Optimization of Fin Arrangement in a Double-Pipe Heat Exchanger to Improve the Storage Performance of Phase Change Materials

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ABSTRACT

Using latent heat storage systems with phase change materials (PCM) is an effective way to store thermal energy, which has been of great interest in recent years. Using fins is one of the simplest and cheapest ways to increase heat transfer in PCMs and increase the performance of the storage system. Since the fin arrangement has a significant impact on the charging time of the PCM, the main goal of this study is to optimize the fin arrangement in the PCM chamber in a double-pipe heat exchanger in order to decrease the charging time, and thus increase the efficiency of the storage system. For this purpose, the governing equations, including conservation of mass, momentum, and energy in a finned double-pipe heat exchanger have been solved using ANSYS-Fluent software to investigate the thermal-hydraulic behavior of PCM. Also, to find the optimal fin arrangement and maximize the storage performance, the response surface method based on the central composite design have been implemented. The results obtained from the response surface with the reduced cubic equaltion show that compared to the case without fins, the charging time reduces by 19% using the uniform fin configuration, while reduces by 56% using the optimal fin arrangemen.

KEYWORDS

Increasing storage performance, Phase change material, Double-pipe heat exchanger, Optimal fin arrangement, Response surface method

1. Introduction

One of the basic challenges in PCMs, which has been as one of the interesting research topics, is the very low thermal conductivity of PCMs [1]. One of the suitable solutions is to use fins due to their significant advantages such as simple configuration, high surface area increase ratio, low manufacturing cost and easy installation [2]. In this regard, various studies have been done by researchers, especially in multi-tube heat exchangers. Singh et al. [3] investigated the use of annular fins to increase the charging efficiency of PCM in a tubular heat exchanger. In order to achieve the optimal performance of the storage system, optimization methods and algorithms [4, 5] such as Response surface method (RSM) should be used.

The main goal of this study is to find the optimal and non-uniform arrangement of annular fins in a double-pipe heat exchanger in order to achieve the minimum storage time, in which the RSM has been used as the optimization method. Camparing the obtained results of optimal solution with the case of uniform fin arrangement and also with the case of no fin, indicates that the use of the optimal arrangement of fins has a significant effect on increasing the performance of the storage system.

2. Mathematical modeling of Storage system

In this study, a storage system consist of a vertical double-pipe heat exchanger with RT-35 PCM has been investigated, whose schematic is shown in Figure 1. In the inner pipe, hot water enters from above with constant velocity and temperature. To increase the efficiency of energy storage in PCM, i.e., reducing the PCM charging time, four copper fins are located inside the PCM chamber, which are connected to the inner tube. Sine the arrangement of the fins greatly affects the charging time of the PCM, an optimization is carried out to achieve the best arrangement of fins.

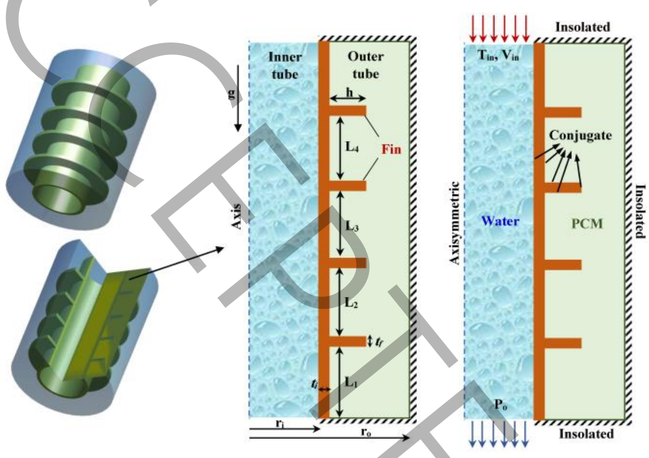

Figure 1. Schematic of storage system

The governing equations of storage system, including conservation of mass, momentum and energy are expressed as fllows:

$$\frac{\partial \rho}{\partial t}+\nabla.\rho\vec{V}=0 \quad (1)$$

$$\rho\frac{\partial \vec{V}}{\partial t}+\rho\left(\vec{V}.\nabla\right)\vec{V}=-\nabla P+\mu\left(\nabla^2\vec{V}\right)- \rho\beta\left(T-T_{ref}\right)\vec{g}-\vec{S} \quad (2)$$

$$\frac{\rho C_p\partial T}{\partial t}+\nabla\left(\rho C_p\vec{V}T\right)=\nabla\left(k\nabla T\right)-S_L \quad (3)$$

where

$$\vec{S}=A_m\frac{\left(1-LF\right)^2}{LF^3+0.001}\vec{V}\,,\quad S_L=\frac{\rho\partial\left(LF\,L_f\right)}{\partial t}+\rho\nabla\left(\vec{V}\,LF\right) \quad (4)$$

The above equations have been solve using ANSYS-FLUENT commercial software in which the SIMPLE algorithm has been implemented to calculate the flow field, while the QUICK and Presto methods have been implemented to discretize the temperature and pressure fields, respectively. Moreover, the enthalpy-porosity approach has been applied to simulate the behavior of the PCM.

3. Optimization of storage system

The main goal of this study is to find the best fin arrangement inside the PCM chamber to achieve the lowest charging time, which can be expressed as follows:

Objective function:

Minimizing the charging time, $t_{\lambda=1}\left(L_1,L_2,L_3,L_4\right)$

Constraints: (5)

$5<L_1<35\ (\text{mm})$ $\quad 5<L_2<35\ (\text{mm})$

$5<L_3<35\ (\text{mm})$ $\quad 5<L_4<35\ (\text{mm})$

where, charging time (liquid fraction=1) is the objective function and four distances between the fins are the optimization variables. To solve the above optimization problem, response surace method (RSM) based on central composite design (CCD) has been applied in Design Expert software. Moreover the analysis of variance (ANOVA) has been used to ensure the accuracy of optimization results.

4. Results and discussion

Using CCD-based RSM, 25 simulations has been carried out for different values of fin distances, Eq. (5). Using reduced cubic model, the response surface relation has been obtained as follows:

$$\begin{aligned} Time &= 6750.8434-2.9852L_1-167.777L_2-31.4L_3+ \\ &8.8638L_4+4.6561L_1L_2+0.9144L_1L_3+1.85144L_1L_4+ \\ &1.0915L_2L_4+0.8233L_3L_4+3.81899L_2^2-1.64101L_4^2- \\ &0.040963L_1L_2L_4-0.02933L_1L_3L_4+0.03958L_1^2L_2+ \\ &0.0022094L_1^2L_4-0.118333L_1L_2^2 \end{aligned} \quad (6)$$

To better understanding the quality of the obtained response surface, the actual values obtained from the simulation are compared with the estimated values from the fitted curve equation (response surface) in Figure 2. As can be seen, the estimated values have a very small deviation from the actual values, which shows that this response surface can be confidently used for other calculations and optimization.

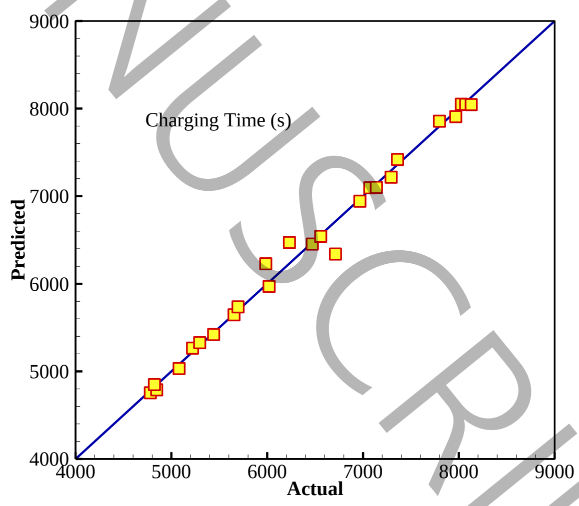

Figure 2. Comparing the actual and predicted values

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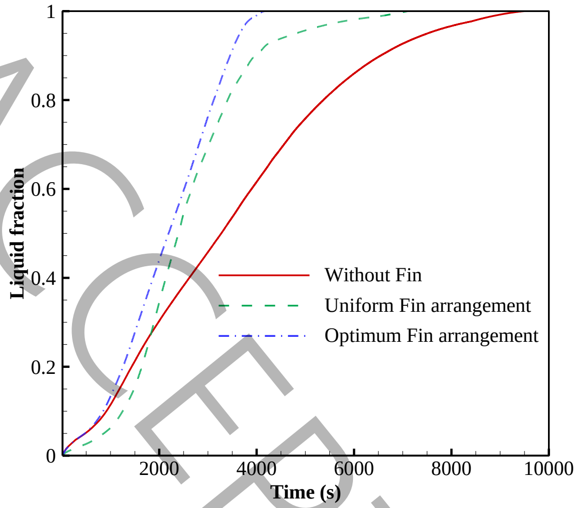

Figure 3. Comparison of time variation of liquid fraction at different fin arrangements

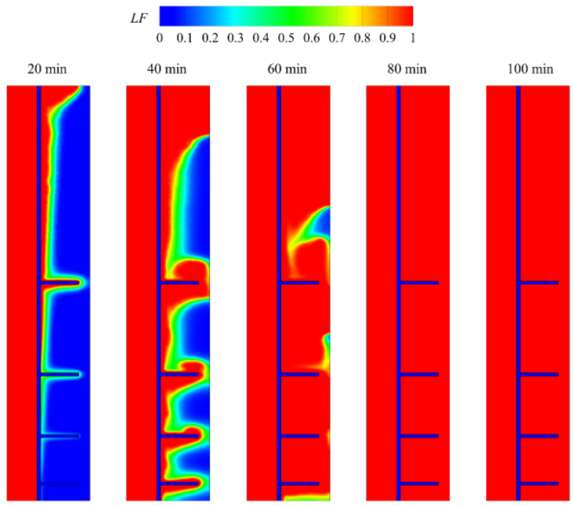

Figure 4. Contours of liquid fraction with optimum fin arrangement

Using above response surface, the minimum value of charging time has been obtained with fin arrangement of L_1=6.051, L_2=17.109, L_2=22.563, L_4=34.142 mm. For a better understanding of the performance of the heat exchanger in PCM charging, the changes in the liquid fraction of the PCM chamber during the charging process are shown in Figure 3 for three different cases, including without fins, uniform, and optimal arrangement of fins. As can be seen, there is a great difference between the PCM charging time in the three cases. It is obseved that comparing to the case without fin, the charging time decreases 19% with uniform fins, while decreases 56% with optimal fin arrangement.

Finally, the heat exchanger with the optimal fin arrangement is simulated and the liquid fraction contours at different times during the charging process are shown in Figure 4. As can be seen, the PCM is fully charged in 80 minutes and the liquid fraction reaches to 1. Moreover, since the PCM at bottom of the chamber is melted with lower speed, the first fin in optimal arrangement is located at the lower area of the PCM chamber to speed up the charging procees and minimze the charging time.

5. Conclusion

In this study, the optimal fin arrangement inside the PCM chamber in a double-pipe heat exchanger has been carried out to find the minimum cahrging time. The RSM based on CCD method has been consideresd as the optimization method. Using Design-Expert software, 25 different arrangements of fins were designed and the performance of storage system was simulated for these arrangements using Ansys-Fluent software. Using ANOVA, a reduced cubic equation was obtained for the response surface. The results showed that minimum charging time of 4310 s could be obtained by L_1=6.051, L_2=17.109, L_2=22.563, L_4=34.142 mm. Moreover, comparing to the case with no fin, 19% and 56% reduction in charging times were achived using uniform and optimal fin arragnements, respectively.

6. References

[1] J.M. Mahdi, S. Lohrasbi, E.C. Nsofor, Hybrid heat transfer enhancement for latent-heat thermal energy storage systems: A review, International Journal of Heat and Mass Transfer, 137 (2019) 630-649.
[2] A.M. Abdulateef, S. Mat, J. Abdulateef, K. Sopian, A.A. Al-Abidi, Geometric and design parameters of fins employed for enhancing thermal energy storage systems: a review, Renewable and Sustainable Energy Reviews, 82 (2018) 1620-1635.
[3] R.P. Singh, H. Xu, S.C. Kaushik, D. Rakshit, A. Romagnoli, Effective utilization of natural convection via novel fin design & influence of enhanced viscosity due to carbon nano-particles in a solar cooling thermal storage system, Solar Energy, 183 (2019) 105-119.
[4] Y. Xu, Z.-J. Zheng, C. Yang, X. Cai, Intelligent optimization of horizontal fins to improve the melting performance of phase change materials in a square cavity with isothermal vertical wall, Journal of Energy Storage, 44 (2021) 103334.
[5] X. Huang, S. Yao, X. Yang, R. Zhou, Melting performance assessments on a triplex-tube thermal energy storage system: Optimization based on response surface method with natural convection, Renewable Energy, 188 (2022) 890-910.

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