

NUMERICAL INVESTIGATIONS OF HEAT TRANSFER ENHANCEMENT IN A LATENT HEAT STORAGE EXCHANGER WITH PARAFFIN/GRAPHITE FOAM

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ABSTRACT

The discrepancy between energy supply and demand can be overcome by the implementation of a proper energy storage system. The latent heat thermal energy storage employing a PCM is the most effective way of the thermal energy storage due to its advantages of high energy storage density and its isothermal operating characteristics during solidification and melting processes. Here high conductivity porosity material-graphite foam is proposed to enhance the phase change materials (PCM), paraffin, in order to solve the problem of its low conductivity in the latent heat storage exchanger (LHSE). The LHSE suggested is like shell-and-tube heat exchanger, which HTF (water) is flowing in the tube while paraffin/graphite foam is in the shell side. And two-dimensional numerical investigations are conducted to predict the heat transfer performance of the PCM/graphite foam for LHSE by CFD software. The results show that graphite foam can improve heat transfer rate effectively, and a series of numerical calculations have been done in order to analyze the influence of several HTF operating conditions on the melting process of the paraffin/graphite foam in LHSE, which will provide guidelines of thermal performance and design optimization for LHSE.

INTRODUCTION

Normal paraffin is an excellent Phase Change Material (PCM) for thermal energy storage due to its large latent heat, good stability, no subcooling degree and no toxicity [1]. The shell-and-tube LHSE unit, which the PCM occupies the space between the tube and the shell, and the heat is transferred from the heat transfer fluid (HTF) which flows through a single tube, is a highly attractive option in the energy storage applications.

In the last few years, several authors numerically or experimentally analyzed the paraffin wax melting process in a shell-and-tube type storage unit, for example, in Ref. [2], the temperature distribution and melting times of the paraffin wax were studied for a shell-and-tube type LHSE system.

NOMENCLATURE

A	[-]	Porosity function
C	[-]	Constant
c	[J/kg K]	Specific heat
C_2	[-]	Inertia coefficient
g	[m/s ²]	Gravity acceleration
h	[J/kg]	Sensible enthalpy
k	[W/mK]	Thermal conductivity
L	[J/kg]	Latent heat of fusion
p	[Pa]	Pressure
u	[m/s]	Velocity in r-direction
v	[m/s]	Velocity in x-direction
t	[s]	Time
T	[K]	Temperature
x	[m]	Cartesian axis direction
r	[m]	Radius
U	[W/ m ² K]	Convective heat transfer coefficient
R_i	[m]	Mean radius of inside tube
Special characters		
α	[m ²]	Permeability
ρ	[kg/m ³]	Density
β	[1/K]	Thermal expansion coefficient
ε	[-]	Porosity of foam material
γ	[-]	Liquid fraction of PCM
μ	[kg/(ms)]	Dynamic viscosity

Subscripts

eff	Effective expression
f	Fluid (Phase change material)
in	Inlet
m	Melting expression
ref	Reference value
s	Graphite foam

However, PCM such as paraffin's low thermal conductivity below 0.4 W/(m K) deteriorates its performance by limiting the achievable heat flux and elongating the phase change processes corresponding to charge and discharge of energy. Different methods have been used to improve the thermal conductivity of

PCM by introducing highly-conductive inserts including metal fins [3] or metal matrices [4] and suspended additives [5]. Experiments were carried out by Bugaje [6] to investigate the methods of enhancing the thermal response of paraffin wax heat storage tubes by incorporating aluminum thermal conductivity promoters of various designs into the body of the wax. It was found that the melting and solidification times were reduced significantly due to these promoters.

Some studies on application of porous structures with PCM for LHSE revealed that highly-porous and highly-conductive structures have a significant potential to improve the effective thermal conductivity and increase PCM's solidification and melting rates. The work in [7,8] showed that the paraffin embedded in metal foam(copper or aluminum) was found to be more effective in improving the heat conduction of PCM.

In recent years, development of high thermal conductivity, graphite foams opened a new horizon to thermal storage and thermal management applications. Graphite foams had densities ranging from 0.2 to 0.6 g/cm³, and the bulk thermal conductivities varied correspondingly with density from 40 to 150 W/m K which makes them desirable for LHSE applications. Having a porous structure with a high porosity, which can reach 95% of the volume consist of void spaces and provides a high ratio of surface area to volume. On the other hand, graphite foam is known to be superior to porous metallic like aluminum, copper or nickel due to having higher thermal conductivity than conductive metals. Py et al. [9] found that the thermal conductivity of the paraffin/graphite matrix composite was equal to that of the sole graphite matrix porous. Zhong et al. [10] characterized the thermal performance of paraffin wax (as the PCM)/graphite foam composites using experimental measurements of thermal diffusivity and latent heat, experimental results indicated noticeable improvements in thermal diffusivity of the composite compared to that of pure PCM, especially with lower porosity of the foam.

A numerical study has been carried out by Lafdi et al. [11] to investigate the thermal performance of graphite foam with different porosities saturated with the PCM (paraffin wax). The energy absorption rate for graphite/PCM composite was compared with that of pure PCM and found a significant improvement in the energy absorption rate.

Considering the above-reviewed papers, it can be concluded that utilizing highly-porous, highly-conductive graphite foam is one of the most effective methods of improving thermal conductivity and heat transfer of phase change processes.

Although previous papers generally focused on the thermal conductivity improvement of a PCM/graphite foam composite. In the present paper, a numerical model for the shell-and-tube LHSE which PCM embedded in graphite foam is developed and parametric study is performed to analyze the effects of influential factors on the LHSE thermal performance.

PHYSICAL DOMAIN

The shell-and-tube LHSE analyzed here is shown in Figure 1. It consists of an inner tube, outer tube and an annulus space filled with porous material, which is paraffin wax embedded in graphite foam. The outer tube is insulated. The heat transfer

fluid (HTF), water, flows through the inner tube and exchanges heat with PCM. During charging process hot water heats the PCM, and when PCM melts, the heat is stored. During discharging process, the PCM solidifies and the stored heat is delivered to the cold fluid.

As presented in Figure 2, the LHSE has the outer radius (R) and inner radius (r) of 63 and 12.5mm, respectively, and the height of tube, H =315mm. Due to the symmetry, only a half of this domain will be considered in numerical simulation. The enthalpy porosity theory is employed to predict the phase change process of PCM/graphite foam in the numerical model. The thermal properties of the paraffin and graphite foam are listed in Table 1.

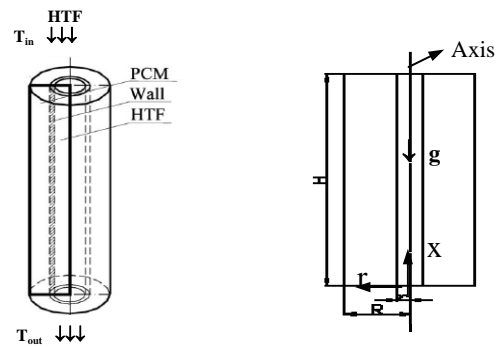


Figure 1 Schematic of the LHSE **Figure 2** 2D Physical domain

The governing equations describing the melting of phase change material inside graphite foam are obtained from volume averaging of the main conservation equations of mass, momentum and energy.

In order to simplify the numerical model, the following assumptions are made:

- the HTF is incompressible and can be considered as a Newtonian fluid, and the flow is laminar, inlet velocity and inlet temperature of the HTF are both constant;
- Thermophysical properties of the HTF, the tube wall and the PCMs are independent of the temperature;
- Natural convection in the liquid phase of PCM is caused by density variation, which is based on the Boussinesq assumption;

Accordingly, the governing equations used here are as follows:

- for the HTF

Continuity:

$$\frac{1}{r} \frac{\partial(\rho_f r u)}{\partial r} + \frac{\partial(\rho_f v)}{\partial x} = 0 \quad (1)$$

Where u, v is the flow velocity of fluid.

Momentum:

$$\frac{\partial(\rho_f u_i)}{\partial t} + \frac{\partial(\rho_f u_i u_j)}{x_j} = \frac{1}{x_j} \left[\mu \left(\frac{\partial u_i}{\partial x_i} + \frac{\partial u_j}{\partial x_j} \right) \right] - \frac{\partial p}{\partial x_i} + S_i \quad (2)$$

Where p is an effective pressure, and μ is the viscosity. Subscribe i and j represents r and x coordinates. S_i is source term.

Energy:

$$\pi R_i^2 \frac{\partial(\rho_f T_f)}{\partial t} + \frac{\partial(\rho_f v T_f)}{\partial x} = \frac{1}{c_f} 2\pi R_i U (T - T_f) \quad (3)$$

For the numerical solution of the phase change, the enthalpy-porosity model developed by Voller [12], which implemented in FLUENT, is applied. In this model, the entire domain is considered as a porous medium where γ takes the value of 1 in the liquid phase, 0 in the solid phase and $0 < \gamma < 1$ in the mushy region between solid and liquid. When PCM and porous media are mixed as composite materials, the flow pressure loss due to the solid PCM and the porous media can be determined by the momentum equations as equation (2), but the source terms are expressed as:

$$S_x = -\rho g \beta (T - T_{ref}) + Av - \left(\frac{\mu}{\alpha} v + C_2 \frac{1}{2} \rho v |v| \right) \quad (4)$$

$$S_r = Au - \left(\frac{\mu}{\alpha} u + C_2 \frac{1}{2} \rho u |u| \right) \quad (5)$$

Where β is a thermal expansion coefficient, and α and C_2 are the permeability and the inertia coefficient of graphite foam, respectively, u and v are the velocity of melting PCM. The function A is the "porosity function", is written as [13]

$$A = -\frac{C(1-\gamma)^2}{(\gamma^3 + \omega)} \quad (6)$$

Where $\omega = 0.001$ is a small computational constant used to avoid division by zero, and C is a constant reflecting the morphology of the melting front. This constant is a large number, usually $10^4 - 10^7$. The value of $C = 10^5$ has been used in the present study.

The equilibrium thermal model is applied to simulate the heat transfer process of PCM in graphite foam, which treats that the liquid PCM and the graphite foam have the same temperature. The energy equation for the LHSE can be described as:

$$\frac{\partial(\rho_{eff,n} h)}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left(k_{eff,n} r \frac{\partial T}{\partial r} \right) + k_{eff,n} \frac{\partial^2 T}{\partial x^2} - \varepsilon \rho_{p,l} L \frac{\partial \gamma}{\partial t} \quad (7)$$

Where ε is the porosity of graphite foam and L is the latent heat of the PCM, h is the sensible enthalpy and can further be written as:

$$h = h_{ref} + \int_{T_{ref}}^T c_{eff,n} dT \quad (8)$$

The effective thermal conductivity k_{eff} and effective density ρ_{eff} in equation (7) are calculated as the volume average of the conductivities and density of porous material and PCM, respectively, which are denoted by:

$$k_{eff,n} = k_s - (k_s - k_{p,n}) \cdot \varepsilon \quad (9)$$

$$\rho_{eff,n} = \rho_s (1 - \varepsilon) + \rho_{p,n} \cdot \varepsilon \quad (10)$$

Where ρ_s and ρ_p are densities of graphite foam and PCM, respectively; k_s and k_p are thermal conductivities of graphite foam and PCM, respectively. Subscribe n represents liquid or solid state of PCM.

The initial temperature of PCM is at melting temperature T_m , and the HTF enters the inner tube at a constant temperature which is a little higher than T_m and causes melting of the PCM in the graphite foam. So the velocity of HTF is specified at the inlet, and pressure outlet condition is set at the outlet. The outer tube is insulated.

NUMERICAL TREATMENT

Equations of the HTF and the PCM, with initial and boundary conditions, have been solved as one domain. The computational domain has been discretised by an unstructured mesh and the calculations are primarily carried out with three different grid densities: 10000, 18000, 25000 elements to perform a grid independency test. The compared result of evolution of melt fraction with time shows that the 18000 elements are suitable for the accuracy of solution. The PISO algorithm has been applied for the velocity-pressure coupling. Presto!, first order upwind and first order upwind have been utilized for pressure, momentum equations and energy equations discretization respectively. The converged results are assumed to be reached when the maximum relative changes of all velocity, temperature and enthalpy values between consecutive iterations are less than 10^{-6} . Time step of 0.05s is conducted to provide a stable convergent solution and accuracy of results.

NUMERICAL MODEL VALIDATION

The proposed numerical model has been checked by comparison between numerical results and existing experimental data obtained by Ref.[14]. In this experiment, a shell and tube LHSE, similar to that proposed in the present work as presented in Fig.1, with PCM1 and copper foam with porosity of 95% filling the annual space and a HTF flowing through the inner tube, is used.

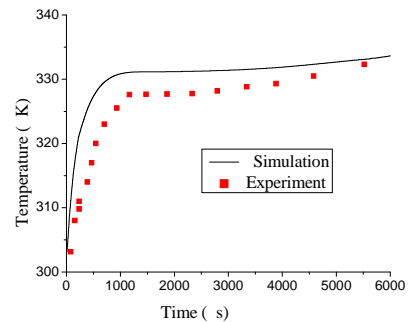


Figure 3 Comparison of experimental and calculated PCM temperature at point2

The thermal properties of the PCM and porous materials are given in Table 1. The melting of the PCM1 is studied

experimentally for HTF inlet temperatures above the initial temperature of the PCM, $T_{f,in} = 343$ K. In this experiment, temperature was measured at representative locations point2 ($r=24$ mm, $x = 215$ mm). Figure 3 shows the comparison of measured and calculated PCM1 temperature at point2. As can be seen in this figure, a good agreement between present predicted and experimental results is observed. Minor discrepancies between predictions and measurements were observed. The reason for this can be ascribed to the measurements uncertainties and model simplifications. Therefore, the present numerical model can be accurately used for the study of the shell-and-tube LHSE proposed.

Table 1: Physical properties of PCM and porous materials

Properties	PCM1	paraffin	Copper foam	Graphite foam
Density (kg/m^3)	1000	747	8920	612
Heat capacity (J/KgK)	1828	2890	390	712
Thermal conductivity (W/mK)	1.568(solid) 1.458(liquid)	0.21(sol.) 0.12(liq.)	401	150
Latent heat (kJ/kg)	220	173.4		
Solidification temperature (K)	331-333	319-321		

NUMERICAL RESULTS AND DISCUSSION

After the validity of the numerical model has been checked, the numerical analysis of the heat transfer during charging of the shell-and-tube LHSE has been performed. A series of numerical calculations have been carried out in order to analyze the transient heat transfer and the effect of graphite foam on the heat transfer of PCM. Initially, PCMs are solids and their temperatures are assumed to 303 K, PCM is paraffin with the properties presented in Table1, and graphite foam has the porosity of 0.728. Analysis has been performed for various HTF operating conditions: the HTF inlet velocities from 0.35 to 0.5 m/s, and inlet temperatures of the HTF varied from 330 to 345 K.

Temperature Distribution

In Comparison with LHSE with pure PCM, Figure 4 gives the temperature distribution at 500s, 1500s and 2500s for the case of HTF temperature of 345 K and inlet velocity of 0.35 m/s.

In the melting process of PCM, Temperature distributions at 500s, 1500s and 2500s in shell and tube LHSE with and without graphite foam are given in Figure 4(b) and Figure 4(a), respectively. It can be seen for pure paraffin, isothermals is almost vertical and temperature distribution is not uniform, which is much higher near the inner tube wall than that of outer tube wall, due to its low thermal conductivity leading to slow heat conduction. However, when PCM is embedded in graphite foam, isothermals of top are tilted to the outside wall gradually with the increase of melting time because liquid phase of paraffin of high temperature rises with the melting of paraffin wax and solid phase of paraffin wax of low temperature sinks

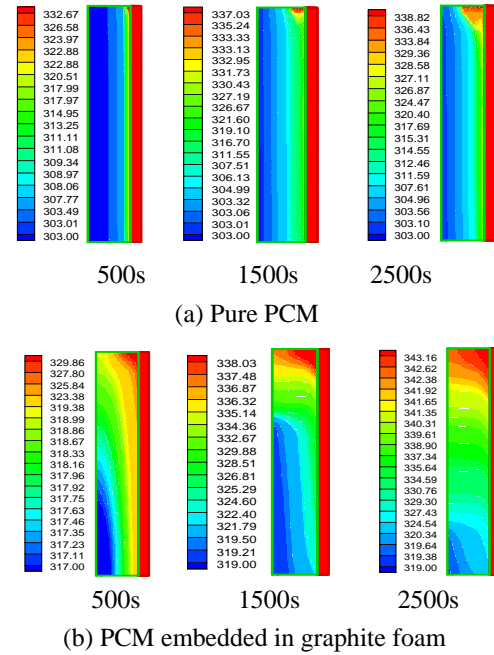


Figure 4 Temperature distributions in LHSE

resulting from the gravity and natural convection, and temperature distribution of phase transition zone tend to be homogeneous with time increase. In the melting process, paraffin of upper and near the inner tube wall melt first and that of lower and away from the inner tube wall melt finally.

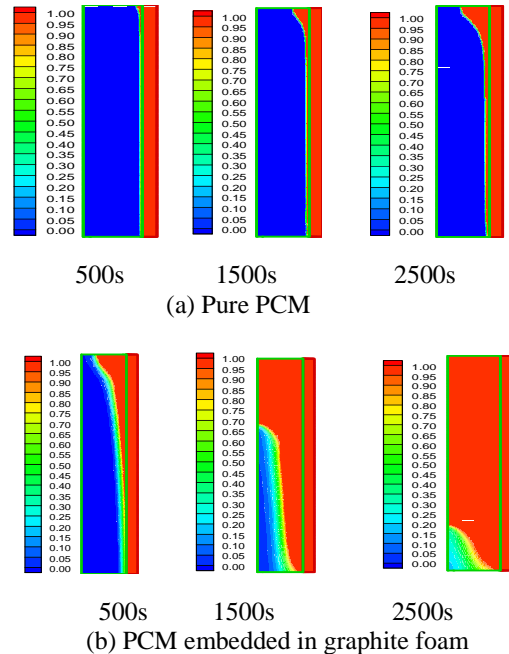


Figure 5 Liquid fraction of PCM in LHSE

Figure 5 shows that liquid fraction of PCMs at 500s, 1500s and 2500s in melting process. It also can be learn that heat transfer can be greatly enhanced by graphite foam compared with the melting of pure paraffin wax in shell-and-tube LHSE.

Influence of the HTF Temperature and Velocity on Melting Time

Influence of the HTF inlet temperature on the melting time is shown in Figure 6. It can be seen that show that the melting time decreases with the increase of HTF inlet temperature.

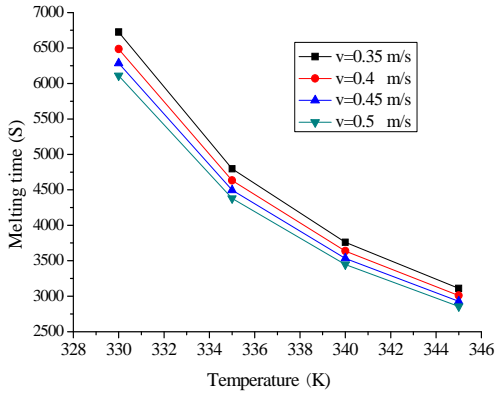


Figure 6 Influence of HTF temperature on melting time

Influences of the different HTF inlet velocity on the melting time of the unit are also presented in Figure 6, the melting time decreases with the flow velocity increase when the HTF inlet temperature is constant. HTF inlet temperature is 330K, the melting time is 6725, 6484.85, 6283.85 and 6111.7s corresponding HTF inlet velocity of 0.35, 0.4, 0.45 and 0.5 m/s, respectively, which means the melting time difference between adjacent velocity is 240.15, 201, and 172.15s, while when HTF inlet temperature is 345 K, the melting time is 3112.5, 3011.35, 2927.85 and 2857.3s for different flow velocity, and the melting time difference of adjacent velocity is 101.15, 83.5 and 70.55s, so the influence of velocity on melting time decreases gradually with the increase of HTF inlet temperature.

Influence of the Temperature Difference on Liquid Fraction of PCM

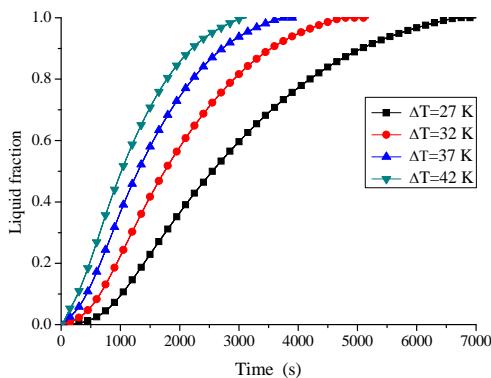


Figure 7 Influence of temperature difference on liquid fraction

The temperature difference between HTF inlet temperature and PCM initial temperature, ΔT , on liquid fraction of PCM is

illustrated in Figure 7. It can be observed that the liquid fraction changes over time at different ΔT , and the bigger the temperature difference causes the faster variation of liquid fraction while HTF inlet velocity is equal to 0.35 m/s. It can also be noted that increasing the temperature difference results also in decreasing of the melting time of paraffin/graphite composite in LHSE.

Influence of HTF Inlet Velocity on Liquid Fraction of PCM

Figure 8 gives the liquid fraction of PCM changes with time under different flow velocity when HTF inlet temperature is set as 345K. Results show that the bigger flow velocity is, the faster melting rate of paraffin wax is. But the influence of HTF inlet velocity on liquid fraction is not obvious.

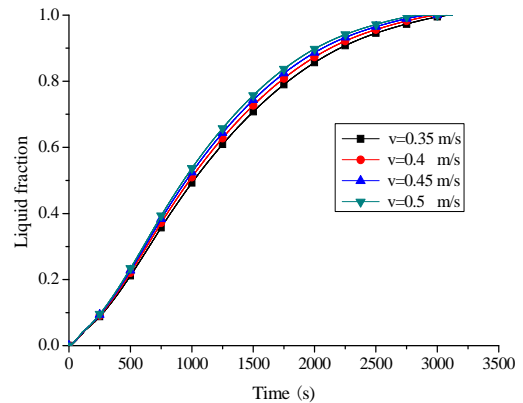


Figure 8 Influence of inlet velocity on liquid fraction

CONCLUSION

Latent heat storage exchanger (LHSE), with paraffin/graphite foam as the PCM filling the shell side and water as HTF circulating inside the tube, has been numerical analyzed in this paper. Compared with the results of the pure PCM, the phase change heat transfer can be greatly enhanced by using graphite foam in TES. Moreover, several simulation calculations have been conducted in order to study the effects of operating parameters: HTF inlet temperature and velocity on melting process of LHSE. It can be concluded that HTF inlet temperature plays a significant role for reducing the melting time and liquid fraction, but the influence of flow velocity on melting process is small although increasing velocity can reduce the melting time.

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