Numerical Simulation of Cyclic Thermal Latent System

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Abstract

In this paper, the thermal behaviour of thermal storage system utilizing encapsulated phase change materials is simulated and studied in terms of first and second law efficiencies for the overall charge-discharge cycle. Numerical results show that the performance of the thermal latent system can be ameliorated by the judicious choice of the melting temperature of the PCM.

Résumé

L'objectif de ce travail est d'analyser le comportement d'un système de stockage d'énergie d'origine solaire qui utilise une cuve de dimension importante, remplie d'un grand nombre de capsules contenant un matériau à changement de phase (MCP). Nous nous sommes intéressés à la phase de stockage et de déstockage, caractérisée, en première approximation, par une puissance variant sinusoïdalement avec le temps. Nous avons appliqué le premier et le deuxième principe de la thermodynamique pour évaluer les performances et irréversibilités au sein de la cuve.

Key-words:

Cyclic melting/freezing, entropy generation, phase change, latent energy

NOMENCLATURE

c_p : specific heat, J/(kg.K)
T : temperature, K
U_f : heat transfer coefficient, W/(m^{2}K)
t : time, s

Greek symbols

β : liquid fraction
ε : porosity
λ : thermal conductivity, W/(m.K)
ρ : density, kg/m^3

Indices

f : fluide
pcm : phase change material

1. INTRODUCTION

Increasing energy cost and associated environmental problems have intensified efforts towards energy storage and sustainable energy technologies. Over the past decade the use of the phase change materials (PCM) have been investigated as an effective way for a better utilization of the thermal energy [1]. These systems are based on the use of phase change materials (PCM).

Different PCM systems were reported in the literature [2]. For instance, water is widely used as the PCM refrigeration storage system because of its high latent heat thermal energy, stability, low cost and environmentally friendly. However, this system presents the disadvantage of supercooling that occurs in the process of solidifying water during charging of the cold storage. On the other hand, paraffin's posses desirable characteristics such as wide ranges of melting temperatures and no supercooling. The theory design and analysis of the PCM systems has been discussed in the literature [2-3]. The data reported are mainly based on the first law of thermodynamics. This law is inadequate in depicting completely the effect of internal irreversibility found in all type of heat transfer processes.

In this sense, the second law of thermodynamics needs to be applied [4-5]. In the present work, we apply the first and second law of thermodynamics model to optimize the performance of the latent energy storage during the charge and discharge cycles. The influence of the melting temperature on the entropy generation during thermal energy storage was investigated.

2. THE HEAT TRANSFER MODEL OF THE LATENT SYSTEM

The latent energy system consists of a solar air collector and a cylindrical storage tank that contains spherical capsules filled with a PCM. Solar energy is intercepted by the air collector is converted into hot air which can be either used directly or stored in PCM within the tank for later use [4]. Obviously, the temperature of the air at the outlet collector depends on the solar radiation. In a first approximation and in order to make our calculations, we have chosen as condition at the exit of the air collector, the sinusoidal temperature:

$$T_{ini} = T_o + A\sin(wt + w_o) \tag{1}$$

In this model, the following assumptions were considered:

- A continuous medium of the PCM capsules and not as a medium of independent particles.
- Thermal gradients within capsules were negligible.
- Thermophysical properties of the PCM and of the heat fluid flow are temperature independent.
- Overall heat transfer coefficients between the capsules and the coolant are constant during the charge period.
- Fluid flow is considered as a plug flow with uniform conditions in the opposite direction.

Based on the above assumptions, the energy equations for the fluid can be written:

$$\varepsilon(\rho c)_f \left(\frac{\partial T_f}{\partial t} + V_e \frac{\partial T_f}{\partial x} \right) = \frac{\partial}{\partial x}\left(k_f \frac{\partial T_f}{\partial x} \right) + U_f A\left(T_{PCM} - T_f\right) \tag{2}$$

During the sensible heat storage, that is, pure solid and complete liquid, the corresponding governing equation can be written in this form:

$$(1-\varepsilon)(\rho c)_{PCM}\frac{\partial T_{PCM}}{\partial t}=\frac{\partial}{\partial x}\left(k^{*}_{PCM}\frac{\partial T_{PCM}}{\partial x}\right)+U_f A(T_f-T_{PCM}) \tag{3}$$

In the latent heat storage (charge or discharge) the corresponding model takes this form:

$$\frac{\partial \beta}{\partial t}=\pm\frac{U_f}{(1-\varepsilon)\rho_{PCM}\,L_F}(T_f-T_F)-\frac{k^{*}_{PCM}}{\rho_{PCM}\,L_F}\frac{\partial^2 T_{PCM}}{\partial x^2} \tag{4}$$

ρ_f and c_f respectively the density and the thermal conductivity the fluid, U_f is the constant heat transfer coefficient, A is the superficial particle area per unit bed volume, V_e is the mean heat transfer fluid flow velocity, ε is the void fraction of the tank, β is the mass fraction of the liquid PCM inside the capsules and L_F is the latent heat of melting of PCM.
In the above equations, the effective thermal conductivity k^{*}_{PCM} is evaluated from the SCHMIT correlation:

$$k^{*}_{PCM}=1.72\,k_f\left(\frac{k_f}{k_{PCM}}\right)^{0.26} \tag{5}$$

The initial and boundary conditions are specified by:

$$T_f(x,0)=T_{PCM}=T_{ini} \tag{6}$$

$$T_f(0,t)=T_{PCM}=T_{\mathrm{int}} \tag{7}$$

$$\frac{\partial T_f(L,t)}{\partial x}=0 \tag{8}$$

$$\frac{\partial T_{PCM}(L,t)}{\partial x}=\frac{\partial T_{PCM}(0,t)}{\partial x}=0 \tag{9}$$

It is noted that $\beta=0$ if the capsules are completely in solid state and $\beta=1$ in the case that the whole containers are in liquid state.
The convection heat transfer condition at the external surface of the capsules can be treated by using the mean Nusselt number given as:

$$Nu=(1-10\varepsilon+5\varepsilon^2)(1+0.7\,\mathrm{Re}^{0.2}\,\mathrm{Pr}^{0.33})+(1.33-2.44\varepsilon+1.2\varepsilon^2)\,\mathrm{Re}^{0.7}\,\mathrm{Pr}^{0.33} \tag{10}$$

The finite difference equations are obtained by integrating the conservation equations over a control volume. The resulting finite difference scheme are solved iteratively at a given time step, with a tridiagonal matrix solver (TDMA).

3. RESULTS AND DISCUSSIONS

For the numerical simulation, we have applied the procedure described in the preceding section. Air is the working fluid and paraffin is the PCM. The values of thermophysical characteristics of the parrafins used in this paper have been obtained from the literature [4].

Fig.1 shows the calculated results of the outlet circulating fluid temperature and inlet temperature of the hexadecane paraffin during the charge and the discharge periods. From the figure, it can be concluded that the outlet working fluid temperature gets the maximum value of 43 °C at the first cycle (i.e. permanent regime) and the temperature varies from 22 °C to 43 °C . The corresponding liquid fraction of PCM is illustrated in Fig.2. It is observed that the liquid fraction reaches the maximum value (100 %), which occurs at sunset, when the system gets the permanent regime. However, at the end of the eclipse phase, approximately 82 % of liquid PCM remains in the tank.

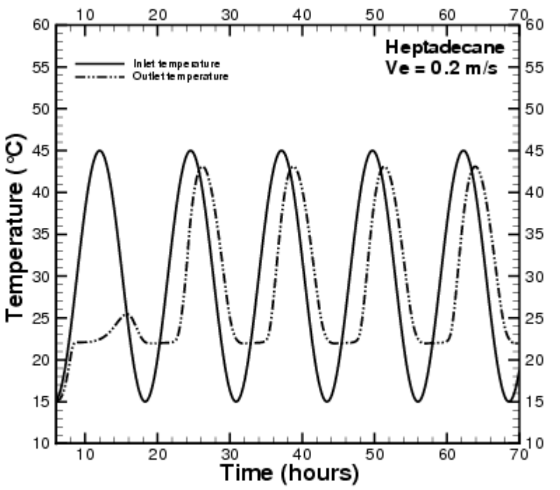

Fig.1: Outlet working fluid temperature versus time.

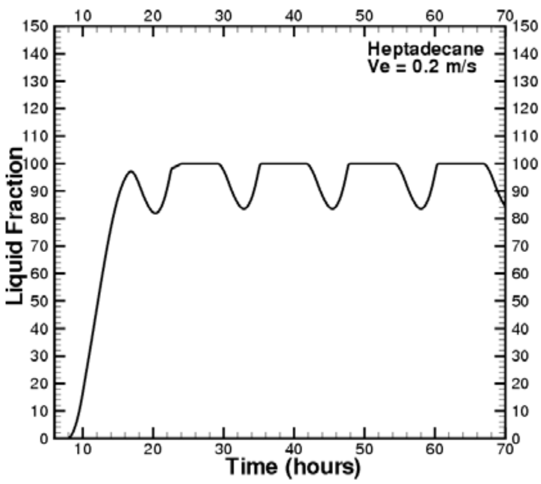

Fig.2: Variation of the liquid fraction versus time.

There are several factors that can affect the thermal behaviour of the latent system. In order to investigate the effect of the melting temperature, the variation of the outlet working fluid temperature for different paraffins is recorded (Fig.3). The corresponding liquid fraction of different PCMs is illustrated in Fig.4. We note that the choice of the melting temperature influences strongly the exit temperature of the circulating fluid. The melting temperature is an important parameter for design in this problem. We can also note that in the case of nonadecane and eicosane, it is impossible to melt and solidify all PCM. In all situations, the time evolution of the system is characterised by the presence of an initial transient period followed by a permanent periodic regime. Obviously, the duration and the nature of the transient regime are heavily dependent on the value of the PCM.

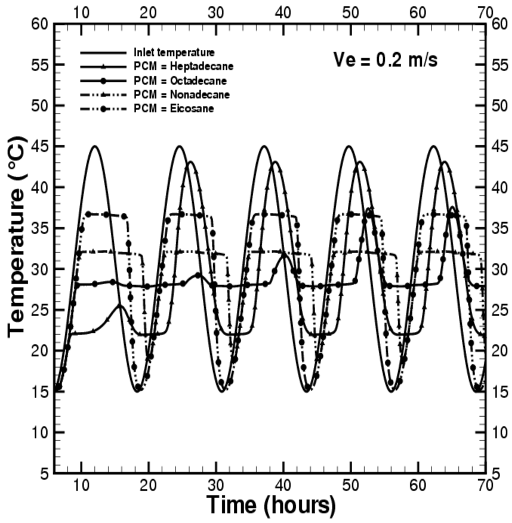

Fig.3: Effect of the melting temperature on the outlet working fluid temperature

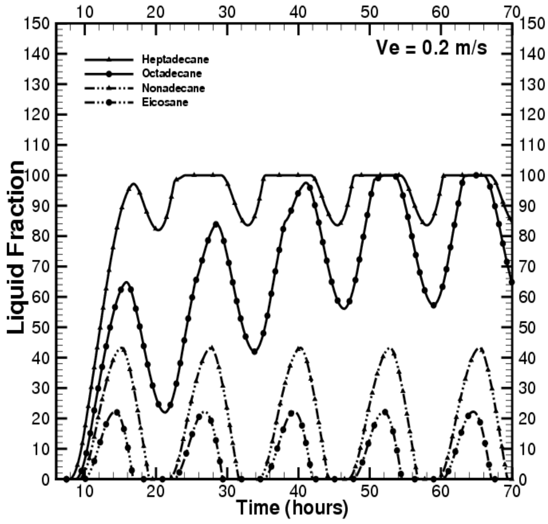

Fig.4: Variation of the liquid fraction versus time for various PCMs.

The first law efficiency of the latent thermal energy storage is defined as the relationship between transferred heat flow and maximal transferable heat flow:

$$\eta(t) = \frac{\dot{Q}(t)}{\dot{Q}_{\max}(t)} = \frac{\left|T_{inlet} - T_{out}\right|}{\Delta T_{\max}} \tag{11}$$

Fig.5 shows the temporary progression of the first law efficiency of the latent storage system during the cyclic melting and freezing for various melting temperatures. We show that for the first charge period, the energy efficiency increases by decreasing the melting temperature of the PCM. We can also note that when the system reaches the permanent regime, the efficiency of the system during the charge period goes up with the melting temperature until it reaches a maximum value and thereafter diminishes with further increases melting temperature. However, the discharge efficiency increases by increasing the melting temperature. As results, the overall efficiency of the energy system shows maximum around the melting temperature 28 °C. From this result, the system filled with PCMs with 28 °C melting temperature gives the best performance.

An important approach in the second law analysis of the thermal latent energy storage system is the calculation of the entropy generation number N_S [4]. This number is defined as the degraded exergy (availability) divided by the total exergy input to the cycle of the storage, that is:

$$N_s = \frac{T_0 \int_0^t \dot{S}_{gen} dt}{\left|\int_0^t \dot{E}x_{cv} dt\right|} \tag{12}$$

$\dot{S}_{gen}$ is the instantaneous rate of entropy, $\dot{E}x_{cv}$ is the time rate of change exergy of the control volume and T_o is the reference temperature.

As it can be seen in Fig. 6, where N_S is plotted against the time. The level of irreversibilities is always maximal during the transient regime before relaxing towards its asymptotic value. We can also note that the entropy generation number Ns shows a maximum around 28 °C during the permanent regime.

5. CONCLUSION

A numerical model for charging and discharging cycle of a latent heat storage system is presented have shown that it possible prevent or to reduce. It is found that the performance of the system can be improved significantly by a proper selection of the melting temperature of the PCM. Calculations have shown that the difference between the results of energy and exergy analyses is significant. Since exergy is a measure of the quality or usefulness of energy, exergy performance measures are more significant than energy performance measures and that the exergy analysis should be considered in the calculation.

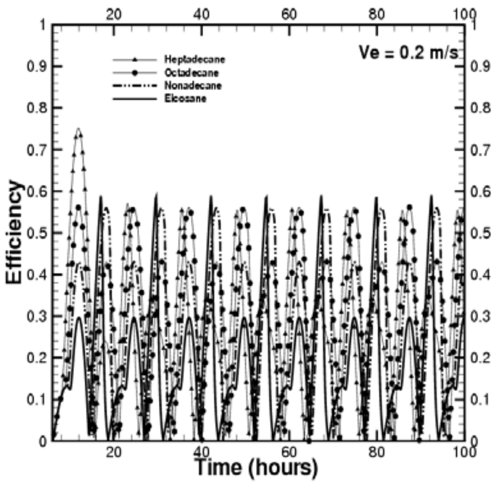

Fig.5: Efficiency of the tank versus time.

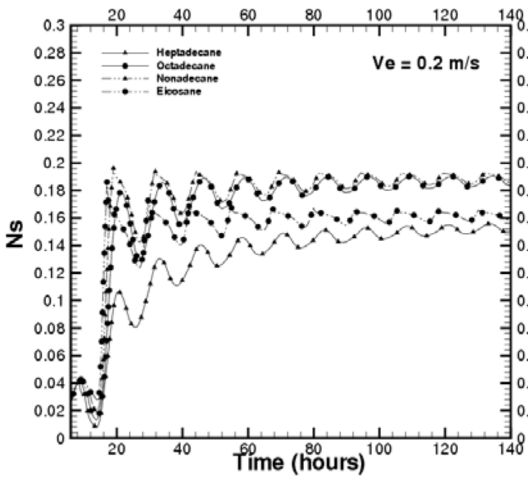

Fig.6: Entropy generation number versus time.

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