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Analysis of Heating Characteristics Using Aluminum Multi-Layer Curtain for Protected Horticulture Greenhouses

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Abstract

Purpose: The purpose of this study was to investigate the energy saving effects and characteristics of plant growth in a greenhouse with an aluminum multi-layer curtain compared to a greenhouse with non-woven fabric. **Method:** The dimensions of both greenhouses 43 m × 3.6 m × 8 m (L × H × W), and both used hot air heater systems for maintaining a constant temperature 15°C. Heating characteristics such as solar intensity, inside and ambient temperatures, and fuel consumption were measured and analyzed. **Results:** The changes of average temperature of both greenhouses during a 15-days (December 06 - 20) showed approximately 26°C at around 2 pm when the ambient temperature was highest. The greenhouses were set by the heater to keep a temperature of 15°C from 4 pm to 8 am the following day. The average heat loss (for 15 days) from the greenhouse with an aluminum multi-layer curtain was 161.2-268.4 kJ/m^2·h during the daytime and 152.3-198.1 kJ/m^2·h during the nighttime. The average heat loss (for 15 days) from the greenhouse with non-woven fabric was 155.7-258.9 kJ/m^2·h during the daytime and 144.9-207.0 kJ/m^2·h during the nighttime. The total heat loss (for one day) from the non-woven fabric system was 7,960 kJ/m^2 (2,876 kJ/m^2 during the daytime, 5,084 kJ/m^2 during the nighttime). The heat supply over 36 days for the non-woven fabric system was higher than the aluminum multi-layer curtain system by 616.3-65,079.4 kJ/m^2. **Conclusions:** These results suggest that a greenhouse with an aluminum multi-layer curtain could save energy usage by 35% over a greenhouse with non-woven fabric.

Keywords: Aluminum multi-layer curtain, Fuel consumption, Heat supply, Non-woven fabric

Introduction

A greenhouse uses an external heat source such as solar heat, heat from a heater, or geothermal heat to maintain the temperature required for plant growth. In the wintertime, a greenhouse uses solar heat during the daytime, but a heater is required during the nighttime to maintain the proper temperature. Therefore, a thermal curtain is essential to save thermal energy in a greenhouse.

Research on greenhouse insulation has been conducted domestically and internationally on the efficient use of energy. South Korea relies on imports to meet energy demands, and the collective area of greenhouses increased from 49,828 ha (in 2007) to 50,297 (in 2008). Non-woven fabric and aluminum are used for the thermal curtain of greenhouses in Korea. Non-woven fabric saves energy and reduces moisture; as a result, the quality of the plant increases by reducing the occurrence of various diseases; for this reason, most greenhouse farmers use the thermal non-woven fabric (Kim et al., 1998). However, Chang et al. (1996) reported the disadvantages of the non-woven fabric: when compression molding with long chopped fiber is used, it shows strength degradation and no recovery from tension. In addition, each manufacturer has a different compression molding process, which results in degradation of physical properties, and the non-woven fabric has different light transmission and insulation due to the materials and thicknesses used; as a

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result, farmers have difficulty in selecting the appropriate fabric (Cho, 1989).

Aluminum has been used recently for the thermal curtain, because it increases insulation and light-shielding. There are several studies on the physical properties of aluminum. Chang et al. (1996) analyzed the optical properties, physical properties, types, and thickness of the thermal curtains used in the greenhouse. Kim et al. (2007) and Ko (2009) studied the direction of the aluminum reflector and found that insulation increased when placing the reflector dull side in and shiny side out. Moreover, studies about the quality improvement and growth characteristics of plants utilizing light shielding cultivation have been conducted (Choi et al., 2001; Kwon et al., 2004; Lee et al., 2007). However, studies on the thermal performance of aluminum curtains and light shielding cultivation are limited. Furthermore, there is no study on the heating characteristics using an aluminum multi-layer curtain, which showed greater energy efficiency than the aluminum curtain currently used.

Thus, this study examined the heating characteristics of a aluminum multi-layer curtain by analyzing the heating effects of a greenhouse with an aluminum multi-layer curtain.

Materials and Methods

Materials

Figure 1 shows the structure of the aluminum multi-layer curtain. It was composed of 12 μm polyethylene terephthalate, 7 μm aluminum, 12 μm polyethylene terephthalate, and 800 μm polyolefin foam. Polyethylene

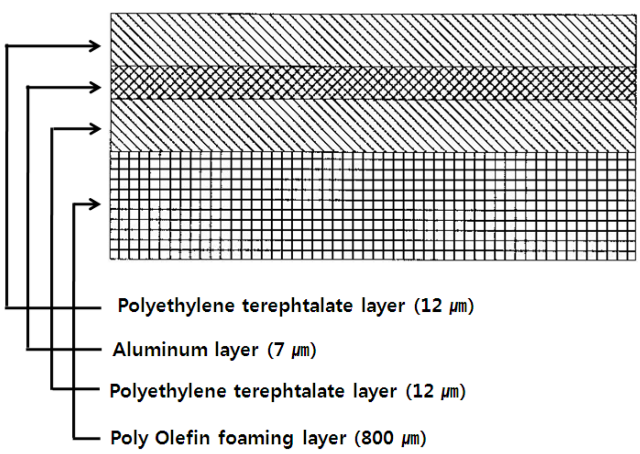

Figure 1. Cross section of the aluminum multi-layer curtain.

non-woven fabric was used as a control group, and the 340 μm thick polyethylene weighed $100g/m^2$.

Methods

Experiments to obtain heating characteristics of the greenhouse were conducted at Namwon. The heat characteristics were analyzed at periods of one day (24 hours) and 15 days (from December 6 to December 20) with an experimental group (a greenhouse with aluminum multi-layer curtain) and a control group (a greenhouse with non-woven fabric). The day having clear and cold weather (December 6) was selected for the analysis of 24 hours, and hourly changes of inside and outside temperatures were analyzed along with calculating heat supply and heat loss. Analysis of the heat characteristics for 15 days used average values of inside and outside temperatures

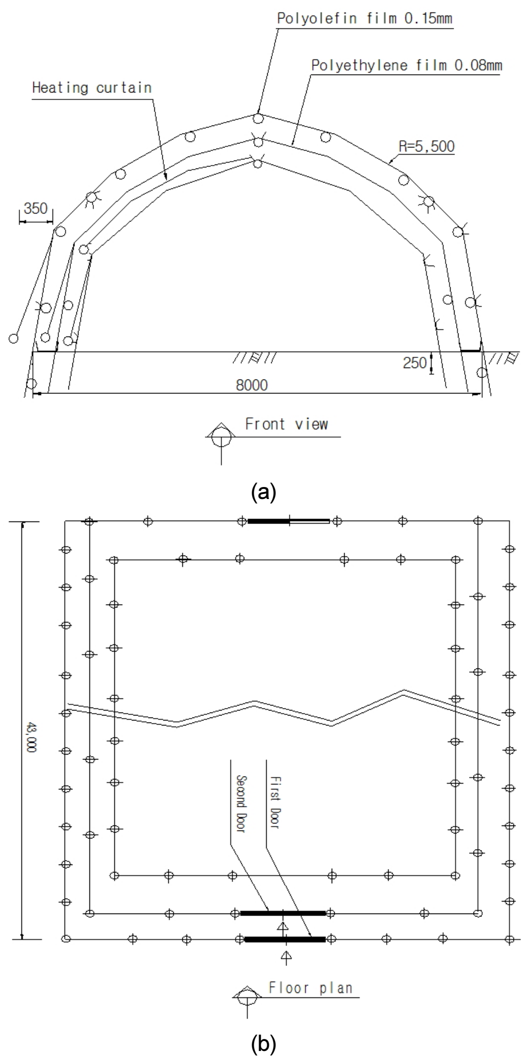

Figure 2. Schematic diagram of the experimental greenhouse: (a) front view, (b) floor plan.

at the same time, heat supply, and heat loss.

Experimental greenhouse

Figure 2 depicts the greenhouse used for this study. The greenhouse had triple structures with dimensions of 43 m × 3.6 m × 8 m (L×H×W). 0.15 mm polyolefin and 0.08 mm polyethylene were used in both groups; the aluminum multi-layer curtain was used for the experimental group while the non-woven fabric was used for the control group. A greenhouse heater (TQ-400, Dongho Agrimeca, Korea) was used for the study, and its heat capacity was 167,200 kJ/h.

Auto switches were installed on the ceiling and side windows to open and close automatically, and a gutter was installed to prevent water from flowing into the greenhouse.

Analysis of heating characteristics

Under the assumption that heat supply from solar energy and the heater was the same with the heat loss, equation (1) for the daytime and equation (2) for the nighttime were used:

$$Q_{Solar} + Q_{Heater} = Q_{Loss-day} + Q_{Vent} + Q_{Soil} + Q_{Air} \quad (1)$$

$$Q_{Heater} = Q_{Loss-night} + Q_{Vent} + Q_{Soil} + Q_{Air} \quad (2)$$

where, Q_{Solar} = Solar radiation in the greenhouse (kJ/h)
Q_{Heater} = Heat gained from the heater (kJ/h)
$Q_{Loss-day}$ = Heat loss through the greenhouse covering during the day (kJ/h)
$Q_{Loss-night}$ = Heat loss through the greenhouse covering during the night (kJ/h)
Q_{Vent} = Heat loss through the greenhouse ventilation (kJ/h)
Q_{Soil} = Heat absorbed and released by the soil in the greenhouse (kJ/h)
Q_{Air} = Air enthalpy in the greenhouse (kJ/h)

Heat supply from solar energy was calculated using equation (3), and heat supply from the heater was calculated using equation (4). The caloric value of the kerosene 1 L was converted to 38,456 kJ. Table 1 represents the hourly transmissivity of the greenhouse covering used in equation (3). Transmissivity used the hourly values measured inside the greenhouse. And only heat supply from the heater was used to analyze the heating characteristics at night time.

Table 1. Hourly transmissivity of the greenhouse covering

Time(h)	Transmissivity
8:00	0.625
9:00	0.675
10:00	0.715
11:00	0.740
12:00	0.740
13:00	0.715
14:00	0.675
15:00	0.625
16:00	0.550
17:00	0.530

$$Q_{Solar} = \tau \times I_s \times A_g \quad (3)$$

where, τ = Transmissivity of the greenhouse covering
I_s = Solar radiation on the horizontal surface (kJ/m^2·h)
A_g = Wall area of greenhouse (m^2)

$$Q_{Heater} = q_{fuel} \times C \quad (4)$$

where, q_{fuel} = Fuel consumption (L)
C = Caloric value per unit area (kJ/L·h)

Daytime heat loss through the greenhouse covering was calculated using equation (5), and nighttime heat loss was calculated using equation (6). Heat loss through the ventilation was calculated using equation (7), and heat absorbed or released by the ground was calculated using equation (8). Air enthalpy in the greenhouse was calculated using equation (9).

$$Q_{Loss-day} = A_g \times h_t \times (T_{in} - T_{amb.}) \quad (5)$$

Where, h_t = Heat transfer coefficient of the greenhouse covering (22.99 kJ/m^2·h·°C)
T_{in} = Inside temperature of the experimental greenhouse (°C)
$T_{amb.}$ = Ambient temperature of the experimental greenhouse (°C)

$$Q_{Loss-night} = A_g \times h_t \times (1 - f_r) \times (T_{in} - T_{amb.}) \quad (6)$$

Where, f_r= Saving factor (Aluminum + Polyethylene: 0.55, Non-woven fabric: 0.30)

$$Q_{Vent} = A_g \times h_v \times (T_{in} - T_{amb.}) \tag{7}$$

Where, h_v = Ventilation heat transfer coefficient of the greenhouse (0.418 kJ/m^2·h·°C)

$$Q_{Soil} = \sum_{i=1}^{n} m_{soil} \times C_{p-soil} \times \triangle T \tag{8}$$

where, m_{soil} = Ventilation heat transfer coefficient of the greenhouse (0.418 kJ/m^2·h·°C)
C_{p-soil} = Specific heat at constant pressure of soil (0.96 kJ/kg·°C)
$\triangle T$ = Temperature difference between soil layers (°C)

$$Q_{Air} = \{h_a + x \times h_{va}\} \times \dot{m}_{air} \tag{9}$$

where, h_a= Enthalpy of dry air (kJ/kg)
x= Absolute humidity in the greenhouse
h_{va}= Enthalpy of vapor in the air (kJ/kg)
$\dot{m}_{air}$= Mass of air (kg/m^2·h)

Measured items

Solar intensity

Solar intensity on the horizontal surface in the greenhouse was calculated using the average daily solar intensity of the near area (Jeonju).

Temperature

Temperature sensors (K-Type, = 6 mm) were installed on 27 points (top, middle, bottom, center, front, and rear) inside and one point outside the greenhouse, and an automatic temperature recording device (DA-100D3-1F, Yokogawa, Japan) measured the temperatures at 10-minute intervals, which were recorded on the computer. Hourly temperatures of the greenhouse were represented by the average temperature of the 27 points in the greenhouse.

Energy consumption

Fuel consumption was calculated by measuring the amount of kerosene on a daily basis using a flowmeter (SSO-8, Yuyuinst, Korea), and the cumulative fuel consumption for 36 days was measured and converted into a calorific value.

Results and Discussion

Temperature changes inside the greenhouse

Figure 3 shows the changes in average temperatures inside the greenhouse and ambient temperatures for 15 days of both the greenhouses with aluminum multi-layers curtain and non-woven fabric.

Average ambient temperatures for 15 days were -1.6 - 6.5°C during the daytime and -0.5 - -2.6°C during the nighttime. The highest average ambient temperature during the daytime was 6°C at 2 pm, and the lowest was -2°C at 8 am.

For both greenhouses, the average inside temperature was 26°C at around 2 pm showing the highest ambient temperature. After 4 pm, the heater was operated to keep the inside temperature over 15°C.

Average inside temperatures of the greenhouse with aluminum multi-layers curtain were 15.2 - 27.0°C during the daytime, and the for the greenhouse having non-woven fabric the average inside temperature were 15.3 - 25.8°C which showed no significant difference between both greenhouses. During the nighttime, average inside temperatures of the greenhouse with aluminum multi-layers curtain were 15.4 - 16.9°C, and the standard deviation was 0.4°C. Average inside temperatures of the greenhouse with non-woven fabric were 15.4 - 17.6°C, and the standard deviation was 0.7°C. Temperature deviations of the greenhouse with aluminum multi-layers curtain were less than the greenhouse with non-woven fabric.

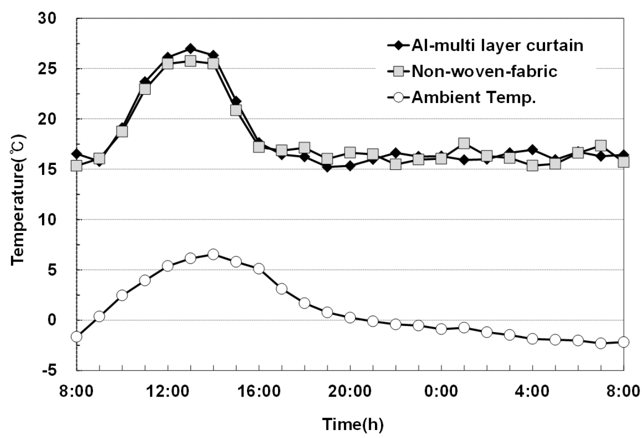

Figure 3. Changes in average temperatures inside the greenhouses with an aluminum multi-layer curtain and non-woven fabric depending on time (15 days).

Analysis of heating characteristics

Greenhouse with aluminum multi-layer curtain

Figure 4 shows the heat capacity and temperature changes of the greenhouse with an aluminum multi-layer curtain based on an hourly average temperature for 15 days.

The minimum heat supply from solar energy for 10 hours was 5.0 kJ/m^2·h at 8 am, and the maximum was 940.3 kJ/m^2·h at 12 - 1 pm. The heat supply after 5 pm was 83.0 kJ/m^2·h. Hourly heat supply from the heater was 289.2 kJ/m^2·h.

Heat stored in the soil and air inside the greenhouse was 13.3 - 106.5 kJ/m^2·h (for daytime) and 13.7 -211.2 kJ/m^2·h (for nighttime), and those were utilized for heating source.

Heat loss through the greenhouse covering during the daytime was 161.2 - 268.4 kJ/m^2·h. During the nighttime it was 152.3 - 198.1 kJ/m^2·h, therefore daytime heat loss was larger than nighttime heat loss by 6 - 35%.

Insulation material installed inside the greenhouse was opened during the daytime; therefore, heat loss during the daytime was larger than at night time.

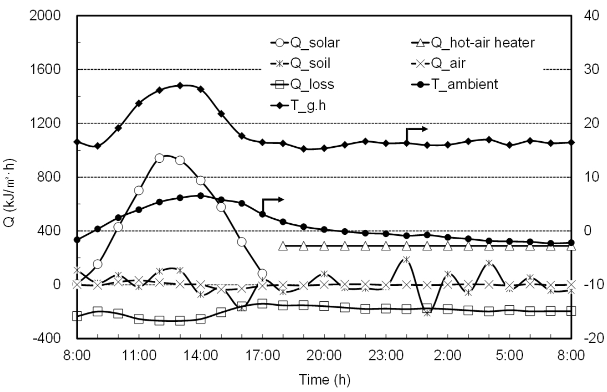

Figure 4. Heat capacity and temperature change of the greenhouse with an aluminum multi-layer curtain (15 days).

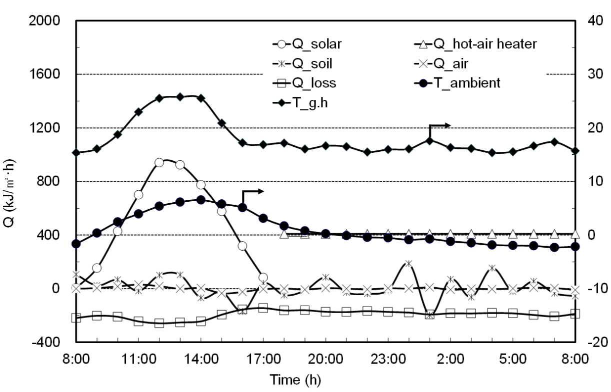

Figure 5. Heat capacity and temperature change of the greenhouse with non-woven fabric (15 days).

Greenhouse with non- woven fabric

Figure 5 represents the heat capacity and temperature changes of the greenhouse with non-woven fabric based on an hourly average temperature for a 15-day period. The heat supply from solar energy over 10 hours was the same as with the greenhouse with an aluminum multi-layer curtain.

The hourly heat supply from the heater was 408.7 kJ/m^2·h. This is more than 110 kJ/m^2·h of the heat supply to the greenhouse with the aluminum multi-layer curtain. Since the inside temperature was set to 15°C, the heat supply from the heater increased. It was considered that the greenhouse with non-woven fabric had less insulation; as a result, a lot of heat escaped.

Heat stored in the soil and air inside the greenhouse was 23.8 - 102.2 kJ/m^2·h (for daytime) and 28.3 -197.7 kJ/m^2·h (for night time), and those were utilized as a heating source.

Heat loss through the greenhouse covering was 155.7 - 258.9 kJ/m^2·h for daytime, and 144.9 - 207.0 kJ/m^2·h for nighttime. Daytime heat loss was larger than nighttime heat loss by 7 - 25%.

Analysis of total heat transmission

Greenhouse with aluminum multi-layer curtain

Figure 6 shows the cumulative heat flow characteristics and temperature changes of the greenhouse with the aluminum multi-layer curtain. The total heat transmission was analyzed by integrating equations (1) and (2) with respect to time.

The total solar energy was calculated by summing the

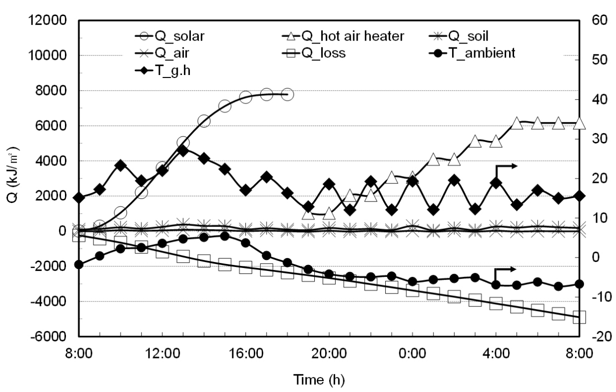

Figure 6. Total heat transmission of the greenhouse with the aluminum multi-layer curtain (1 day).

hourly solar energy produced by equation (3); and for nine hours of daytime, 7,788 kJ/m^2 of solar energy was supplied to the greenhouse with the aluminum multi-layer curtain.

Similarly, the total heat from the heater was calculated by summing the hourly heat produced by equation (4); 6,162 kJ/m^2 of heat was supplied to the greenhouse.

The heat loss through the greenhouse covering was 2,416 kJ/m^2 for daytime and 3,504 kJ/m^2 for nighttime. The total heat loss for day and night combined was 5,920 kJ/m^2.

As a result of the heat flow, the inside temperature was in the range of 12.0 - 27.0°C, and the temperature at 7 am, which showed the lowest ambient temperature (-7.3°C), was 15.0°C, which was higher than the outside temperature by 22.3°C.

Greenhouse with non-woven fabric

Figure 7 shows the cumulative heat flow characteristics and temperature changes of the greenhouse with non-woven fabric. The total heat transmission was analyzed by integrating equations (1) and (2) with respect to time. For nine hours of daytime 7,788 kJ/m^2 of solar energy was supplied to the greenhouse and 7,189 kJ/m^2 of heat from the heater was also supplied.

The heat loss through the greenhouse covering was 2,876 kJ/m^2 for daytime and 5,084 kJ/m^2 for nighttime. The total heat loss for day and night was 7,960 kJ/m^2.

The heat loss of the greenhouse with the aluminum multi-layer curtain was decreased by 460 kJ/m^2 for daytime and 2,080 kJ/m^2 for nighttime compared to the greenhouse with non-woven fabric. From this result, it is considered that the aluminum multi-layer curtain showed a higher insulation effect than the non-woven fabric.

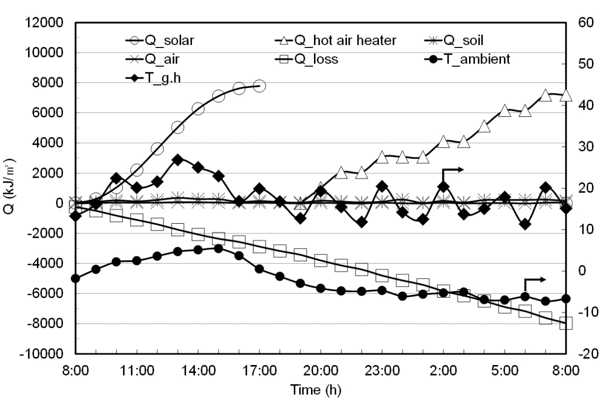

Figure 7. Total heat transmission of the greenhouse with non-woven fabric (1day).

As a result of the heat flow, the inside temperature was in the range of 11.3 - 26.8°C, and temperature at 6 am, which showed the lowest ambient temperature (-6.2°C), was 11.3°C, which was higher than the outside temperature by 17.5°C.

Analysis of heat supply from the hot air heater

Figures 8 and 9 represent heat supply of the greenhouses from the heater which was calculated by equation (4) splitting the period from day 1 to day 36.

Maximum heat supplies for one day were 7,395.4 kJ/m^2·day at the greenhouse with the aluminum multi-layer curtain and 9,367.5 kJ/m^2·day at the greenhouse with non-woven fabric. The greenhouse with non-woven fabric had 1,972.1 kJ/m^2·day more heat supply than the aluminum multi-layer curtain greenhouse.

Minimum heat supplies were 1,782.2 kJ/m^2·day at the

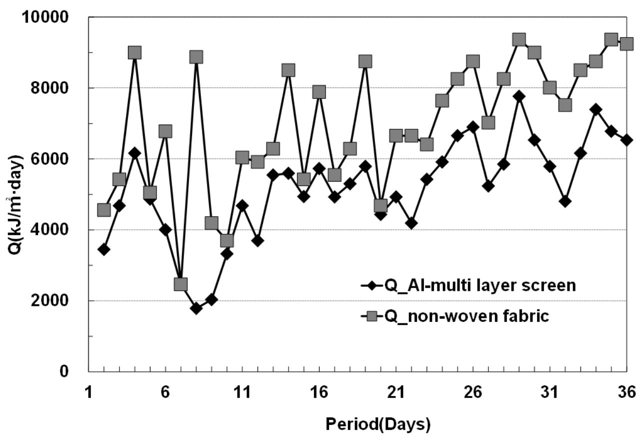

Figure 8. Daily heat supply of the aluminum multi-layer curtain and non-woven fabric during the 36-day period.

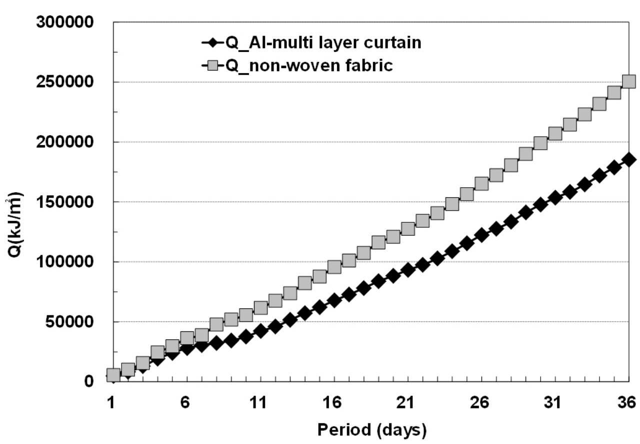

Figure 9. The cumulative heat supply of the aluminum multi-layer curtain and non-woven fabric over 36- day period.

greenhouse with the aluminum multi-layer curtain and 2,465.1 kJ/m^2·day at the greenhouse with non-woven fabric. The greenhouse with non-woven fabric had 38% more heat supply from the heater than the greenhouse with the aluminum multi-layer curtain.

This is because the insulation efficiency of the non-woven fabric was lower than the aluminum multi-layer curtain. Therefore, the aluminum multi-layer curtain was more effective for greenhouse covering than the non-woven fabric.

Figure 9 shows the cumulative heat supply over a 36-day period. The cumulative heat supply of the non-woven fabric was greater than the aluminum multi-layer curtain by 616.3 ~ 65,079.4 kJ/m^2·day. The difference in energy consumption increased over the operating period.

This result showed that the greenhouse with the aluminum multi-layer curtain reduced energy consumption by 35.1% (over 36 days) compared to the greenhouse with non-woven fabric.

Conclusions

The need for insulation is emerging in order to reduce heating costs due to the rise of fuel costs. Several studies have been conducted to reduce heating costs, however, there is little research on aluminum multi-layer curtains which provide high energy saving efficiency as shown in this study; furthermore, there is no research on the characteristics of the greenhouse heating using aluminum multi-layer curtains.

Therefore, this study constructed a greenhouse with an aluminum multi-layer curtain to examine the characteristics of greenhouse heating and compared the results with the a greenhouse with non-woven fabric. As a result, this study analyzed the energy saving efficiency and growth characteristics of plants. The results are as follows:

The average inside temperature of the greenhouse for a certain period (December 6 - 20) was 26°C at 2 pm, which showed the highest ambient temperature, and after 5 pm the heater was operated to maintain the temperature 15°C. The hourly average inside temperature was maintained at a minimum temperature setting of 15°C.

From the analysis of the heat characteristics for the period, it was observed that the heat loss through the greenhouse covering was 161.2 - 268.4 kJ/m^2·h in the greenhouse with the aluminum multi-layer curtain. During the nighttime it was 152.3 - 198.1 kJ/m^2·h, and daytime heat loss was larger than the nighttime heat loss by 6 - 35%. Meanwhile, in the greenhouse with non-woven fabric, the heat loss was 155.7 - 258.9 kJ/m^2·h for daytime and 144.9 - 207.0 kJ/m^2·h for nighttime. Daytime heat loss was larger than the nighttime heat loss by 7 - 25%.

From the results of the heat transmission of both greenhouses, the heat losses in the greenhouse with the aluminum multi-layer curtain were 2,416 kJ/m^2 for daytime and 3,504 kJ/m^2 for nighttime. The total heat loss for day and night combined was 5,920 kJ/m^2. However, in the greenhouse with non-woven fabric, heat losses were 2,876 kJ/m^2 for daytime and 5,084 kJ/m^2 for nighttime, and the total heat loss for day and night combined was 7,960 kJ/m^2.

From the results of the heat supply provided by the heater, it was found that the cumulative heat supply of the non-woven fabric was greater than the aluminum multi-layer curtain by 616.3 - 65,079.4 kJ/m^2·day. This result showed that the greenhouse with the aluminum multi-layer curtain reduced energy consumption by 35.1% (over 36-day period) compared to the greenhouse with non-woven fabric.

Conflict of Interest

The authors have no conflicting financial or other interests.

Acknowledgment

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