Usage strategy of phase change materials in plastic greenhouses, in hot summer and cold winter climate

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Abstract

Plastic greenhouses are basically used to create a warmed and protected growing area for plants. In the hot summer and cold winter climate, the consumption of the heating system for a greenhouse is the major operating cost. To reduce the production cost and limit the release of greenhouse gases, this investigation proposed the design of a latent heat storage system using phase change material for plastic greenhouses in this climate. Using a pilot in southern China, this study established a test bed of a greenhouse and developed a numerical model for designing the all-day use strategies in winter. The experimental data confirmed the feasibility of the strategy and validated the numerical model. Without using phase change material, the air temperature within the greenhouse could be as low as 3.7 ^{o}C; while the proposed strategy was able to maintain the indoor air temperature no less than 10 ^{o}C. The numerical model was further applied to design the all-day use strategies with different combinations of phase change material and insulation in a real greenhouse. The numerical simulations were able to help find the combination that satisfied the temperature requirement with the least investment. The payback time of the designed strategy was less than the lifespan.

Keywords: experiment, greenhouse, usage strategy in winter, numerical

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model, hot summer and cold winter climate

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1. Introduction

Greenhouses are basically used to create a warmed and protected growing area for plants [1]. In regions with excessively cold climate, greenhouses are used extensively for growing vegetables [2]. A green house is basically a building with its envelope made of glass or plastic, so that sunlight can pass through. Since the transparent envelope has high transmissivity for short wave radiation, solar radiation easily enters the greenhouse in daytime. At the same time, as the greenhouse envelope has low transmissivity for the long wave radiation from the inside of the greenhouse, the air temperature in the plastic greenhouse would increase. Therefore, the greenhouse is a sustainable way to increase agricultural production through micro-environment control [3].

The investment in a greenhouse includes mainly the capital cost and operating cost [4]. Greenhouses made of plastic are very popular because the investment is at the lower end of the pricing scale. However, space heating is one of the most significant costs, particularly in regions with a cold climate [5]. In general, the greenhouse itself is able to maintain a suitable indoor temperature for the growth of plants during the daytime in sunny winter. But during the night, the air temperature inside the greenhouses would drop significantly, due to the low ambient air temperature, low heating capacity, and poor thermal insulation of the greenhouse envelope, which frequently makes the plants freeze to death [6]. Then a variety of heating systems, such as hot water boiler, hot air furnace, electric heater, and heat pump [7] is gradually added to stop the air temperature from becoming too cold for the plants in some plant factories, in which plants are grown on a large scales. The added heating system would commensurately increase the capital cost and operating cost of the greenhouses.

To reduce the production cost and limit the release of greenhouse gases, a latent heat storage system using phase change material (PCM) has been integrated with the greenhouse heating system. The PCM absorbs the excess heat during the day and releases heat during the night. With its high heating capacity, the application of PCM is able to greatly reduce the operating cost. To make use of the PCM, in regions with cold climate such as northern China (where the average outdoor temperature of the coldest month is between 0 and -10 °C; the number of days when the daily mean temperature is less than 5 °C is between 90 and 145 days per year, the annual solar radiation intensity is 4200 $\sim$ 6700 MJ/(m^2·year) [8]), a solar greenhouse (Figure 1(a)) with its north wall made of bricks is mainly used. One of the most commonly used ways is to install the PCM to the solid envelope, as indicated by Singh, R.D. and Tiwari [9] and Bouadil *et al.*[10].

(a) (b)

Figure 1: (a) Solar greenhouse and (b) Plastic greenhouse.

In other climatic regions, where the winter is not as cold as the cold climate region, such as the hot summer and cold winter region (continental temperate zone, where the the average outdoor temperature of the coldest month is between 0 and 10 °C, the number of days when the daily mean temperature is less than 5 °C is between 0 and 90 days per year, the average outdoor temperature of the hottest month is between 25 and 30 °C, the number of days when the daily mean temperature is greater than 25 °C is between 40 and 110 days per year, and the annual solar radiation intensity 4200 $\sim$ 5400 MJ/(m^2·year) [8]) in Eastern Europe [11], Western Asia [12], and Southern China, plastic greenhouses as shown in Figure 1(b) are mainly used to reduce the capital cost. However, the greenhouse air temperature during winter nights could be below zero °C, which is not suitable for the plants. Hence one needs to find an approach to install the PCM, since there is no solid wall in a plastic greenhouse. A simple way is to store the PCM in containers and put the containers in the greenhouses. Beyhan *et al.*[13] used plastic boxes to keep the PCM and simply put the boxes in a soil-less greenhouse. They found that the added phase change materials had a positive effect on the growth of the plants. To further enhance the heat exchange, the PCM is usually integrated with a heat exchange system. Lazaar *et al.*[14] put the PCM in a latent polypropylene heat exchanger and the heat exchange was enhanced by a ventilated tunnel. Benli *et al.*[15] did likewise but connected the wind tunnel with a solar collector. The latent heat storage system was able to maintain the desired temperature in the greenhouse for 3$\sim$4 hours without extra heating. A heat exchanger filled with PCM could also be integrated with ground-source heat pump [16]. Table 1 summarises the critical parameters in applying the PCM in greenhouses. The effectiveness of latent heat storage systems using PCM is dependent on the placement of the PCM and the heat exchanger.

Table 1: Summary of the information on applying PCM in greenhouses from literature.

Ref.	PCM				T_{in} (^oC)		Heat exchanger
	Type	Freezing point (^oC)	Melting point (^oC)	Mass (kg)	Without PCM	With PCM	
[1, 17]	$CaCl_2 \cdot 6H_2O$	N/A	32∼45	300	N/A	8.0∼ 27.5	Cylindrical tank placed inside the greenhouse
[13]	Oleic acid	12.0	16.0	4.4	3.4∼32.5	4.0 ∼28.0	Rectangular container placed inside the greenhouse
	40% oleic acid + 60% capric acid	12.6	N/A	2.6	-0.1∼37.5	N/A	
[14]	$CaCl_2 \cdot 6H_2O$	N/A	26∼29	10	18∼58	27∼51	Polypropylene heat exchangers
[15]	$CaCl_2 \cdot 6H_2O$	N/A	29	300	$6 \sim 9$ ^oC temperature difference between inside and outside of the greenhouse		Cylindrical tank placed inside the greenhouse

This study also found the related numerical studies. As for the PCM application in solar green houses, Kumari *et al.*[18] adopted Fourier analysis and analyzed a greenhouse with PCM and insulation applied to the north wall for a typical winter day. Ziapour and Hashtroudi [19] used the genetic algorithm optimisation method, combined with the phase change material, to enhance the performance of solar greenhouse. Berroug *et al.*[20] developed a numerical thermal model that considered the different components of the greenhouse, including cover, plants, inside air and north wall PCM, to investigate the impact of the PCM on greenhouse temperature and humidity. Some scholars have also carried out numerical simulation studies on phase-change materials placed in plastic greenhouses. Zhou *et al.*[21] established a one-dimensional dynamic model to assist the design of a solar energy storage and heating system and to evaluate the system performance, and they obtained the date-hour change patterns of characteristic temperatures in the plastic greenhouse, where the PCM is put in a heat storage box using the model developed in MATLAB. Najjar and Hasan [22] developed a mathematical model for the PCM storage and the greenhouse to calculate the maximum temperature change inside the greenhouse and investigated the effect of different parameters on the inside greenhouse temperature. The coupled models are solved using numerical methods and Java code program.

Besides, the performance of a latent heat storage systems using PCM in a greenhouse is highly dependent on the PCM itself as well. Since the environmental temperature in hot summer and cold winter climate is different from that in cold climate, accordingly, the melting point and freezing point of the PCM should be different. The PCM used in the cold climate may not be appropriate for the hot summer and cold winter climate. There are mainly three categories of PCM: inorganic, organic, and eutectic [23]. In general, an eutectic PCM has better performance than the other two. For example, it was found that the expanded graphite prepared at 800W irradiation power for 10s exhibited the maximum sorption capacity of 92% for paraffin. The thermal energy storage charging duration for the composite PCM was reduced obviously compared to paraffin [24]. It was also found that eutectics have sharp melting temperature and high volumetric thermal storage density [25]. However, due to the varied thermal and chemical behaviour, the selection of PCMs is closely related to the design of latent heat storage systems.

Based on the above literature review, there are currently two major problems concerning the application of PCM in plastic greenhouses. Firstly, the current researches mainly focus on the integration of PCM in part of the envelopes of the solar greenhouses in cold climate regions. Such latent heat storage systems using PCM cannot be directly implemented to the plastic greenhouses in hot summer and cold winter climates, because there is no solid wall in a plastic greenhouse. No scientific way has been found to reasonably install the PCM and effectively operate this latent heat storage system in plastic greenhouses until now, which hinders its application. Secondly, although there are researches on the placement of PCM painted in the wall or sealed in containers inside the greenhouses to release the heat, most of the corresponding experimental and numerical studies investigated the temperature elevation during the period of heat release by a certain amount of PCM. There is little research on the design of such heat storage systems and the development of operational strategies in order to keep the inside temperature within a desirable range during the whole winter with the least investment. The design of latent heat storage systems using PCM for plastic greenhouses is dependent on the local climate, the desired control range of temperature inside the greenhouses, and the local resources such as ground heat, etc. This investigation thus proposed a design of a latent heat storage system using suitable PCM for plastic greenhouses in southern China, where the climate is typical hot summer and winter. The all-day use strategies were also developed by the experimental and the numerical models, to ensure the required temperature range inside the plastic greenhouses.

2. Methodologies

To design a latent heat storage system using PCM for plastic greenhouses and its use strategy, one can use experimental measurement or numerical simulation. The experimental measurement is normally used to validate the numerical simulation. Then a validated numerical tool could be used to analyse multiple scenarios. This study followed this strategy and this section first introduces the setup of a testbed of two greenhouses. One of the greenhouses was equipped with a latent heat storage system using PCM. Then a corresponding numerical model was introduced to analyse the performance of the greenhouse.

2.1. Experiment setup

This study built a test bed of two plastic greenhouses on an open field in Hangzhou, a city with typical climate of hot summer and cold winter in southern China, where the plastic greenhouses are widely used. In January, the daily mean air temperature is between 2∼9°C and the coldest air temperature could be -6°C. The two greenhouses were identical, with dimensions of 1.5 m $\times$ 2.0 m $\times$ 0.8 m. One was the no-treatment control group (group A) and another one was the experimental group (group B), as shown in Figure 2. Group A was used as a reference to quantify the improvement in the experimental group. In group B, latent heat storage systems using PCMs were established.

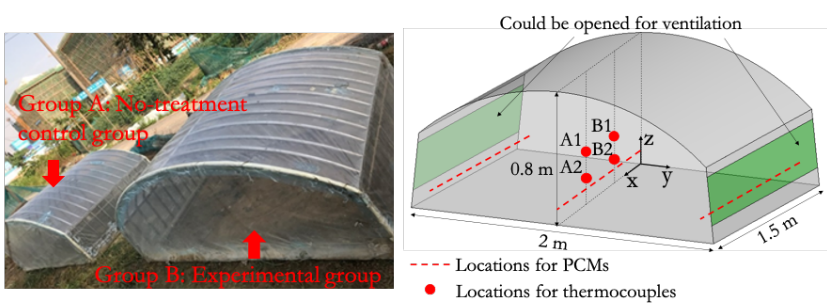


Figure 2: Experiment setup and digital model.

The PCMs for the plastic greenhouses that grow vegetables are expected to have the following features:

- The phase change temperatures should be appropriate for the plants. PCM with high meting point would lead to excessive air temperature in the greenhouses; PCM with low solidification point would be unable release of the latent heat. In southern China, farmers plant mainly hardy vegetables in greenhouses during winter. The appropriate temperature for the seed to germinate is between 10~18 °C and the highest affordable temperature to grow is between 30~35 °C. The temperature inside the greenhouses is suggested to be kept above 10 °C, lest the plants stop growing [26]. Therefore, the phase change temperatures for the PCM should be within 10~35 °C and the lowest value for the temperature control range inside the greenhouses is set as 10 °C.
- The PCM should be non-toxic, non-corrosive, and stable in terms of food security.
- The price of the PCM should be cheap for the farmers.

Based the above requirements for plants and the properties of different types of PCM, this study selected a eutectic PCM that consists of 70% paraffin, 22% fatty acid, and 8% tetradecanol. The density of the PCM in liquid state and solid state are almost the same (ρ_{PCM} = 750 kg/m^3) and the measured heat conductivity is $\lambda_{PCM} = 0.2$ W/(m·K).

The phase change temperatures for the eutectic PCM was determined by using differential scanning calorimetry (DSC) in the previous study, which was a thermos-analytical technique. The amount of heat required to increase the temperature of a sample was measured as a function of temperature. This study used differential scanning calorimeters Q20 from TA instrument to test the PCM. The temperature was varied between 0 °C and 70 °C, at the rate of 5 K per minute. Figure 3 shows the measured results. The melting occurred between 17.11 °C and 27.6 °C, with peak temperature at 21.79 °C. The corresponding melting heat was 163.9 J/g. The solidification had two phases: the major solidification occurred between 16.77 °C and 9.72 °C, with peak temperature at 14.68 °C. The solidification heat was 108.9 J/g. Therefore, this eutectic PCM

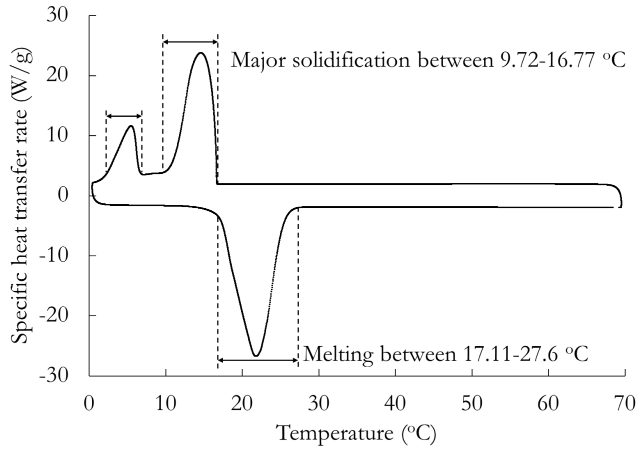


Figure 3: Specific heat transfer rate vs. temperature measured by DSC.

has the anticipated performance in absorbing and releasing heat and evident phase changes within the desired temperature range.

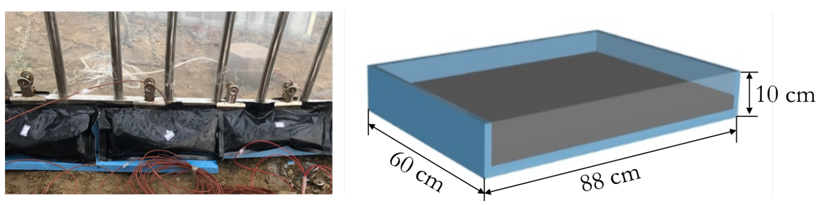


Figure 4: PCM sealed in black aluminium foil bags (left) and heat collection device to store the sealed PCMs for thermal storage in day time (right).

This study proposed a simple but effective way to place the PCMs. The approach was first to seal the PCMs in black bags made of aluminium foil, as shown in the left photo of Figure 4. In the daytime, the approach then stored the sealed PCMs in a heat collection device, as shown in the right photo of Figure 4. This is because our preliminary experiments found that simply placing the sealed PCMs in the greenhouse would be unable to fully melt the PCMs. The heat collection device was made of extruded polystyrene boards with one bottom and three side walls. The thickness of the board was 2 cm. The bottom was further insulated by 3 cm-thick rubber insulation cotton, since the bottom had the major contact with the PCMs. The other sides were wrapped with transparent plastic film. This investigation insulated the heat collection device by rubber insulation cotton at 15:00, because it is the time that solar radiation weakens significantly in winter. After sunset, the sealed PCMs were moved and hung on three sticks 10 cm above the ground. One can refer to the picture on the right in Figure 2 for the locations of the three sticks. Due to the cold air temperature during the night, after 17:30, this study covered the greenhouses by rubber insulation cotton with a 7 cm thickness. To further avoid the sky radiation, the rubber insulation cotton was wrapped in aluminium foil. At 8:00 am the next day, the rubber insulation cotton was removed and the PCMs were then put back in the heat collection devices. Figure 5 shows the schedule.

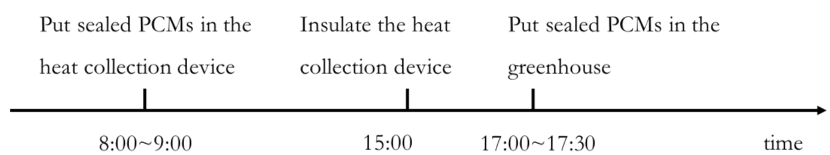


Figure 5: Schedules for the placement of PCMs with the heat collection device.

In order to monitor the thermal performance of the PCMs inside the greenhouse, this study measured the solar radiation, indoor/outdoor air temperature, and the temperature of PCMs. Solar radiation was measured by a pyranometer (model TBS-2-2), and the outdoor air temperature was measured by a data logger for air temperature (Testo 174H) with the accuracy of $\pm 0.5^{o}$C within the temperature range of -20^{o}C $\sim$ $+70^{o}$C. The indoor air temperature and the PCMs' temperature was measured by type T thermocouples, which were calibrated by using a thermostatic water tank with the accuracy of $\pm 0.05^{o}$C. To measure the air within the greenhouse, the experiment placed the thermocouples in four positions: A1 $(133.2\text{ cm}, 0, 37.5\text{ cm})$, A2 $(133.2\text{ cm}, 0, 12.5\text{ cm})$, B1 $(66.6\text{ cm}, 0, 37.5\text{ cm})$, and B2 $(66.6\text{ cm}, 0, 12.5\text{ cm})$ (refer to Figure 2). The reason for choosing these locations is that the recommended locations for measuring the air temperature in a full-scale greenhouse are 0.2 m, 0.5 m, and 1.5

m from the ground, according to the standard [27]. For this small-scale model, which is one fourth of a full-scale one, the corresponding heights for measuring the air temperature are 0.05 m, 0.125 m, and 0.375 m from the ground. Since z = 0.05 m would be too close to the soil, this study thus measured the air temperature at two heights: z = 37.5 cm and z = 12.5 cm. The experimental group and the no-treatment control group had the same setup in measuring the air temperature.

In Hangzhou, the daily mean air temperature is between $-6 \sim 15$ °C during winter (Nov 28 ~ Mar 17). Table 2 summarises the typical daily mean air temperature during winter based on the data of typical meteorological year in Hangzhou. Using the lowest daily mean air temperature, this study estimated the mass of PCMs by using its major solidification heat and the heating load of the greenhouse test bed during the night. To maintain the indoor air temperature above 10 °C on the coldest night, the mass of PCMs was estimated to be 24 kg. However, since the occurrence of the daily mean air temperature within $-6 \sim 0$ °C was only 2 days per year (Table 2), in order to develop a general operational strategy for the PCM system during the typical winter climate, this study conducted the experiment when the daily mean air temperature was between $0 \sim 5$ °C. The occurrence of the daily mean air temperature within $0 \sim 5$ °C for 45 days per year, amounting to 41% of the total winter days, was more representative. Therefore, this investigation conducted the experiment and repeated experiment on February 5 ~ 8, 2018. There were four scenarios in total and Table 3 gives a summary. This study used the estimated 24 kg of PCMs in the first two scenarios. The PCM mass of 24 kg was calculated by a numerical model in the following section, assuming the air temperature within the greenhouse to be 10 °C and the outdoor temperature to be -3 °C, which was the lowest outdoor temperature in that February. Therefore, the PCM mass of 24 kg was expected to ensure the air temperature within the greenhouse to be no less than 10 °C. The PCM mass of 30 kg in scenarios 3 and 4 was to check how the increased amount of PCM improved the thermal environment within the greenhouse.

Daily mean air temperature (^{o}C)	Number of days	Percentage
-6∼0	2	2%
0∼5	45	41%
5∼10	51	47%
10∼15	11	10%

Table 2: Typical daily mean air temperature during typical winter in Hangzhou, China.

Scenario	Date	Daily mean air temperature (^{o}C)	Mass of PCMs (kg)
1	2018/02/05	0.92	24
2	2018/02/06	0.57	24
3	2018/02/07	2.62	30
4	2018/02/08	3.45	30

Table 3: Summary of the experimental scenarios.

2.2. Numerical model

This study developed a numerical model for predicting the transient air temperature within the plastic greenhouse by analysing the basic heat transfers. To simplify the numerical model, this investigation made the following assumptions:

- No plant in the greenhouse since there is no plant in the experiment;
- Ignore the latent heat transfer of the moisture;
- Uniform air temperature within the greenhouse;
- Uniform surface temperature for the plastic envelope, rubber insulation cotton, and the soil;
- Ignore the radiation within the plastic greenhouse;
- Ignore the thermal resistance of the black aluminum foil that seals the PCMs;

- Ignore the thermal resistance of the plastic envelop during night.
- Ignore the heat loss due to air infiltration since the greenhouse was well sealed.

Then, the heat transfer model for the plastic greenhouse was established as shown in Figure 6. The corresponding heat balance model for the air within the plastic greenhouse is:

$$\rho_{air} c_{air} V_{air} \frac{dT_{air}}{d\tau} = Q_{env} + Q_{soil} + Q_{PCM} \tag{1}$$

where $\rho_{air} = 1.29$ kg/m^3 is the air density, $c_{air} = 1.0$ kJ/(kg · K) is the air heat capacity, $V_{air} = 1.86$ m^3 is the air volume within the greenhouse, T_{air} is the air temperature, τ is the time, Q_{env} is the heat convection between the envelope (plastic film in the daytime and rubber insulation cotton in the night) and air, Q_{soil} is the heat convection between the soil and air, Q_{PCM} is the heat dissipated by the PCMs during the night. Applying the heat convection equation to each term of the right hand side of Equation 1, we have:

$$\begin{aligned} \rho_{air} c_{air} V_{air} \frac{dT_{air}}{d\tau} &= h_{env} A_{env} (T_{env} - T_{air}) \\ &+ h_{soil} A_{soil} (T_{soil} - T_{air}) + h_{PCM} A_{PCM} (T_{PCM} - T_{air}) \end{aligned} \tag{2}$$

where T_{env} is the temperature in the envelope (plastic film in the daytime and rubber insulation cotton in the night), T_{soil} is the surface temperature of the soil, T_{PCM} is the surface temperature of the PCM. The h and A are the corresponding convective heat transfer coefficients and areas, respectively. For the PCM, the convective heat transfer coefficient is $h_{PCM} = 8.7$ W/m^2 [28]. Referring to [29] and [30], we also have:

$$h_{env} = 1.25(T_{env} - T_{air})^{0.25} \tag{3}$$

$$h_{soil} = 2.17(T_{soil} - T_{air})^{0.25} \tag{4}$$

To solve Equation 2, it is necessary to know the temperature of all surfaces with respect to time. Then we further established the heat balance equations for the envelope, soil, and PCM.

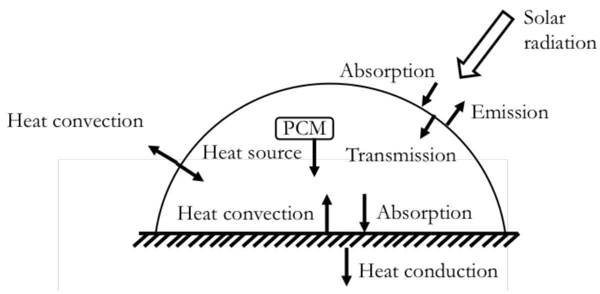


Figure 6: Heat transfer within the greenhouse.

2.2.1. *Heat balance analysis of the envelope*

In the daytime, the envelope of the green house is plastic film. The physical properties are as follows: thickness $L_{pla} = 0.1$ mm, density $\rho_{pla} = 0.9$ kg/m^3, heat capacity $c_{pla} = 2.3$ kJ/(kg·K), and heat conductivity $\lambda_{pla} = 0.45$ W/(m · K). During the night, the envelope of the green house is rubber insulation cotton, the physical properties are: $L_{ins} = 7$ cm, $\rho_{ins} = 40$ kg/m^3, $c_{ins} = 1.38$ kJ/(kg · K), and $\lambda_{ins} = 0.035$ W/(m · K). The area of the envelope is $A_{env} = 6.71$ m^2. Using the heat transfer for the rubber insulation cotton as an example, this study assumed one dimensional heat conduction within it. This investigation considered the heat convection between the envelope, air and sky radiation, and established the heat balance equation thus:

$$\frac{\partial T(x,\tau)}{\tau} = \frac{\lambda_{ins}}{\rho_{ins} c_{ins}} \frac{\partial T^2(x,\tau)}{\partial x^2} \tag{5}$$

with boundary conditions:

$$x = 0, \lambda_{ins} \frac{\partial T}{\partial x} = h_{ins,in}(T - T_{air,in}) \tag{6}$$

$$x = L_{ins}, \lambda_{ins} \frac{\partial T}{\partial x} = h_{ins,out}(T - T_{air,out}) + q_{sky} \tag{7}$$

$$\tau = 0, T(x,0) = T_{ins0} \tag{8}$$

where x represents the distance along the thickness of the envelope, subscript $_{in}$ represents the value on the inner surface of the envelope, while subscript

$_{out}$ represents the value on the outer surface. Therefore $h_{ins,in} = h_{env}$ and $h_{ins,out} = 23.3$ W/m^2 [28]. T_{ins0} is the initial temperature of the envelope. q_{sky} is the sky radiation that could be calculated by:

$$q_{sky} = \varepsilon\sigma(T^4 - T_{sky}^4) \tag{9}$$

where $\varepsilon = 0.09$ is the emissivity of the aluminum foil that wraps the rubber insulation cotton, $\sigma = 5.67 \cdot 10^{-8}$ W/(m^{2}K^4) is the Stefan–Boltzmann constant, $T_{sky} = 0.0552T_{air,out}^{1.5}$ [30] is the effective sky temperature.

2.2.2. Heat balance analysis of the soil

To obtain the surface temperature of the soil, this study assumed one-dimensional heat conduction within the soil along the depth and the soil temperature below 1 meter depth was constant [31]. According to [32], the constant soil temperature is almost the same with the annual mean air temperature, then $T_{soil,1\mathrm{m}} = 16.5$ ^{o}C. The heat balance equation is:

$$\frac{\partial T(x,\tau)}{\tau} = \frac{\lambda_{soil}}{\rho_{soil}c_{soil}}\frac{\partial T^2(x,\tau)}{\partial x^2} \tag{10}$$

with the boundary conditions:

$$x = 0, \lambda_{soil}\frac{\partial T}{\partial x} = h_{soil}(T_{soil} - T_{air,in}) + q_{solar} \tag{11}$$

$$x = 1\ \mathrm{m}, T(1\mathrm{m},\tau) = T_{soil,1\mathrm{m}} \tag{12}$$

$$\tau = 0, T(x,0) = T_{soil0} \tag{13}$$

where T_{soil} is the surface temperature of soil, $\rho_{soil} = 1600$ kg/m^3 is the soil density, $c_{soil} = 2200$ kJ/(kg · K) is the heat capacity, $\lambda_{ins} = 0.8$ W/(m · K) is the thermal conductivity. T_{soil0} is the initial soil temperature. q_{solar} represents the solar energy absorbed by the soil during the daytime, then:

$$q_{solar} = \alpha_{soil}\gamma_{pla}q_s \tag{14}$$

where α_{soil} is the absorptivity of soil, γ_{pla} is the transmissivity of plastic film, and q_s is the solar irradiance.

2.2.3. Heat balance analysis of the PCM

This study analyzed the thermal characteristics of phase transition for PCM by using the effective heat capacity which was dependent on the temperature [33]:

$$c_{PCM}(T) = \frac{q(T)}{m\beta} \tag{15}$$

where $q(T)$ was the heat transfer rate of the PCM with temperature T measured by the DSC, $m = 0.0092$ kg was the mass of the PCM in the DSC test, and $\beta = 5$ K/min was the temperature gradient in the DSC test. Figure 7 shows the effective heat capacity of the PCM in releasing the heat. The effective heat capacity could be expressed by a regression piece-wise function:

$$c_{PCM}(T) = \begin{cases} 5, & T < 9.72 \\ -0.66T^3 + 24.5T^2 - 293.7T + 1152, & 9.72 \leq T \leq 14.68 \\ -6.3T^3 + 287.2T^2 - 4373T + 22233, & 14.68 \leq T \leq 16.77 \\ 2.5, & T > 16.77 \end{cases} \tag{16}$$

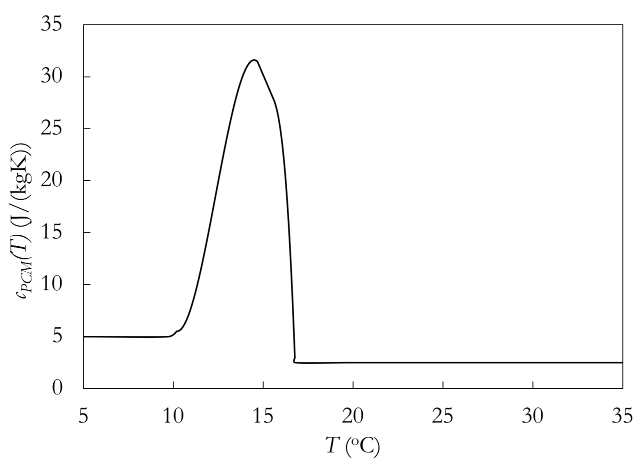


Figure 7: Effective heat capacity of the PCM in releasing the heat.

The sealed PCM mainly dissipated heat from the two side surfaces to the air through natural convection. Within the PCM, this study assumed one-dimensional heat conduction along the thickness $L_{PCM} = 2$ cm. Then the heat balance equation is:

$$\frac{\partial T(x,\tau)}{\tau} = \frac{\lambda_{PCM}}{\rho_{PCM} c_{PCM}} \frac{\partial T^2(x,\tau)}{\partial x^2} \tag{17}$$

with boundary conditions:

$$x = 0, x = L_{PCM}, \lambda_{PCM} \frac{\partial T}{\partial x} = h_{PCM}(T - T_{air,in}) \tag{18}$$

$$\tau = 0, T(x, 0) = T_{PCM0} \tag{19}$$

where $\lambda_{PCM} = 0.2$ W/(m $\cdot$ K) and $\rho_{PCM} = 750$ kg/m^3.

By using the experimental data in the previous section as the initial conditions, this study calculated the air temperature within the greenhouse by numerically solving Equations 2, 5 - 8, 10 - 13, and 17 - 19, simultaneously. The partial differential equations were discretized by the finite difference method with Euler scheme for the temporary term and central difference scheme for the diffusion term. In the heat balance equation for the PCM, the effective heat capacity was dependent on the temperature and the explicit scheme was adopted to simplify the computation. Otherwise, this study adopted implicit schemes. To ensure the stability of the numerical solution, this study determined the grid size and time step size by making the Fourier number $Fo < \frac{1}{2Bi+2}$, where Bi is the Biot number. The solver was programmed in Matlab [34] for calculations.

3. Results

To validate the developed model for predicting the air temperature within the plastic greenhouse, this section first presented the experimental results. Then, this study validated the numerical model with the experimental data.

3.1. Experimental results

This study first verified that the greenhouse of the experimental group was exactly the same as that of the no-treatment control group. Figure 8 compares the air temperature measured within the two greenhouses for 96 hours. The outdoor air temperature was also measured as a reference. Without using the PCM, the air temperature within the greenhouses could be as low as 3.7 ^{o}C. In general, the greenhouses were able to maintain the indoor air temperature $2 \sim 3$ ^{o}C higher than the outdoor air. But they were unable to maintain the indoor air temperature at greater than 10 ^{o}C. When the PCM was not used, the measured air temperatures within the two greenhouses were almost identical, so the no-treatment group could be used to imply the effect of applying the PCMs in the greenhouse of the experimental group.

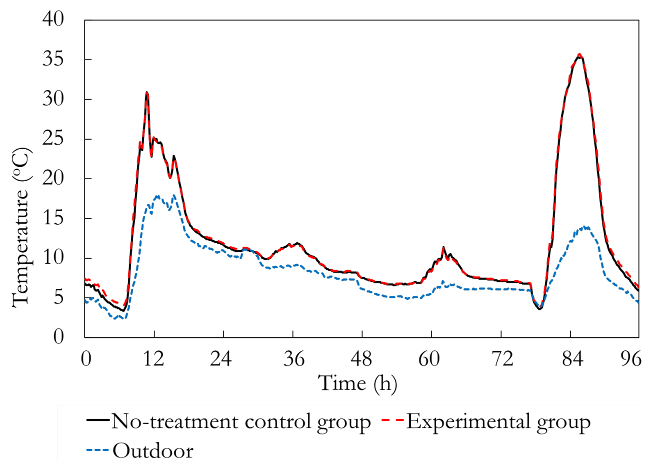


Figure 8: Measured air temperature in the no-treatment control group, experimental group and outdoor, when the PCM was not used.

With the application of PCMs, this investigation first compared the air temperature measured at different heights in Figure 9. Since the measured air temperatures at the same height were almost identical, Figure 9 presented the averaged values at position A1 and B1 for $z = 37.5$ cm and A2 and B2 for $z = 12.5$ cm, respectively. It is evident that the air temperature difference along the height was minimal, which confirmed the assumption of uniform air temperature within the greenhouse in section 2.2. Therefore, the greenhouse air temperature was regarded as the average of the two values measured at positions

A1 and B1. Figure 10 shows the air temperature measured and solar irradiance for the four scenarios. The weather for the four scenarios was sunny, as one can observe from the solar irradiance. In the daytime, the indoor air temperature of the experimental group was almost the same as that of the no-treatment control group, since there was no PCM in either group. During the night, the mean indoor air temperatures in the experimental group were 12.9 ^{o}C, 13.2 ^{o}C, 13.8 ^{o}C, and 15.4 ^{o}C, respectively. For the no-treatment control group, the greenhouse was unable to maintain the hourly indoor air temperature at greater than 10 ^{o}C during the night for scenarios 1, 2 and 3. Scenario 4 was an exception, due to the high ambient air temperature. Table 4 summarizes all the measured data. The difference of the mean indoor air temperature between the two groups was greater for scenarios 3 and 4 because 30 kg of PCMs were used, while scenarios 1 and 2 used only 24 kg of PCMs.

Table 4: Summary of measured results

Scenario	Group	$T_{air,in}$ in the night (^oC)	$\overline{T_{air,in}}$ in the night (^oC)	$\Delta\overline{T_{air,in}}$	Percentage of time when $T_{air,in} \geqslant 10^oC$
1	A	$7.8 \sim 13.4$	10.3	2.6	47%
	B	$10.7 \sim 14.7$	12.9		100%
2	A	$8.4 \sim 13.4$	10.7	2.5	60%
	B	$10.9 \sim 14.8$	13.2		100%
3	A	$9.1 \sim 13.1$	10.7	3.1	67%
	B	$11.5 \sim 15.7$	13.8		100%
4	A	$10.3 \sim 15.2$	12.2	3.2	100%
	B	$12.3 \sim 18.2$	15.4		100%

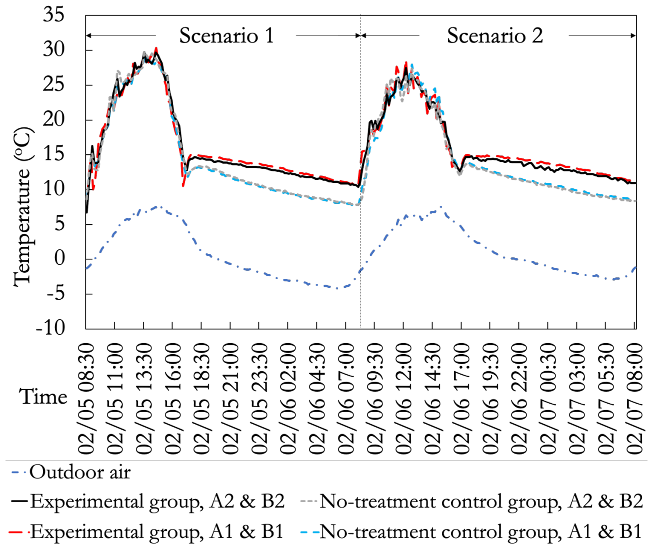
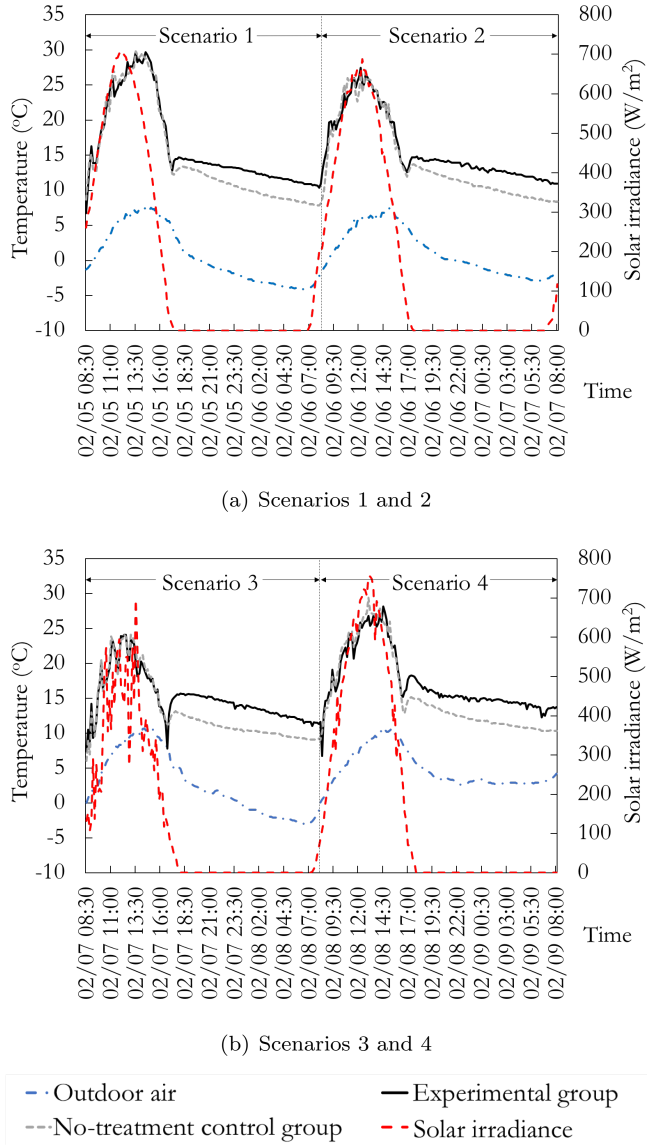


Figure 9: Measured air temperature at different heights in the plastic greenhouse.



(a) Scenarios 1 and 2

(b) Scenarios 3 and 4

Figure 10: Measured air temperature and solar irradiance for (a) scenarios 1 and 2 and (b) scenarios 3 and 4.

3.2. Numerical model validation

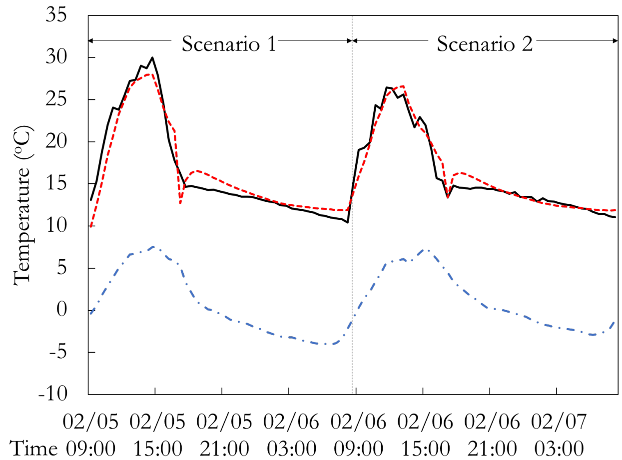
With the measured data, this study conducted the numerical simulations with the developed model for day and night. This is because of the difference in the physical conditions during day and night. During day, the greenhouse envelope was a plastic film and there was no PCM. During night, the greenhouse was covered with rubber insulation cotton and there were PCMs inside. Besides, it took about 15 minutes to move in/out the PCMs and put on/take off the rubber insulation cotton, as using the measured values as the initial conditions for the day and night respectively would lead to accurate predictions. Table 5 summarizes the initial conditions. Please note that L_{PCM} was the effective thickness of the sealed PCMs.

Figure 11 compares the measured air temperature with simulated values in the greenhouse. In general, the simulated air temperature within the greenhouse agreed well with the experimental data. To quantitatively evaluate the difference between the measured and simulated values, this study calculated the normalized mean bias error (NMBE) and coefficient of variation of root mean square error (CVRMSE). The equations for NMBE and CVRMSE are as follows:

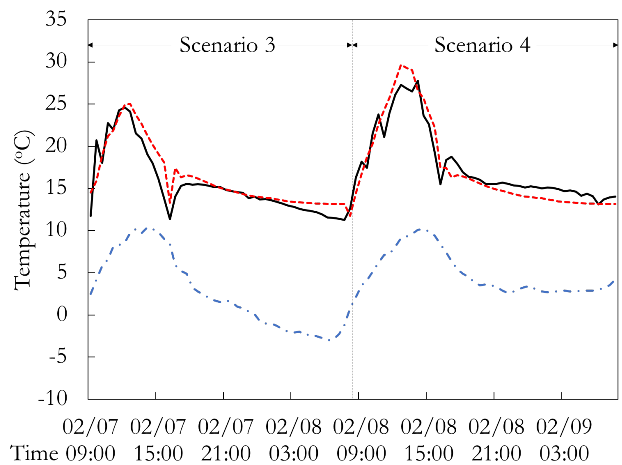
$$NMBE = \frac{\int_{i=1}^{N}(S_i - M_i)}{\int_{i=1}^{N} M_i} \tag{20}$$

$$CVRMSE = \frac{\left[\int_{i=1}^{N} \frac{(S_i - M_i)^2}{N}\right]^{\frac{1}{2}}}{\frac{1}{N}\int_{i=1}^{N} M_i} \tag{21}$$

where S_i and M_i are simulated and measured air temperature, respectively. N is the number of simulated air temperatures. Table 6 provides the quantitative comparisons between the simulated results and measured results, as well as NMBE and CVRMSE. According to [35], the NMBE and CVRMSE are supposed to be within -10% $\sim$ 10% and less than 30%, respectively. Therefore, the developed numerical model was able to accurately predict the air temperature in the greenhouse.



(a) Scenarios 1 and 2



(b) Scenarios 3 and 4

Figure 11: Comparison of measured air temperature with simulated values in the greenhouse.

Table 5: Initial conditions for the numerical simulations.

Variables	Scenario 1		Scenario 2		Scenario 3		Scenario 4	
	Day	Night	Day	Night	Day	Night	Day	Night
$T_{air,in}$ °C	11.6	12.8	14.1	12.7	11.1	12.0	11.3	17.9
T_{soil} °C	13.8	14.3	15.1	14.8	12.0	14.0	12.3	14.8
T_{env} °C	8.8	5.2	9.5	4.4	8.5	7.0	9.8	4.4
T_{PCM} °C	/	30.0	/	28.0	/	28.0	/	30.0
L_{PCM} (m)	/	0.07	/	0.07	/	0.09	/	0.09

Table 6: Comparison of measured data with simulated results.

Scenario/ Group	Measured $T_{air,in}$ in the day (°C)	Simulated $T_{air,in}$ in the day (°C)	Measured $T_{air,in}$ in the night (°C)	Simulated $T_{air,in}$ in the night (°C)	NMBE (day/night)	CVRMSE (day/night)
1/B	13.1 ∼ 30.0	10.0 ∼ 28.0	10.7 ∼ 14.7	11.6 ∼ 16.2	-6.1%/4.5%	10.1%/10.1%
2/B	12.8 ∼ 26.5	10.1 ∼ 26.7	10.9 ∼ 14.8	12.3 ∼ 16.3	0.2%/3.2%	7.6%/6.2%
3/B	11.7 ∼ 24.6	11.6 ∼ 25.0	11.5 ∼ 15.7	12.2 ∼ 16.8	-0.3%/5.8%	13.8%/8.8%
4/B	12.6 ∼ 27.7	11.7 ∼ 29.0	12.3 ∼ 18.2	13.5 ∼ 16.6	5.6%/-6.1%	9.4%/6.6%

4. All-day use strategy of PCM in real greenhouses

With the developed numerical model, this study further investigated the all-day use strategies of combining different quantities of PCM and the thickness of rubber insulation cotton in a real, commonly-used greenhouse. Then by the simulation for the whole winter, this investigation conducted the economic analysis to calculate the payback time for the most economic combination.

4.1. Development of all-day use strategy

This study considered a type GP-825 greenhouse as shown in Figure 12, which is widely used in the hot summer and cold winter zone of China. The dimensions were 40 m in length, 8 m in width, and 3.2 m in height. Since this plastic greenhouse is much larger than the one in the experiment, the assumptions in section 2.2 should be justified before applying the developed numerical model. For example, in a large greenhouse, if there is strong temperature stratification and further natural convection, the developed numerical model would be not applicable. To ensure the similarity of the physical conditions of the two greenhouses, this study conducted on-site measurements in a type GP-825 greenhouse. This investigation measured the air temperature at three heights: $z = 1.5$ m, 0.5 m, and 0.2 m according to the standard [27]. Figure 13 shows the measured air temperatures and solar irradiance in the full-scale plastic greenhouse, which confirmed the uniform temperature within the large greenhouse. Therefore, the assumed uniform air temperature within the greenhouse and uniform surface temperature for the plastic envelope should be applicable. Further, as the small-scale greenhouse was built with the same structure and materials as the large one, the ignored heat loss due to air infiltration should be applicable.

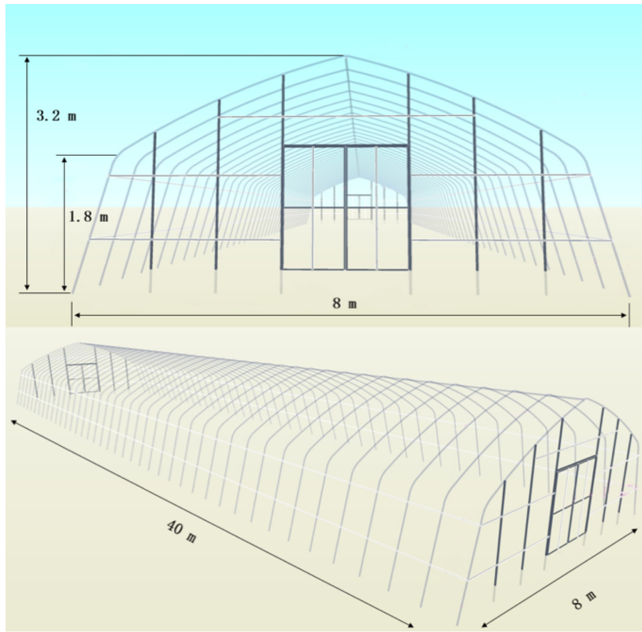


Figure 12: Sketch of a type GP-825 vegetable greenhouse.

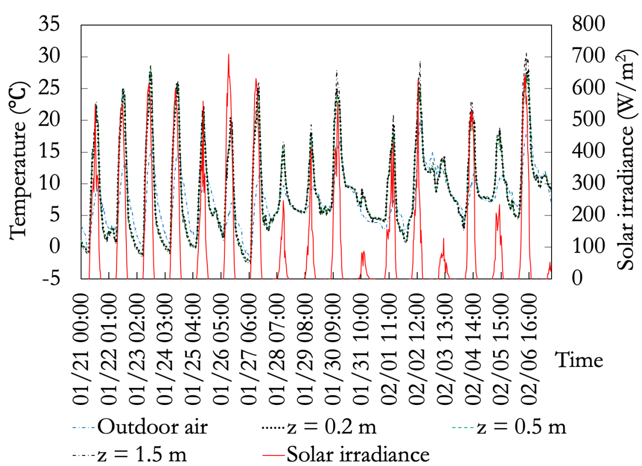


Figure 13: Measured air temperature and solar irradiance in a full-scale plastic greenhouse.

To ensure that the air temperature within the greenhouse is always greater than 10 °C, this study considered the meteorological data of the coldest day in a typical meteorological year in Hangzhou, China. The ambient air temperature varies between -7 ~ -4 °C. Since there was no measurement for this greenhouse, the initial conditions such as the T_{ins0}, T_{soil0}, and $T_{air,in}$ were unknown. To eliminate the effect of given initial conditions, this study ran the numerical model for days until a steady-state was achieved. For example, assuming the greenhouse was covered by rubber insulation cotton with the thickness of 7 cm and without using the PCM, Figure 14 shows the simulated air temperature in the greenhouse at steady-state. It is clear the air temperature in the greenhouse was not always greater than 10 °C. Therefore, PMCs should be used to satisfy the temperature requirement. The placement of PCMs exactly followed the schedules in Figure 5.

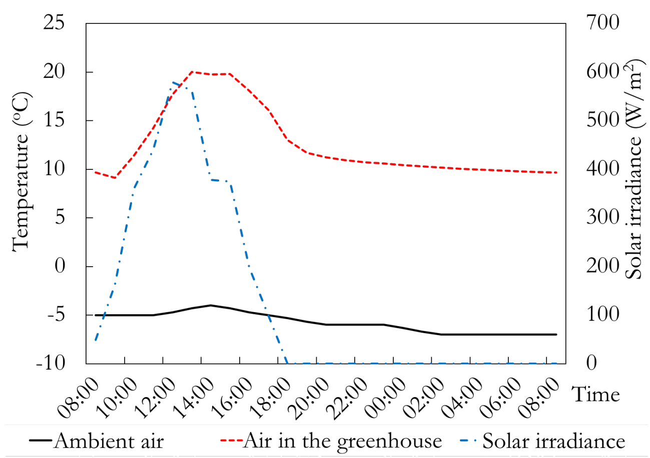


Figure 14: Simulated air temperature in the greenhouse at steady-state.

In our design, on the one hand, the PCMs store the solar irradiation in the day and release heat in the night; on the other hand, the rubber insulation cotton reduces the heat dissipation in the night. A combination of appropriate thickness of rubber insulation cotton and appropriate mass of PCMs should be determined to ensure the temperature requirement with the least investment. The desirable temperature range is between 10 °C and 35 °C. With the assumed thickness of rubber insulation cotton, this investigation tried different mass of PCMs to ascertain the mass that maintained the lowest air temperature within the greenhouse exactly above 10 °C in the sunny days of the whole winter, in which the PCMs can be used to store the solar energy. Figure 15 provides the combinations of the thickness of rubber insulation cotton and the mass of PCMs. The PCMs were assumed to be placed within rows of plants with the cross section size of 2 cm (L_{PCM}) × 40 cm (height). Then the mass of PCMs corresponds to the length. This study assumed L_{PCM} = 2 cm to ensure the efficient heat dissipation from the PCMs. One can notice that if the thickness of rubber insulation cotton is 8 cm, the greenhouse is able to maintain the desired air temperature without using any PCMs. The price of the rubber insulation cotton is 10 CNY/m^3, while that of the PCM is 16 CNY/kg. Figure 16 further shows the investment for the combinations. The combination 4 with 4 cm of rubber insulation cotton and 720 kg PCMs was able to maintain the air temperature within the greenhouse at greater than 10 °C with the least investment (30,600 CNY).

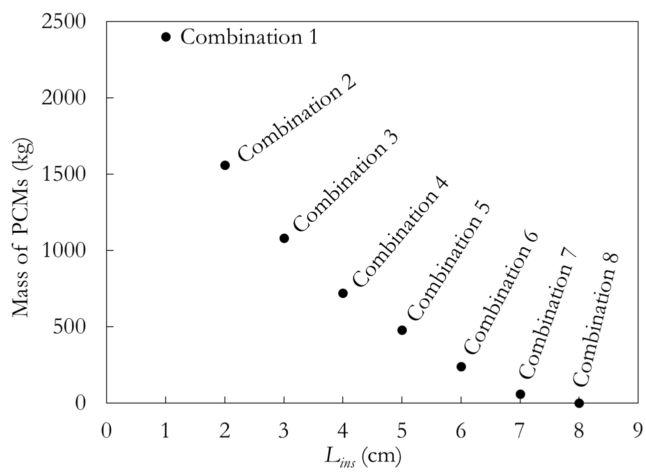


Figure 15: Combinations of the thickness of rubber insulation cotton and the mass of PCMs that maintain the hourly air temperature within the greenhouse above 10 °C.

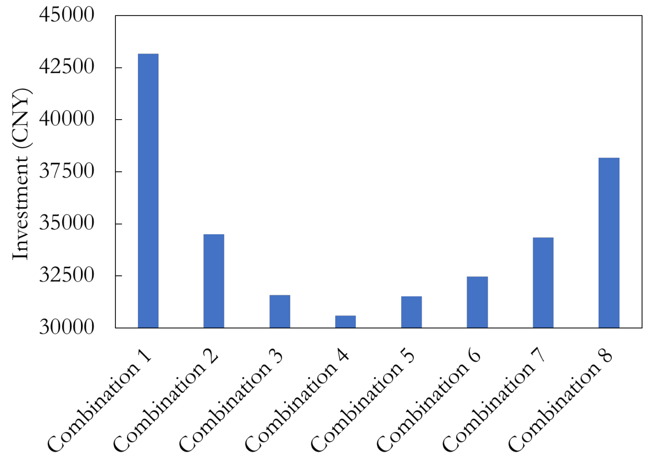


Figure 16: Investments for all the combinations.

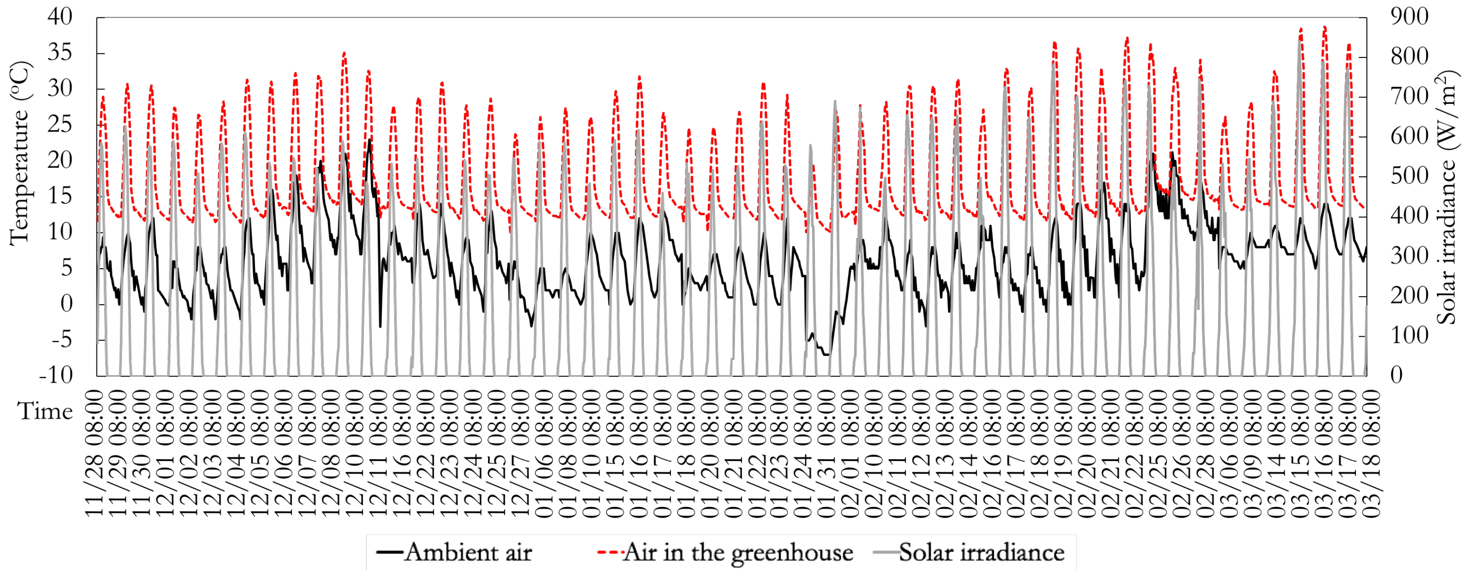


Figure 17: Simulated air temperature in the greenhouse for the sunny days in a whole winter.

4.2. Economic analysis

With the combination four, this study ran the numerical simulation for the sunny days for the whole winter (November 28 ∼ March 17). For the cloudy and rainy days, as the PCMs could not store the solar energy, there was no energy saved, and hence these days were not accounted in the simulation and economic analysis. As for the reference scenario, electric heating was used to achieve the same indoor air temperature for sunny days in Figure 17, as it is the most popular approach in this climate zone, due to the cheap initial cost and convenience. When electric heating is used, the heat transfer process in the greenhouse is as follows: the heat provided by electric heaters to the air in the greenhouse is equal to the heat dissipation of air in the greenhouse to the outside of the greenhouse through the film, plus the heat transfer between the air and soil in the greenhouse. In order to calculate the heat load in the reference scenario of electric heating, the previous simulated inside air temperature and soil temperature in the scenario applied with phase-change material and thermal insulation cotton were used to calculate the night heat load when only electric heating was used. In this way, the calculated heating load by electric heaters was 21,700 MJ or 6028 kWh. With electricity price being 0.73 CNY/kWh, the estimated payback time of combination four was 6.95 years, less than the lifespan (10 years). In summary, the proposed strategy will significantly reduce the investment and the CO_2 emissions. However, this study did not consider the extra operating cost due to increased labour for two reasons. First, this cost is not dependent on the PCM use strategies. Second, the extra cost for the increased labour work is very low in China. If the labour charge increases in future or in other regions where labour is expensive, the corresponding extra cost should be considered.

5. Discussions

This study did not consider the impact of the plants in both experiment and numerical simulation. The basic reason was to avoid the uncertainties brought in by the plants and the corresponding agricultural behaviours. However, the existence of the plants would affect the radiation within the greenhouse and the latent heat. So the next step of this investigation is to revise the developed numerical model by using the experimental measurements in a real greenhouse.

The proposed strategy of PCMs is only applicable for sunny days. During the cloudy days or even rainy day, how to keep the desired temperature inside the greenhouses is still a problem. An integration of the PCM and the renewable energy storage may be a sustainable way, but further research is needed. In 2016, the area of greenhouses in China was about 20,800 km^2 and that of plastic greenhouses was about 65.8%. Therefore, there is significant potential to save energy and to lower energy costs.

6. Conclusions

This investigation proposed a design and usage strategy of a latent heat storage systems using phase change material for plastic greenhouses during winter, in hot summer and cold winter climate. A pilot in southern China was used for validation and demonstration. The design and operation strategy was verified by experimental measurements in a full-scale plastic greenhouse. The experimental data was also used to validate a developed numerical model for predicting the air temperature inside the greenhouse. This study further applied the numerical model to develop a combination of phase change material quantity and thickness of rubber insulation cotton for a type GP-825 greenhouse, which is widely used in southern China. The combination was able to maintain the desired indoor air temperature inside the plastic greenhouse with the minimum cost. The results lead to the following conclusions:

- The experiment verified that a good combination of insulation for the plastic envelope and phase change materials and the designed schedules for phase change material placement was able to maintain a desired air temperature in a greenhouse on sunny winter days. Without using the phase change materials, the air temperature within the greenhouses could be as low as 3.7 ^{o}C due to low ambient air temperature during winter night. Eutectic phase change material with specific melting temperature from 17.11 ^{o}C to 27.6 ^{o}C and solidifying range from 16.77 ^{o}C to 9.72 ^{o}C is appropriate for the hot summer and cold winter climate zone and the required temperature range at night in winter. The phase change materials were sealed in black bags and placed in the heat collection device between 8:00 $\sim$ 9:00 in the morning to absorb the solar radiation. The heat collection device was insulated at 15:00 and later the sealed phase change materials were put in the greenhouse between 17:00 $\sim$ 17:30 to release heat in the greenhouse during night;

- The developed numerical model is able to predict the air temperature in a plastic greenhouse with acceptable accuracy;
- The developed numerical model could be used to find the combinations of insulation and phase change materials that satisfy the temperature requirement, then one can choose the one with least investment. In this investigation, the combination of 4 cm of rubber insulation cotton and 720 kg phase change materials was able to maintain the air temperature within the greenhouse of Type GP-825 at greater than 10 ^{o}C with the least investment.
- For the case in this investigation, the payback time for the strategy with the least investment was 6.95 years, which was less than the lifespan.

Acknowledgment

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