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Experimental and numerical investigation of a solar collector/storage system with composite phase change materials

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ABSTRACT

This paper proposes a novel solar collector/storage system using erythritol as phase change material (PCM). The expanded graphite (EG) in mass fraction of 3% was added into the PCM to form a composite PCM, so as to enhance the thermal conductivity of the PCM. An experimental investigation was carried out to study the performance of the solar collector/storage system in charging process. Then, based on the enthalpy-porosity and melting/solidification models, a numerical model was established and experimentally validated. Furthermore, the heat transfer characteristics in the solar collector/storage system was simulated. Finally, the heat discharging performance of the system was predicted under different inlet temperatures and inlet flow velocities. The results show that the solar collector/storage system with composite PCM has good thermal storage performance, and the daily average storage efficiency reached 39.98%. Meanwhile, when the daily irradiance is larger than 15.23 MJ/m^2, the system could completely finish the latent heat charging process.

1. Introduction

With the continuous increasing of greenhouse gas emission and the growing shortage of fossil energy, solar energy technologies are gaining momentum (Belessiotis and Papanicolaou, 2012; Su et al., 2017; Duffie and Beckman, 2006; Kannan and Vakeesan, 2016). However, the innate drawbacks of solar energy are its intermittent and periodic nature in solar irradiation. Thermal energy storage (TES) has been proposed as one of the most potential solution for solving the drawbacks, because it is capable of shifting peak load by absorbing extra heat at the peak irradiation hours and releasing it when there's insufficient irradiation (Pelay et al., 2017; Sansaniwal et al., 2017; Guney, 2016).

Basically, TES can be divided into three types: sensible thermal energy storage, thermo-chemical storage and latent thermal energy storage (LTES) (Alva et al., 2017; Wenger et al., 2017). LTES has received tremendous attention in recent years due to its high energy storage density and near isothermal operation characteristics during melting and solidification (Wang et al., 2016). For decades, researches on LTES for solar thermal engineering mainly focused on the development of PCMs, the storage structural design, and the integration methods with solar collectors.

Since many PCMs have low thermal conductivity values, which seriously slows down the heat charging and discharging process, some thermally conductive additives have been explored for improving their thermal conductivities. Sarı and Biçer (2012) prepared some form-stable PCMs by absorbing galactitol hexa myristate (GHM) and galactitol hexa laurate (GHL) esters into porous networks of diatomite, perlite and vermiculite. The expanded graphite (EG) in mass fraction of 5% was added into these PCMs in an effort to increase their thermal conductivities. The results showed that the thermal conductivities of these PCMs had increased by about 26.3–66.7%. Jin et al. (2015) developed paraffin based composite PCMs with different EG concentration. The results indicated that the latent heat of the composite PCMs were decreased after adding EG, but their thermal conductivities were significantly improved, resulting better heat transfer performance. In order to get higher thermal conductivity, Gilart et al. (2012) embedded paraffin wax, stearic acid and polyethylene glycol in a carbon-containing host matrix (EG or multiwall carbon nanotubes) to. As a result, an increase of up to 576% in thermal conductivity for EG + 75% RT-50 was obtained.

In addition to the efforts on improving the thermal-physical properties of PCMs, many experimental and theoretical studies were conducted to investigate the heat transfer mechanism of various LTES systems. The effects of the structural and operating parameters on the performance of the LTES systems have also been discussed. Meng et al. (2017) built a tube-in-tank LTES unit using paraffin as PCM. The results showed that the unit has the best heat transfer performance when the volume fraction of PCM is 91.45%, the temperature field of the PCM was uniform and almost symmetric to the center axis of the LTES unit. Zhang et al. (2016) built a shell-tube LTES system using eutectic molten

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Nomenclature

A_f	porosity function in Carman-Kozeny equation
C	constant in Eq. (5)
c_p	heat capacity (J/(kg·K))
f	liquid fraction
g	gravitational acceleration (m/s^2)
H	enthalpy (J/kg)
h	heat transfer coefficient (W/(m^2·K))
k	thermal conductivity (W/(m·K))
P	pressure (Pa)
q	heat flux (W/m^2)
T	temperature (°C)
t	time (s)
U	heat loss coefficient (W/(m·K))
u	velocity in x-direction (m/s)
v	velocity in y-direction (m/s)
w	velocity in z-direction (m/s)
x	coordinate (m)
y	coordinate (m)
z	coordinate (m)

Greek symbols

β	thermal expansion coefficient (K^{-1})
ζ	constant in Eq. (5)
ε	emissivity
ρ	density (kg/m^3)
σ	Stefan-Boltzmann constant
μ	dynamic viscosity (Pa·s)
η	storage efficiency

Subscripts

a	air
c	convective
ref	reference state
i	inner
l	liquid state of phase change materials
o	outer
r	radiant
s	solid state of phase change materials
w	water
wind	wind

salt as PCM. The nickel foam was used as an additive to the PCM for improving its thermal conductivity. The system performances during the heat charging and discharging processes were experimentally and numerically compared between the unit with and without nickel foam. The results showed that the nickel foam could effectively enhance the thermal conductivity of the PCM. Atal et al. (2016) investigated a LTES device with a shell and tube arrangement. The paraffin wax was saturated with two different aluminum foam with porosity of 95% and 77%. Both experimental and numerical investigations were performed to study the thermal performance of the device. The results showed that the use of aluminum foam significantly reduced the time needed of a charging-discharging cycle.

In view of the drawbacks of solar energy and advantages of LTES, the integration of LTES with the solar collector is advantageous in reducing the temperature fluctuations during the peak solar radiation hours. Besides, the integration of LTES is capable of minimizing the heat loss from the solar collector by absorbing the excess heat from the absorber. Kürklü et al. (2002) developed a solar collector/storage system by integrating paraffin into a solar collector with 1.44 m^2 aperture area. A short term experiment was carried out to investigate the system performance. The experimental results indicated that the collector efficiency could reach 80%. Moreover, the collector was able to maintain the water temperature above 36 °C during the whole night. Khalifa et al. (2013) connected six pipes with the diameter of 80 mm in series as an absorber and integrated it with a back container filled with paraffin wax. The experimental investigation was performed both under clear day and semi-cloudy day. The results showed that the instantaneous efficiency of the storage system varied from 45% to 54% and the average solar collector top loss coefficients were 6.22 W/(m^2·K), 6.39 W/(m^2·K) and 6.23 W/(m^2·K) at the month of January, February and March, respectively. The variation of the mean plate and wax temperatures with time showed a similar trend for the clear days of January and February. Al-Hinti et al. (2010) encapsulated paraffin wax into small cylindrical aluminum containers. A total of 38 such containers were fixed in a water tank to form a TES, and each container contains 1.0 kg of paraffin wax. When integrated with conventional flat plate collectors, the water-PCM storage succeeded in keeping the water temperature over 45 °C under all operating and climatic conditions. Bouadila et al. (2014) integrated two rectangular cavities with a flat plate solar collector. Paraffin was used as PCM. The experiments were carried out under different weather conditions. The results showed that the solar collector remains a uniform output power around 400 W for 5 h after sunset and the energy efficiency varied between 25% and 35%.

Although many studies were directed for the utilization of LTES in solar thermal systems, those studies are mainly applied for low-temperature utilization (< 80 °C). The application of LTES in mid-temperature utilization (80–250 °C) is relatively few. Solar energy has many valuable applications in mid-temperature region, such as a hot water heating system (about 95 °C), a thermally driven single stage BrLi/H_2O cooling system (about 95 °C) and etc. As a result, the application of LTES in solar mid-temperature utilization has a great research prospect.

In this paper, a novel solar collector/storage system using erythritol as PCM was proposed. For the purpose of enhancing the thermal conductivity of PCM, 3 wt% EG was embedded into erythritol. Based upon the thermal-physical properties of the composite PCM, the performance of the solar collector/storage system with the composite PCM was investigated experimentally. Meanwhile, a mathematical model based on enthalpy-porosity and melting/solidification models was established to investigate the heat transfer characteristics of the solar collector/storage system. Finally, the numerical simulations were conducted to predict the variations in system performance with daily solar irradiance. In addition, the heat discharging performances of the system under different inlet temperatures and inlet flow rates were also predicted.

2. Experimental setup

2.1. Experimental setup of the collector/storage unit

A novel solar collector/storage system using composite PCM was designed. In a practical application, such a solar collector/storage system is firstly put in the sun exposure to collect and store heat by the charging process of PCM. And then, the stored heat is delivered to a heat consumer by the discharging process of PCM when required. The structure of a collector/storage unit is shown in Fig. 1. As shown, the unit is composed of four parts. The external one is the evacuated pipe, which is 1800 mm in length and 58 mm in diameter. An aluminum pipe with the diameter of 42 mm is coaxially inserted next to the evacuated pipe, which is used for encapsulating the composite PCM. Each aluminum pipe is filled with 1.7 kg composite PCM. A copper pipe is also fixed in the center of the aluminum pipe, which acts as the flow passage