Energetic Analysis of Packed Bed Latent Heat Storage Systems

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Abstract. Nowadays, with the rapid growths in world population and economy, the world energy demand and consumption have increased enormously which led to a wide variety of harsh environmental impacts [1]. As a potential solution for energy conservation storing the excess energy to fill the gap between energy supply and demand, using phase change materials (PCMs) has received much attention. Thermal energy storage with PCM is a promising technology based on the principle of latent heat thermal energy storage (LHTES)[2], where PCM absorbs or releases large amounts of energy at a certain temperature during the phase change transition period (charging and discharging process), with a high heat of fusion around its phase change temperature range [3]. Thermal energy storage in packed beds is receiving increased attention as a necessary component for efficient implementation of concentrated solar power plants. In this study, the thermal characteristics, during a single charge period, of a packed bed made of PCM filled spherical capsules is presented. It was found that the energy efficiency of the system proved to be very sensitive to the choice of the PCM melting temperature.

1 Introduction

Thermal energy storage is considered as one of the key elements to accomplish energy recovery and utilization of solar energy, industrial waste heat, and off-peak electricity. The simplest way of storing thermal energy is as sensible heat i.e. when a material absorbs energy by increasing its temperature without any change of phase. However, this type of storage is the least efficient method because of the low thermal capacity of the medium. In return, thermal energy storage by phase change energy (latent heat) of a suitable material has the advantage of featuring a much higher energy density level (given the smaller volumes involved) and a fairly isothermal behavior[4,5]. In such systems, the PCM can be encapsulated by using different confinement configurations (cylindrical geometries with or without fins, plates, or spherical capsules). The spherical geometry seems to offer a number of advantages which ranks it among the most attractive methods of encapsulation.

Indeed, the spherical capsules are preferred due to their favorable ratio of volume of stored energy to surface of heat transfer and the easiness of their packing into the storage tank with good bed porosity [6, 7].

The proper selection of the storage material depends largely on the temperature properties of the primary source of energy. In any case though, the "ideal" PCM candidate for storing energy should i) possess a high latent heat of transformation, ii) be stable, cheap and widely available, iii) environmentally friendly and last but not least iv) compatible with the other materials of the system equipment [8][9][10].

As far as thermal energy storage systems are concerned, Bejan [11] pointed out that their primary purpose is not to store energy (as suggested by the name), but rather to store useful work e.g. thermodynamic availability. Based on this, many researchers carried out extensive analyses of latent thermal energy storage systems using the second law of thermodynamics [12-14]. Most of these analyses were limited though to study separately a charge and discharge single period and a small number of studies have been devoted so far to study cyclic melting/freezing of simple systems using PCM [15]. Gong and Mujumdar [16] were apparently the first authors to analyze alternating melting/freezing processes involving composite multi-layer PCM slabs. For such a configuration, they found that the energy charge/discharge rate could be increased. Gong and Mujumdar [17] further investigated the effect of different layouts of PCM on the charge/discharge rates of thermal energy in the cyclic melting/freezing in composite slabs of multiple PCM. Their results showed that different combinations of the melting temperatures produce different enhancement of the energy charge/discharge rates compared with single PCM slabs. Brousseau and Lacroix [18] carried out a numerical analysis of the cyclic behavior of alternative melting/freezing in a multi-plate latent heat energy storage exchanger. Their results indicated that the

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average output heat load during the recovery period was strongly dependent on the minimum operating temperature, the thermal diffusivity of the liquid phase, the thickness of the PCM layer and the heat transfer fluid inlet mass flow rate and temperature. Hasan et al. [19] carried out experimental and analytical studies of cyclic charge and discharge of latent energy in a planar slab. Hall et al. [20] developed a physical and numerical model to study the cyclic behavior of a solar heat receiver employing encapsulated phase change materials. They showed in particular that the receiver gas exit temperatures were quite sensitive to a change in the receiver gas inlet temperature.

This investigation deals with the thermal characterization of a packed bed made of PCM filled spherical capsules is presented under a sinusoidal inlet temperature.

2 Packed Bed Modelling

Thermal storage in packed beds involves several heat transfer mechanisms, including convective heat transfer between the fluid and solid, conduction along the length and radius of the store, and heat leakage from the container walls. Heat transfer between the fluid and solid results in a temperature change along the bed that is referred to as the 'thermal front', 'thermal gradient', or 'thermocline'. In an ideal reservoir with no thermal resistance between the fluid and solid, the thermal front is a step-function shape. However, dissipative processes (irreversible gas-solid heat exchange and axial conduction) lead to the thermal front spreading out during the charge discharge process, thus affecting the storage performance.

2.1 PCM packed bed system

A schematic of the cylindrical bed storage of length L packed with spherical capsules of diameter d filled with PCM is presented in Figure 1. The air mass ow rate is supposed to be large enough so that the fluid ow can be considered as unidirectional. There is no heat transfer between the bed and its surroundings. All the PCM capsules contained in a given slice are supposed to behave in the same way. Hence, it is sufficient to simulate the behaviour of one single PCM capsule per slice in order to take into account the interaction of the working fluid with the spheres contained in each individual slice.

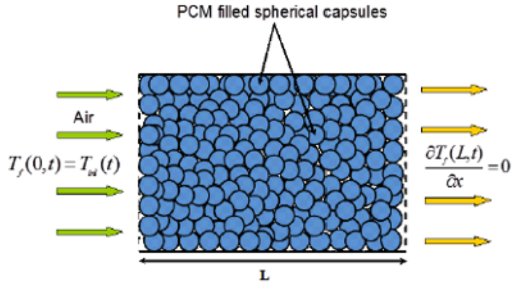

Fig. 1. Schematic of the packed bed

2.2 Governing equations

The main assumptions of the model concerning the PCM behaviour inside a capsule are now recalled:

- Melting and solidification processes occur at the same and constant temperature.
- The PCM field is supposed to be spherically symmetric.
- The PCM density does not depend on the PCM phase.
- The thermophysical properties of the PCM and of the working fluid are temperature independent.
- The convection effects present in the liquid region of the PCM contained in the spheres are taken into account via the use of an effective conduction coefficient in the energy equation.

With the foregoing assumptions, the energy equation for HTF can be written as:

$$\varepsilon(\rho c)_f\left[\frac{\partial T_f}{\partial t}+u\frac{\partial T_f}{\partial x}\right]=\frac{\partial}{\partial x}\left[K_f\frac{\partial T_f}{\partial x}\right]+U.A[T_{PCM}-T_f] \quad (1)$$

During sensible heat storage, when the PCM is completely solid or liquid, the corresponding governing equation can be written in this form:

$$(1-\varepsilon)(\rho c)_{PCM}\frac{\partial T_{PCM}}{\partial t}=\frac{\partial}{\partial x}\left[K^*_{PCM}\frac{\partial T_{PCM}}{\partial x}\right]+U.A[T_f-T_{PCM}] \quad (2)$$

Where:
ε is the bed porosity
K is the thermal conductivity

3 Behaviour of the Modelled Packed Bed with a Sinusoidal Inlet temperature of the Working Fluid

3.1 Configuration and simulations parameters

The system inlet temperature was supposed to vary in a one-day period purely sinusoidal way, namely:

$$T_{inl}(t)=A\sin(2\pi f+\theta_0)+K$$

with $f = 1.15710^{-5}Hz$. The two constants θ_0 and K were determined by supposing that the inlet temperature at the time origin i.e. $T_{inl}(t=0)=T_{ini}$ was equal to the minimum of T_{inl}. This implies that θ_0 is equal to $-\frac{\pi}{2}$ and that $K=T_{ini}+A$. Next, the choice $A = T_{ini}$ led to $T_{inl}(t)=A(\sin\left(2\pi f-\frac{\pi}{2}\right)+2)+K$.

Finally, a temperature signal amplitude of 30 °C was chosen which corresponds to $A = T_{init}$ =15 °C. Virtual paraffin were considered in order to reveal some specific behaviors associated to the absence of any phase change in the bed (T_m = 15 °C or T_m = 40°C) or to a zero value of the average Stefan number (T_m = 30 °C). The x-length L of the tank, the capsule diameter d and the bed porosity ϵ were equal to 1.5m, 0.06m and 0.4m, respectively.
Equations should be centered and should be numbered with the number on the right-hand side.

3.2 Results and discussion

In all situations, the time evolution of the system was characterized by the presence of an initial transient period followed by a permanent periodic regime. This is illustrated in Figures 2 and 3 which display the time evolution of the working fluid outlet temperature and of the corresponding mass fraction of liquid PCM in the bed, respectively. Obviously, the duration and the nature of the transient regime are heavily dependent on the value of Tm. Indeed, for the minimum value Tm = 15 C, the transient regime corresponds almost entirely to the plateau related to the immediate phase change at constant temperature and the subsequent asymptotic regime is characterized by the absence of phase change in the bed, i.e. the energy storage is uniquely due to the sensible part of the liquid PCM. This is also the case for Tm = 45 C, but in that situation, the sensible storage occurs in the solid PCM only (see Figure 3).

In that case, the outlet temperature is almost constant and the storage process is essentially latent since the liquid fraction exhibits a saturation free quasi-sinusoidal temporal behavior. The level of the outlet temperature is close to the cycle average of the inlet temperature (and to Tm since Ste = 0). Thus, in such a situation, the bed acts as a quite perfect reject band filter centered at the frequency f = $1.15710{-}5Hz$. Such a quasi-constant outlet temperature feature can be of great interest for many industrial or domestic applications. It should be emphasized though, that such a behavior was obtained for a very specific symmetric inlet signal which was moreover invariant from one cycle to another. So, the present interpretation cannot be readily extrapolated to other type of signals without further investigation. In addition to that, even with the present inlet sinusoidal signal, a velocity change, keeping constant the tank length or vice versa, proved to alter the outlet temperature signal.

This is illustrated in Figure 3 where it can be seen that a reduction of the transit time achieved through a velocity increase (keeping constant the bed length) leads to the reappearance of some periodic oscillations of the outlet temperature.

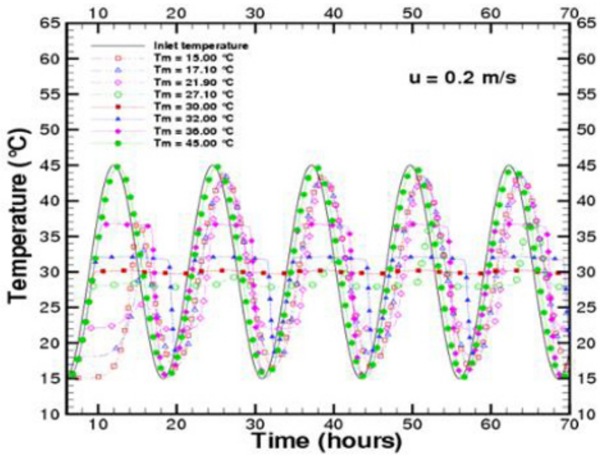

Fig. 2. Time evolution of the working fluid inlet and outlet temperatures for different PCM melting temperatures (sinusoidal inlet temperature)

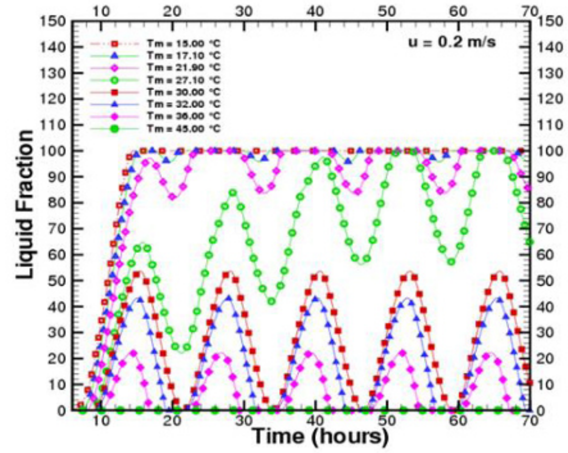

Fig. 3. Time evolution of the PCM liquid mass fraction for different PCM melting temperatures (sinusoidal inlet temperature)

4 CONCLUSION

The results presented in this paper show that subject to a sinusoidal inlet temperature evolution of its working fluid, the outlet temperature of a bed packed with paraffin filled spherical capsules always reaches an asymptotic regime. This asymptotic regime is characterized by a quasi-constant outlet temperature of the working fluid when the average of the Stefan number over one cycle is equal to zero.

The application of efficiency criteria based either on energy or exergy based analyses yields opposite trends i.e. the maximum of energy efficiency is obtained for the minimum exergy efficiency and only for the paraffins whose melting temperature is equal to the 1-day time average of the input temperature of the working fluid.

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