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Thermal performance of an active-passive ventilation wall with phase change material in solar greenhouses

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HIGHLIGHTS

- An active-passive ventilation wall with PCM was developed.
- A two-dimensional unsteady numerical heat transfer model was established.
- The effect of the proposed wall on its middle layer and occupants was assessed.
- There was no thermal-stable layer in the proposed wall.
- The plant height, stem diameter and fruit yield were increased by 30%, 25% and 28%

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ABSTRACT

Using phase change material (PCM) in the north wall of solar greenhouses has been recommended as an efficient solution for promoting their indoor thermal environment. In this type of walls, however, there is always a thermal-stable layer, which would greatly decrease their heat storage capacity. To solve this problem, an active-passive ventilation wall with PCM has been developed in this study, and a comparative study was carried out using both experimental and numerical methods to justify its advantages over conventional walls. Several important parameters have been monitored or calculated to reflect the contribution of the newly proposed method to the performance of the middle layer of the wall, the indoor thermal environment and the plants' growth. The obtained results confirmed the great effectiveness of the proposed wall in promoting the temperature of its middle layer and irradiated surface. In the newly proposed wall, there was no thermal-stable layer observed, resulting in a minimum temperature rise of 1.34 °C. The proposed solution also enhanced the wall's heat storage capacity by 35.27–47.89% and the heat release capacity by 49.93–60.21%, resulting in an average increase of indoor air temperature, daily effective accumulative temperature and soil temperature by 1.58–4.16 °C, 33.33–55.06% and 0.53–1.09 °C, respectively. The plant height, stem diameter and fruit yield have been increased by 30%, 25% and 28%, respectively.

1. Introduction

With the continuous expansion of population, increasing food production using advanced technologies has become a crucial research area [1–4]. Solar greenhouses are advanced agricultural buildings, popularly used to provide suitable thermal environment for off-season crops [5–7]. Their indoor thermal environment is mainly affected by the thermal performance of the building envelops, especially the north wall in northern hemisphere [8–10]. Enhancing the thermal performance of the wall can increase the indoor air temperature by up to 10 °C, fulfilling 35–82% heating requirement depending on their locations [11,12].

A number of studies have confirmed that using phase change material (PCM) in the north wall of solar greenhouses in northern hemisphere was an efficient way to improve their indoor thermal environment [13–15], due to its high heat storage density and nearly isothermal nature during the charge/discharge process [16–18]. Guarino et al. [19] used PCM at the inner layer of walls in solaria in a

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Nomenclature

Symbols

c	specific heat capacity, J/(kg °C)
d	equivalent diameter, m
$DEAT$	daily effective accumulative temperature, °Ch
f	friction coefficient
I	solar radiation, W/m^2
k	thermal conductivity, W/(m^2 °C)
Pr	Prandtl number
Q	heat capacity, J/m^3
r	absolute roughness, m
St	Standon number
t	temperature, °C
v	velocity, m/s
x	length, m
y	thickness, m

Greek letters

α	natural convection heat transfer coefficient, W/(m^2 °C)
β	forced convection heat transfer coefficient, W/(m^2 °C)
ε	solar absorptance, %
ζ	open (1) and close (0) status
ρ	density, kg/m^3
τ	time, s
χ	solar transmittance, %

Subscripts

Acse	east surface of air channel
Acsn	south surface of air channel
Acss	north surface of air channel
air	hot air inside the air channel
Br1	hollow block
Br2	solid block
fl	front roof
hsc	heat storage capacity
hrc	heat release capacity
id	indoor
In	polystyrene boards
min	minimum
od	outdoor
PCM	PCM wallboards
v	vertical
w	wall
Wh	whole wall

cold climate. Based on experimental results, they found that the PCM wall provided benefits through the whole year, due to the PCM's ability of storing solar radiation during the daytime and releasing the stored heat during the nighttime, which could be up to 6–8 h after sunset. Berroug et al. [20] used $CaCl_2{\cdot}6H_2O$ as PCM and analyzed its effectiveness on the north wall of solar greenhouses, based on simulation. The study found that the north wall with PCM performed a higher heat storage potential, leading to an increase of indoor air temperature by 6–12 °C. Najjar and Hasan [21] developed a mathematical model for a greenhouse with PCM. Prediction results indicated that PCM could decrease the swing of indoor air temperature during the 24 h period by 3–5 °C. Guan et al. [22] developed a three-layer wall with PCM for solar greenhouses. By doing this, the effective heat storage capacity of the wall was increased by 12.2–14.0%, and the indoor air temperature at night was raised by 2.5 °C. In a previous study carried out by the authors of this paper [5], the thermal performance of walls with and without PCM was evaluated in a solar greenhouse, using both experimental and numerical methods. The study demonstrated a positive contribution to operative temperature, with a maximum temperature increase of 1.1 °C.

Although using PCM in walls of solar greenhouses can promote indoor thermal environment, they absorb and accumulate solar energy touching their irradiated surfaces in a passive way [23,24]. The stored heat would then be transferred into middle layer through heat conduction [25,26]. Due to the limited thermal conductivity of PCM, the heat could not be efficiently transferred to the middle layer of the walls, forming a thermal-stable layer inside the walls. The existence of this thermal-stable layer greatly decreases the wall's heat storage capacity. In previous studies carried out by the authors [27,28], PCM wallboards with a thickness of 200 mm have been incorporated into the standard greenhouse north wall, which had a thickness of 850 mm. Its temperature distribution was then calculated using a one-dimensional unsteady numerical heat transfer model, with calculation results shown in Fig. 1. The results reflected that solar energy received by the greenhouse had little influence on PCM after a depth of 150 mm. For the experimental wall, the thickness of the thermal-stable layer inside the wall has reached 750 mm. Guan et al. [22] also suggested that for a three-layer PCM wall with a thickness of 900 mm, the part that was affected by solar gains was only about 300 mm, and the thermal-stable layer had a thickness of 400 mm. Wang et al. [29] carried out a numerical study to predict the temperature distribution inside the north wall with an average thickness of 3.0 m. Based on the results, they suggested that the temperature of the middle part of walls, especially between 0.7 m and 2.3 m, would hardly change.

To improve the temperature of the middle layer and promote the heat storage capacity of north walls in solar greenhouses, an active method is highly required, by using ventilation to heat the middle layers effectively. Some researchers have explored the effectiveness of this method on promoting building performance [30,31]. Evola et al. [32] carried out a numerical study on a PCM wall, and found that the daily storage efficiency of the PCM wall could be improved by 78.2% when adding a ventilated cavity, with an increased thermal comfort frequency to 91.52%. El Mankib et al. [33] predicted the thermal behaviors of an active multi-layer ventilation wall with PCM using simulation. According to the prediction results, a maximum saving of 95% for heating could be achieved when using the ventilated wall with PCM. Diarce et al. [34,35] designed a PCM wall with a ventilated active façade and carried out an experimental study to identify its thermal performance. Their results showed that about 10–12% incident radiation could be stored by the ventilated active facade, with an increase of average indoor temperature of 1.1 °C.

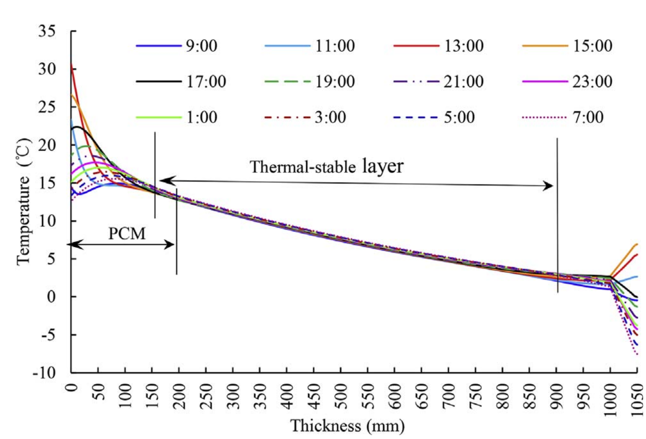

Fig. 1. Calculated temperature distributions of a PCM wall.