·h)

$T_\in$: Indoor setting temperature(℃)

T_{out}: Outdoor temperature(℃)

(a) Vernal equinox/autumnal equinox
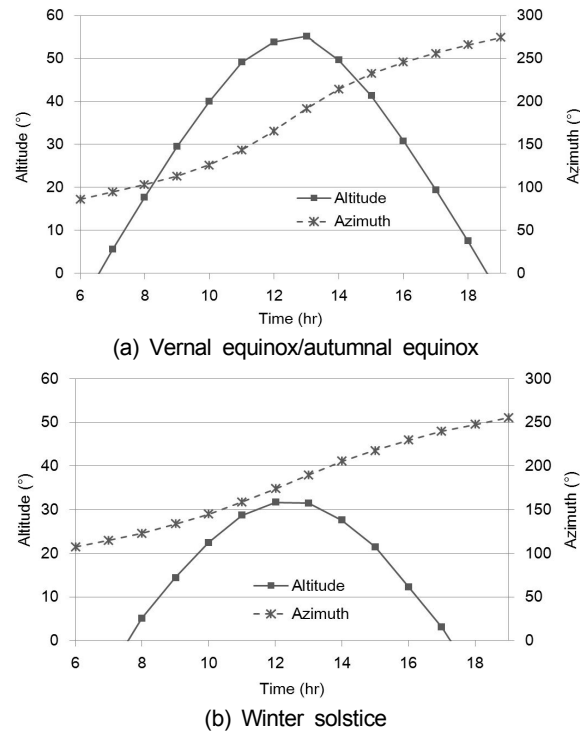

(b) Winter solstice

Figure 4. Solar altitudes and azimuths (Haman-gun).

Results and Discussion

Meteorological environments and crop growth status in the greenhouses for tests

To judge whether the developed greenhouse is suitable for crop growth and development, indoor environments of the semi-basement type greenhouse and the control greenhouse were compared with each other. The indoor and outdoor environments of the greenhouses for the tests conducted from January 23 to 27 of the crop growth period are shown in Figure 3 (a), (b), and (c). The indoor temperatures of the greenhouses for tests did not show any large differences between the semi-basement type greenhouse and the control greenhouse, and they were shown to be maintained at the set temperature of 16℃ in the nighttime. The humidity levels inside the greenhouse varied slightly between greenhouses. The semi-basement type greenhouse was approximately 8% higher in the daytime and 4% higher during the night compared to the control greenhouse. This was considered to be due to the larger soil surface area as the semi-basement structure. The maximum value of insolation during daytime in the semi-basement type greenhouse was shown to be a little larger compared to that in the control greenhouse, but the difference was not significant.

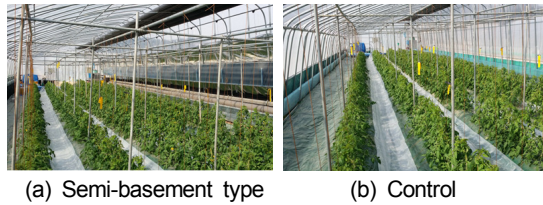The length of shadows due to the underground drop is

(a) Semi-basement type   (b) Control

Figure 5. Tomato growth states.

Figure 6. Relationship between the fuel consumption of the greenhouses and outdoor temperature at night time.

(a) Semi-basement type

$y = 1.2167x - 1.2418$
$R^2 = 0.681$

(b) Control

$y = 1.5427x - 4.8966$
$R^2 = 0.737$

Figure 7. Relationship between fuel consumption and air temperature difference of indoor/outdoor at night time.

calculated according to the changing solar altitudes and azimuths. Figure 4 (a) shows the solar altitudes and azimuths at the vernal and autumnal equinox. In the semi-basement type greenhouse, the length of shadows due to the underground drop was approximately 0.42 m regardless of time passage. It had no effect on the crop ridges adjacent to the underground drop. However, solar altitudes at the winter solstice were much lower compared to those at the vernal and autumnal equinox as shown in Figure 4 (b). Even when the solar altitudes were the highest at the meridian passage, the length of the shadows due to the underground drop were maintained at around 1 m. At the beginning of crop photosynthesis, the length of shadows formed from the underground drop was about 3.7 m at 08:00 am. It was then reduced to 1.6 m at 09:00 am and 1.2 m at 10:00 am. If the crop on the ridge adjacent to the underground drop was 1.5 m away from the drop, the height of the shadows on the crop should be 35 cm at 08:00 am and 3 cm at 09:00 am. If the fruit and vegetable crops are cultivated by stem training, the stems will grow to over 1 m by this time. Therefore, the shadows will not limit crop growth much. The results of the growth of tomatoes, which were planted on December 30, 2015 close to the winter solstice, indicate that there were significant differences between the semi-basement type greenhouse and the control greenhouse at the T-test significance level of 5%, but tomato growth situations actually showed very little variation, as shown in Figure 5. Even if crops were planted at a disadvantageous time when the sunlight came into the greenhouse, there were no growth limitations.

Fuel consumption of the greenhouses for tests

In the analysis of the relationships between outdoor temperature and fuel consumptions measured in the greenhouses for tests at night, outdoor temperature and fuel consumptions were symmetrical as shown in Figure 6. The accumulated fuel consumptions during the heating period from Jan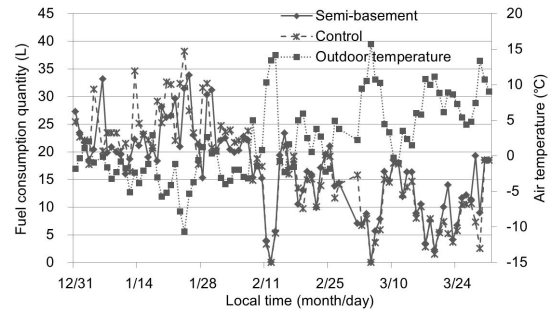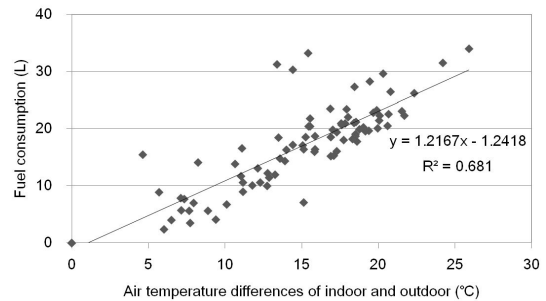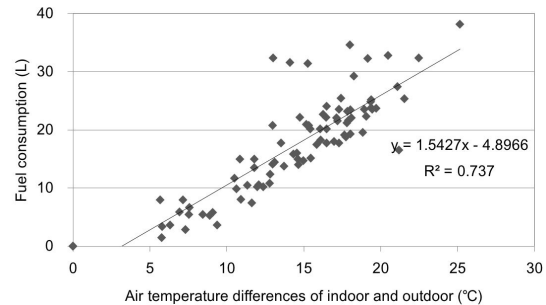uary to March were 1,531 L in the semi-basement greenhouse and 1,537 L in the control greenhouse. This indicated that there was no difference between the two greenhouses despite the fact that the internal volume of the semi-basement greenhouse was larger than the control greenhouse up to its underground depth. It is likely that the insulation blocked the heat transmitted to the outside of the greenhouse due to the influence of the insulation installed on the underground side wall.

The relationship between fuel consumptions and the air temperature difference in the outdoor and indoor sections of the greenhouse at night is shown in Figure 7 (a) and (b). It was indicated that the fuel consumption also increases as the temperature difference between the indoor and outdoor sections of the greenhouse increases.

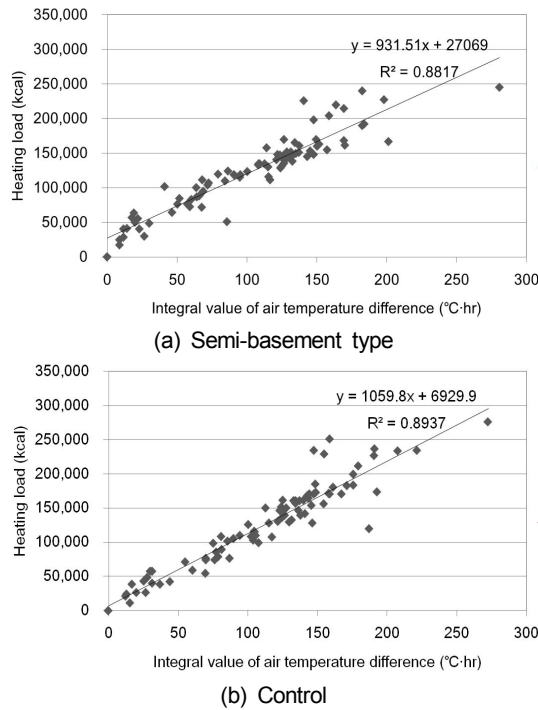The gradient of fuel consumption increments according

(a) Semi-basement type

(b) Control

Figure 8. Relationship between heating load and integral value of indoor/outdoor temperature differences during heating.

(a) Semi-basement type

(b) Control

Figure 9. Distribution of heating load coefficients in the greenhouses for tests.

to the air temperature difference of the indoor and outdoor sections was a little different between the semi-basement type greenhouse and the control greenhouse. The fuel consumption of the semi-basement type greenhouse was a little higher when the air temperature difference between the indoor and outdoor sections of the greenhouse was small. When the air temperature difference was large, the fuel consumption of the control greenhouse was a little higher. This was considered to be due to the fact that when the air temperature difference between the indoor and outdoor sections was small, heater operation time was longer in the semi-basement type greenhouse because its internal space volume was larger than that of the control greenhouse. On the contrary, when the air temperature difference between the indoor and outdoor sections was large, the operation intervals of the heater were longer because the amount of heated air was larger as the internal space volume was larger, thus allowing the air temperature inside of the greenhouse to drop slowly. From the results of this study, if insulation materials are installed to a certain height on the bottom of the greenhouse in order to reduce heat transferred to the outside, the fuel consumptions could be decreased even in general greenhouses. In addition, if the greenhouse for high crop cultivation by stem training is constructed, the structures should be better designed so
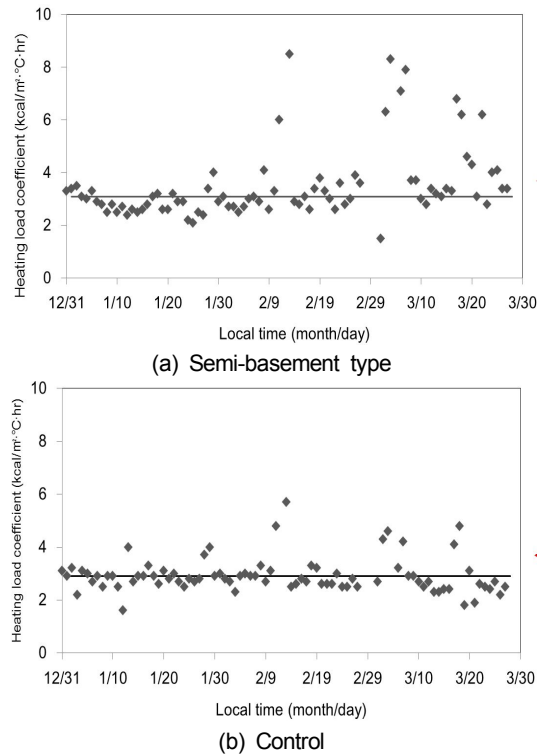
as to accommodate wind loads and snow loads in order to safely cultivate crops. However, if the semi-basement greenhouse structures of a certain depth are constructed as shown in the present experiment, it should not be necessary to strengthen the structure and it is possible to operate with the same fuel usage as general greenhouses.

Heating load analysis

Figure 8 (a) and (b) show the analysis results of the heating load obtained from the fuel consumption of the greenhouses for tests, and the integral value of indoor and outdoor temperature differences over time. During the heating, it was found that the heating load increases with the increasing integral value of indoor and outdoor temperature difference. The relationship between the fuel consumption and temperature difference between the indoor/outdoor sections showed a slight difference in the slope of the rising curve between the semibasement type greenhouse and the control greenhouse. The slight difference in the slope of the rising curve occurred similarly in the relationship between the heating load and the integral value of the indoor/outdoor temperature difference during heating.

The integral values of indoor/outdoor temperature

differences during heating are a function of the heating time and indoor/outdoor temperature differences. Therefore, it was indicated that heating load in the semi-basement type greenhouse were larger because heater operation time was longer due to the inner volume of the greenhouse when temperature differences were small. When the temperature differences were large, the heating load was larger because the indoor air temperature dropped faster in the low-volume control greenhouse, making the intervals of heater operation relatively shorter.

From this, it was confirmed that the difference in slope of the rising curve related to the inside volume size of the greenhouse.

Heating load coefficients of the greenhouses for tests were calculated from the relationship between the heating load and the integral value of the indoor/outdoor temperature difference during heating. The calculated heating load coefficients were as shown in Figure 9. The higher values of heating load coefficients in the semi-basement type greenhouse and control greenhouse occurred on some dates as shown in Figure 9 (a) and (b). This phenomenon occurred on around February 12, March 5, and March 19 when fuel consumptions were relatively small as shown in Figure 7. In general, the heater operation time was shorter on days when the indoor/outdoor temperature difference was small. It seemed that the integral values of the indoor/outdoor temperature differences during heating became smaller due to the heater operation time becoming short enough that the increased temperature value was not reflected on the data of indoor temperatures measured at intervals of 10 min. Therefore, the heating load coefficients on these days were excluded from estimations of the average value of heating load coefficients. The average heating load coefficient of the semi-basement type greenhouse was shown to be 3.1 kcal/m^2·°C·h, and that of the control greenhouse was shown to be 2.9 kcal/m^2·°C·h. In general, it is known that the heating load coefficient changes with outdoor wind velocities (Horiguchi, 1978; Mihara et al., 1979). However, in the present study, heating load coefficients were calculated based only on temperatures. ASABE (2008) presents the heating load coefficient for double polyethylene, single glass, and thermal blankets as 3.4 kcal/m^2·°C·h, and Kim et al. (2000) presents the heating load coefficient for double PE (Polyethylene) films as 3.5 kcal/m^2·°C·h. Therefore, it could be confirmed that the greenhouses for tests had energy effects since the heating load coefficient in the greenhouses for tests were

lower compared to the previous ones. Kim et al. (2000) presented the heating load coefficient as 3.1 kcal/m^2·°C·h for a triple layer plastic greenhouse and as 2.9 kcal/m^2·°C·h for greenhouses with single PE and aluminum metalized film curtains. Compared to these, the heating load coefficients obtained from the semi-basement type greenhouse and the control greenhouse were at the same level. Therefore, it could be seen that thermal curtains of multi-layered materials used for heat insulation of greenhouses are effective in reducing heat losses from the surface of greenhouse.

The heating load coefficients for conditions where two or more layers of heat insulation materials are used as with the greenhouses for tests are indispensable in the calculations of greenhouse heating loads, but the relevant heating load coefficients were not present in precedent research. Therefore, it is considered that the presentation of research data, which could be utilized for greenhouses of the various covering conditions in relation to the heating load, is required in the future.

Conclusions

To develop a conceptually new greenhouse model for energy saving, a semi-basement type greenhouse that allowed the entry of sunlight, was designed and constructed (single-span greenhouse-10-8 type in the protected horticulture and herbal facilities disaster resistant types designs and specifications), which was a three quarter vinyl greenhouse of an advantageous structure to inflow sunlight. To test the performance of the developed semi-basement type greenhouse, a general greenhouse of the same structure was installed as a control plot, and tests of those were conducted under the same conditions. In the case of the semi-basement greenhouse, long shadows appeared immediately after sunrise in winter when the solar culmination altitude was the lowest due to the underground drop, but it did not affect crop growth as the shadows decreased over time. According to the results of growth tests of tomatoes planted on December 30, there was no difference in growth between the semi-basement type greenhouse and the control greenhouse. The fuel consumptions during the heating period from January to March showed no difference between the two greenhouses, despite the fact that the internal volume of the semi-basement greenhouse was larger than the control greenhouse up to its underground depth. The semi-basement type greenhouse was considered advantageous due to the fact that it could be

operated with the same fuel consumption as a general greenhouse, although its volume was as large as the depth of the ground. The results of heating load coefficients estimation tests for the semi-basement type greenhouse was 3.1 kcal/m^2·°C·h and that of the control greenhouse was 2.9 kcal/m^2·°C·h. Compared to similar previous research results, although the conditions were different from those of the greenhouse for tests, the heating load coefficients of the greenhouses for tests were lower than that of double layered covering PE films of 3.5 kcal/m^2·°C·h . The heating load coefficients of the greenhouses for tests were at the same level as that of the triple layer plastic greenhouse or the single PE and aluminum metalized film curtains (Kim et al, 2000). In conclusion, it was confirmed that the semi-basement type greenhouse with a thermal curtain of multi-layered materials is highly effective for energy saving and in terms of utilizing the inner greenhouse space

Conflict of Interest

The author(s) of the manuscript should mention any potential conflicts of interest related to the paper. If there are none, the following statement may be used:"The authors have no conflicting financial or other interests."

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