Applied Energy 140 (2015) 329–337

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Effect of phase change materials on indoor thermal environment under different weather conditions and over a long time

Haoshu Ling [a,*], Chao Chen [a,*], Shen Wei [b], Yong Guan [a], Caiwen Ma [c], Guangya Xie [a], Na Li [a], Ziguang Chen [a]

[a] College of Architecture and Civil Engineering, Beijing University of Technology, Beijing 100124, PR China
[b] Building Performance Analysis Group, Plymouth University, Plymouth PL4 8AA, UK
[c] Institute of Agricultural Mechanization, Xinjiang Academy of Agricultural Science, Urumqi 830091, PR China

HIGHLIGHTS

- Indicators evaluating the performance of PCMs in greenhouses are introduced.
- Real equivalent specific heat capacity of PCMs is embedded in a numerical model.
- Real behaviour of PCMs has been monitored over a long time.
- Efficiency of PCMs walls are compared for sunny and cloudy days.
- Heat storage and release amounts of PCMs walls have been calculated.

ARTICLE INFO

Article history:
Received 7 June 2014
Received in revised form 28 October 2014
Accepted 10 November 2014

Keywords:
Greenhouse
Phase change materials
Heat storage
Thermal environment
Evaluation methodology

ABSTRACT

To evaluate the effect of phase change materials (PCMs) on the indoor thermal environment of greenhouses under different weather conditions and over a long time in the heating season, a study was carried out using both experimental method and numerical method. The study was conducted in a typical greenhouse located in Beijing, China, and important parameters have been monitored continuously for 61 days, including indoor air temperature, outdoor air temperature, solar radiation, surface temperature of greenhouse envelopes and soil temperature. Based on these parameters, a number of indicators, namely, operative temperature, daily effective accumulative temperature, irradiated surface temperature of the north wall, average temperature of PCMs, and daily heat storage and release, have been used to evaluate the performance of PCMs in greenhouses. All indicators have provided consistent results that confirm the positive effect of PCMs on improving the indoor thermal environment of greenhouses over a long time. Additionally, the paper has demonstrated that a sunny weather could help to promote the efficiency of PCMs, comparing to a cloudy weather.

1. Introduction

Nowadays, the continuous increase of societal energy consumption has become a global issue. Buildings have contributed a lot to this issue [1], mainly due to the growing population and the increasing requirement of comfortable indoor thermal environment [2]. In order to reduce energy consumption of buildings without sacrificing occupants' comfort, incorporating phase change materials (PCMs) in building walls has been tested in a number of studies [3,4] and then been suggested as an efficient method [5–13], thanks to the high energy-storage density of PCMs within a relatively narrow temperature range [14–20].

Kuznik and Virgone [12] have investigated the thermal performance of a PCMs copolymer composite wallboard through experiment carried out in a test room. Based on the results, they concluded that the PCMs wallboard could help to keep the indoor air temperature within the thermal comfort zone. Similarly, Evola et al. [21] have suggested that the installation of PCM wallboards on the inner surface of partition walls could contribute to a reduction of peak operative temperature for about 1 °C. In an east–west oriented greenhouse, Berroug et al. [13] explored the thermal performance of the north wall made by PCMs as a storage medium, and they concluded that with an equivalent of 32.4 kg PCMs per square meters of the greenhouse ground surface area, the indoor

* Corresponding authors. Tel./fax: +86 10 67391608 201.
E-mail addresses: linghaoshu@163.com (H. Ling), chenchao@bjut.edu.cn (C. Chen).

http://dx.doi.org/10.1016/j.apenergy.2014.11.078
0306-2619/

Nomenclature

Symbols

B	lower limit of comfort (°C)
c	specific heat capacity (J kg^{-1} °C^{-1})
$DEAT$	daily effective accumulative temperature (°C h)
F	angle factor
h	heat transfer coefficient (W m^{-2} °C^{-1})
η	growth rate or rate (%)
Q	heat (kJ m^{-2})
t	temperature (°C)
τ	time (s)
ρ	density (kg m^{-3})
λ	thermal conductivity (W m^{-1} °C^{-1})
δ	thickness (m)

Subscripts

a	air
Br	brick
c	convection
$conw$	conventional wall
ehs	daily heat storage
ehr	daily heat release
hs	accumulated heat storage
i	node position
in	irradiated surface
In	polystyrene board
k	envelope and soil
op	operative temperature
ou	outer surface
PCM	phase change materials wallboard
$PCMw$	phase change materials wall
r	radiation
wa	wall

Superscript

j	time coordinate

Abbreviations

PCMs	phase change materials
EVAC	ethylene vinyl-acetate copolymer

air temperature at night was found to be 6–12 °C higher in winter with less fluctuations. Meng et al. [22] carried out both experimental and numerical studies for rooms with and without PCMs, and found out that the room with PCMs had a much less indoor air temperature fluctuation in winter, comparing to that without PCMs. Kumari et al. [23] have developed a thermal model of a greenhouse with a PCMs north wall, based on which they suggested that the PCMs north wall could contribute significantly to increasing the indoor air temperature. Najjar and Hasan [24] established two mathematical models for the heat storage material and the greenhouse, respectively. Using these models, they found that the fluctuation between the maximum and the minimum temperatures during 24 h was reduced by 3–5 °C by using PCMs. In a numerical study, Zhou et al. [5] have chosen the inner surface temperature and the diurnal energy storage to evaluate the effects of the thermal properties of PCMs wallboard on its thermal performance. From the study, they reported that a larger latent heat of PCMs could help to enhance the diurnal energy storage.

Based on the above review, it is found that although a number of studies have been carried out to explore the use of PCMs in building applications, there are still many problems with respect to both the analysis method and the indicators that are used to evaluate the effect of PCMs on the indoor thermal environment.

(1) Firstly, it has been widely known that the numerical analysis is an effective method to analyse the thermal performance of PCMs. However, during the calculation process, the equivalent specific heat capacity of PCMs was popularly simplified as a single value or a simple mathematical equation, and this simplification will increase the uncertainty of the analysis. PCMs are a kind of inhomogeneous materials [25], so their real thermal characteristics cannot be represented accurately by a single value or a simple mathematical equation.

(2) Secondly, when evaluating the thermal performance of PCMs incorporated in building walls, it has been very popular to examine the behaviour of PCMs in a representative sunny day. However, in reality, PCMs could work properly in sunny days, although the solidification is not effectively performed; it could also result useful in cloudy days, although melting is not produced effectively. Therefore, studies conducted on sunny days only might not be enough to prove the actual performance of PCMs in real buildings [26], and further studies should be carried out under different weather conditions and over a long time (a number of weeks or even months).

(3) Thirdly, the aim of using PCMs in building applications is to store heat during the daytime and release heat during the night-time. However, in existing studies, the amount of heat stored and released by PCMs walls was usually ignored from the analysis, but focusing on parameters such as indoor air temperature and wall surface temperature.

In this study, therefore, both experimental studies and numerical studies have been carried out for a greenhouse with and without PCMs, over a long time (61 days) and during both sunny days and cloudy days. In the analysis, a series of indicators, such as operative temperature, daily effective accumulative temperature, irradiated surface temperature of the north wall, average temperature of PCMs, and daily heat storage and release, have been used to evaluate the performance of PCMs in the case study building, aiming to provide a comprehensive evaluation of the effectiveness of PCMs in building applications.

2. Materials and methods

2.1. Experimental setup

The greenhouse used in this study is an agricultural building located in Beijing (40°N, 116°E). It is built to provide suitable micro-climate for plants during the off-season, without using heating in winter. The greenhouse faces south and extends along the east–west direction, as shown in Fig. 1a. It has a length of 54.0 m and a width of 5.8 m, and consists of a solid north wall (2.3 m height), a partial roof on the top of the north wall and a cover over the south part, as shown in Fig. 1b. The cover is made of transparent ethylene vinyl-acetate copolymer (EVAC) films with a thickness of 0.1 mm, which allows solar energy go into the greenhouse during the daytime (09:00 to 16:00). During the night time (16:00 to 09:00 day + 1), a 40.0 mm thick cotton blanket will be added onto the top of the EVAC cover, aiming to reduce heat