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Novel Fin for Effective Heat Transfer in Shell-and-Tube Latent Heat Storage System

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Abstract

Due to the low thermal conductivity of phase change materials (PCMs), latent heat storage (LHS) technology has not yet commercialized to its fullest capability. Many heat transfer enhancement techniques were studied by several researchers and each of the techniques put forward has its own pros and cons. In the present study, a novel fin is proposed for effective heat transfer in shell-and-tube LHS devices. A numerical model is developed to study the performance characteristics of the proposed novel fin and to compare it with no fin and standard fin configurations. Effective heat capacity method is used to simulate the phase change mechanism. Sodium nitrate is used as the PCM and air is used as the heat transfer fluid. Performance parameters such as melt fraction and charging time are evaluated. Axial temperature variation of PCM in the LHS models is also studied.

Keywords: *Heat transfer enhancement, Latent heat storage, Novel fin, Phase change material.*

1. Introduction

The most intensely examined LHS system is the shell-and-tube system. This is due to the fact that many engineering systems employ cylindrical pipes and also heat loss from the shell-and-tube system is minimal (Agyenim et al., 2010). Several techniques were reported to improve the overall heat transfer effectiveness of the LHS system (Kurnia et al., 2013; Li et al., 2013; Rathod and Banerjee, 2015). Extensive reviews in this context were also published (Fan and Khodadadi, 2011; Kenisarin and Mahkamov, 2007; Liu et al., 2012). Every heat transfer enhancement technique has certain disadvantages:

- Sprinkling of high thermal conductivity metallic particles – the metallic particles settle down due to its high density after repeated charging and discharging cycles.
- Extended heat transfer surfaces (Fins) – materials having a high corrosion resistance and high/moderate thermal conductivity are suitable for heat transfer media in LHS systems. Materials having these properties (eg: stainless steel) are denser and hence the total weight of the system becomes high.

To increase the overall heat transfer in the LHS devices, a novel fin is proposed in the present study. Figure 1 shows the schematic of the shell-and-tube LHS module and the inner tube with and without novel/standard fins. The novel fin proposed here is half of the standard fin cut diagonally. This will reduce the weight and cost of the fin material by a factor of 0.5 and hence making the LHS system, light weight and cost-effective. For comparing the performance characteristics of the basic and proposed novel technique, capsules having a LHS capacity of 0.5 MJ are considered. Sodium nitrate and air are selected as the PCM and heat transfer fluid (HTF). SS 304 is selected as the HTF tube. The thermo-physical properties of sodium nitrate are given in Tab. 1. Figure 1 shows the schematic of the no fin, standard fin and novel fin configurations. The length of the LHS models is 0.5 m. The height and width of the fin is 10 mm and 2 mm in the standard fin configuration. The design of LHS models is made in such a way that the volume of PCM in all the configurations are same.

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Tab. 1: Thermo-physical properties of sodium nitrate

Properties	Values	References
Density (ρ, kg m^{-3})		
Solid phase	2130	
Mushy zone	Linear interpolation	Bauer et al., 2012
Liquid phase	1908	
Latent heat of fusion (ΔH_f, J kg^{-1})	178,000	
Dynamic viscosity (μ, Pa s)	$0.0119 - 1.53 \times 10^{-5}\ T$	Janz et al., 1979
Melting point (T_m, K)	579.95	
Specific heat (c, J kg^{-1} K^{-1})	$444.53 + 2.18\ T$	Lan and Kou, 1991
Thermal expansion coefficient (β, K^{-1})	6.6×10^{-4}	
Thermal conductivity (k, W m^{-1} K^{-1})	$0.3057 + 4.47 \times 10^{-4}\ T$	White and Davis, 1967

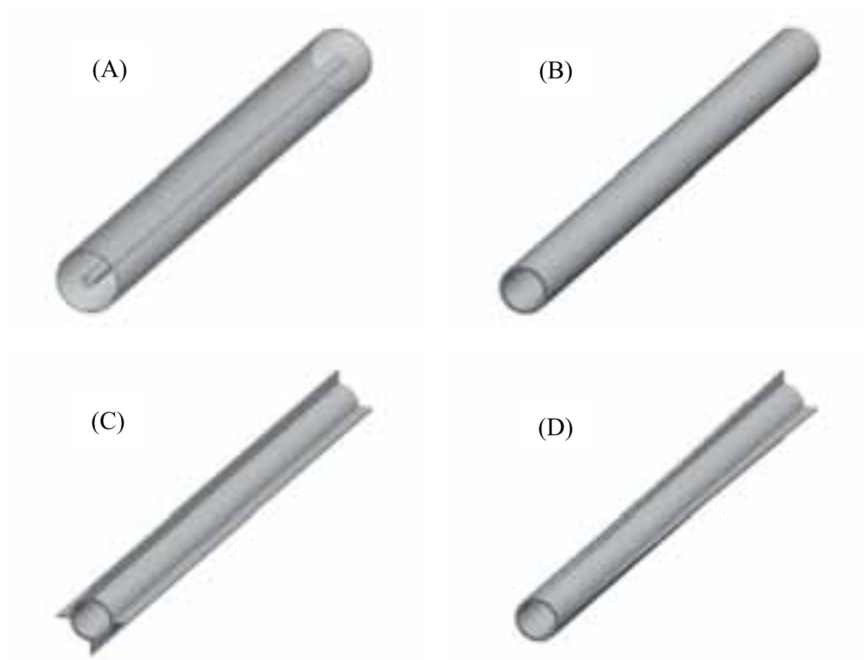

Fig. 1: Schematic of (A) shell-and-tube LHS module (B) inner tube without fin (C) inner tube with standard fin (D) inner tube with novel fin

2. Numerical Model

A 3-D conjugate heat transfer model is developed to simulate the flow characteristics of HTF and heat transfer characteristics of PCM. The major difficulty in the modeling of LHS system is the inclusion of latent heat and this has been implemented using effective heat capacity method. The simulation is modelled using COMSOL Multiphysics software. Buoyancy effect has been incorporated using Boussinesq approximation. To properly interpret the velocities in mushy zone, Darcy law's source term was added in the momentum equation. The governing equations and their corresponding sub-equations are given in Eqs. (1-8). LHS models are initially kept at 564.95 K during the charging process. At any time ($t > 0$), the inlet of the model is given a temperature of 594.95 K and a constant velocity of 2 m/s. The major performance parameter used in LHS is melt fraction. Melt fraction of the PCM can be calculated based on the lever rule applied between the solidus and liquidus temperatures and it is given by Eq. (8). During charging, melt fraction of the PCM possess a value of 0 initially and when it reaches a value of 1, it is said to be completely charged.

$$c=\begin{cases} c_{ps} \ \ for\ T<T_S \\ c_{p,eff}\ for\ T_S \le T \le T_L \\ c_{pl} \ \ for\ T>T_L \end{cases} \quad \text{(Eq. 1)}$$

$$c_{p,eff}=\frac{c_{ps}+c_{pl}}{2}+\frac{\Delta H_f}{2\Delta T_m} \quad \text{(Eq. 2)}$$

$$\nabla.\vec{V}=0 \quad \text{(Eq. 3)}$$

$$\frac{\partial \vec{V}}{\partial t}+(\vec{V}.\nabla)\vec{V}=\frac{1}{\rho}\left(-\nabla P+\mu\nabla^2\vec{V}+F+\vec{S}\right) \quad \text{(Eq. 4)}$$

$$\rho c\frac{DT}{Dt}=k\nabla^2 T \quad \text{(Eq. 5)}$$

$$F=\rho\vec{g}\beta(T-T_m) \quad \text{(Eq. 6)}$$

$$\vec{S}=\frac{(1-\theta)^2}{(\theta^3+\varepsilon)}A_{mush}\vec{V} \quad \text{(Eq. 7)}$$

$$\theta=\frac{T-T_S}{T_L-T_S}=\frac{T-T_m+\Delta T_m}{2\Delta T_m}=\begin{cases} 0 \ \ for\ T<T_S \\ 0-1\ for\, T_S \le T \le T_L \\ 1 \ \ for\ T>T_L \end{cases} \quad \text{(Eq. 8)}$$

3. Results and discussions

3.1. Temperature Distribution

Figure. 2 shows the comparison of the average temperature variation of the single tube shell-and-tube LHS model with no fin, standard fin and novel fin during charging process. PCM kept in the capsules is initially in the solid state at 564.95 K. When an uniform high temperature of 594.95 K and velocity of 2 m/s are given on the inlet of the LHS model, heat is transferred from the fluid and gets stored in PCM in the form of sensible and latent heat. It is inferred from Fig. 2 that the increase in average temperature is faster in LHS model having standard fin than that of no fin and novel fin, initially. This is due to the higher surface area available for heat transfer. But after a certain period of time, say t = 360 min, the increase in average temperature is faster in LHS model having novel fin than that of other two cases. The reason for this is the configuration of the novel fin, wherein the heat transfer area is more in the less heat transfer potential region, i.e. near the outlet portion of the model. Screenshots of temperature variation at different times are given in

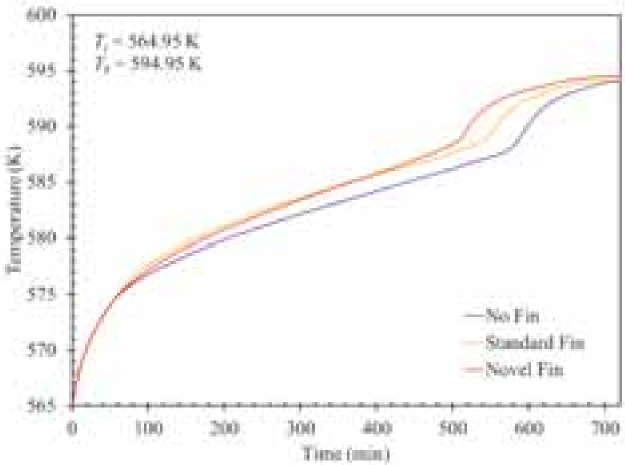

Fig. 2: Temperature distribution

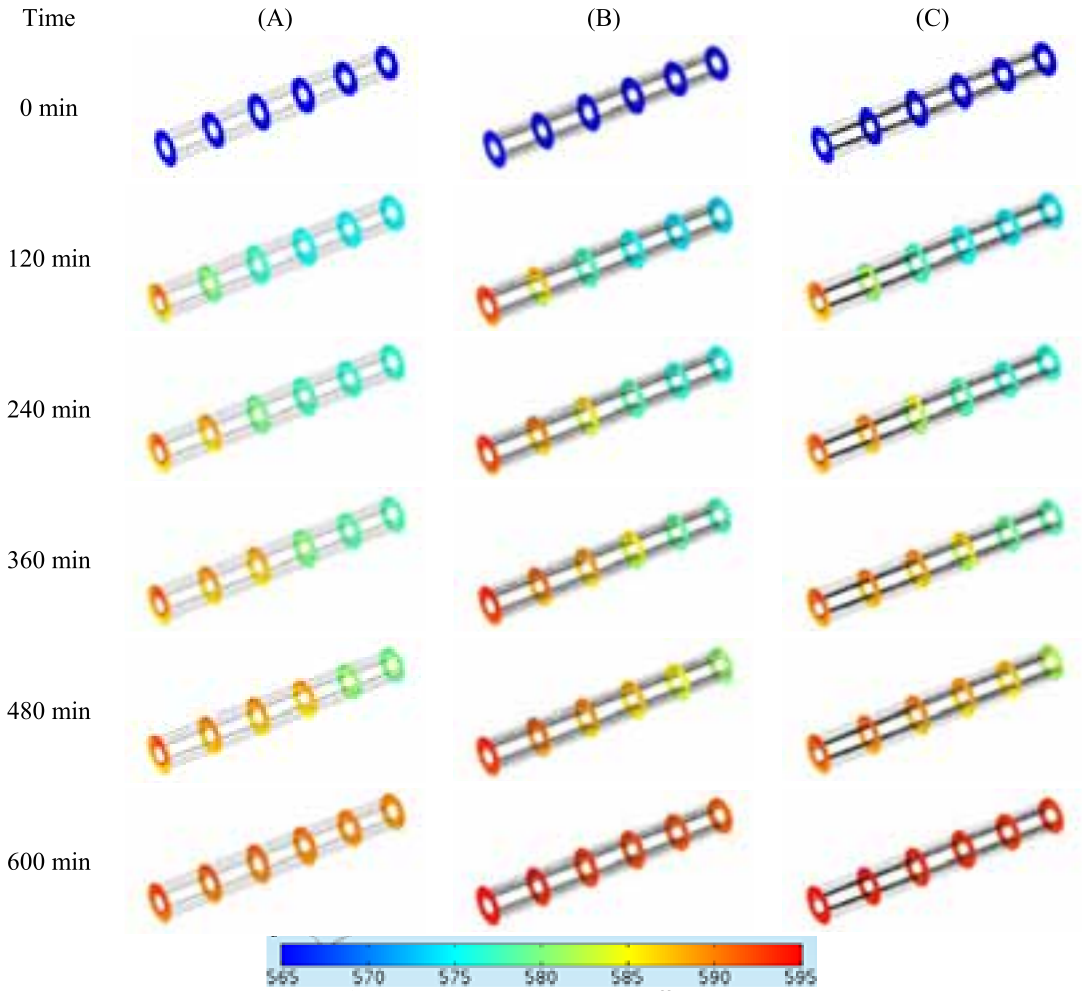

Fig. 3: Temperature distribution at different times

Fig. 3. It can be noted from Fig. 3 that the standard fin configuration dominates in temperature rise of PCM than the other two configurations, initially (t = 120 min, 240 min, 360 min) and novel fin configuration dominates in temperature rise of PCM during the last period (t = 480 min, 600 min).

3.2. Charging Time

Charging time of the LHS model is defined with respect to the melt fraction of the PCM. The LHS model is said to be fully charged when the melt fraction of the PCM reaches unity. Figure. 4 shows the comparison of average melt fraction variation of LHS model with no fin, standard fin and novel fin during charging process. It can be noted from Fig. 4 that the charging time of novel fin configuration is lesser than the no fin and standard fin configurations. It takes about 597 min, 551 min and 518 min for complete charging in the LHS model with no fin, standard fin and novel fin. It can be noted that the charging time has decreased by about 13.2 % and 6 % when using novel fin configuration with respect to no fin and standard fin configurations.

3.3. Axial Temperature Variation

Figure. 5 shows the axial temperature variation of the PCM in the LHS model. Surface average temperature of LHS model at x/L = 0, 0.1, 0.2, 0.3, 0.4 and 0.5 are plotted with respect to time. It can be noted from Fig. 5 that temperature of PCM in the inlet side of the LHS module increased faster in all the three configurations than that of the outlet side which is due to the presence of high temperature difference between the PCM and HTF at the inlet side. It is also noted from Fig. 5 that in both no fin and standard fin configurations, the difference between the temperature of PCM in the inlet and outlet portion is more than that of the novel fin configuration.

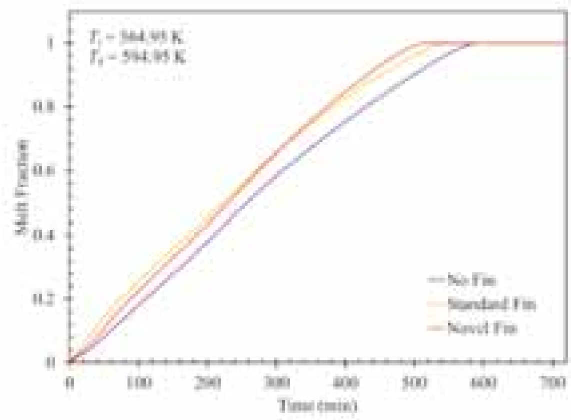

Fig. 4: Melt fraction distribution

(A)

(B)

(C)

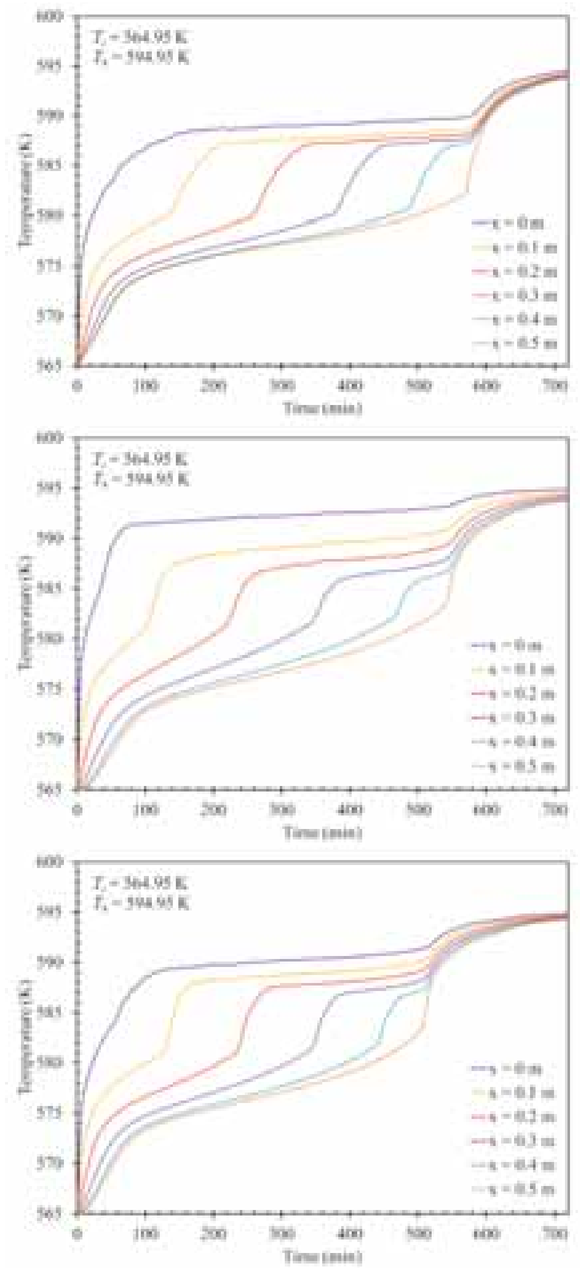

Fig. 5: Axial Temperature Variation (A) No fin (B) Standard fin (C) Novel fin

4. Conclusions

A novel fin is proposed for effective heat transfer in shell-and-tube LHS devices. A numerical model is developed to study the performance characteristics of the proposed novel fin and compare it with no fin and standard fin configurations. It is found from the numerical study that it takes about 597 min, 551 min and 518 min for complete charging in the LHS system with no fin, standard fin and novel fin. It can be noted that the charging time has decreased by about 13.2 % and 6 % when using novel fin system with respect to no fin and standard fin configurations. The novel fin proposed has also an additional advantage of weight and cost reduction by a factor of 0.5.

5. Acknowledgements

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