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Effect of Finned-Tube on the Enhancement of Melting Process of PCM in Eccentric Cylinders

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The process of melting of a phase-change material (PCM) in eccentric horizontal cylinders geometry is studied numerically. Numerical simulations are performed for symmetric melting of phase change material between the two cylinders using the finite volume method. The inner cylinder is a finned-tube to enhance the heat transfer between the inner cylinder and the PCM. Inner cylindrical is considered as hot wall while outer is insulated. These simulations show the melting process from the beginning to the end. As result, it is found that the use of fins on the inner tube increases the melting process by decreasing the time of melting by 72.72 %.

Keywords: PCM, enhancement melting, eccentric cylinders, fins, LHS.

1. Introduction

Solar power has been widely used in our daily lives for decades. This unique and abundant resource can be utilized even in the most remote territories to generate electricity and thermal energy, as long as there is plenty of sunshine. The discontinuous nature of the solar energy forces to use thermal energy storage (TES) because it is recognized as a key technology for further deployment of renewable energy and to increase energy efficiency in our systems. Latent heat storage (LHS) is considered to be one the preferred TES patterns. A lot of researches on the performance of LHS systems have performed in recent years by testing different PCMs [1, 2].

Other works studied the effects of geometry parameters and boundary conditions on the PCM LHS performance [3–6]. Phase change in cylindrical geometry is of great interest from the theoretical point of view and is of importance for the development of processes based on the use of latent heat. The melting process inside a cylinder, which is usually accompanied by natural convection, has been

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frequently studied by Ahmad et al. [7]. They discussed a numerical study of melting process between two cylinders for concentric and eccentric state. This study was done to investigate the effect of position of inner cylindrical tube on melting of PCM (charging) in outer cylindrical shell. They found that heat conduction to the PCM is dominant at the beginning of melting for all zones through contact melting. After a few minutes, natural convection becomes dominant at top half of hot cylinder while heat conduction remains dominant in bottom of hot cylinder.

Melting rate in top half becomes faster than the bottom half of the cylinder. It is interesting when inner cylinder tube moves toward down of the centre, the melting rate increases sharply. Tao and He [8] proposed a compound enhancement method, which is consisted of internal enhanced tube (ET) and multiple phase change materials. Four different cases were designed to compare and validate the performance of the presented compound enhancement method. Case 1 is a basic case with smooth tube (ST) and single PCM (PCM1). Case 2 is a simple enhanced case with internal helically-finned enhanced tube (ET) and single PCM (PCM1). They found that compound enhancement method can further improve the PCM melting rate and total TES rate. But the synthesized enhancement effects (TES rate and TES capacity) greatly depend on the thermal properties of the selected PCMs. With appropriately selecting the PCMs (for example case 4), both the TES rate and TES capacity can be enhanced.

Tao and He [9] presented a numerical studies on the effects of natural convection on latent heat storage performance of latent heat storage (LHS) process of salt in a horizontal concentric tube. They designed a fin-tube to improve the uniformity of the melting process. They found that the designed local enhanced finned tube can both improve the uniformity for the melting process and enhance the LHS performance. The fin parameters should be appropriately selected. The excessive large fin number, fin thickness or fin height will break the uniformity again and reduce the heat storage capacity. In order to further enhance the LHS performance of shell-and-tube LHS unit. The melting process in the eccentric cylinders with inner finned-tube is studied in this work.

2. Physical model and governing equations

2.1. *Physical model*

The physical model is shown in Fig. 1, which is a shell-and-tube configuration. The geometric parameters are as follows: the radius and wall thickness for the inner tube are 20 and 1.5mm respectively, and inner radius for the outer tube is 40mm.

The cylinders are eccentric and the centre-to-centre distance is 10mm. The inner tube is smooth in Fig. 1(a), and with fins in Fig. 1(b). The inner cylinder tube is hot and outer cylinder tube is insulated. The temperature of the inner cylinder fixed to the 329.15K. The geometric parameters of the triangle fins are as follows: high and base are 10 and 5mm respectively Fig. 1(b).

CN-eicosane is taken as PCM which is filled in the circular space between the two tubes. The solid PCM was subcooled at 301.15K. The thermophysical properties of PCM and inner cylinder are taken from reference [7]. In order to simplify the mathematical model and save the computational time and due to the symmetry, a half of the eccentric cylinders are chosen as the computational domain.

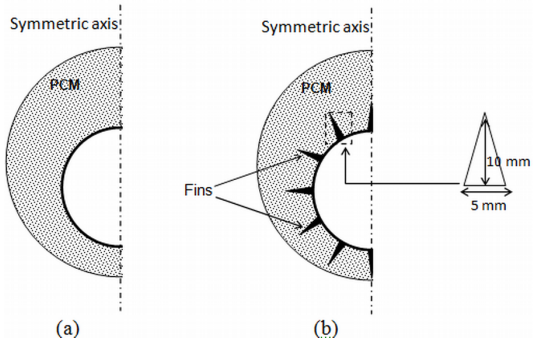

Figure 1 Schematic of the LHS unit

2.2. *Governing equations*

This model is based on the conservation equations of fluid mechanics: the continuity the momentum and the energy equations.

- Continuity:

$$\partial_t (\rho) + \partial_i (\rho u_i) = 0 \tag{1}$$

- Momentum:

$$\partial_t (\rho u_i) + \partial_i (\rho u_i u_j) = \mu \partial_{jj} u_i - \partial_i p + \rho g_i + S_i \tag{2}$$

- Thermal energy:

  The mathematical equations used to solve the solidification and melting models depend on the enthalpy–porosity technique [10, 11].

$$\partial_t (\rho H) + \nabla (\rho \overline{v} H) = \nabla (k \nabla T) + S \tag{3}$$

  In these equations, $\overline{v}$ is the fluid velocity, ρ is the PCM's density, k is the thermal conductivity, H is the enthalpy and S is the source term.

  The sensible enthalpy can be expressed as:

$$h = h_{ref} + \int_{Tref}^{T} C_p dT \tag{4}$$

  where h_{ref} is the reference enthalpy at the reference temperature T_{ref}, C_p is the specific heat.

The enthalpy of the material is computed as the sum of the sensible enthalpy, h, and the latent heat, ΔH:

$$H = h + \Delta H \tag{5}$$

where ΔH can be written in terms of the latent heat of the material, L

$$\Delta H = \beta \ L. \tag{6}$$

ΔH may vary between zero for solid and 1 for liquid, and β is the liquid fraction during the phase-change which occurs over a range of temperatures: $T_s < T < T_l$, defined by the following relations:

$$\begin{cases} \beta = 0 \text{ if } T < T_s \\ \beta = 1 \text{ if } T > T_l \\ \beta = \frac{T-T_s}{T_l-T_s} \text{ if } T_s < T < T_l \end{cases} \tag{7}$$

where: T_s and T_l are the solidus and liquidus temperatures of the PCM respectively.

The source term S_i in the momentum equation, Eq. (2), is given by:

$$S_i = -A(\beta)u_i \tag{8}$$

where $A(\beta)$ is the "porosity function" defined by Brent et al. [12].

$$A(\beta) = \frac{C\ (1-\beta)^2}{\beta^3 + \varepsilon} \tag{9}$$

where $\varepsilon = 0.001$ 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 $10^4 - 10^7$. A value of $C = 10^5$ has been used in a previous study [13], where its effect was discussed. The coefficient C is fixed at a value of 10^5kg/m^{3}s for the present study [14].

2.3. *Boundary Conditions*

This work adopts a phase change state. The boundary conditions are chosen according to the work of Ahmad et al. [7].

2.4. *Model Validation*

The system of conservative equations (1 to 3) is solved with finite volume method and SIMPLE algorithm was used for pressure-velocity coupling. The convergence of solutions is assumed when the maximum normalized residue for all cells is less than 10^{-5}.

A grid independence test analysis showed that the mesh of 5643 grids is good enough for the studied geometry. Several values of time step Δt have been examined ($\Delta t = 0.07, 0.06, 0.05, 0.01$)s for the chosen grid, the time step used in computations is 0.05s.

After that, the comparisons between the present numerical predictions and the results in [7] were performed to validate the reliability of the simulation. The comparative results are shown in Fig. 2. We can see that the predicted liquid fraction curves of the present work and the results in [7] are well accordant with each other. The good agreements show that the physical model and simulation in the present paper are correct and reliable.

3. Results and Discussions

In order to investigate the effects of fins on the melting of PCM and on the LHS performance, two models were adopted. One is a LHS with a smooth inner tube and the other is an inner tube with fins. In the following section, the prediction results for the two models will be compared.

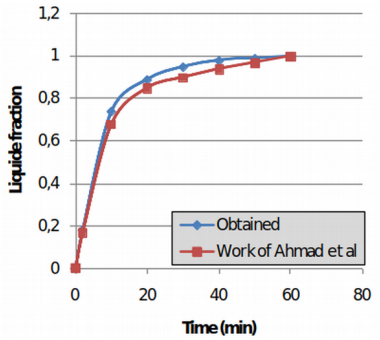

Figure 2 Comparison of our results in terms of liquid fraction with those obtained by Ahmed et al. [7]

3.1. *LHS with Smooth Inner Tube*

The instantaneous contours of the colorized temperature fields and liquid fraction after 2, 10, 20, and 30min are given in Fig. 3.

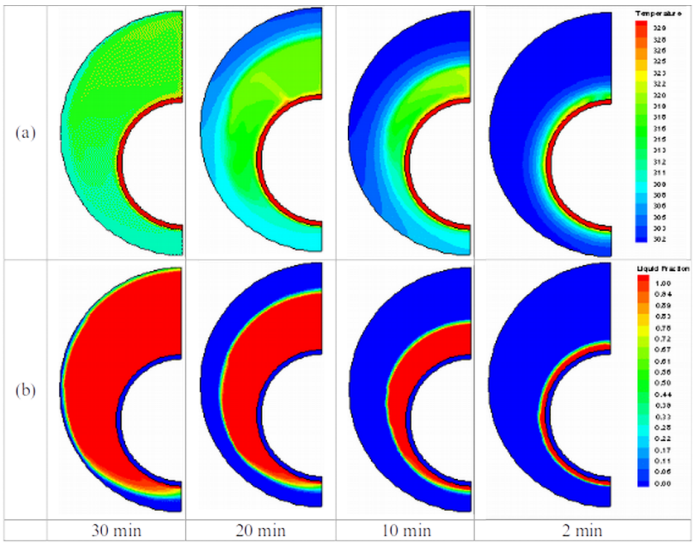

Figure 3 Temperature contours (a) and melting patterns (b) at different times: 2, 10, 20, 30min (smooth tube)

It is observed that at the beginning of the process a small melting area was created because of the small amount of heat transferred. The conduction inside the solid matrix of the PCM is responsible for the heat transfer process inside and this region receives heat from the melted part by convection. The physical mechanisms of the PCM melting process were explained in detail by Aydin et al. [15,16]. Results show that heat conduction is the dominant heat transfer mechanism at the beginning

of the melting for all the annulus space. After a few minutes, natural convection becomes the dominant mode. Melting behavior in the upper half of the annulus was much more enhanced than that in the lower half because of the ascending melt flow due to the buoyancy-induced or natural convection. In order to obtain the uniform PCM melting rate and temperature distribution, an inner finned tube is designed and the effects of presence of fins on the performance will be numerically investigated.

3.2. *LHS with Inner Finned-Tube*

Fig. 4 shows the heating and melting processes of the PCM, It can be showed that melting starts in the below region close to the inner wall and, in the following, molten PCM ascends to the top part of the PCM container as A result of natural convection boundary layers existing near the tube wall. Then, two regions coexist during the charging processes, which are the melted PCM region in the liquid phase and the non-melted PCM region in the solid phase. The results showed an increase in the heat transfer rate when using inner tube with fins. This effect can be measured by the time needed by the inner tube to melt the PCM.

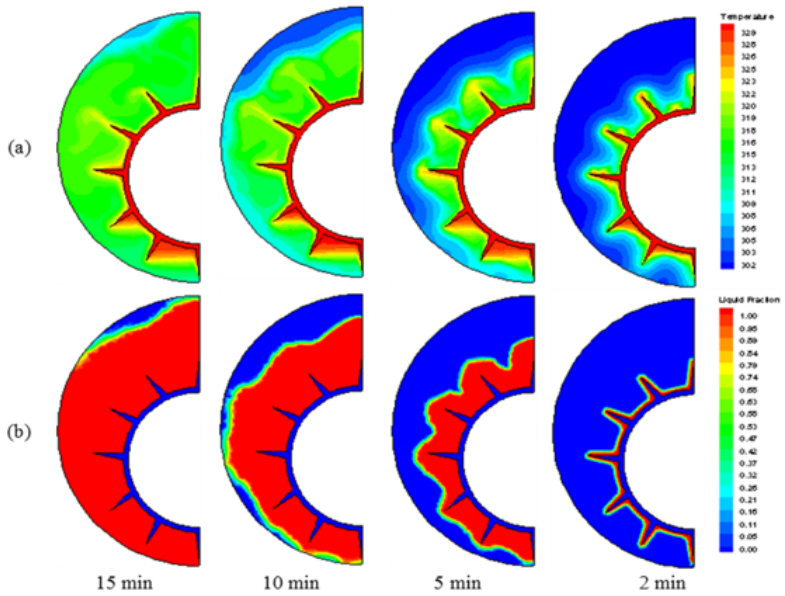

Figure 4 Temperature contours (a) and melting patterns (b) at different times: 2, 5, 10,15 minutes (finned tube)

Fig. 5 shows the time needed to melt the PCM due to the heat transferred by the inner tube for the two cases with and without fins. To melt the PCM from the solid state to the liquid state using an inner tube without fins, the time needed was about 30 min to get 88% of liquid fraction. When using fins, to achieve the same liquid fraction (88%), the time necessary was about 14min (a reduction of 46.66%), knowing that the space taken by the fins is just 2.5% of the space between the two

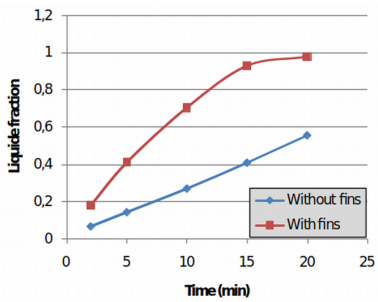

Figure 5 Comparison of liquid fraction variation versus time for the two cases with and without fins

cylinders.

4. Conclusions

In the present numerical study, the melting processes in horizontal eccentric cylinders with a finned-tube have been investigated. Results show that heat conduction is the dominant heat transfer mechanism at the beginning of the melting for all the space considered. After a few minutes, natural convection becomes the dominant mode.

For the case of the finned inner tube, melting behavior was much more enhanced than that in the case of smooth tube. The use of fins in eccentric cylinders reduced the time necessary for the melting process; in this case the time was reduced by 72.72%.

References

[1] **Fang, M., Chen, G.M.**: Effects of different multiple PCMs on the performance of a latent thermal energy storage system, *Appl. Therm. Eng.*, **27**, 994–1000, **2007**.

[2] **Akgun, M., Aydin, O., Kaygusuz, K.**: Thermal energy storage performance of paraffin in a novel tube-in-shell system, *Appl. Therm. Eng.* **28**, 405–413, **2008**.

[3] **Guo, C.X., Zhang, W.J.**: Numerical simulation and parametric study on new type of high temperature latent heat thermal energy storage system, *Energy Convers. Manag.*, **49**, 919–927, **2008**.

[4] **Tao, Y.B., He, Y.L.**: Numerical study on thermal energy storage performance of phase change material under non-steady-state inlet boundary, *Appl. Energy*, **88**, 4172–4179, **2011**.

[5] **Tao, Y.B., Li, M.J., He, Y.L., Tao, W.Q.**: Effects of parameters on performance of high temperature molten salt latent heat storage unit, *Appl. Therm. Eng.*, **72**, 48–55, **2014**.

[6] **Tao, Y.B., He, Y.L., Cui, F.Q., Lin, C.H.**: Numerical study on coupling phase change heat transfer performance of solar dish collector, *Sol. Energy*, **90**, 84–93, **2013**.

[7] **Ahmad, A., Rabienata,j D., Farhadi, M., Sedighi, K.**: Numerical study of melting inside concentric and eccentric horizontal annulus, *Applied Mathematical Modelling*, **36**, 4080–4086, **2012**.

[8] **Tao, Y.B., He, Y.L.**: Numerical study on performance enhancement of shell-and-tube latent heat storage unit, *International Communications in Heat and Mass Transfer*, **67**, 147–152, **2015**.

[9] **Tao, Y.B., He, Y.L.**: Effects of natural convection on latent heat storage performance of salt in a horizontal concentric tube, *Applied Energy*, **143**, 38–46, **2015**.

[10] **Voller, V.R., Prakash, C.**: A fixed grid numerical modelling methodology for convection-diffusion mushy region phase-change problems, *International Journal of Heat and Mass Transfer*, **30**, 1709–1719, **1987**.

[11] **Al-Abidi, A., Bin Mat, S., Sopian, K., Sulaiman, M.Y., Abdulrahman, T.M.**: CFD applications for latent heat thermal energy storage: a review, *Renewable and Sustainable Energy Reviews*, **20**, 353–363, **2013**.

[12] **Brent, A.D., Voller, V.R., Reid, K.J.**: Enthalpy-porosity technique for modeling convection-diffusion phase change: application to the melting of a pure metal, *Numerical Heat Transfer*, **13**, 297–318, **1988**.

[13] **Shatikian, V., Ziskind, G., Letan, R.**: Numerical investigation of a PCM-based heat sink with internal fins, *Int. J. Heat Mass Transfer*, **48**, 3689–3706, **2005**.

[14] **Brent, A.D., Voller, V.R., Reid, K.J.**: Enthalpy-porosity technique for modeling convection-diffusion phase change: application to the melting of a pure metal, *Numerical Heat Transfer*, **13**, 297–318, **1988**.

[15] **Aydin, O., Akgun, M., Kaygusuz, K.**: An experimental optimization study on a tube-in-shell latent heat storage, *Int. J. Energy Res.*, **31**, 274– 287, **2007**.

[16] **Yusuf Yazici, M., Mete, A., Aydin, O., Akgun, M.**: Effect of eccentricity on melting behavior of paraffin in a horizontal tube-in-shell storage unit: An experimental study, *Solar Energy*, **101**, 291–298, **2014**.