An experimental study on the application of polyalcohol solid-solid phase change materials in solar drying with cross-corrugated solar air collectors

W F Gao[1,3], W X Lin[1,2], T Liu[1] and M Li[1]

[1]Solar Energy Research Institute, Yunnan Normal University, Kunming 650500, P.R. China

[2]School of Engineering and Physical Sciences, James Cook University, Townsville, QLD 4811, Australia

E-mail: wenfenggao@163.com

Abstract. In this paper, two identical solar driers with the same cross-corrugated solar air collectors and drying chamber were developed, one with phase-change materials (PCMs) and the other without PCMs. These two solar drying systems were tested in typical sunny and cloudy days in Kunming and their thermal performances were analyzed. The experimental results show that the temperature changing is smoother in the collector with the PCMs, which is beneficial for the drying as the useful drying time was prolonged. The same trend was also found in the chamber with the PCMs. The PCMs in solar drying system was found to play a role in temperature regulating. There were several cycles of heat charging-discharging in a cloudy testing day while the temperatures on collectors and in chambers with the polyalcohol PCMs is higher than each phase-change temperature. Nevertheless, there was only one cycle of heat charging-discharging in a sunny testing day. The collector with PCMs has higher daily useful heat gain than the collector without PCMs.

1. Introduction

Solar drying technology has long been recognized as a very promising renewable energy technology, especially for rural regions and developing countries, as evidenced by its utilization in a wide range of applications such as the drying of crops, timber, fish, paddy, fruit, vegetable, etc. With the urgent request for a substantial reduction of global greenhouse gas emission to avoid a catastrophic climate change, the significance to develop and expand this promising renewable energy technology is becoming more evident and many new and improved solar drying facilities and technologies have been developed.

A solar air collector is a key component in a solar drying facility and its thermal performance dictates the efficiency and effectiveness of the drying facility. It is therefore essential for a solar drying facility to be equipped with a high thermal performance solar air collector. Nevertheless, due to the poor thermal conductivity and small heat capacity of air, the convective heat transfer rate inside the air flow channel formed by the absorbing plate and the bottom plate in a solar air collector, where the air is heated, is not high, resulting in a relatively poor thermal performance of the collector. A great deal of effort has been made to increase this rate [1]. Among many effective ways to augment the convective heat transfer rate in channel flows, those by increasing the heat transfer surface area and

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turbulence inside the channel with fins or corrugated absorbing surfaces and/or bottom surfaces have been the most popular [2] and many studies have been carried out on them [3,4]. A cross-corrugated solar air collector with a wavelike absorbing plate and a wavelike bottom plate which are positioned crosswise has attracted many interests attributed to its high thermal performance. For example, Piao *et al* [5] investigated experimentally the natural, forced and mixed convective heat transfer in a cross-corrugated channel solar air collector; Noorshahi *et al* [6] conducted a numerical study on the natural convection in a corrugated enclosure with mixed boundary conditions; Karim and Hawlader [7] evaluated, both analytically and experimentally, the thermal performance of a v-groove solar air collector under the meteorological conditions of Singapore; and more recently, we have made a comprehensive study on the thermal performance of v-groove and cross-corrugated solar air collectors under a wide range of configurations and operating conditions [8,9].

For many solar drying products, such as timber, vegetables, crops, fruits, etc., a lower temperature than that achieved by a high thermal performance solar air collector is usually required. Furthermore, to be cost effective, it is usually desirable for the solar drying facility to overcome the intermittence and diurnal nature of solar radiation. To meet this two-fold aim, this paper proposes an effective way to equip a high thermal performance solar air collector with heat storage materials that have suitable working temperatures for these low-temperature solar drying applications.

Among different types of heat storage, phase-change heat storage has the advantages of larger energy storage density, smaller volume, higher efficiency, fixed charging and discharging temperatures, etc. Many studies have been carried out using paraffin wax as Phase Change Material (PCM) in solar dryer [8-12]. Solid-solid phase-change heat storage is the process in which solid materials absorb a great deal of heat at a fixed temperature (charging temperature) and transfer from a low-symmetry crystal structure to a high-symmetry one, in which the materials store a great deal of heat which can then be discharged reciprocally. Compared to solid-liquid phase-change materials (PCMs), solid-solid PCMs have the advantages of smaller volume change during the phase-change process, no leakage, smaller erosion to the device, longer lifespan, etc., which make them particularly suitable for solar air collectors.

One of the most promising solid-solid PCMs are polyalcohols, polyethylenes, layered perovskites, etc. Among polyalcohols, neopentyl glycol (NPG, $C_5H_{12}O_2$), pentaerythritol (PE, $C_5H_{12}O_4$), trihydroxy methyl-aminomethane (TAM, $C_4H_{11}O_3N$), pentaglycerol (PG, $C_5H_{12}O_3$), etc., are the prevailing subjects of investigations. Benson [1], Son and Morehouse [13] made extensive experimental investigations into the heat storage performance of solid-solid polyalcohols including PE, NPG and trimethylol ethane and found that the mixtures of several different polyalcohols have the advantage of having adjusted transition temperatures which makes them attractive for low and medium-temperature utilizations such as in solar drying applications considered here. More recently, we have conducted a comprehensive experiment study on the heat storage performances of polyalcohols NPG, TAM, PE, and AMPD and their mixtures as solid-solid phase-change materials for solar energy applications [14-16].

In this paper, we carried out an experimental study on combining the advantage of the high thermal performance of the cross-corrugated solar air collector with the suitable working temperature of polyalcohols to construct solar drying facilities for low-temperature solar drying applications.

2. Experimental setup and method

2.1. Solar air collectors and the drying chamber

The experimental study was carried out in the solar drier sketched in figure 1. Air was pumped into the cross-corrugated solar air collector, where it was heated by solar radiation, before it passed through the drying chamber to carry away the moisture contained in the product to be dried in the chamber.

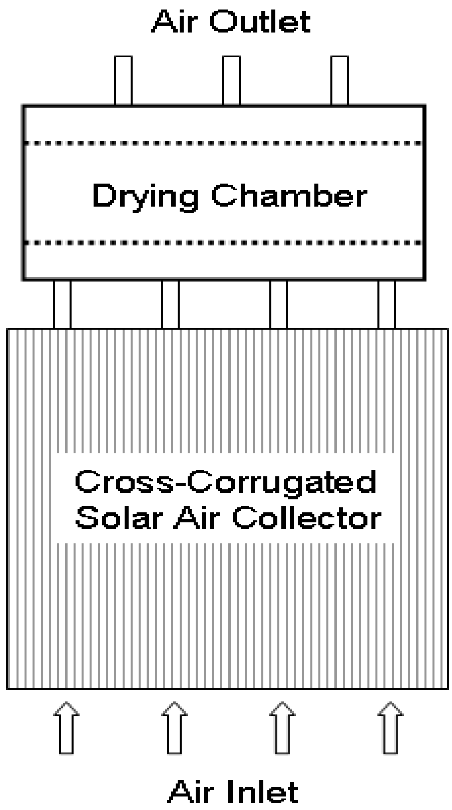

Figure 1. Schematic of the solar drying facility with a cross-corrugated solar air collector.

The cross-corrugated solar air collector was 1 m wide and 2 m long and consisted of a wavelike absorbing plate and a wavelike bottom plate, which were positioned crosswise to form the cross-corrugated air flow channel, as sketched in figure 2. The collector had a single flat glass cover, and the wavelike bottom plate was attached by a back insulation underneath. The air was heated by the absorbed solar radiation on the absorbing plate. Our previous studies [8, 9, 16] demonstrated that this type of cross-corrugated solar air collectors have significantly improved thermal performance compared to flat-plate solar air collector (with about 16% increase in efficiency).

The drying chamber, 0.8 m wide and 1 m long inside, was positioned higher than the collector and supported by a metal frame. On the top of the chamber, 3 chimneys were installed for the exiting of the air containing the removed moisture. Three mesh trays made of perforated stainless steel panels, on which the materials to be dried laid, were placed with equal spaces in the vertical direction inside the chamber.

Two identical such solar driers were constructed and installed in Kunming, China. In one drier, there were no PCMs used in the collector and the drying chamber. In the other drier, however, polyalcohol PCMs were used both in the collector and in the chamber. The locations of the PCMs in the collector, which were in direct contact with the absorbing plate, were inside the cross-corrugated air channel as sketched in figure 3, whereas the PCMs were placed on the bottom floor in the drying chamber.

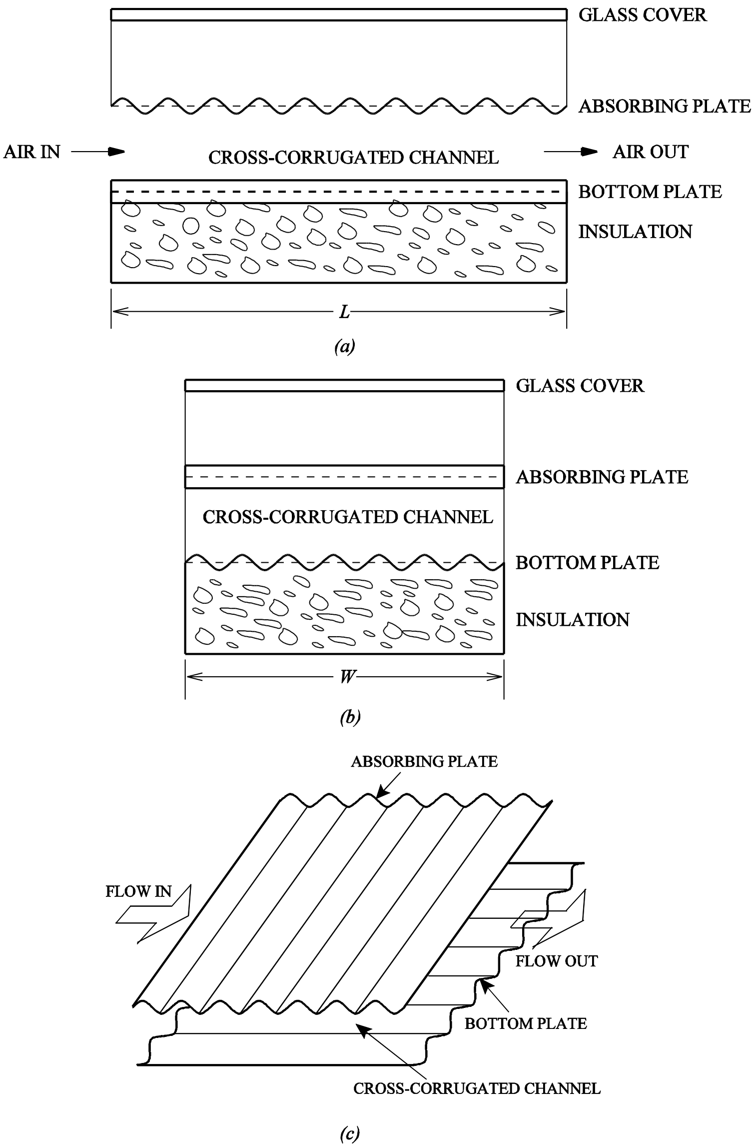

Figure 2. Schematic of the cross-corrugated solar air collector which has the cross-corrugated absorbing plate and bottom plate. The wavelike shape of the absorbing plate is along the flow direction and that of the bottom plate is perpendicular to the flow direction. (a) View on the cross section perpendicular to the flow direction; (b) View on the cross section along the flow direction; and (c) Isometric view of the cross-corrugated absorbing plate and bottom plate.

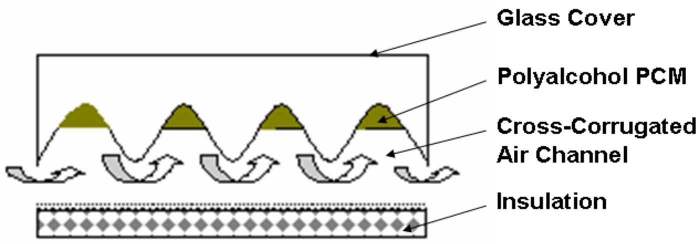

Figure 3. Schematic of the cross-corrugated solar air collector with polyalcohol phase-change materials.

2.2. PCM preparation

In order to choose appropriate PCMs for experiments, the data of phase-change temperature and enthalpy for the binary mixtures of polyalcohols NPG/TAM, NPG/PE and NPG/PG which approach the working temperature of solar drying are listed in table 1. It is found that the phase-change temperature and enthalpy decrease with the decrease of the weight ratio of NPG in the binary mixtures. It is also found that binary mixtures with higher weight ratios of NPG are more suitable for lower temperature (30-50℃) solar thermal applications, and those with higher weight ratios of TAM or PG are more suitable for higher temperature (70-150℃) solar thermal applications.

Table 1. Phase-change temperatures and enthalpies of polyalcohol mixtures.

Polyalcohol mixtures	Weight percentage x (%)	Phase-change temperature (°C)	Phase-change enthalpy (J/g)
TAMxNPG1-x	0	44.09	116.54
	20	37.86	95.23
	35	36.48	82.50
	50	38.45	38.46
	65	36.45	12.88
	80	39.54	6.34
	100	133.83	270.31
PExNPG1-x	0	44.0	116.5
	16	34.0	99.03
	20	33.5	57.7
	28	33.5	26.0
	30	33.5	13.4
	40	33.0	13.0
	60	35.0	10.7
	80	32.0	N/A
	90	35.0	N/A
PGxNPG1-x	0	44.09	116.54
	30	31.14	73.55
	50	38.09	55.28
	70	40.32	27.79
	89	36.62	6.18
	100	81.76	172.58

The PG was selected as PCMs for the solar collector because it has higher working temperature and NPG was selected as PCMs for the drying chamber as it has lower working temperature. To improve the poor heat conductive performance of PCMs in practical applications, the aluminum powder was well mixed with the prepared polyalcohols by a weight ratio of 1:1.

2.3. Experimental methodology

To measure the thermal performance of the solar driers, a series of sensors were placed in the two driers. In each drier, three PT-100 temperature sensors were placed at the lower, middle and upper section on the absorbing plate of the collector along the air channel direction to measure the temperatures in the channel; three PT-100 temperature sensors were also placed inside the drying chamber with equal spaces to measure the temperatures in the chamber. The average values from the respective three sensors were taken to be the average temperatures of the collector and the chamber respectively. Two PT-100 temperature sensors were placed at the outlets of the collector and the chamber in each drier. One PT-100 temperature sensor was used to measure the ambient air temperature. A CM11 pyranometer manufactured by Kipp & Zonen with the measuring error less than 1% was used to measure the solar radiation fallen on the collector's surface. The temperatures and solar radiation from these sensors and the pyranometer were collected and recorded every 5 minutes by a data logger.

A fine leaf plant named Solidago Decuurrens, which is usually dried as dried flowers, was selected and placed onto each tray of the two chambers with the same amount before the testing day. There were 15 kg of Solidago Decuurrens in each chamber. The tests were carried out under several different weather conditions. In every testing day, the experiment started at 9:00 am and ended at 6:00 pm. The data under two typical weather conditions, that is, in a sunny day and in a cloudy day, were selected for analysis in the subsequent section.

3. Experimental results and discussions

The time series of the measured average collector temperature, the outlet temperature, and the ambient temperature in a typical sunny testing day are presented in figure 4 for both the solar driers with and without the polyalcohol PCMs. It is seen that the average temperatures of both collectors rose promptly after the testing started, and attained their maxima at about 1:00 pm at which time the incident solar radiation also reached its maximum, as shown in figure 5, where the time series of solar radiation incident on the collector surface in a typical sunny testing day and in a typical cloudy testing day are presented, respectively. The PCMs in the collector started charging heat while the temperature of the collector was more than 82℃, which was higher than the phase-change temperature of the PG. Consequently, the rate of the temperature increase on the collector with the PCMs became smaller than that on the collector without PCMs. The temperatures of both collectors declined promptly with the fall of the incident radiation after it attained its maximum at 1:00 pm; but after 3:00 pm, the rate of the temperature drop on the collector with the PCMs became slower than that on the collector without PCMs, in particular during the period of 4:00-5:00 pm of the testing period, as the PCMs were discharging heat due to the collector temperature being lower than the phase-change temperature of the PG. This trend can also be seen from the time series of the outlet temperature of the collector as shown in figure 4.

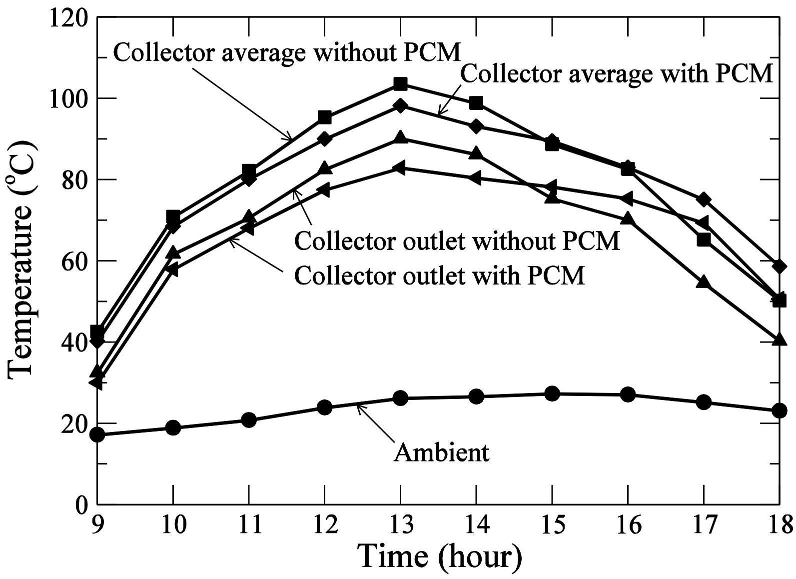

Figure 4. Measured collector average and outlet temperatures, both with and without the polyalcohol PCMs, and the ambient temperature in a sunny testing day.

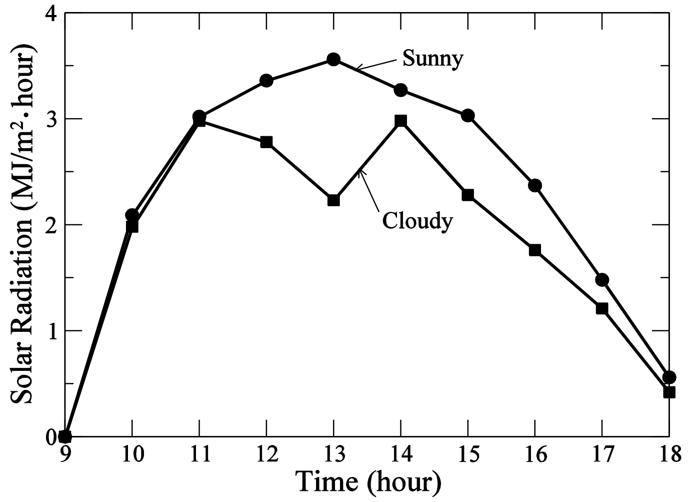

Figure 5. Time series of solar insolation incident on the collector surface both in a sunny testing day and in a cloudy testing day.

Figure 6 presents the measured average temperatures and outlet temperatures in the drying chambers with and without the polyalcohol PCMs in a typical sunny testing day. It is seen that the PCMs started charging heat while the temperature in the chamber was more than 45℃, which is higher than the phase-change temperature of the NPG, leading to slower rate of the temperature rise in the chamber with the PCMs than that in the chamber without PCMs. The temperature in the chamber with the PCMs gradually decreased after 13:00 pm in the sunny testing day as the PCMs started discharging heat after that instant when the temperature in the chamber with the PCMs began to fall below 40℃. The actual drying time was prolonged one hour in the chamber with PCMs than that in the chamber without PCMs. Although the temperature drop in the chamber with the PCMs had the similar trend as that in the collector with the PCMs, however, the rate of the drop was smaller, as clearly shown in figures 4 and 6. The outlet temperatures of the chambers were lower than those inside the chambers. Obviously, this is a result that the drying plants had absorbed a significant portion of heat.

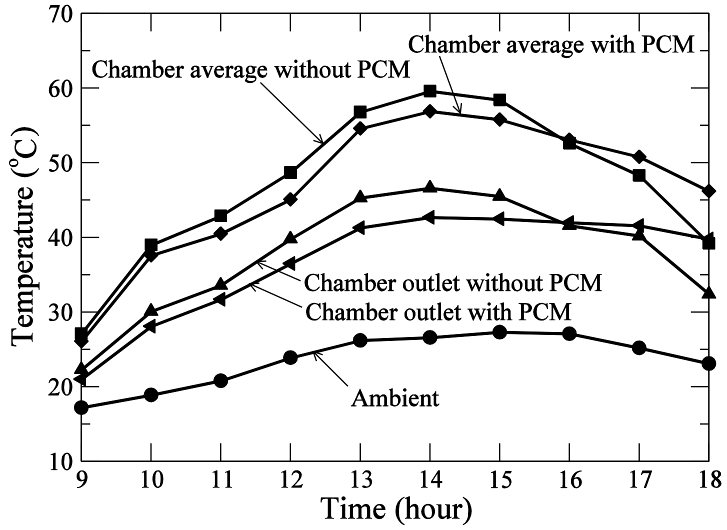

Figure 6. Measured average and outlet temperatures in the drying chamber, both with and without the polyalcohol PCMs, and the ambient temperature in a sunny testing day.

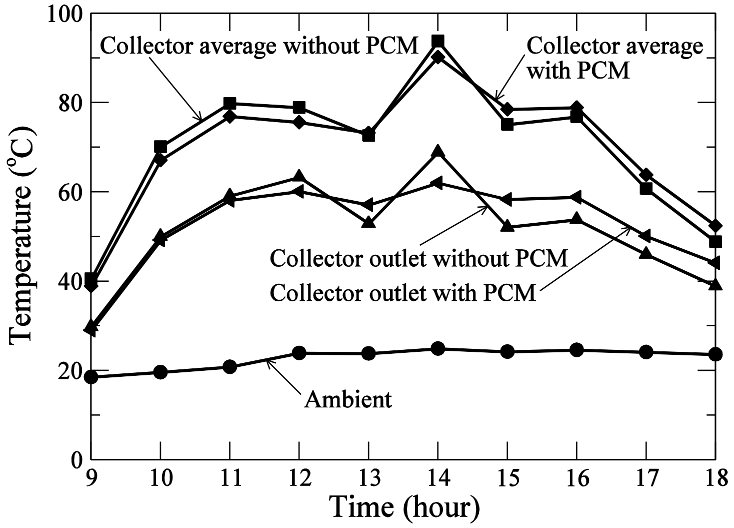

Figure 7. Measured collector average and outlet temperatures, both with and without the polyalcohol PCMs, and the ambient temperature in a cloudy testing day.

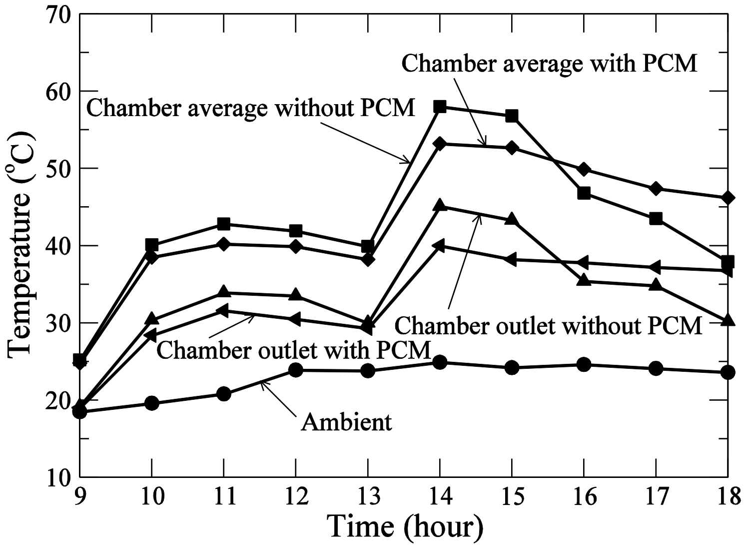

Figure 8. Measured average and outlet temperatures in the drying chamber, both with and without the polyalcohol PCMs, and the ambient temperature in a cloudy testing day.

The time series of the measured average collector temperature, the outlet temperature, and the ambient temperature in a typical cloudy testing day are presented in figure 7 for both the solar driers with and without the polyalcohol PCMs, whereas the measured average temperatures and outlet temperatures in the drying chambers with and without the polyalcohol PCMs in a typical cloudy testing day are shown in figure 8. It is clear that there were several charge-discharge processes in the typical cloudy day due to the intermittence of the incident solar radiation, in contrast to the single charge-discharge process in the typical sunny day. When the working temperatures in collectors with and without PCMs are compared, it can also be concluded that the collector with PCMs has lower working temperature, but it is high enough for the drying applications. This means that the collector with PCMs has smaller heat loss and higher thermal efficiency than the collector without PCMs. Meanwhile, the temperature changing is much smoother in the drier with PCMs, which benefits the drying and the useful drying time was prolonged. Furthermore, it is clear that the PCMs in solar drying system play an important role in the temperature regulating of the drying applications.

4. Conclusions

The polyalcohol PCMs has the advantages of larger energy storage density, smaller volume, higher efficiency, fixed charging and discharging temperatures, among others. It can be used in solar thermal applications which require appropriate phase-change temperatures and enthalpies. In this paper, the cross-corrugated solar air collector with the PG PCMs and the chamber with the NPG PCMs in solar drying systems were developed and the characters of drying systems were investigated and compared to the identical solar drying system without PCMs under sunny and cloudy testing conditions.

The experimental results show that there were several charging-discharging processes in the solar drier with PCMs in a typical cloudy testing day while there was only one charging-discharging process in the solar drier with PCMs in a typical sunny day. The cross-corrugated solar air collector with PCMs has lower heat loss and higher heat efficiency than the collector without PCMs. The temperature changing is more smoother which benefit for drying and the useful drying time has been prolonged. It has similar trend in the chamber with PCMs as the collector with PCMs. The PCMs in solar drying system play a role in temperature regulating.

Acknowledgments

The authors would like to acknowledge the support from the National Natural Science Foundation of China (51469035, 11662021) and the Australian Research Council (ARC, DP160102134).

References

[1] Benson D K, Burrows R W and Webb J D 1986 Solid-state phase-transitions in pentaerythritol and related polyhydric alcohols *Solar Energy Materials* **13** 133-52
[2] Goldstein L and Sparrow E M 1977 Heat/mass transfer characteristics for flow in a corrugated wall channel *ASME J Heat Transf* **99** 187-95
[3] Meyer B A, Mitchell J W and El-Wakil M M 1982 Convective heat transfer in Vee-trough linear concentrators *Solar Energy* **28** 33-40
[4] Stasiek J A 1998 Experimental studies of heat transfer and fluid flow across corrugated-undulated heat exchanger surfaces *Int. J. Heat Mass Transfer* **41** 899-914
[5] Piao Y, Hauptmann E G and Iqbal M 1994 Forced convective heat transfer in cross-corrugated solar air heaters *ASME J. Solar Energy Eng* **116** 212-4
[6] Noorshahi S, Hall III C A and Glakpe E K 1996 Natural convection in a corrugated enclosure with mixed boundary conditions *ASME J. Solar Energy Eng* **118** 50-7
[7] Karim M A and Hawlader M N A 2006 Performance evaluation of a v-groove solar air collector for drying applications *Applied Thermal Eng* **26** 121-30
[8] Gao W F, Lin W X and Lu E R 2000 Numerical study on natural convection inside the channel between the flat-plate cover and sine-wave absorber of a cross-corrugated solar air heater *Energy Conversion & Management* **41** 145-51
[9] Gao W F, Lin W X, Liu T and Xia C F 2007 Analytical and experimental studies on the thermal performance of cross-corrugated and flat-plate solar air heaters *Applied Energy* **84** 425-41
[10] Khadraoui A E, Bouadila S, Kooli S, Farhat A and Guizani A 2017 Nocturnal usage of solar air collector with PCM *Journal of Cleaner Production* **148** 37-48
[11] Shalaby S M and Bek M A 2014 Experimental investigation of a novel indirect solar dryer implementing PCM as energy storage medium *Energy Conversion and Management* **83** 1-8
[12] Jain D and Tewari P 2015 Performance of indirect through pass natural convective solar crop dryer with phase change thermal energy storage *Renewable Energy* **80** 244-50
[13] Son C H and Morehouse J H 1991 An experimental investigation of solid-state phase-change materials for solar thermal storage *ASME Journal of Solar Energy Engineering* **113** 244-9
[14] Wang X W, Lu E R, Lin W X and Wang C Z 2000 Micro-mechanism of heat storage in a binary

systems of two kinds of poly-alcohols as a solid-solid phase change material *Energy Conversion & Management* **41** 135-44

[15] Wang X W, Lu E R, Lin W X, Liu T, Shi Z S, Tang R S and Wang C Z 2000 Heat storage performance of the binary systems NPG/PE and NPG/TAM as a solid-solid phase change material *Energy Conversion & Management* **41** 129-34

[16] Gao W F, Lin W X, Liu T and Xia C F 2007 An experimental study on the heat storage performances of polyalcohols NPG, TAM, PE, and AMPD and their mixtures as solid-solid phase-change materials for solar energy applications *Int. J. Green Energy* **4** 301-11