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Thermal performance enhancement of energy storage systems via phase change materials utilising an innovative webbed tube heat exchanger

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Abstract

In this study, the phase change materials (PCM) thermal energy storage system utilizing a novel webbed tube heat exchanger was designed and numerically investigated. The obtained simulation results were then compared with three types of conventional heat exchangers. These included: shell and tube heat exchanger, triplex tube heat exchanger and multi-tube heat exchanger. The proposed innovative webbed tube heat exchanger consisted of four horizontal inner heat transfer fluid tubes contained in a shell. The inner heat transfer fluid tubes were connected together by using metal plates welded to these tubes. The additional plates were designed to increase heat transfer surface area. Two-dimensional numerical models were developed. The process of melting (charging) was monitored during the simulation. The acceleration in melting process in the new design was observed owing to improved thermal conductivness.

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Keywords: Phase change materials; melting; webbed tube heat exchanger; thermal energy storage; numerical simulation

1. Introduction

In order to reduce the mismatch between energy supply and demand, latent heat thermal energy can be stored by using PCMs. The main challenge related to such solutions can be characterized by poor thermal conductivities of PCMs, which leads to the increase of energy charge and discharge time. Many researchers considered various modifications to PCM based heat exchangers to enhance their performance. The proposed techniques included using fins [1,2], dispersing of high thermal conductivity nanoparticles [3,4], impregnating PCM in a porous structure such

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as metal foams [5] and using expanded graphite [6]. Agyenim et al. [7] experimentally compared the thermal performance of a shell and tube heat exchanger with a multi-tube heat exchanger. The experiments used the same amount of PCM in both tests. The results indicated that both charging and discharging process required shorter time in case of using a multi-tube system as compared to a single tube system. Pahamli et al. [8] numerically studied thermal performance enhancement of PCM in a double pipe thermal energy storage system. The flow of heat transfer fluid (HTF) takes place in the inner pipe, while PCM fills the space between the inner and outer pipes. The altering of the geometrical position of the inner pipe was studied to investigate the effect of natural convection for PCM melting. The results demonstrated that it is possible to reduce the total PCM melting time when the inner pipe is moved downward from the center.

The present study introduces numerical investigations that were carried out to improve the thermal performance of PCM thermal energy storage system by utilizing webbed tube heat exchanger (WTHX). An innovative design of WTHX heat exchanger lead to enhance the heat transfer between HTF and PCM. The thermal performance of this heat exchanger was compared to conventional heat exchangers.

Nomenclature

PCM	Phase change material
HTF	Heat transfer fluid
WTHX	Webbed tube heat exchanger

2. Research methodology

2.1. Physical model

The WTHX consisted of four horizontal inner tubes and an outer shell. These tubes are connected together by using plates welded to the inner tubes. The HTF (water) passes through the inner tubes, while the PCM is contained in the shell side. The PCM used in this study was (RT82). The thermal and physical properties of PCM (RT82) are shown in Table 1. The cross-sectional area of WTHX physical model and its dimensions are shown in Fig. 1 (a). This model has inner tubes with inner diameter of d_i = 20 mm and 3 mm thickness, the outer shell has an inner diameter d_o = 150 mm and thickness of 2 mm. The plates dimensions are 144 mm (L), 144 mm (W1), 26.5 mm (W2) and 3 mm thickness. Copper was used for pipes and plates. The schematic diagram of the domain used in the numerical simulations with the indicated boundary conditions is shown in Fig. 2(d).

Table 1. Thermal and physical properties of PCM (RT82) [9].

Properties	Values	Units
Conductivity, k	0.2	$W.m^{-1}.K^{-1}$
Latent heat of melting, L	176	$kJ.kg^{-1}$
Thermal expansion coefficient, β	0.001	K^{-1}
Solid density, ρ_s	950	$kg.m^{-3}$
Liquid density, ρ_l	770	$kg.m^{-3}$
Specific heat, C_P	2	$kJ.kg^{-1}.K^{-1}$
Dynamic viscosity, μ	0.03499	$kg.m^{-1}.s^{-1}$
Melting temperature, T_m	77-85	°C

2.2. Governing equations

The governing equations for PCM can be written as follows:
Mass conservation equation is

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

Momentum conservation equations are

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

Energy conservation equation is

$$\partial_t(\rho h) + \partial_t(\rho\Delta H) + \partial_i(\rho u_i h) = \partial_i(k\partial_i T) \tag{3}$$

The PCM density is denoted by ρ, u_i is the fluid velocity, μ is the dynamic viscosity of the fluid, P is the pressure, g is the gravity acceleration, S_i is the source term (porosity function), k is the thermal conductivity, and h is the sensible enthalpy.

The sensible enthalpy can be defined as: -

$$h = h_{ref} + \int_{T_{ref}}^{T} C_p \ \Delta T \tag{4}$$

where h_{ref} is the reference enthalpy at the reference temperature T_{ref}, and C_P is the specific heat.
The total enthalpy H can be calculated as: -

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

where $\Delta H = \gamma L$ is the latent enthalpy that could take the value within the range (0, L).
L denotes the value of the latent heat of PCM.
The liquid fraction γ during the phase change process is defined according to the following formula:

$$\gamma = \begin{cases} 0 \quad if\ T < T_s \\ (T - T_s)/(T_l - T_s) \quad if\ T_s < T < T_l \\ 1\ if\ T > T_l \end{cases} \tag{6}$$

The finite volume numerical method implemented in Ansys – Fluent software was used to solve the continuity, momentum and energy equations. The solidification and melting model was utilized to account for PCM melting process. The (SIMPLE) scheme was employed for pressure-velocity coupling. Mesh and time step independence tests were performed and showed that the grids sizes of 59372 elements and the time step of 10 s were adequate for current numerical calculations.

(a) (b)

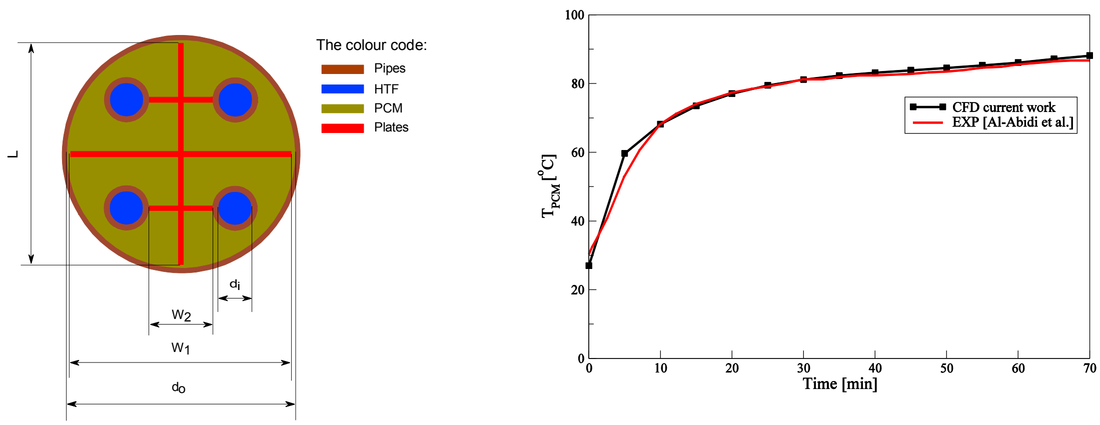

Fig. 1. (a) the cross-sectional area of WTHX physical model with the major dimensions; (b) comparison of the average PCM temperature results obtained from the current numerical model with those of Al-Abidi et al. [9].

2.3. Initial and boundary conditions

At the initial time (t = 0), the PCM was in the solid state, and hence its temperature is 27 °C. HTF has a constant temperature ($T_w = T_{HTF}$ = 90 °C) which is higher than PCM melting temperature. This temperature is imposed along the inner and outer tubes walls of the triple tube heat exchanger as shown in Fig 2 (a). It is imposed along the inner tube wall of shell and tube heat exchanger as shown in Fig 2 (b). It is also imposed along the inner tubes walls of multi-tube heat exchanger or WTHX as shown in Fig 2 (c) and Fig 2 (d).

3. Results and discussion

To test the accuracy of the current numerical model, the numerical results were compared with the experimental results of Al-Abidi et al. [9]. The melting of PCM inside a triplex tube heat exchanger was chosen as a case study. The results were presented in terms of average PCM temperature as shown in Fig. 1 (b). The comparison of PCM temperature shows a good agreement between the present model results and those of Al-Abidi et al. [9].

Different heat exchanger types were compared with WTHX. The numerical domains of these heat exchangers are shown in Fig. 2. These heat exchangers include: triple tube heat exchanger (TTHX) as shown in Fig. 2 (a), shell and tube heat exchanger (STHX) as shown in Fig. 2 (b), multi-tube heat exchanger (MTHX) as shown in Fig. 2 (c) and webbed tube heat exchanger (WTHX) as shown in Fig. 2 (d). For TTHX the HTF flows through the inner and outer tubes while the PCM is contained in the middle annular. For STHX the HTF flows through the inner tube and the PCM is contained in the shell side. For MTHX and WTHX the HTF flows through the inner four tubes and the PCM is contained in the shell side. Additional plates were used in WTHX to connect the HTF tubes to increase the heat transfer surface area and enhance the PCM thermal performance. The WTHX is proposed as a novel design to reduce the charging and discharging time for the PCM thermal energy storage system. Fig. 3 (a) presents the liquid fraction for different heat exchanger configurations cases. This figure shows that for WTHX the PCM total melting time decreases significantly as compared to other heat exchangers types. The PCM completely melted after 180 minutes of using WTHX, while at the same time only around 10%, 30% and 60% of PCM melted in STHX, MTHX, and TTHX solutions respectively. The acceleration of melting process in WTHX configurations is due to the increase of heat transfer area as a result of using plates. The average PCM temperature for different cases is shown in Fig. 3 (b). This figure shows that the PCM average temperature in case of WTHX was higher compared to other heat exchangers in all time intervals. This leads to the enhancement in PCM thermal performance for WTHX compared to the other heat exchangers. Liquid fraction contours of the PCM for various configurations of heat exchangers at different times are shown in Fig. 4. In case of using WTHX, the heat transfer by conduction from the plates to the PCM increased leading to the acceleration in melting process and the increase of liquid fraction.

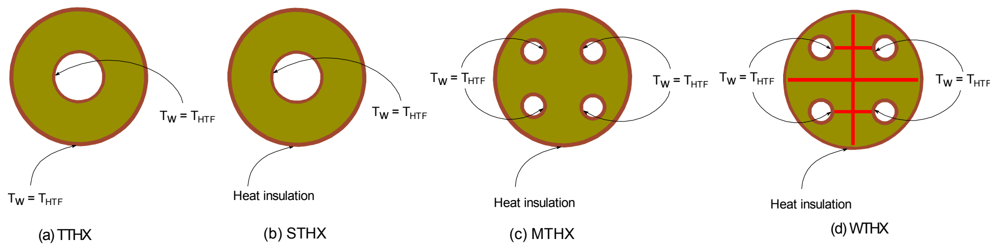

Fig. 2. Computational domains with the indicated boundary conditions for (a) triple tube heat exchanger (TTHX); (b) shell and tube heat exchanger (STHX); (c) multi tube heat exchanger (MTHX); (d) webbed tube heat exchanger (WTHX).

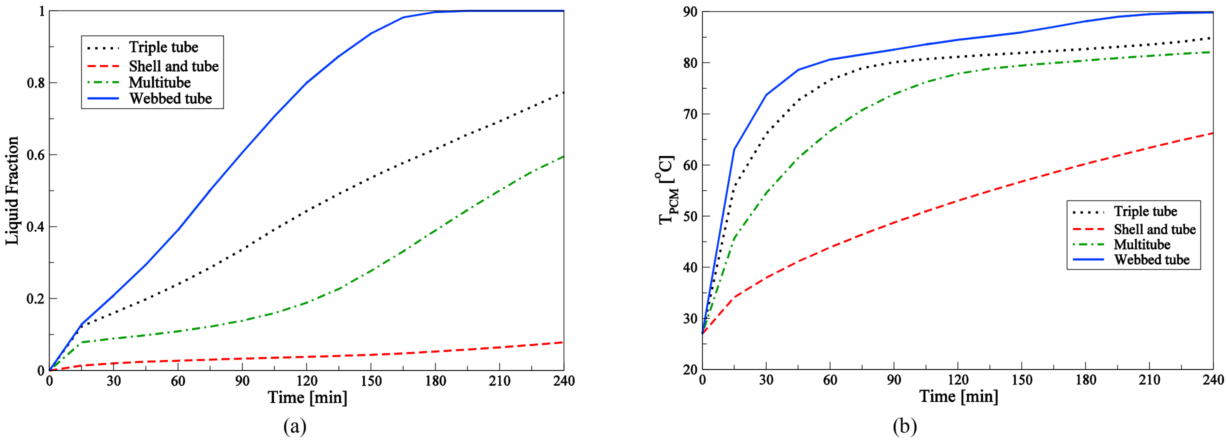

Fig. 3. Comparison of different heat exchangers types: (a) liquid fraction; (b) average PCM temperature.

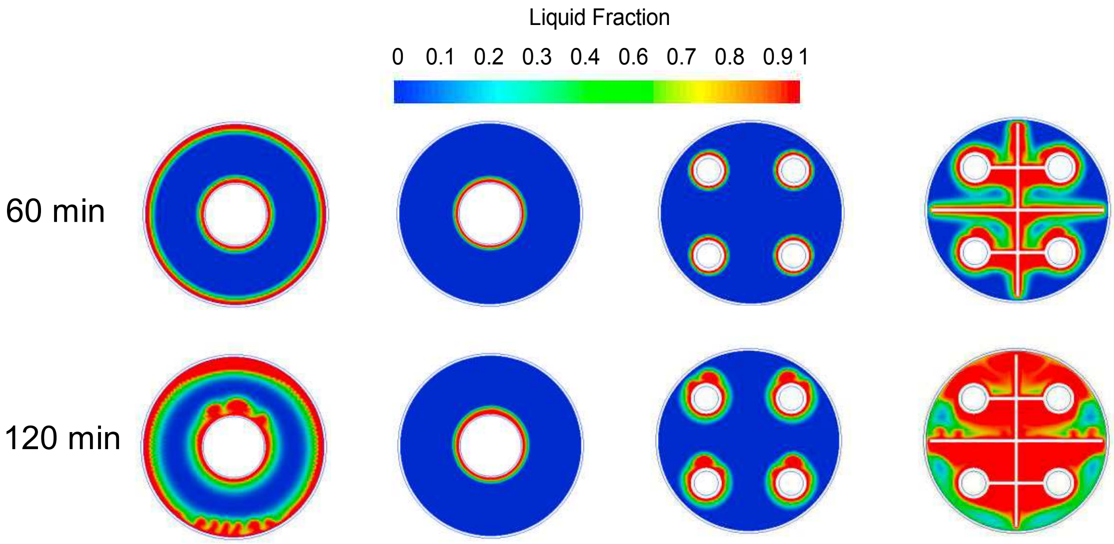

Fig. 4. Contours of liquid fraction at various time moments during the melting process for different heat exchanger configurations. From left to right: triple tube heat exchanger, shell and tube heat exchanger, multi-tube heat exchanger and webbed tube heat exchanger.

4. Conclusions

The results showed significant improvement in PCM thermal performance for the case of the proposed webbed tube heat exchanger as compared to shell and tube heat exchanger, multi-tube heat exchanger and triplex tube heat exchanger. The total PCM melting time in the proposed novel solution decreased significantly compared to the considered other heat exchangers types. The PCM completely melted after 3 hours for the case of the webbed tube heat exchanger. During the same time interval of 3 hours only around 10%, 30% and 60% of PCM melted while using the shell and tube heat exchanger, multi-tube heat exchanger and triplex tube heat exchanger respectively.

The observed acceleration in melting process resulted from the increase of heat transfer area owing to the additional number of plates used in the webbed tube exchanger.

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