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REVIEW

Development of a New Energy-Saving Pipe-Framed Greenhouse

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Abstract

We summarize the basic techniques used to save energy in a greenhouse and discuss the development of a new energy-saving pipe-framed greenhouse, similar to the type used on most small-scale farms in Japan. To enhance the thermal insulation performance of a pipe-framed greenhouse, a multi-layered thermal curtain was installed. As a result of our experiments, both the heating load and the heating oil consumption in the greenhouse with a multi-layered thermal curtain (M-house) were approximately 40% lower than those in the control greenhouse with a conventional thermal cover (C-house). Furthermore, the heating oil consumption was also reduced by approximately 60% in the M-house equipped with water heat storage, which stored solar energy in daytime and released heat to the greenhouse at night. This multi-layered thermal curtain is expected to gain recognition as the most effective energy-saving material available and immediate widespread use nationwide is expected. Another experiment was performed concerning the structural reinforcement of pipe-framed greenhouses. Pipe-framed greenhouses are usually constructed with single-arch pipes in Japan and there has been a recent increase in greenhouses collapsing due to strong winds. Accordingly, techniques to reinforce the structure of pipe-framed greenhouses were also developed.

Discipline: Horticulture
Additional key words: heating load, heat transmission, multi-layered thermal curtain

Introduction

In Japan, greenhouses used for protected horticulture take up an area of approximately 50,000 ha, about 40% are equipped with a heating system and more than 90% depend on fossil fuel. In Japan, protected horticulture is responsible for 45% of all carbon dioxide emissions (about 611 million tons) derived from fossil fuels used for agriculture, forestry and fisheries (Hayashi 2008). Most fossil fuels are used in protected horticulture for heating oil and the amount of fuel consumed for this purpose increased about 2.2 times from 1990 to 2005. Energy costs have also been steadily increasing, which has become an important factor influencing the management of farms. Accordingly, it has become necessary to develop energy-saving techniques for protected horticulture. In Japan, approximately 80% of all greenhouses are high-tunnel and high tunnel-like greenhouses; these are referred to as pipe-framed greenhouses, where the frames are constructed from steel pipes. The high tunnel, where sidewalls are not round like a hooped house, has no electrical service, automated ventilation or heating system (Lambert 2009). This review focuses on pipe-framed greenhouses in Japan with a heating system and other environmental control equipment.

Basic energy-saving techniques for greenhouses have been classified into three groups: 1) reducing heating load, 2) introducing a high-efficiency heating system and 3) temperature management, namely, varying night temperature control, local air heating, the usage of cultivars for low-temperature tolerance and so on (Hayashi 2008). These techniques are usually used in combination.

The key energy-saving technique in greenhouses involves reducing heating load or loss by installing a fixed or movable covering, an air-inflated covering, etc. (Naito 1981). Overnight, heat loss from greenhouses occurs due to overall heat transmission through coverings and structures. It is also caused by air infiltration and heat flux of the inside-air to the soil, although this is reversed in some cases. Heat transmission accounts for a large part of the total heat loss from a greenhouse, followed by heat transfer due to air

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infiltration, which is responsible for approximately 20% of heat loss (Takakura & Okada 1972). To reduce the heating load, it is important to minimize heat loss by reinforcing the greenhouse covering (e.g. adding two or more layers of coverings to increase insulation performance).

One of the techniques to reduce heat loss from a greenhouse involves using an air-inflated or double-layered-polyethylene film (Gene et al. 1993, Mears et al. 1972, Robert et al. 1972). The use of air-inflated greenhouses has been increasing in Japan. Iwasaki et al. (2011) reported that fuel consumption was reduced by 16% and the fruit yield of semi-forcing cucumbers increased by 21% with an air-inflated plastic greenhouse compared to a standard plastic greenhouse covered with a single layer of outer plastic film and a movable insulated plastic curtain.

Researchers have also developed and studied some energy-saving greenhouse structures, such as the pellet-greenhouse. This was constructed with a double-layer of covering materials, which are filled with polystyrene pellets before sunset and then emptied at sunrise (Miyagawa 1967, Short & Shah 1981). The insulation performance of a pellet-greenhouse is relatively high (thermal conductivity is 0.3-0.43W · m^{-2} · $°C^{-1}$). However, this system has not been widely used due to some problems, such as operation and construction costs, difficulty with automation, decreasing inside radiation and so on (Hayashi 2008, Yuhashi et al. 1984, Short & Shah 1981). The earth-air heat exchange greenhouse, in which air is circulated inside the greenhouse to pipes installed underground, has also been studied (Santamouris et al. 1994, Yamamoto 1973). This system, in which excessive heat accumulates in the ground through heat exchange pipes in daytime and is returned to the inside the greenhouse at night, decreased heating oil consumption remarkably and allowed energy costs to be reduced by 20-30% (Santamouris et al. 1994). However, this system involves higher construction costs compared with a conventional greenhouse.

One of the most effective and unique structures in China is the sunlight greenhouse, which occupies more than 0.7-0.8 million ha there (Chen et al. 2000, Gao et al. 2010). A sunlight greenhouse has a transparent film facing south, with support and rigid insulation walls on the north, east and west sides. These walls serve to store heat in daytime and release it at night and the south surface is perfectly covered with an insulating blanket that diminishes heat loss overnight (Ma et al. 2001, Yamaguchi et al. 2003). The internal temperature can be maintained under minimum conditions for plant cultivation with no or minimal heating in winter, even when the outside temperature is below 0°C (Chen et al. 2000). Sunlight greenhouses are used in locations at latitudes of 32°N to 43°N and can also be adopted by countries such as Japan, Korea and Russia (Gao et al. 2010). However, some problems may arise when the sunlight greenhouse is introduced in Japan. For example, 1) internal relative humidity (RH) increases in winter due to the lack of ventilation; 2) the land usage ratio is as low as about 50% because of its back and side walls, which shade the area around the sunlight greenhouse and 3) they do not control the indoor temperature well under very hot conditions, such as in summer (Gao et al. 2010, Ma et al. 2001).

To decrease heat loss from the greenhouse surface, an insulation screen, which has high thermal performance, will be available for practical use (Naito 1981). Straw-matting has high insulation performance because of its air-layer, but is not presently in use in Japan. A multi-layered thermal curtain comprising a single layer of polyester cotton between the top and bottom with woven fabrics, such as in Korea, or an insulating blanket used for some sunlight greenhouses in China is expected to perform well as an insulation covering for greenhouses.

A multi-layered thermal curtain, which has not been of interest in Japan until recently, is one of the most effective techniques to reduce heating load, as mentioned above. Initially, the heat transmission coefficients of the insulation coverings were measured with measuring equipment developed by Hayashi et al. (2011). This equipment can simulate atmospheric long-wave radiation under clear or cloudy conditions by controlling the temperature of a cooling panel installed on the ceiling of the cooling chamber. It can also measure the overall heat transfer coefficient of plastic films or certain kinds of covering materials. A low overall heat transmission coefficient indicates high thermal insulation efficiency. The overall transmission coefficient of the multi-layered thermal curtain was 1/2 to 1/3 of the other conventional thermal insulation coverings used in Japan (Hayashi 2012). Accordingly, the multi-layered thermal curtain is expected to greatly decrease the heating load in greenhouses.

Effective use of solar energy is also expected to decrease the heating load in greenhouses. Excessive heat that accumulates with heat storage in daytime can be released at night such as a sunlight greenhouse (Naito 1981, Santamouris 1994). One of the techniques involves using latent heat storage, which uses phase change materials, to store heat (Nishina & Takakura 1983). This system could be used to collect and store heat in a greenhouse, but there are some problems such as high cost and concerns over performance stability with regard to the heat storage and release (Nishina & Takakura 1985). Other systems using water to collect and store solar energy in a greenhouse have also been researched around the world (Santamouris et al. 1994). In Japan, an air-water exchange system has been tried where water is pooled underground below the greenhouse (Kozai et al. 1983) or in a nutrient solution for hydroponics (Okano & Yamamoto 1986). The other air-water exchange system named 'Green solar' has been used in practical applications (Hirao et al. 1985, Imamura et al. 1983, Morita & Fukai 1982). Water to store heat has been studied in combination with a heat pump (Shintou & Wasa 1987) and a tube filled with water and placed on the ground in a greenhouse is a simple way of achieving this purpose (Santamouris 1994). Using water to store heat to maintain the inside temperature in a greenhouse with no heating system also has been studied in Japan (Hanyu et al. 1983, Ichimura 1983, Obayashi & Kono 1982, Tataki et al. 1982).

To develop some energy-saving techniques, we have also investigated the effect of the multi-layered thermal curtain and water heat storage on decreasing the heating load of a pipe-flamed greenhouse (Kawashima et al. 2013a). This review presents some results from a research project in which the objectives included to develop energy-saving techniques to reduce the heating oil consumption of a common greenhouse in Japan by 50% or more and develop a technique to reinforce the structure of a pipe-framed greenhouse.

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Outline of pipe-framed greenhouses for the experiment

The effect of a multi-layered thermal curtain on decreasing the heating load of a pipe-framed greenhouse was investigated (Kawashima et al. 2013a). Fig. 1 shows the experimental pipe-framed greenhouses constructed at Kagawa Agricultural Experimental Station (lat. 34°N and long. 133°E). Two experimental greenhouses, which were covered with 0.15-mm-thick polyolefin film, were oriented in an east-west direction, 20 m long and 6 m wide. In the conventional pipe-framed greenhouse (C-house), a 0.075-mm-thick polyolefin film was used for the inner covering as a conventional technique. A multi-layered thermal curtain was added inside the other pipe-framed greenhouse, of which the frames were doubled; this is the developed pipe-framed greenhouse (M-house). The multi-layered thermal curtain in the M-house was rolled up in daytime, rolled down at night and moved on the inner frame of the south surface. The multi-layered thermal curtain, which was about 8 mm thick, comprised one layer of polyester cotton between the top and bottom with woven fabrics. The north wall, namely, the north side of the M-house, was a fixed structure with another type of multi-layered thermal curtain. In addition, to investigate the effect of water heat storage on the heating load of a pipe-framed greenhouse, eight polyvinyl chloride tubes filled with water, with a total amount of about 2,244L per 120m^2 in the floor area, were placed along the inner surface of the north side of the M-house (MW-house).

The effect of the multi-layered thermal curtain on decreasing the heating load of a pipe-framed greenhouse

The internal temperature of both pipe-framed greenhouses, which were unheated, declined with decreasing outside temperature at night. In this actual measuring test, the indoor temperature of the M-house, which was maintained at 5.3-8.5°C, exceeded that of the C-house, when the outside temperature was below 0°C. In this case, the internal temperatures of the C- and M-houses were estimated at 2.4

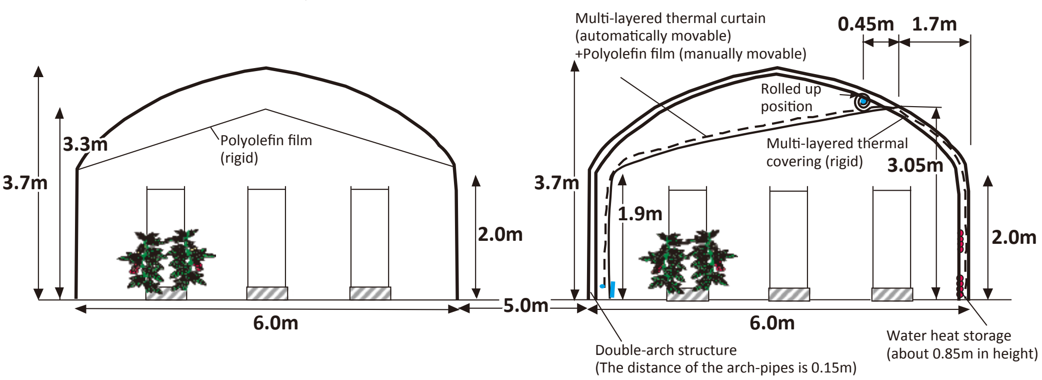

Fig. 1. Outline of pipe-framed greenhouses used for experiment (Kawashima et al., 2013a)

and 7.1°C, respectively, when the outside temperature was 0°C at night (Fig. 2). When using an oil-fired hot air heater set at 12°C in both houses, the heating oil consumption of the M-house was 38-50% (average about 44%) lower than that of the C-house during the test period (Kawashima et al. 2013a). In addition, the soil to inside-air heat flux of the C- and M-houses were 11.3 and 10.4W · m^{-2}, respectively. It is clear that the multi-layered thermal curtain can effectively reduce the heating load of a greenhouse and save energy. The overall heat transmission coefficients of the multi-layered thermal curtains, which were equipped as movable and fixed inner coverings with the M-house, were 2.48 and 1.26W · m^{-2} · °C^{-1}, respectively (Kawashima et al. 2013a). The latter has high insulation performance, but is unsuitable for a movable inner covering due to its lack of flexibility. To improve the energy-saving performance in a greenhouse, there is a need to develop a multi-layered thermal curtain with higher insulation performance, flexibility or ease of rewinding up compactly, lightness of handling and low cost (Kawashima 2014).

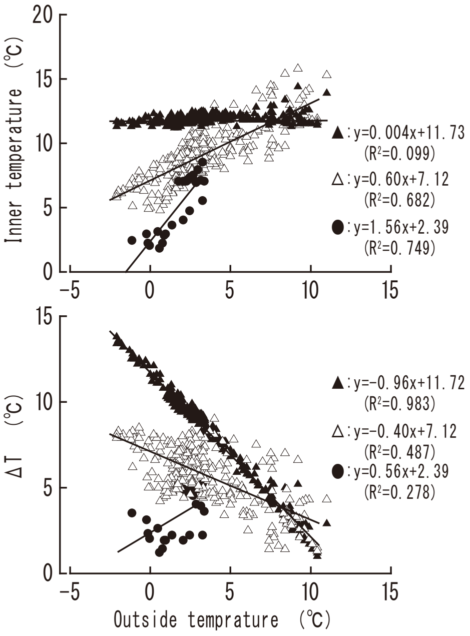

Fig. 2. Relationships between outside and indoor temperatures and temperature difference between outside and indoor temperatures (Δ*T*) in C- and M-houses (Kawashima et al. 2013a)

●, C-house (unheated, treatment time from 15 to 16 Dec, 2010); ▲, C-house (with heating, treatment time from 17 to 4 Jan, 2011); △, M-house (unheated, treatment time from 15 Dec, 2010 to 4 Jan, 2011)

Values are hourly averages overnight (from 18:00 to 6:00 the next morning) during the measurement period for analysis (from 15 Dec., 2010 to 4 Jan., 2011).

The combined effect of water heat storage and multi-layered thermal curtain on decreasing the heating load of the pipe-framed greenhouse

The effect of water heat storage and a multi-layered thermal curtain on the heating load of the pipe-framed greenhouse was investigated (Kawashima et al. 2013a). The average temperature difference between the outside and inside temperature of the unheated MW-house was 7.2°C when the average outside temperature was 4.0°C during the test period. In the MW-house, the maximum heat flux from the water heat storage was observed at about 21:00 and the heat flux from the water heat storage gradually declined toward daybreak. The heat losses of the C-house heated at 12°C and that of the unheated MW-house were 45.5 and 19.8W · m^{-2}, respectively (Fig. 3). The internal temperature of the unheated MW-house was estimated at about 9.4°C when the outside temperature was 0°C (Fig. 4). When the MW-house was heated, the average heat flux from the soil and water storage at night were 9.6 and 10.2W · m^{-2}, respectively (Fig. 5). The average water temperature of the water heat storage and the temperature difference between it and the indoor temperature of the greenhouse at night were 18.3 and 6.1°C, respectively.

The time course changes of the ratio of the amount of heat transfer released from the soil and water storage and the heat generated from the heater are shown in Fig. 6. In the C-house, the amount of heat generated from the heater far exceeded that of the heat transfer from the soil, while the amount of heat generated from the heater in the M-house was about 10% less than that in the C-house. In addition, the amount of heat generated from the heater in the MW-house, particularly after dark when the heat started, was less than that of the C- and M-houses. The amount of heat radiation and convection from the water heat storage peaked after dark and decreased gradually toward daybreak. The ratio of the heat transfer from the soil and water relative to the total heating load was 34% during the measurement period. The heating oil consumption at night, which was averaged over the same measurement period in the C- and MW-houses, was 9.7 and 3.5L, respectively (Kawashima et al. 2013a). In the unheated MW-house, the average ratios of heat transfer from the soil and water heat storage were 45 and 55%, respectively.

Comparing the performance of decreasing the heating load in the pipe-framed greenhouse, the heating load coefficients were estimated (Kawashima et al. 2013a). The heating load coefficients of the C-, M- and MW-houses were 2.39, 1.43 and 0.91W · m^{-2}, respectively. It was clear that the multi-layered thermal curtain could decrease the heating load of a pipe-framed greenhouse by about 40%

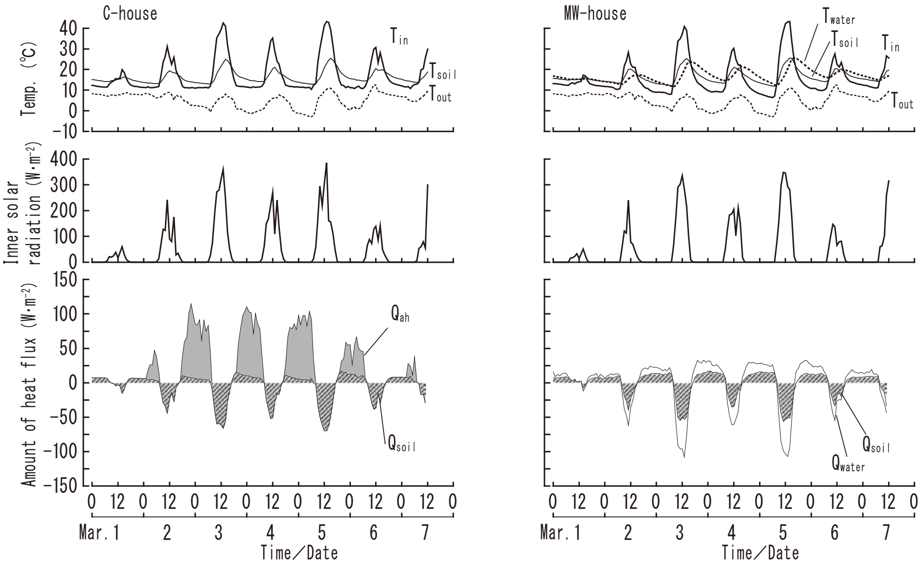

Fig. 3. Changes in outside and indoor temperature (T_{in} and T_{out}, respectively), heating value generated by heater (Q_{AH}), soil heat flux (Q_{soil}) and heat stored or released by the water heat storage (Q_{water}) per unit area of the greenhouse floor, respectively. The C-house was heated with an oil-fired air heater set at 12 °C and the MW-house was unheated (Kawashima et al., 2013a)

The direction of heat flux to and from the greenhouse is shown by '+' and '−', respectively.

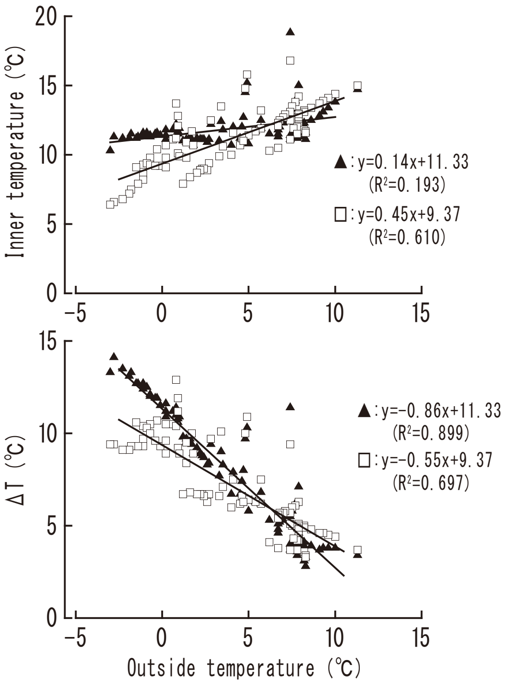

Fig. 4. Relationships between outside and indoor temperatures and the difference between indoor and outside temperatures (Δ*T*) in the C-house with a heater set at 12 °C (▲) and the unheated MW-house (□) (Kawashima et al., 2013a)

Values are hourly averages overnight (from 18:00 to 6:00 the next morning) during the measurement period for analysis (from 28 Feb. 2011 to 7 Mar. 2011).

and the water heat storage could also decrease the heating load more effectively by more than 60%, namely, underlining the effectiveness of these techniques for saving energy in a greenhouse.

However, the effect of water heat storage on the heating load of a greenhouse is expected to be limited under some conditions. The heating load coefficient decreased when the inside temperature of a pipe-framed greenhouse was set higher (Kawashima 2013b) (Table 1). When the MW-house was heated at 12°C, the average night temperature of the water heat storage during the measurement period was about 18°C (Kawashima et al. 2013a). The amount of heat radiation and convection from the water heat storage should increase when the inside temperature in a pipe-framed greenhouse is set lower. Fig. 7 shows the relationship between Δ*Ta*, which is the difference between the inside temperature and that of the water heat storage and the heat released from the water heat storage when the inside temperature in the MW-house was set at 12°C. The heat fluxes from the water heat storage to the inside-air were estimated at about 3 and 10W · m^{-2} for Δ*Ta* of 2 and 6°C, respectively. This was far less than the total flux from the three solid side walls of the sunlight greenhouse, which was approximately 60W · m^{-2} (Yamaguchi et al. 2003). If the heating load needs to be further decreased, the heat storage volume will need to be increased (Santamouris 1994). Despite being shaded by tomato plants, the water heat storage was able to accumulate solar radiation. It seems that a temperature difference between the inside

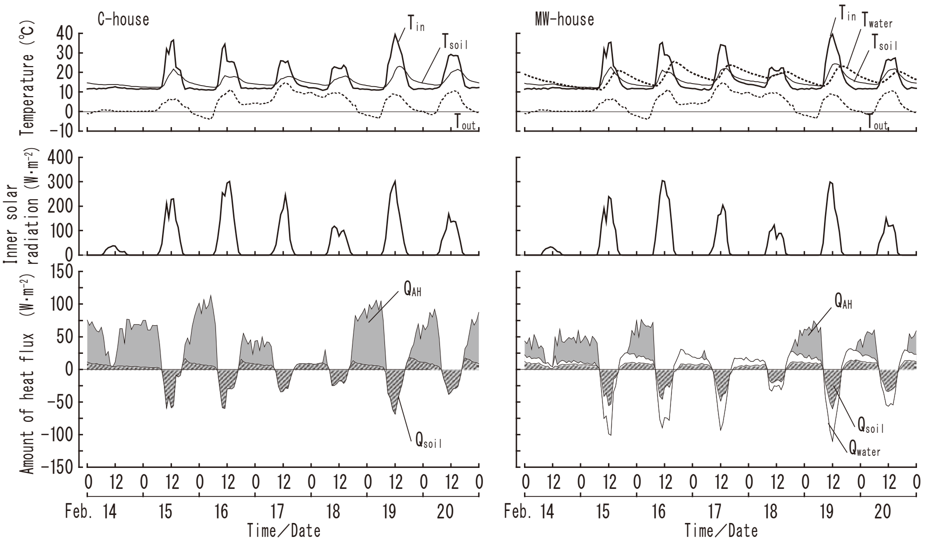

Fig. 5. Changes of outside and indoor temperature (T_{in} and T_{out}, respectively), heating value generated by heater (Q_{AH}), soil heat flux (Q_{soil}) and heat stored or released by the water heat storage (Q_{water}) per unit area of the greenhouse floor, respectively. C- and MW-houses were heated with an oil-fired air heater set at 12 °C (Kawashima et al., 2013a)

The direction of heat flux into and from the greenhouse is shown by '+' and '−', respectively.

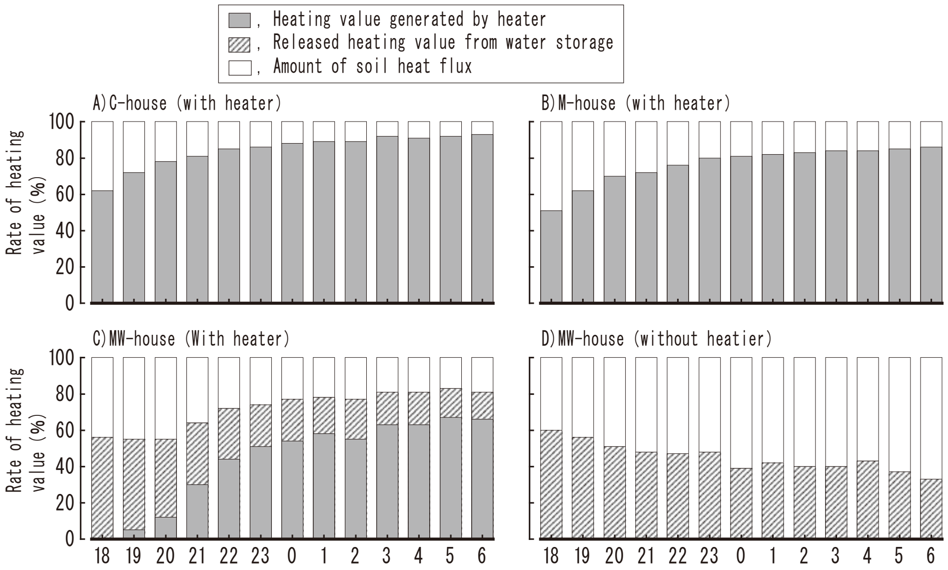

Fig. 6. Change of the rate of heating values in the C-, M- and MW-houses with or without a heater at night (Kawashima et al., 2013a)

Values are hourly averages during each measurement period. The period of A and B was from 17 Jun. to 2 Feb, 2011; C and D were from 4 Feb. to 21 Feb, 2011 and from 28 Feb. to 7 Mar, 2011, respectively.

■, Heating value generated by an oil-fired hot air heater; ▨, released heating value from water heat storage; □, amount of soil heat flux.

temperature and the water heat storage is needed rather than direct radiation onto the surface of the water heat storage. A passive solar system, such as in this case, strongly depends on the prevailing outdoor weather conditions or the location where the system is applied (Santamouris 1994). Accordingly, more investigation is needed to clarify the conditions for the application of heat storage.

Table 1. Environmental factors inside and outside the experimental greenhouses during the measurement period with different indoor temperatures (Kawashima et al., 2013b)

Temperature set poiint	House	Tout (˚C)	Tin (˚C)	ΔT (˚C)	Twater (˚C)	ΔTa (˚C)	QAH (W · m-2)	Heating load coefficient (W · m-2 · ˚C-1)
12˚C	C-house	5.7	11.6	5.9	−	−	51.3	3.76
	MW-house		12.9	7.6	17.5	4.6	13.7	0.73
15˚C	C-house	2.3	14.0	11.7	−	−	85.4	3.10
	MW-house		15.8	13.4	18.3	2.5	32.8	1.04
18˚C	C-house	5.8	17.3	11.5	−	−	91.4	3.42
	MW-house		18.3	12.5	19.7	1.4	39.0	1.31

T_{out}, Outside temperature; T_{in}, Indoor temperature; ΔT, $T_{in}-T_{out}$; T_{water}, Temperature of water in water heat storage; ΔT_a, $T_{water}-T_{in}$; Q_{AH}, Heating value generated by oil-fired hot air heater per unit area of the greenhouse floor. The measurement period was from 22 Nov. to 14 Dec, 2011, 18 Jan. to 14 Feb, 2012 and 15 Feb. to 21 Feb, 2012 and from 28 Feb. to 7 Mar, 2011, with the indoor temperature set at 12, 15 and 18 °C, respectively.

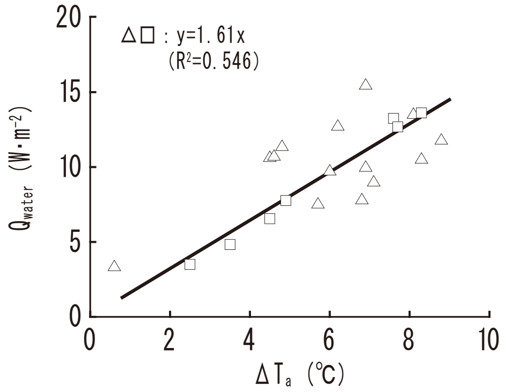

Fig. 7. Relationship between the temperature difference between the indoor temperature and the water temperature of the heat storage (ΔT_a) and heat released from the water heat storage per unit area of the greenhouse floor (Q_{water}) (Kawashima et al., 2013a)

△, Heating set point at 12 °C (from 4 to 21 Feb, 2011); □, unheated (from 28 Feb. to 6 Mar, 2011).

Renovation to reinforce the structure of pipe-framed greenhouses in practical use

In our project, a technique to reinforce the structure of pipe-framed greenhouses was also developed, because incidents of greenhouses collapsing due to strong winds have recently been increasing.

One solution to reinforce the structure of a pipe-framed greenhouse involves doubling the arch pipes. The conventional structure of a pipe-framed greenhouse in Japan is constructed with single-arch pipes, although a double-arch structure was constructed with new fittings we have developed. One of the new fittings joins two arch pipes that are set in parallel, while another kind of fitting joins the double-arch pipe to the ridge pipe at right angles (Satoh-Sangyo Co., Ltd. 2013). The double-arch pipe structure is placed at intervals of 1.5 m, but is much stronger than a conventional single-pipe structure placed at intervals of 0.5 m. Wind load tests on the double-arch structure and a conventional single-arch structure found that they could resist wind speeds of around 35 to 50 m · s^{-1} and 20 m · s^{-1} , respectively (*Jitsuyo-gijutsu 22046 consortium* 2012). The foundation was also improved to resist the lift force caused by strong winds. It was reinforced using screw-type piles developed by GT Spiral Co. which were sunk into the ground and their heads connected to a straight pipe. The straight pipe was then connected to the base of the arch pipes on each side of the pipe-framed greenhouse (Kawashima 2014). The screw-type piles were placed at intervals of 3.0m and could resist wind speeds of 35 m · s^{-1} when the N-value (i.e. foundation strength) was 4 and the ridge height of the pipe-framed greenhouse was 3.7m (*Jitsuyo-gijutsu 22046 consortium* 2012).

Introducing the new pipe-framed greenhouse to small-scale farms in Japan, may be difficult because most farmers lack economic resources to use for investment. A reinforcing structure that is easy and inexpensive to construct is needed. New developed technologies must also be applicable to existing greenhouses, which is the case for the new technologies developed in our project. These techniques are practical and will promote renewal or renovation and reuse of greenhouses at relatively low cost.

These techniques were applied to an existing pipe-framed greenhouse to construct a double-arch structure (Kawashima 2014). In this test, the double-arch structure was renovated using arch pipes removed from the original structure using the developed new fittings. The removed arch pipes were added to the outer part of the original arch pipes with new fittings, while the renovated double-arch pipe-framed greenhouse was also equipped with a multi-layered thermal curtain. Accordingly, the renovated greenhouse was strongly reinforced and the heating oil consumption was halved. This will be a useful technique for renewing or renovating a pipe-framed greenhouse.

Conclusions

It was shown that a multi-layered thermal curtain and water heat storage could reduce heating load and the heating oil consumption in a pipe-framed greenhouse. It is expected that a multi-layered thermal curtain will be immediately recognized as the most effective material for energy saving and its use will expand in Japan. Futon screens are currently being developed with the cooperation of some companies and research institutes. Further investigation and improvement will be needed to use heat storage effectively for saving energy. Developed technologies to reinforce the structure of pipe-framed greenhouses are of interest to many farmers and those that we have developed can be applied for practical use.

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