Heat transfer enhancement in triplex-tube latent thermal energy storage system with selected arrangements of fins

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Abstract. The use of thermal energy storage systems can effectively reduce energy consumption and improve the system performance. One of the promising ways for thermal energy storage system is application of phase change materials (PCMs). In this study, a two-dimensional numerical model is presented to investigate the heat transfer enhancement during the melting/solidification process in a triplex tube heat exchanger (TTHX) by using fluent software. The thermal conduction and natural convection are all taken into account in the simulation of the melting/solidification process. As the volume fraction of fin is kept to be a constant, the influence of proposed fin arrangement on temporal profile of liquid fraction over the melting process is studied and reported. By rotating the unit with different angle, the simulation shows that the melting time varies a little, which means that the installation error can be reduced by the selected fin arrangement. The proposed fin arrangement also can effectively reduce time of the solidification of the PCM by investigating the solidification process. To summarize, this work presents a shape optimization for the improvement of the thermal energy storage system by considering both thermal energy charging and discharging process.

1. Introduction

The application of thermal energy storage is the most effective method to solve the mismatch between the energy demand and energy supply. Moreover, the application of thermal energy storage could increase the efficiency of thermal energy system. Thermal energy storage can be classified as latent heat storage, sensible energy storage and chemical energy storage. As the most attractive way, the latent heat storage has the merits that it has a wide range of phase change temperatures and higher energy storage density. In the past three decades, the thermal energy storage system based on the application of phase change materials has been applied in many different engineering and civil fields, such as thermal energy storage of buildings [1], air conditioning systems [2], hot water tanks, waste heat recovery, solar air collectors, solar water heaters and solar cookers [3], and so on.

To choose a suitable PCM for thermal energy storage, the properties that are associated with high thermal storage densities, wide range of melting temperatures, noncorrosive, chemically stable, and cheap should be followed [4]. There are various PCMs, which can be divided into three groups, the organic PCMs, the inorganic PCMs and the eutectic PCMs, respectively. Due to the excellent properties, the organic PCMs are the most popular PCMs. While the drawbacks of low thermal conductivity and time consuming for thermal energy charging and discharging process significantly restrict their application on a large scale. Many researchers have proposed a lot of methods for improving the heat transfer during phase change [5]. Almost every method aims to expand the heat transfer surface to accelerate the heat transfer rate. Due to the low cost, simplicity and easiness, it seems that fin is a kind of effective way to increase heat transfer rate during thermal energy charging/discharging process for the widely used TTHX which is a more advanced type than a double tube heat exchanger. Because the TTHX has extra contact surface with the fluid and its efficiency is also higher. Various forms of fins are proposed and proved to be effective to enhance the thermal conduction of PCMs, including circular, tree-shaped, outer fins and inner fins, and longitudinal. Based on the enthalpy-porous medium model, A. Al-Abidi et.al [6] presented a numerical simulation to investigate the influence of various heat transfer enhancement of PCM unit geometry in the TTHX to the PCM melting process. They recommended that the 8-cell PCM unit geometry can effectively reduce the time of the energy charging process in TTHX. H.ESlamnezhad and Asgher B. Rahimi [7] proposed five different fin arrangement to accelerate the melting rate of PCM in the TTHX. They found that the eccentricity of inner tube and fin arrangements are all influential factors in shorting the melting time. Then the best type of fin arrangement to increase efficiency of heat exchanger was suggested. Sciacovelli et al. [8] used the tree shaped fins to improve the thermal performance of a shell-and-tube latent heat thermal energy storage unit. The results showed that the Y-shaped fins with wide angles between branches were the most promising method to short the operating time. Many recent researches by Ho and Siao [9], Ho and Liu [10] had given efforts to investigate the influence of the different operation conditions and designed parameters to the heat transfer performance of the thermal energy storage exchanger.

From above literature reviews, many researchers have tried kinds of designed parameters to optimize the geometry of TTHX for reducing melting time. While in the practical application, the energy charging process and discharging process all play important roles, which all need to be improved, shorten and investigated for improving the efficiency of the TTHX. Although increasing the volume fraction of fins can considerably reduce melting/solidification time, the thermal energy storage would be decreased. Thus it is crucial that the volume of the PCM inside the middle tube should be constant for comparing the thermal energy charging/discharging rate of TTHX with different fin arrangement. And there has been little research about fin arrangement optimization that the volume fraction of the fins is kept to be a constant. In this article, two models with half fin arrangement are proposed to numerically study the thermal performance of the TTHX. It is meaningful to find a promising fin arrangement for improving the efficiency of TTHX, and to propose an effective way for optimization of fin arrangement.

2. Research methodology

2.1. Physical model

The physical configuration of the origin triplex tubes heat-exchanger is shown in figure 1 as proposed in Ref. [6], which has outer tube radius of 100mm with a thickness of 2mm, middle tube radius of 75mm with a thickness of 2mm, and inner tube radius of 25.4mm with a thickness of 1.2mm. The fin thickness has been investigated and optimized, which was set to be 1mm.The tubes and fins were made of copper. For optimizing the fin arrangement that the volume fraction of fins is kept to be a constant (eight fins with a length of 42mm) just as that in the origin TTHX, two kinds of physical structures of TTHX were proposed and listed in the following figures (figure 2 and 3). Similarly, the RT82 [11] was applied as the PCM for thermal energy storage, and water was used as HTF. The physical and thermodynamic properties of the PCM and copper are presented in Table1.

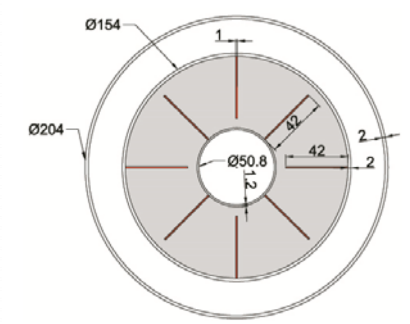

Figure 1. Physical model of a triplex tubes heat-exchanger with fins, Ref. [6]

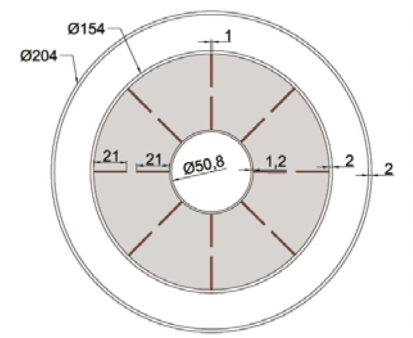

Figure 2. Model A

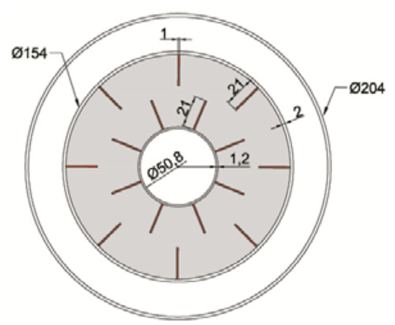

Figure 3. Model B

Table 1. Thermo-physical properties of the PCM

Property	RT82	Copper
Density of PCM, solid, ρ_s (kg/m^3)	950	8978
Density of PCM, liquid, ρ_l (kg/m^3)	770	-
Specific heat of PCM, liquid, C_{p_l}, C_{p_s} (J/kg K)	2000	381
Latent heat of fusion, L (J/kg)	176000	-
Melting temperature, T_m (K)	350.15-358.15	-
Thermal conductivity, k (W/mK)	0.2	387.6
Thermal expansion coefficient (1/K)	0.001	-
Dynamic Viscosity, μ (kg/m s)	0.03499	-

2.2. Numerical modeling

Based on the finite volume methods and the enthalpy-porosity technique, the PCM melting/solidification process was conducted by using ANSYS Fluent V17.2. The pressure-velocity was coupled by SIMPLE. The second-order upwind difference scheme was used for discretizing the momentum and energy equations. The PRESTO scheme was applied for the pressure correction. The under relaxation value factors for pressure, velocity, energy, and liquid fraction were set to be 0.3, 0.2, 1, and 0.9, respectively. Convergence criterion for energy equation was 10^{-5} and for continuity and momentum was 10^{-8}.

2.3. Mesh independency and time-step independency

The independency of the time step and the grip size were investigated before simulation. The time steps of 1s, 0.5s, 0.2s and 0.1s were tested. To investigate the independence of the grip size, the number of elements of 20249, 30978, 43730, 63975 and 73267 were used with the time step of 0.1s. The numerical results show that the number of elements of 43730, 63975 and 73267 propose almost the same value of liquid fraction. Thus, the time step of 0.2s and the number of element of 43730 were selected for efficient calculation.

3. Result and discussion

In Ref. [6], they have proposed an optimized fin arrangement that the sum of the fin length is 336mm. And it also gave the opinion that the number of fins has a significant effect during the melting process. Thus, in the following sub-sections the liquid fraction change with different fin arrangement is analysed for the fin arrangement optimization with the same volume fraction of PCM. Comparing with the proposed fin arrangement in the Ref. [6], both the melting and solidification are discussed to find out a more efficient fin arrangement for the heat transfer enhancement in TTHX.

3.1. Melting process

3.1.1. Model A and model B. The model A with 16 fins of 21mm long is proposed and discussed in this section. Liquid fraction for model A along with the validation model are shown in figure 4. The faster melting rate in model A can be observed easily. The complete melting for model A happens at 3394s. Comparing with the validation model, the reduction in melting time could reach 16.77%. It also means that the model A is more efficient. In the Model A, it is tried to increase the efficiency of the TTHX and reduce the time of PCM melting by change the fin arrangement, while the sum of the fin length keep to be a constant. It is found that the application of half fin is a promising way to enhance the heat transfer in TTHX. It has been reported in many papers that natural convection plays an important role during the PCM melting process. In the former section, the leakage between the fin and the tube keeps to be 6.4mm that may constrains the natural convection between adjacent unit cells. For further releasing the natural convection, the model B that the inner tube with fins rotated by 25^o is proposed.

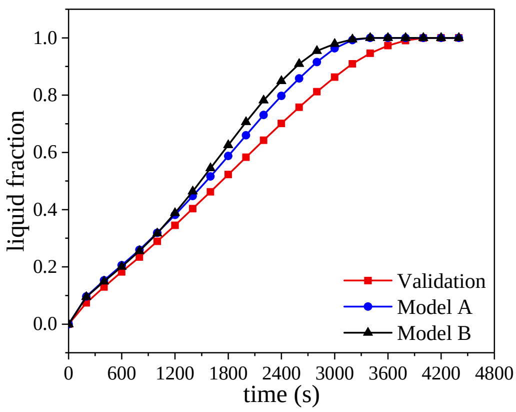

Figure 4. Liquid fraction versus time for Model A along with the results of Ref. [6]

The accurate results are shown in figure 4, which manifest that the model B has a much faster melting rate at the latter half stage. The reason is that the half fin arrangement give more space for the natural convection to progress, then the heat can transfer upward more freely during the melting process, which would be more obvious at latter half stage. It can be concluded that the complete melting time for model B happens at 3386s, and the reduction in melting time can reach 16.9%.

3.1.2. Rotation of model B. Many researchers have contributed efforts to change the angle of the fins and apply the eccentric inner tube to realize the heat transfer enhancement, which significantly relies on the accurate installation, although the results show that the improvements are promising. While in actual application of the TTHX, the installation errors are not easy to be avoided, which could reduce the melting rate. And for manufacture, the angle of fins and the eccentric of inner tube would lead to a series of difficulties.

In this section, the influence of the installation is investigated by rotating the thermal energy storage unit of model B by 5.625, 11.25 and 25^o, respectively. When comparing the curves of the liquid fraction change, this rotation shows that the influence of the half fins location on a TTHX is not as effective as detailed in Ref. [6]. Because the application of half fins provides more space to release the natural convection, and the blocking of natural convection is weaken enough. In other words, the fin arrangement in model B could reduce the influence of installation errors more than that in other former fin arrangement which is also reflected in the figure 5. But the rotation of the unit also shows some phenomenon that there is still a little difference among these four models. The complete melting for rotating the unit by 5.625^o , 11.25^o and 25^o are 3602s, 3522s and 3607s, respectively.

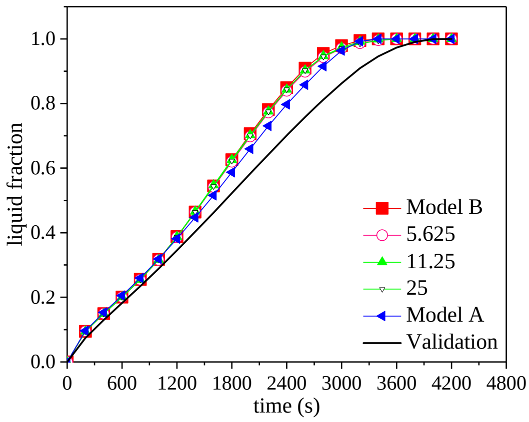

Figure 5. Liquid fraction versus time for Model B with different angle

Though the improvement is less compared to model B but it still has better melting time than the validation model. The difference shows that the reduction for these four models in melting time is up to 12%. But for better melting, the model B without rotation seems to be the most promising fin arrangement among these models.

3.2. Solidification

As former mentioned, despite most of the studies in the literature deal with the melting process, the severe heat transfer reduction also takes place during the solidification process. In this section, the comparison is made between the model B and the validation model to investigate the thermal energy discharging process of the TTHX. Unlike the melting process, the dominant heat transfer mechanism for solidification process is thermal conduction. As introduced in some papers, the buoyancy has almost no effect during the solidification process [12]. Even for efficient computation, it is said that the continuity and momentum equations are not necessary, and the entire system is studied by considering just a sector of 45^o in the Ref. [8]. While in this study, we think that the continuity and momentum equations are still necessary to predicting the PCM solidification phenomenon more accurately.

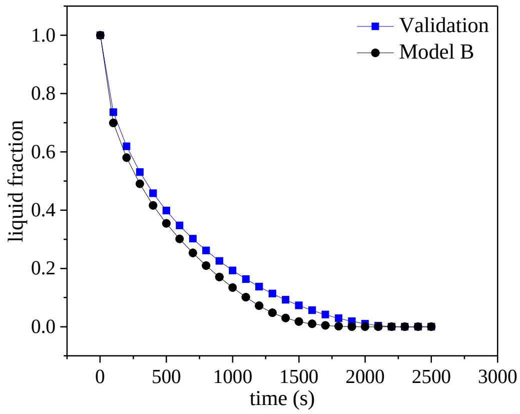

Figure 6. Liquid fraction versus time for Model B along with the results of Ref. [6]

Liquid fraction for model B along with its comparison with model Ref. [6] are shown in figure 6. The trend of solidification in both models only seems to be similar for the first several seconds, then this trend varies greatly until all the PCM changes to be solid phase. The complete solidification for model B happens at 1923s, whereas this time for model B is 2233s. This difference manifests 13.8% reduction in solidification time for model B. The reduction of solidification time again shows the advantage of the fin arrangement of the model B, which not only can accelerate the melting rate, but also can reduce the solidification process effectively. It can be explained that before the PCM solidifies, the hot liquid goes toward the top and the cold liquid moves toward the lower part freely. Although the natural convection in the liquid phase is weak, it still effects the temperature distribution in the PCM unit. It manifests that the PCM at the upper part of unit solidifies a little slowly, which needs to be further enhanced. It also can be concluded that the eccentric form and changing of fin angle could reduce the melting process, but they may lead to time delay during the solidification process.

4. conclusion

As former mentioned, the impact of fin location, fin length and fin thickness on melting and solidification of the phase change material is very significant in TTHX. In this paper, two kinds of fin arrangement were proposed and numerically studied to find out a more appropriate and efficient heat transfer enhancement for TTHX with considering both the melting and solidification process. Comparing with the model published in Ref. [6], the shape of the fin arrangement was obtained that the volume fraction of the fin was kept to be constant. In other words, the contact area of fins and PCM was kept to be same, the changes were the fin length and the fin numbers. Then the conclusion can be drawn as following:

(1) Although the model A and model B both can reduce the melting time more than 12% comparing with the model Ref. [6], it seems that half fin arrangement (model B) is the most efficient way since the conduction and convection are both enhanced. Due to the larger gap between the fin and the tube, the heat can transfer more freely during the melting process.

(2) The advantage of the model B is also verified by rotating the unit a certain angle to realize the effect of the installation error. It seems that the rotation has little effect on the melting rate, and the melting time all can be reduced by more than 12%.

(3) The simulation of solidification process shows that the model B can also effectively reduce the solidification time up to 13.8% comparing with the validation model Ref. [6]. Although the solidification mechanism is dominated by heat conduction, the weaker natural convection still effects the solidification process that the PCM at the bottom solidifies a little faster than that at the top of the unit in the model B.

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Such important results show that the model B is the most promising heat enhancement, and the melting process and solidification process all should take into account in designing of the TTHX.

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