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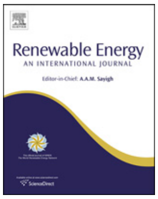

Dynamic discharging characteristics simulation on solar heat storage system with spherical capsules using paraffin as heat storage material

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ABSTRACT

The dynamic characteristics of solar heat storage system with spherical capsules packed bed during discharging process are studied. According to the energy balance of solar heat storage system, the dynamic discharging processes model of packed bed with spherical capsules is presented. Paraffin is taken as phase change material (PCM) and water is used as heat transfer fluid (HTF). The temperatures of PCM and HTF, solid fraction and heat released rate are simulated. The effects of inlet temperature of HTF, flow rate of HTF and porosity of packed bed on the time for discharging and heat released rate are also discussed. The following conclusion can be drawn: (1) the heat released rate is very high and decreases rapidly with time during the liquid cooling stage, it is stable at the solidification cooling stage, then it decreases to zero at the solid cooling stage. (2) The time for complete solidification decreases when the HTF flow rate increases, but the effect is not so obvious when the HTF flow rate is higher than 13 kg/min; (3) compared to the HTF inlet temperature and flow rate, the influence of porosity of packed bed on the time for complete solidification is not so significant.

1. Introduction

Thermal storage is classified as sensible and latent heat storage systems or the combination of these. The advantages of the latent heat system (LHS) in comparison with sensible storage system are high heat storage density, small size of the system and a narrow temperature change during charging and discharging processes. In the latent heat storage system, energy is stored during melting process while it is recovered during the freezing process. The latent heat systems using phase change material as storage medium are not well in commercial use because of the poor heat transfer rate during the storage and recovery process [1].

Phase change materials (PCMs) which can absorb/release high latent heat during the melting/solidifying process, have been receiving attention for various applications such as waste heat recovery [2–4], solar heating system [5–7] and building energy conservation [8–10] in recent years. Many materials were chosen as PCMs which are grouped into two categories, namely, organic and inorganic PCMs. Compared to inorganic material, organic materials melt and freeze repeatedly without phase segregation and consequent degradation of their latent heat of fusion; with little or no super-cooling and usually non-corrosiveness. Fatty acid such as stearic acid, palmitic acid, myristic acid and lauric acid, etc. are promising PCMs for LHS [11–16]. Sari and Kaygusuz [17] studied the thermal performance and phase change stability of stearic acid as heat storage material experimentally. Sharma et al. [18] conducted 1500 accelerated thermal cycle tests to study the changes in latent heat of fusion and melting temperature of commercial grade acetamide, stearic acid and paraffin wax. It has been noticed that the stearic acid melts over a wide range of temperature, has shown two melting points and has large variations in latent heat of fusion. Mazman et al. [19] performed the method to enhance the heat transfer and fatty acids were taken as PCM.

Some paraffins were used as PCMs in latent heat storage system. A lot of investigation on latent heat storage system was carried out in the past [20–24]. Nallusamy et al. [25] performed experimental investigation on a combined sensible and latent heat storage system integrated with constant/solar heat sources. Paraffin was used as PCM filling in the spherical capsule. The effects of variation in the inlet temperature and the flow rate of the HTF on the performance of the storage unit were studied. Cho and Choi [26] investigated thermal characteristics of paraffin in a spherical capsule during freezing and melting processes. Paraffin, i.e. n-tetradecane, and a mixture of n-tetradecane (40%) and n-hexadecane (60%) were taken as PCMs. The average heat transfer coefficient were affected by the inlet and initial temperature and Reynolds number more during the melting process

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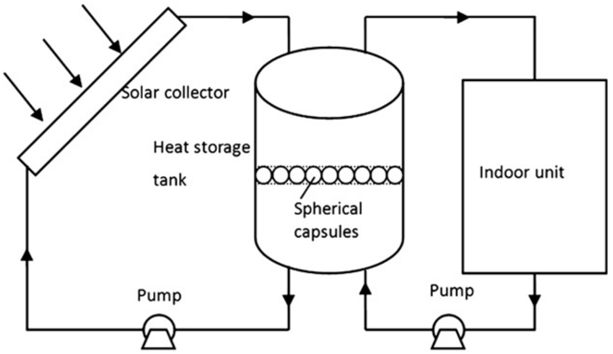

Fig. 1. The schematic diagram of solar heat storage system with spherical capsules.

than during the freezing process. Kousksou et al. [27] developed a theoretical model for analysis and optimization of the solar system with cylindrical tank which contains spherical capsules filled with PCM. Energy and exergy analyses were carried out to understand the behavior of the system using single or multiple PCMs. Akgun et al. [28] experimentally studied the latent heat thermal energy storage system of the shell-and-tube type. Three kinds of paraffin with different melting temperature were used as PCMs. The effects of the Reynolds and the Stefan number on the melting and solidification behaviors were determined. Qarnia [29] presented a theoretical model based on the energy equations to predict the thermal behavior and performance of a solar latent heat storage unit consisting of identical tubes embedded in the PCM. A series of numerical simulations were conducted for three kinds of PCM (n-octadecane, paraffin wax and stearic acid) to find the optimum design and also made to study the effect of flow rate on its outlet temperature during the discharging mode.

The present work presents a numerical model and studies the dynamic characteristics of packed bed using paraffin as PCM during solar heat releasing process. Numerical studies are carried out to discuss the influences of the inlet temperature, flow rate of HTF and porosity of packed bed on the solidification time and heat released rate.

2. Mathematical model on solar heat storage system

The schematic diagram of the solar heat storage system is shown in Fig. 1. It consists of a solar collector, indoor unit and a cylindrical storage tank. The storage unit, which is called as packed bed, is a cylindrical storage tank containing spherical capsules filled with PCM (paraffin). The packed bed is a cylindrical storage tank of height *H* and internal diameter *D*. In the discharging process, the cool heat transfer fluid (water) flows over the spherical capsules in packed bed and the PCM in the spherical capsules solidifies. In this study, only discharging process is studied numerically.

The energy equations that govern heat transfer in system are based on the following assumptions: (1) temperatures of PCM and HTF only vary along the axial direction, (2) thermo-physical properties of the PCM and HTF are constant, (3) the effect of natural convection in the PCM is neglected, (4) the PCM has a constant phase change temperature, (5) the velocity profile is regarded as fully developed flow in axial direction.

In this model, the PCM capsules behave as a continuous medium and not as a medium comprised of individual particles. With abovementioned assumptions, the conservation equations for PCM and HTF are stated.

Heat transfer fluid:

$$\rho_f \cdot c_f \cdot \varepsilon \frac{\partial T_f}{\partial t} + \rho_f \cdot c_f \cdot \varepsilon \cdot u \frac{\partial T_f}{\partial x} = k_f \cdot \varepsilon \frac{\partial^2 T_f}{\partial^2 x} + h_{eff} \cdot a_p \left(T_p - T_f\right) - h_w \cdot a_w \left(T_f - T_{sur}\right) \tag{1}$$

where ρ_f, c_f, k_f, T_f and u are the density, specific heat, thermal conductivity, temperature and velocity of HTF, respectively. T_p is the temperature of PCM, T_{sur} is the temperature of surroundings, a_p is the surface area of spherical capsules per volume, a_w is the convective wall area of packed bed per volume, h_{eff} is the effective coefficient of convective heat transfer, h_w is the convective coefficient of heat transfer between packed bed and ambient, ε is the void fraction of packed bed, x is the location of the flow direction, t is time.

The first term of the left hand side of Eq. (1) represents the change rate of internal energy of HTF, while the second term accounts for energy change due to the HTF flow. The three terms on the right hand represent the heat change by conduction, the energy transfer by convection between the HTF and the capsules, and the heat leak through the wall of the cylindrical container, respectively. While in the solidification process, T_p should be equal to T_s.

Phase change material (PCM):

Liquid phase:

$$\rho_l \cdot c_l (1-\varepsilon) \frac{\partial T_p}{\partial t} = h_{eff} \cdot a_p \left(T_f - T_p\right) \tag{2}$$

where ρ_l and c_l are the density and specific heat of liquid phase PCM, respectively.

Solidification process:

$$\rho_s \cdot L (1-\varepsilon) \frac{\partial \Phi}{\partial t} = h_{eff} \cdot a_p \left(T_s - T_f\right) \tag{3}$$

where L is the solidification latent heat of PCM, Φ is the solid fraction of PCM, T_s is solidification temperature of PCM.

Eq. (3) represents the latent heat released from PCM is equal to the heat transfer to the HTF during the solidification process.

Solid phase:

$$\rho_s \cdot c_s (1-\varepsilon) \frac{\partial T_p}{\partial t} = h_{eff} \cdot a_p \left(T_f - T_p\right) \tag{4}$$

where ρ_s and c_s are the density and specific heat of solid phase PCM, respectively.

Eq. (4) represents the internal energy change of PCM is equal to the heat transfers by convection from PCM capsules to HTF.

The initial and boundary conditions for the above equations are stated in the following. At the beginning of the discharging process, the temperatures of HTF and PCM are above the solidification temperature. So,

$$T_f(t = 0) = T_i \tag{5}$$

$$T_p(t = 0) = T_i \tag{6}$$

where T_i is the initial temperatures of PCM and HTF.

At the inlet of packed bed, the fluid is assumed to be at constant temperature. Therefore,

$$T_f(x = 0) = T_{in} \tag{7}$$

where T_{in} denotes the inlet temperature of HTF.

The temperature of HTF at the bed outlet for $x > H$ is assumed to be constant. Therefore,

$$\frac{\partial T_f}{\partial x}(x = H) = 0 \tag{8}$$

In the present study, the form of correlation used for the heat transfer coefficient of the spherical capsules and HTF was developed by Beek [30] for the case of capsules arranged in a random form.

$$Nu = 3.22 Re^{1/3} Pr^{1/3} + 0.117 Re^{0.8} Pr^{0.4} \tag{9}$$