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Energy Procedia 142 (2017) 3381–3387

Energy Procedia

www.elsevier.com/locate/procedia

9th International Conference on Applied Energy, ICAE2017, 21-24 August 2017, Cardiff, UK

Optimizing LHS system using PCM in a tube-in-tank design for emergency cooling

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Abstract

Thermal Energy Storage (TES) systems are normally utilized to assist water chillers to cut down operational cost. With the development of heat-transfer-enhancement technique, there is potential for TES systems using the latent heat of Phase Change Materials (PCMs) for emergency cooling applications. The Latent Heat Storage (LHS) systems might be able to provide thermal energy around PCM melting temperature. This study numerically calculated the basic unit of the system in a tube-in-tank design and analyzed the results by the characteristic figure, which shows the relationship between the capacity effectiveness and the heat transfer effectiveness. The parameter of the equivalent thermal conductivity of the PCM is investigated to improve the characteristic capacity effectiveness of the LHS, and the parameter of inlet temperature is evaluated by testing the operational stability of the LHS when the thermal load is unsteady. According to the numerical results, most of the stored thermal energy in the LHS can be discharged effectively around the PCM melting temperature. The characteristic capacity effectiveness can reach approximate 3 at 80% heat transfer effectiveness, indicating a three times quantity of the thermal energy provided by an equivalent water tank.

Peer-review under responsibility of the scientific committee of the 9th International Conference on Applied Energy.

Keywords: LHS, PCM, emergency cooling, capacity effectiveness, heat transfer effectiveness;

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Peer-review under responsibility of the scientific committee of the 9th International Conference on Applied Energy.
10.1016/j.egypro.2017.12.474

1. Introduction

Emergency cooling refers to the temporary cooling during a power outage or the temporary cooling in temporary shelters. Such systems are required to consume less power compared to water chillers, and some simple heat exchangers with simple thermal source might be able to provide emergency cooling as an alternative of water chillers. A Thermal Energy Storage (TES) device/system can store thermal energy and acts as both the thermal source and the heat exchanger in an emergency cooling solution. Intel IT implemented a TES system using two 24,000-gallon tanks containing chilled water at 279K (42 °F/ 5.5°C) for the emergency cooling. This system saved a high-density data center from a power outage of several hours in 2006 [1]. The Latent Heat Storage (LHS) utilizing PCMs (such as the ice cooling) provides a greater energy density than the sensible heat storage (such as the cold-water cooling) under the same temperature range. However, many PCMs have a poor thermal conductivity.[2]. A normal LHS performance with a tube-in-tank design can be read from the study of Tay et al.[3]: the averaged heat transfer effectiveness of a LHS is normally below 60% and the energy storage effectiveness at high heat transfer effectiveness is correspondingly low. Therefore, the ice-cooling LHS systems always need the assistance of water chillers[4]. Alternately, the heat transfer effectiveness of the LHS can be improved by the heat-transfer-enhancement technique. For example, according to the experimental results by Liu et al.[5], the use of annular fins was able to improve the equivalent thermal conductivity of PCMs by three times. Haillot et al.[6] reported an increase of thermal conductivity from 0.2–1 W/m K to 5–50 W/m K by compositing compressed expanded natural graphite (CENG) in a pure PCM. Such heat-transfer enhancement techniques enable LHS to achieve high thermal effectiveness as well as high capacity effectiveness.

This study optimizes the LHS system with a tube-in-tank design for maximizing the capacity effectiveness at the high heat transfer effectiveness. A numerical model in the geometry of concentric cylinder was built in FLUENT 13.0. The numerical results were analyzed to obtain the relationship between capacity effectiveness and heat transfer effectiveness, which is drawn as the characteristic figure of a LHS system. And the capacity effectiveness at the heat transfer effectiveness of 80% is regarded as the characteristic capacity effectiveness for emergency cooling. The parameter of the equivalent thermal conductivity of the PCM and the parameter of inlet temperature were studied to assess the applicability of utilizing LHS system in emergency cooling.

Nomenclature

cw	cold wall
cyl	cylinder
e	exit
eff	effective
hw	hot wall
i	inner pipe
in	inlet
l	pipe length
o	outer pipe
p	Phase Change Material (PCM)

2. Methods

For a LHS system with a tube-in-tank design, the design can be regarded as a PCM bulk with some hollow and concentric cylinders for a Heat Transfer Fluid (HTF) to be pumped through. One of the cylinders was selected, based on which a mathematical model was built (Figure 1), and such a cylinder can be regarded as the basic unit for various LHS systems, irrespective whether the tubes in the tank are arranged in a spiral or folded.

The modeling was conducted by using ANSYS FLUENT 13.0. The Solidification and Melting model was selected to deal with the phase change processes of PCM, which depends on the enthalpy-porosity technique. The PCM was heated by the inner pipe in the center. Thus, the temperature distribution in the tangential direction is always identical. Accordingly, the centerline of the inner pipe is regarded as axial symmetry, and the modeling is simplified to 2D axisymmetric as Figure 1-c. Water was used as the heat transfer fluid in this study. Moreover, thermal properties of the selected PCM are listed in Table 1, and the PCM was composed of tetradecane and hexadecane at a fixed mass ratio[7]. The thermal conductivity of the PCM here is an equivalent thermal conductivity, provided by some thermal conductivity enhancement solutions (fins[5], metal foam[8], expanded graphite[6]).

For the pipe flow, the standard pressure staggering option was used for pressure correction equation, and a SIMPLE algorithm was used for pressure-velocity coupling. Else, a second order upwind scheme was used to solve the momentum and energy equations. Since the geometry (Figure 1-c) is axisymmetric and has a large l/D ratio, double precision was utilized in this transient calculation to lower down the trade-off error.

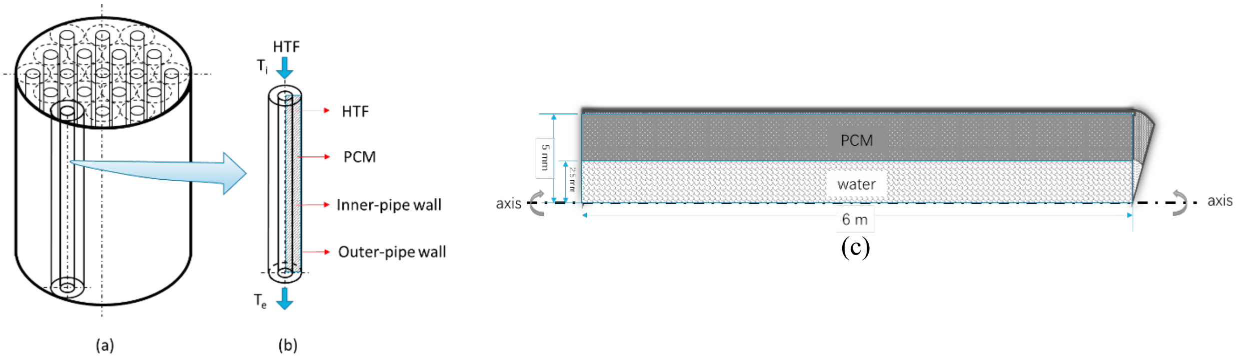


Figure 1 Schematic of the tube-in-tank design of LHS system: (a) complete system; (b) basic unit with a single pipe and PCM; (c) the 2D axisymmetric numerical model calculated in FLUENT 13.0.

Several assumptions were proposed to solve this problem:

- The pipe flow is considered as a fully developed laminar flow with velocity inlet (0.2m/s) at uniform temperature 293K and pressure outlet.
- The thickness of the inner pipe is regarded as zero, and the thermal resistance between pipe flow and PCM is neglected.
- The outer pipe is considered adiabatic, and the whole PCM zone is deemed to be motionless, and natural convection is neglected here.
- The initial temperature of the whole system (both water and PCM) is assumed as 288 K.

Table 1. Parameters of materials used in Fluent simulation

Material	Density (kg/m^3)	Thermal conductivity (W/m·K)	Specific heat (kJ/kg·K)	Viscosity ($N·s/ m^2$)	Latent heat of fusion (J/kg)	Melting temperature (K)
PCM	800	0.2/1/5	1.25	0.008	125000	288~288.01
water	998.2	0.6	4.2	0.001003	-	-

The above numerical model was validated by Trp et al[10]. Despite the fact that enhancing the natural convection in half-melted PCM accelerates the melting process[11], the natural convection is negligible in our design. According to Mills[12], when the fluid layers locate between parallel plates maintained at different temperatures, an observable natural convection occurs when $Ra_l > 0$; however, when $Ra_l < 1000$, the heat transfer is mainly under pure conduction. The calculated Rayleigh number in our model was 677, and the conduction inside the melted PCM was enhanced approximate 1.96 times under the weak convection, when the PCM was melted completely. Such enhancement is far less than that of metal foam (25 times enhanced), and the porous structure of metal foam will further hinder the formation of natural convection. In fact, even if the natural convection in PCM is calculated with the Bousinessq approximation, there is a minor difference (~1%) between the results. Therefore, it is reasonable to neglect the influence of the natural convection in our case.

During the mesh check, the domain was discretized into 5 grid/mm, 10 grids/mm or 20 grids/mm radially and 1 grid/cm, 2 grids/cm or4 grids/cm axially, while the time step was set as 0.01s, 0.1s or 1s. According to the simulation results, the mesh was determined to be 6,000 grids with radial 10 grids/mm and axial 1grid/cm at the time step of 0.1s for the accuracy and the efficiency. The transient calculation confirmed with the convergence criterion of 1E-06 in continuity, momentum and energy equations. The distribution of pressure and velocity in the HTF was also verified by the analytical results.

A new index is proposed to make a comparison between the energy density of the LHS system and that of the water tank, namely capacity effectiveness (see Eq. (1)). The water tank here possesses the identical volume of the LHS and storing water at the temperature of the PCM melting temperature in Eq.(2).

$$\gamma = Q/Q_{\tan k} \tag{1}$$

$$\text{where} \quad Q = \int_0^\tau \dot{m} c_{p,w} (T_{in} - T_e) \cdot d\tau \quad \text{and} \quad Q_{\text{tank}} = \rho_w c_{p,w} V_{\tan k} (T_{in} - T_p) \tag{2}$$

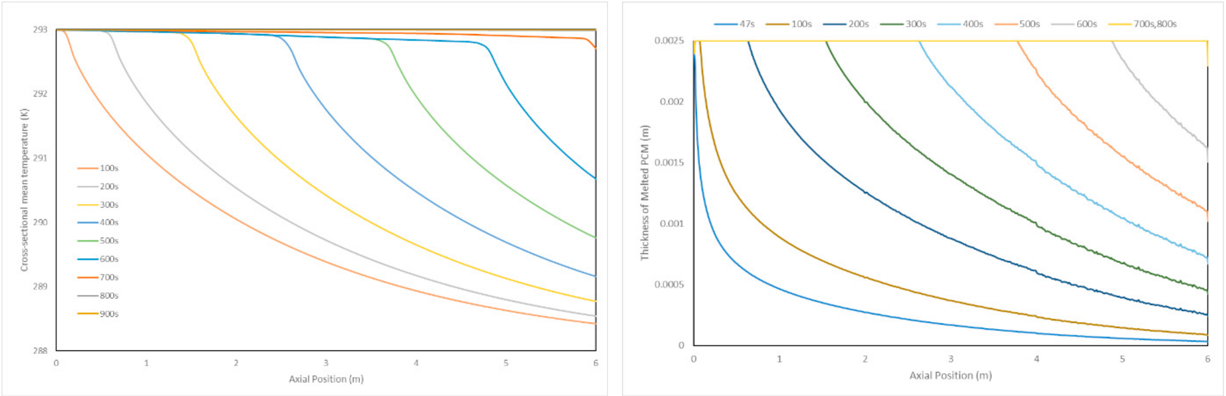
The heat transfer effectiveness[13] in literature represents the averaged effectiveness over the whole melting process, which is used to characterize the system for the off-peak application. Since the system is optimized for emergency cooling, the heat transfer in this study represents the transient heat transfer effectiveness as described in Eq. (3), which decreases over time. The value of capacity effectiveness at heat transfer effectiveness of 80% is regarded as the characteristic capacity effectiveness for each LHS system.

$$\eta = \left(T_{in} - T_e\right) \big/ \left(T_{in} - T_p\right) \tag{3}$$

3. Results

3.1. Characteristic of melting process in the LHS system

The melting process of PCM can be divided into three periods (Figure 2): a) Intrusion period ($0 \sim l/u_m$): the warm water ($T_{in}=293\ K$) gradually replaces the stored water ($288\ K$) in the inner pipe. b) quasi-steady period: the melting front of PCM grows radially and finally touches the wall of the outer pipe, and c) Retreating period: the melting front of PCM grows axially till the end.



(a) (b)

Figure 2 (a) Cross-sectional mean temperature variation of the water flow along axial position, and (b) the melting front position during melting process (k=5W/m·K) in the retreating period of the melting process in the LHS system.

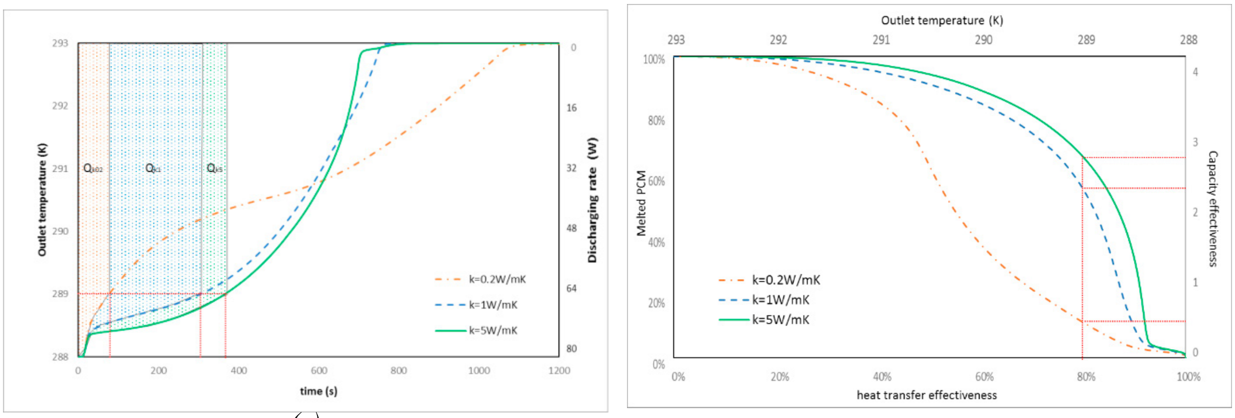
The outlet temperature increases as PCM melts. The thermal resistance in the melted PCM and the effective heat transfer area are both decisive factors to the outlet temperature. During the intrusion period, the inner pipe wall is surrounded by unmelted PCM, and outlet temperature is approaching the PCM melting temperature. During quasi-steady period, the outlet temperature gradually increases as a result of the increasing thickness of the melted PCM layer. Since the heat flux along the pipe direction is not uniformly distributed, the melting interface in PCM region is always not parallel to the pipeline. During the retreating period, the thermal resistance of the melted PCM is still growing, while the effective heat transfer area is decreasing. As a result, the outlet temperature increases more significantly in the retreating period compared to the quasi-steady period.

In this LHS system, the outlet temperature is determined by the melting interface of PCM or the volume fraction of the melted PCM. Thus, there are different volume fractions of the unmelted PCM at different outlet temperatures. The dimensionless parameters of the capacity effectiveness and the heat transfer effectiveness are utilized describe the characteristic of LHS systems.

3.2. Parameter of equivalent thermal conductivity of PCM

The equivalent PCM thermal conductivity of 0.2 W/m·K, 1 W/m·K, 5 W/m·K were selected to conduct the parametric study. Such values represent that the thermal conductivities of PCM in these cases are enhanced by 1 time, 5 times, 25 times, respectively. These improvements of equivalent thermal conductivity is feasible by using metal foam or graphite matrix in PCMs[14]. Using PCMs with a higher thermal conductivity can effectively speed up the melting process and increase the dischargeable heat below the outlet temperature of 289K, which is drawn as the shadowed area in the Figure 3-a. As showing in Figure 3-b, when the PCM is thermally enhanced by 5 times, the characteristic capacity effectiveness of the LHS can be improved from 0.57 to 2.46, which is approximate 5 times higher than that without the enhancement. However, at heat transfer effectiveness 20%, the capacity effectiveness is improved subtly by the increase of equivalent thermal conductivity.

The improvement of the capacity effectiveness at high heat transfer effectiveness is limited. As presented in Figure 3, the curve of 1W/m·K and the curve of 5W/m·K almost overlap. Such phenomenon indicates that the thermal resistance in the PCM side can be neglected when the equivalent thermal conductivity is above 1W/m·K.



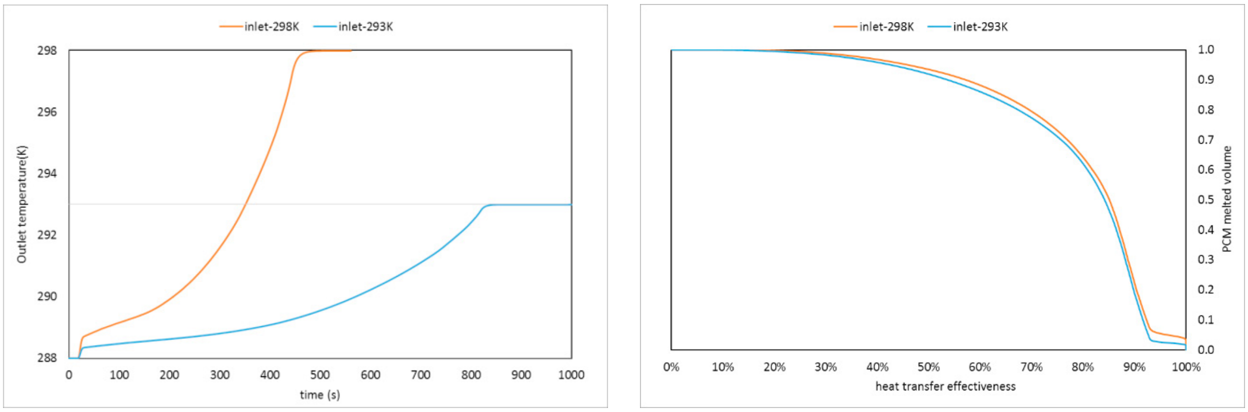
(a)

(b)

Figure 3 (a) Variation *of outlet temperature during melting process (b) characteristic figure of LHS system. (PCM is thermally enhanced by 1 time, 5 times and 25 times respectively. The area with pattern represents the discharged heat before the heat transfer effectiveness of 80%.)*

3.3. Parameter of inlet temperature (temperature difference)

The temperature difference between the HTF and the PCM melting interface determines the melting speed, however, such temperature difference has a minor influence on the characteristic figure of a LHS system. As indicated by Figure 4-b, when the inlet temperature is changed, the relationship between the PCM melted volume (dimensionless capacity effectiveness) and heat transfer effectiveness is unvaried. Such phenomenon implies that the characteristic figure of LHS system is able to predict the performance of a LHS system even under the condition of unsteady inlet temperature, and the optimized LHS system can provide high capacity effectiveness under varying conditions.



(a) *(b)*

Figure 4 (a) Variation of outlet temperature during melting process (b) characteristic figure of LHS system. (where k_p=1 W/m·K, and the inlet temperature is set at 293K and 298K respectively)

4. Conclusions

This study numerically calculated the basic LHS unit in a tube-in-tank design and analyzed the results by comparing the characteristic capacity effectiveness at the heat transfer effectiveness of 80%. The parameter of the equivalent thermal conductivity of the PCM and the parameter of inlet temperature were studied to assess the applicability of applying LHS system for emergency cooling. According to the numerical results, on the one hand, when the equivalent thermal conductivity of PCM is well enhanced, the characteristic capacity effectiveness can be significantly improved to approximate 3, indicating that it can provide three times effective thermal energy compared to that of an equivalent water tank. On the other hand, the characteristic figure of LHS is less influenced by the inlet temperature in operation, and the LHS can always effectively discharge the thermal energy as designed. Therefore, the LHS system with a tube-in-tank design is a feasible technique for emergency cooling from the perspective of the energy capacity.

Acknowledgements

This study was financially supported by the Research Grant Council, Hong Kong, China, under the project No. RGC GRF 152129/14.

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