Applied Thermal Engineering 113 (2017) 813–821

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Enhance heat transfer for phase-change materials in triplex tube heat exchanger with selected arrangements of fins

H. Eslamnezhad, Asghar B. Rahimi *

Ferdowsi University of Mashhad, P.O. Box No. 91775-1111, Mashhad, Iran

HIGHLIGHTS

- Heat transfer enhancement in a triplex tube heat exchanger using phase change materials.
- Proposed different fin arrangements to increase convection heat transfer.
- Select the best fin arrangement in order to have the best melting time for the PCM material.

ARTICLE INFO

Article history:
Received 27 August 2016
Revised 13 October 2016
Accepted 8 November 2016
Available online 11 November 2016

Keywords:
Phase-change materials melting
Heat exchanger
Rectangular fins
Heat transfer enhancement

ABSTRACT

The use of new energy resources and inventing new methods for the sake of decline of energy usage are always important. The use of energy storage systems not only reduces energy consumption but also enhances system performance as well. One of the new and efficient methods in the field of thermal energy storage is use of phase-change materials that have high latent heat. In this paper, enhancement of heat transfer method using rectangular fin to melt the phase-change material in a triplex tube heat exchanger has been investigated numerically. A two-dimensional numerical model using fluent software is chosen and conduction and natural convection are taken into account in this simulation. The arrangement of the rectangular fins along the triplex tube heat exchanger is one of the most influential factors in the process of melting which has been studied and also the best type of this arrangement to increase efficiency of heat exchanger and reduce the time of melting of the phase-change material have been suggested in the form of different proposed models.

1. Introduction

One of the new and efficient methods in the field of thermal energy storage is usage of phase change materials. The importance of thermal energy storage in the form of latent heat energy in contrast with energy storage in the form of sensible heat due to the high density stored energy of fixed thermal energy is significant. Phase-change materials store energy as melting latent heat. These materials almost release the energy in the same degree of energy that they absorb it. The measure of this material energy storage is 5–14 times more than the energy of the materials such as water or rock that can be stored in the form of sensible heat. To select a suitable phase-change material one should note the following points, such as having a melting point in the range of system operation, a high latent heat per unit mass, high thermal coefficient, a high conductivity, small changes in volume during phase change, a high chemical stability, being non-toxic and non-burning, high availability along with the right price.

In the past three decades, thermal energy storage using phase-change materials has been studied by many researchers because of its high energy density and potential abilities for use in various fields of engineering with wide temperature range. Phase-change materials applications are in various fields of engineering such as thermal storage of a building structure [1], building equipments such as domestic hot water, heating and cooling systems [2], electronics products [3], drying technology [4], waste heat recovery [5], refrigeration and cold storage [6], solar air collector [7] and solar cookers [8].

Thermal energy storage systems, in particular in the form of latent heat energy storage, have attracted attentions because of the global environmental problems and improving energy efficiency. The disadvantages of phase-change materials are their low thermal conductivity and time consuming period during the charging process and thermal discharging properties prevent the use of these materials for thermal energy storage. Different

* Corresponding author.
E-mail address: rahimiab@um.ac.ir (A.B. Rahimi).

http://dx.doi.org/10.1016/j.applthermaleng.2016.11.067
1359-4311/

Nomenclature

C	porous section constant (kg/m^3 s)
C_p	specific heat (j/kg)
g	gravity (m/s^2)
h	sensible enthalpy (j/kg)
H	enthalpy (j/kg)
K	conductivity (W/mK)
L	latent heat (j/kg)
m	mass (kg)
P	pressure (Pa)
r	pipes radius of heat exchangers (m)
S_i	source term added to momentum Eq. (pa/m)
T	temperature (°C or K)
u_i	velocity (m/s^2)

Greek symbols

α	thermal diffusivity (m^2 s)
β	thermal expansion coefficient (–)
γ	liquid fraction (–)
ε	constant (–)
μ	viscosity (kg/ms)
ν	kinematic viscosity (m^2 s)
ρ	density (kg m^3)

Subscriptions

i,j	directions
ini	initial
HTF	working fluid
m	melt
ref	reference
PCM	phase change material
s	solid
l	liquid
t	time

methods for improving heat transfer between the phase-change material and the participant fluid have been studied. These methods are executed by increasing the heat transfer surface area, using finned tubes [9] or by use of multi-tube heat exchanger [10], improving of thermal conductivity of phase-change material such as metal matrix inserted into the phase-change material, saturated Porous materials. Most researchers have reported that an increase of heat transfer surface lead to increase of heat transfer between the working fluid and the phase-change material. Use of fins is the best way to increase heat transfer in the phase-change material which is because of its simplicity, easiness and low cost of making them. Various forms of fins are available to enhance the effect of conduction of phase-change materials, including outer fins and inner fins, circular, and longitudinal. In general, the time melting of the phase-change material is very important and all researches done are toward reducing this time. This is because as the melting time of phase-change material reduces the heat transfer process takes place quicker which improves the system performance. [11,12] studied the cooling technology in a handheld electrical device using phase-change material, numerically. They presented a simulated three-dimensional model for measuring the effect of number of different fins and different heating surfaces and used an outer rectangular fin for enhancing heat transfer during the melting and freezing time for thermal energy storage in building applications. Agyenim et al. [13] studied testing of the heat transfer characteristics, melting (charge) and freezing process (discharge) of RT35 in a small double tube heat exchanger with a 13- circular fin and phase-change material in helical space. Fang et al. [14] used an internally finned tube for heat transfer fluid, while the phase-change material was placed in circular shell space. The results showed that the addition of internal fins was an efficient way to increase heat transfer in thermal energy storage systems, especially when a poor conductor of heat, such as air was used as a heat transfer fluid. Jegadheeswaran et al. [15] studied the characteristics

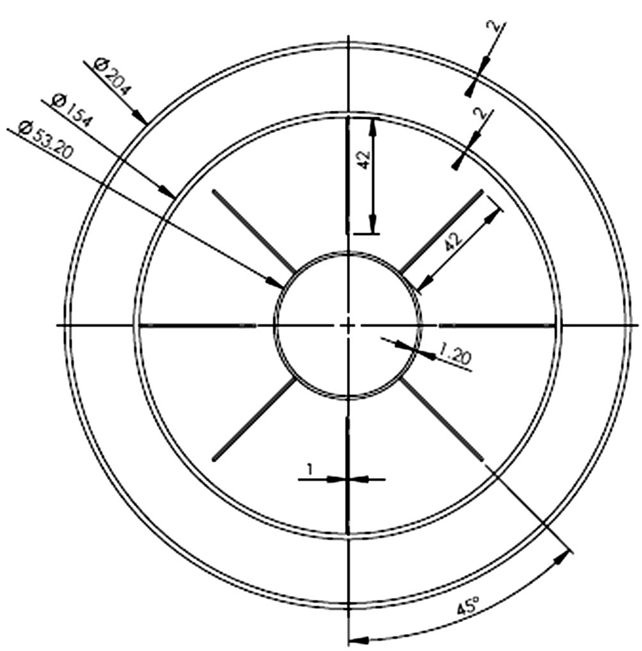

Fig. 1. Physical model of a triplex tubes heat- exchanger with fins, Ref. [12].

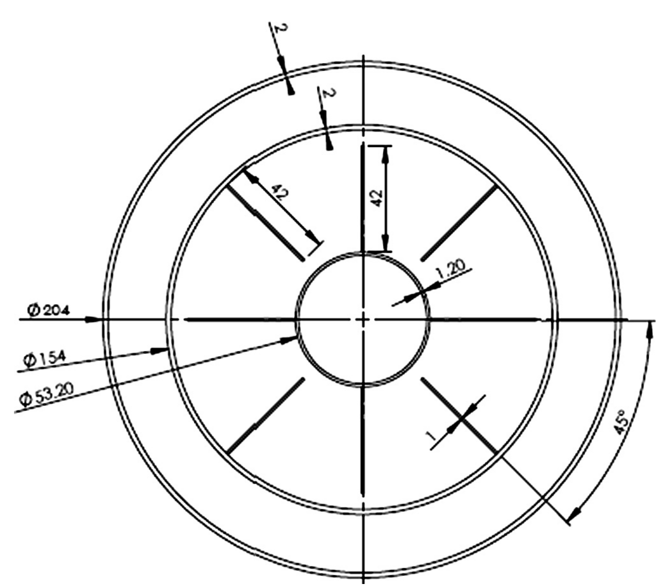

Fig. 2. Model #1, 45° angle changes of model in Ref. [12].

of melting and freezing of CaCl2-6H20 as a phase-change material in a vertical concentric double tube energy storage system. They studied the design and operation of various parameters such as the number of fins inside the phase-change material, the mass flow rate and temperature of the heat transfer fluid and they found that the effect of the design parameters are more important than the performance parameters. In other word the time required to complete the phase-change material freezing and melting is important to be able to absorb or release thermal energy. Charging process depends on the speed of the mass flow rate of heat transfer fluid and its inlet temperature. Oscillations in inlet temperature of the heat transfer fluids can affect the charging process. To determine the time required to complete freezing, Darzi et al. [16] studied the effect of preservatives of phase-change materials, configuration and dimensions in the phase-change material freezing, numerically and experimentally. Al-Abidi et al. [17,18] introduced the internal and external fins attached to the triplex tube heat exchanger as a way of increasing the heat transfer. They studied the effect of the designed parameters and different operations, including the fin length, the fin thickness, the number of fins, and geometry of the storage location of phase-change material and also the materials used in the manufacturing the triplex tube heat exchanger on the process of the phase- change material melting, along others [19–20]. The most recent studies are by Siao and Yan [21], Liu and Yan [22], and Siao, Yan, and Lai [23].

In this article rectangular longitudinal fins inside a triplex heat exchanger will be investigated. Triplex tube heat exchanger is more advanced type than a double tube heat exchanger which is because of its extra contact surface with the fluid and thus its efficiency is also higher. Triplex tube heat exchangers are used in

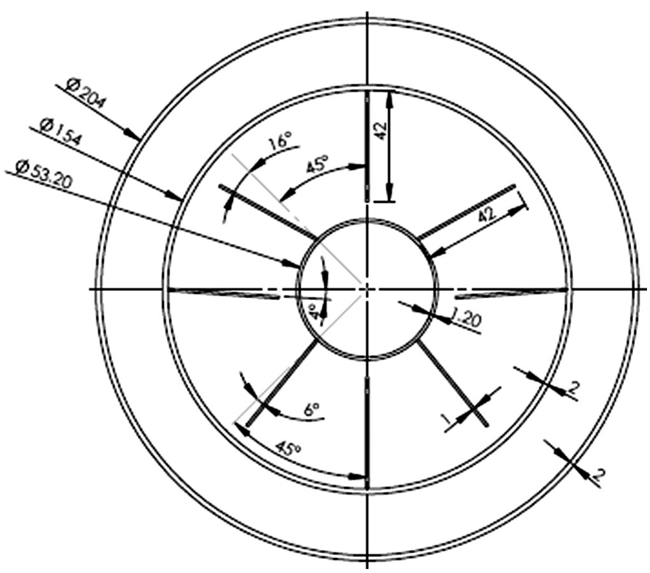

Fig. 3. Model #2, change of angle in fins.

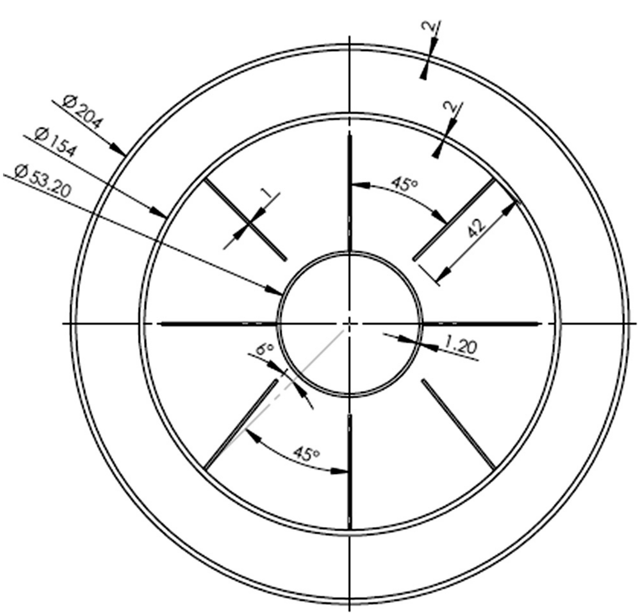

Fig. 4. Model #3, combination of Model #1 & Model #2.

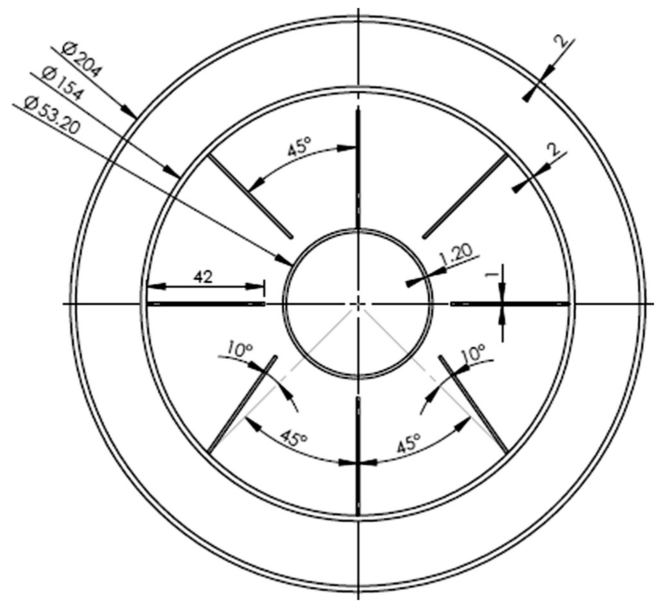

Fig. 5. Model #4, combination of model in Ref. [12] & Model #3.

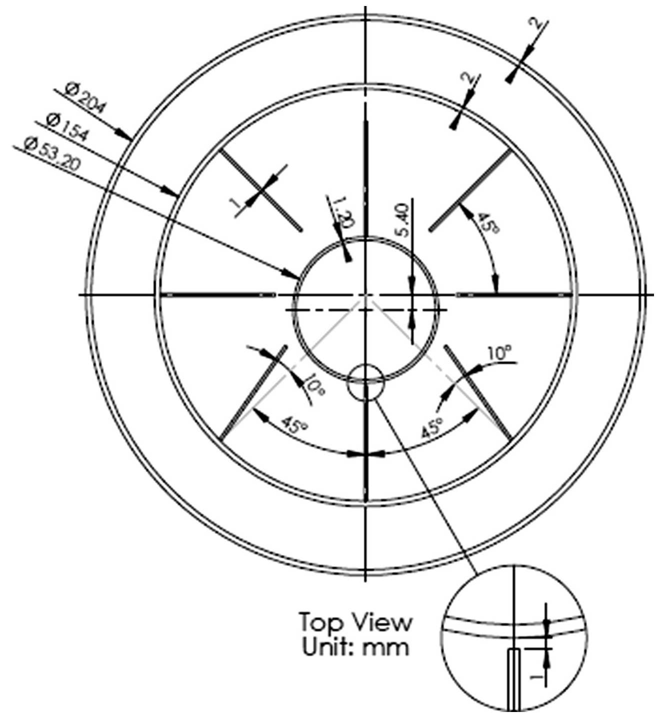

Fig. 6. Model #5, eccentric form of Model #4.

various industries, have special applications in the food industry, freezing, pasteurization, dairy products, manufacture of beverages, processes with high pressure and temperature, processes of antisepticising fruits and so on. Here, it is tried to increase the efficiency of the heat exchanger and to reduce the time of phase-change material melting by changes done in the structure of the fins inside of the triplex tubes when the fin contacting surface with the phase-change material has kept constant. This is done in the form of different proposed models in which the fin arrangements are selected in certain ways and also eccentricity effects are taken into accounts.

2. Research methodology

2.1. Physical model

The physical structure of a triplex tube heat exchanger is shown in Fig. 1, [12]. The model has inner tube radius of 25.4 mm (r_i) and a thickness of 1.2 mm. Central tube (r_m) and the radius of the outer tube (r_o) are 75 and 100 mm with a thickness of 2 mm. Copper pipes were used to ensure high thermal conductivity. As shown in this Fig. 8 fins in length of 42 mm and a thickness of 1 mm are attached to external and internal surfaces.

The outer and inner tubes were used for heat transfer fluid (water), while the middle tube was used for the phase-change materials based on the commercial availability of their materials (RT82). The physical and thermodynamic properties of the phase-change material used are presented in Table 1. Other models under investigation are presented in Figs. 2–6.

Table 1
Physical thermodynamic properties of phase-change material (RT82) and copper.

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, $C_{p_{mhboxl}}$, C_{p_s}, (J/kg K)	2000	381
Latent heat of fusion, L (J/kg)	176,000	–
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	–

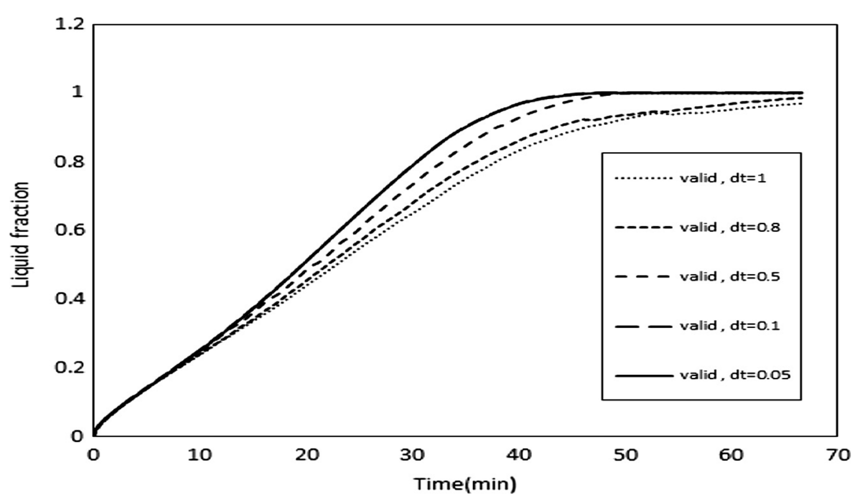

Fig. 7. Time-step independency for validating model, Ref. [12], with 30,312 number of meshes.

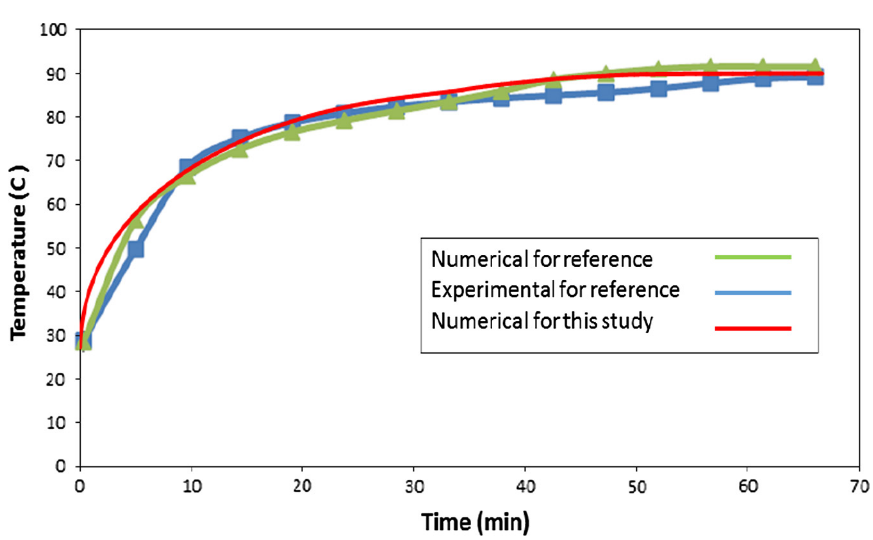

Fig. 8. Comparison of our numerical code with numerical results of Ref. [12].

2.2. Initial and boundary conditions

PCM initial temperature is 27° C and exists in the solid form. The temperature of the walls of the middle space of PCM material, r_m and r_i are the same as the heat transfer working fluid which is 90 °C. Since heat transfer from both tubes are high in this research then the boundary conditions are introduced on this base. That is:

$$r = 26/6 \rightarrow T = T_{htf} \tag{1}$$

$$r = 75 \rightarrow T = T_{htf} \tag{2}$$

Since the fins in the middle space are thin and quickly catch the temperature of the heat transfer working fluid, then their temperature from the beginning are 90 °C. All these assumptions are the same as Ref. [12] which we are validating our results with.

2.3. Governing equations

The governing equations for melting of the PCM material are assumed to be laminar, incompressible, transient, and with very low viscosity. Its thermo-physical properties such as thermal capacity, conductivity, and viscosity are assumed to be constant. These properties are different in the states of solid and liquid so the volume variations of the PCM material is taken to be negligible and the effect of natural convection is according to the Boussinesq approximation. The continuity, momentum, and thermal energy equations are respectively defined as follows:

Continuity equation:

$$\partial_t(\rho) + \partial_i(\rho\, u_i) = 0 \tag{3}$$

Momentum equation:

$$\partial_t(\rho\, u_i) + \partial_i(\rho\, u_i\, u_j) = \mu\, \partial_{jj}\, u_i - \partial_i\, p + \rho\, g_i + S_i \tag{4}$$

Energy equation:

$$\partial_t(\rho\, h) + \partial_i(\rho\, \Delta H) + \partial_i(\rho\, u_i h) = \partial_i(k\, \partial_i T) \tag{5}$$

In which ρ is the density of the phase-change material, u_i is the fluid velocity, μ is dynamic viscosity, p is pressure, g is the gravity acceleration, k is thermal conductivity, T is the fluid temperature, and h is sensible enthalpy for RT82 as the PCM material. This sensible enthalpy is expressed as:

$$h = h_{ref} + \int_{T_{ref}}^{T} c_p \Delta T \tag{6}$$

The total enthalpy can be defined as follows:

$$H = h + \Delta H \tag{7}$$

in which h_{ref} is the reference enthalpy at the reference temperature T_{ref}, c_p is the specific heat, and ΔH refers to the latent heat of PCM material that causes a phase from solid to liquid. This quantity is related to the fraction of the liquid phase generated during the PCM melting process, γ, as:

$$\gamma = \Delta \mathrm{H}/L \tag{8}$$

$$\gamma = \begin{cases} 0 & if \quad T < T_s \\ 1 & if \quad T > T_l \\ (T - T_s)/(T_l - T_s) & if \quad T_l > T > T_s \end{cases} \tag{9}$$

This phase-change process occurs when it is between solid and liquid phase temperature. The source term S_i in momentum equation, Eq. (4), can be defined as:

$$S_i = C(1-\gamma)^2 \frac{u_i}{\gamma^3 + \varepsilon} \tag{10}$$

Which is called porosity function defined by, Brent et al. [24], and is related to the momentum equations and follows the Carmane Kozeny equations presented for the flow of the porous environment. Here, C describes how steeply the velocity is reduced to zero when the material solidifies. The value of this constant due to PCM properties varies between 10^4 to 10^7. In this paper, the value of this constant is considered 10^5 and ε is a small number (0.001) introduced in Ref. [25]. In the same references the Boussineq approximation is defined as:

$$\rho = \frac{\rho_l}{\beta(T - T_l) + 1} \tag{11}$$

where ρ_l is the density of the PCM material at the melting temperature and β is the thermal expansion coefficient.

2.4. Numerical model

The modelling in this work is done using ANSYS Fluent V16. Mesh production is done by the help of ANSYS Meshing after selecting the desired geometry. The employed elements are with the shape of Quad. The reason for using this kind of elements is that their numbers are less than the Tri elements for the same geometry and therefore the calculation time becomes less. Also the meshing near the walls were chosen much finer because of the existing high gradients. The model used is planar and for simulation a transient Pressure-based model is employed since the flow is with low velocity. The discretization of the momentum and energy equations is with second-order accuracy and the pressure term is discretized using PRESTO method. The under-relaxation factors for pressure, velocity, and volume fraction are 0.3, 0.2, and 0.9, respectively. Convergence criterion for continuity and momentum equations is considered 10^{-5} and for energy equation is 10^{-6} .

2.5. Mesh independency and time-step independency

To investigate the number of elements independency on the results, the validating model [12], was simulated for time-step of 0.1 using different types of meshing. The measured parameter is the volume fraction which is presented in Table 2 and at different times. This Table shows that number of elements of 30,312 and 45,798 produce nearly the same value for volume fraction. So, to reduce the cost of calculation the number of elements are chosen as 30,312. To investigate time-step independency, different time-steps were used with 30,312 number of elements meshing. This is shown in Fig. 7 and as seen the time-step of 0.1 and 0.5 produce same results. The time-step 0.1 is used in order to reduce the cost of calculations.

2.6. Validation

In order to validate our numerical code, the results of the model in Ref. [12] have been reproduced. This comparison is shown in Fig. 8. As it can be seen in this figure, our numerical code is producing the numerical results of this reference with acceptable match.

Table 2
Mesh independency of the results.

No. of elements	Liquid fraction for 5 min	Liquid fraction for 30 min	Liquid fraction for 45 min
15,378	0.1181	0.7619	0.9703
30,312	0.1399	0.7890	0.9951
45,798	0.1403	0.7899	0.9956

3. Results and discussions

3.1. Rectangular fins

3.1.1. Model #1

One way for showing the effect of the fins location on the trend of melting the PCM material is to rotate the heat exchanger in Ref. [12] by 45°. This rotation shows the fins location on a triplex tube heat exchanger in which the dominant heat transfer mechanism is natural convection. Contours of liquid fraction for this model along with validating model, [12], are depicted in Fig. 9 at several selected times

The trend of melting in both models is almost the same for the first 10 min but this trend changes afterwards. Because of the collocation of the cold material in the lower part and the existence of hot liquid in the top section a route for heat to go to the upper section and at the same time for the cold material to go to the lower part must be opened. This way the fluid flows through the heat exchanger in such a way that the hot liquid goes toward the top and the cold material moves toward the lower part freely. The fins in Ref. [12] model are blocking the heat moving to the top section. This blocking is specifically because of the fins in the south eastern and south western of the model where in model #1 these fins are attached to the outer tube and the heat is moved to the upper section of the heat exchanger. The arrangement of the fins in north eastern and north western is also important. Generally speaking, the heat transfer process at the outset is conduction and after partial melting of the PCM material this heat transfer mode changes gradually into natural convection and after the first 15 min the heat transfer mode is solely convection. At the time interval of forty minutes the fins arrangement in northern hemisphere in Model #1 shows its superiority in comparison to the validating model Ref. [12]. Also the melting process in southern hemisphere in Model #1 is better in comparison to [12] at time interval of 35 min. The liquid fraction for Model #1 in comparison to model Ref. [12] is shown in Fig. 10. As can be seen in this figure there is a better trend of melting in the case of Model #1 compared to the validating model, Ref. [12]. The complete melting for Model #1 happens at 42 min and 32 s whereas this time for model Ref. [12] is 47 min and 32 s which is showing a five minutes' difference. This difference means 10.5% reduction in melting time for this model.

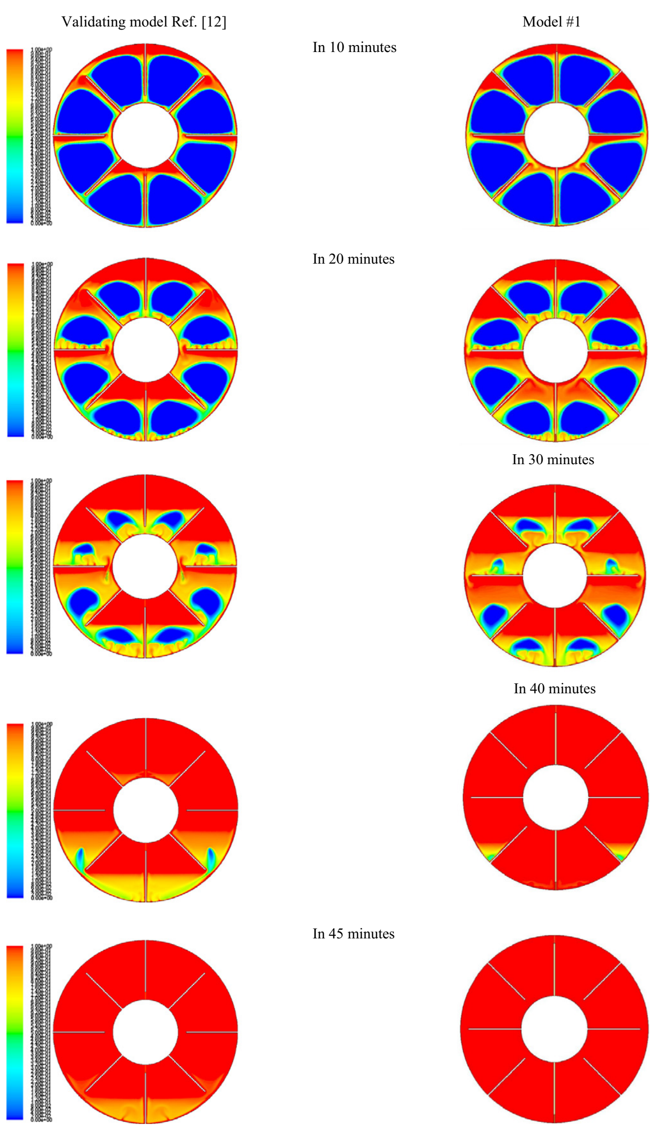

Fig. 9. Liquid fraction contours for Model #1 along with the results of Ref. [12].

3.1.2. Model #2

In this model the angle of the south western and the southeastern fins as well as the eastern and the western fins and also north western and north eastern ones were changed downward so that heat could transfer upwards. The reason for all these movements is to bring about concentration of fins in the lower section of the heat exchanger. The contours for liquid fraction for this model along with model Ref. [12] are presented in Fig. 11 at selected time intervals. Reduction in melting time can be seen easily in these contours in the center of the heat exchanger at time interval of 30 min.

Liquid fraction for Model #2 along with its comparison with model Ref. [12] are shown in Fig. 12. The complete melting for Model #2 happens at 45 min and 1 s whereas this time for model Ref. [12] is 47 min and 32 s. This difference means 5.3% reduction in melting time for this model.

3.1.3. Model #3

This model is a combination of Model #1 and Model #2. In this model the fins in northern hemisphere are like Model #1 but the fins in south western and south eastern are rotated like in Model #2. Also, the southern fin was attached to the outer tube. The contours of liquid fraction for Model #3 along with its comparison to Model #1 are shown in Fig. 13. The change in angle made in Model

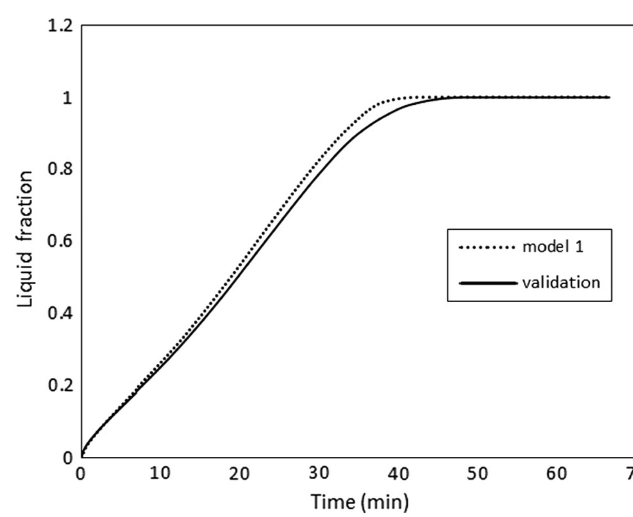

Fig. 10. Liquid fraction versus time for Model #1 along with the Ref. model [12] comparison.

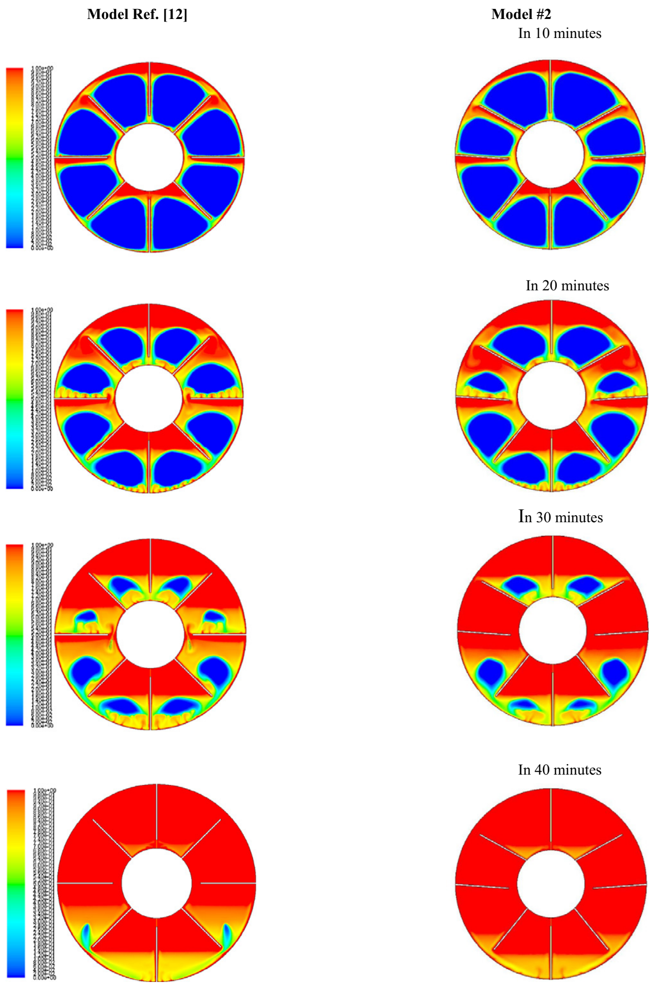

Fig. 11. Liquid fraction contours for Model #2 along with the results of Ref. [12].

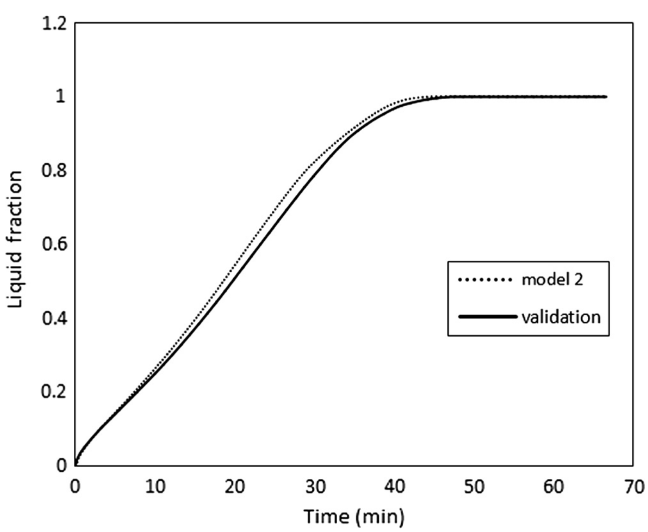

Fig. 12. Liquid fraction versus time for Model #2 along with the Ref. model [12] comparison.

#3opened more space for the heat to move to the upper part of the heat exchanger which causes increase of liquid volume in northern hemisphere from time interval 25 min on. Also caused quick melting of the liquid in lower part which was a weakness in Model#1. Liquid fraction for Model #3 along with its comparison with model Ref. [12] are shown in Fig. 14. The complete melting

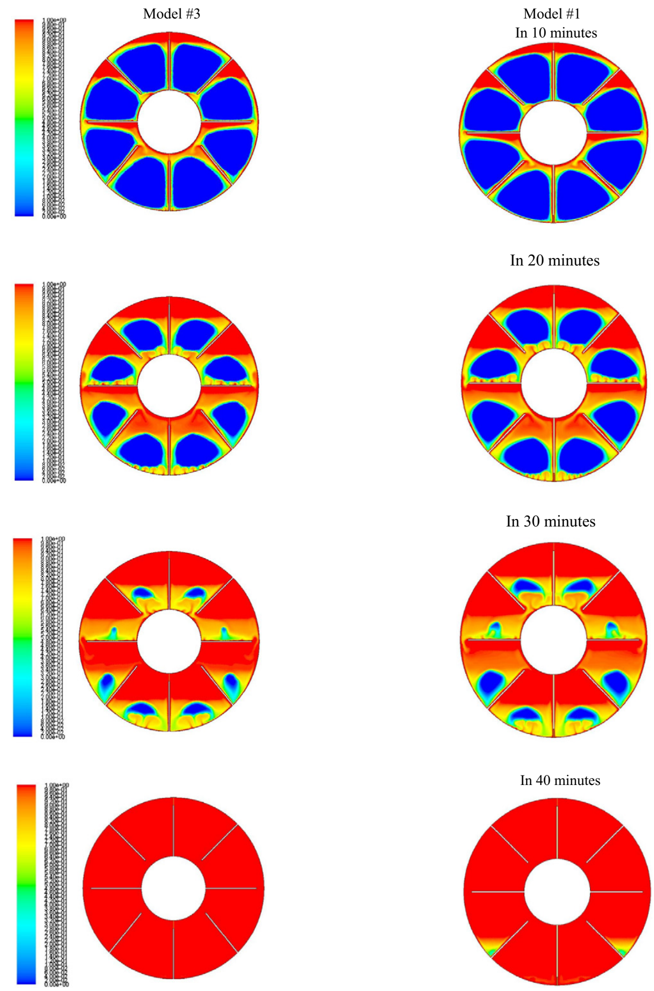

Fig. 13. Liquid fraction contours for Model #3 along with the results of Model #1.

for Model #3 happens at 40 min and 5 s whereas this time for model Ref. [12] is 47 min and 32 s. This difference means 15.7% reduction in melting time for this model.

3.1.4. Model #4

This model is actually the same as Model #3 except that the eastern and the western fins were attached to the outer tube. It turns out that the angles involved in Model #3 are appropriate and therefore are kept the same in Model #4. The contours of liquid fraction for this case are depicted in Fig. 15 at selected time intervals.

Liquid fraction for Model # 4 along with its comparison with model Ref. [12] are shown in Fig. 16. The better melting time in this model is seen easily. The complete melting for Model # 4 happens at 41 min and 33 s whereas this time for model Ref. [12] is 47 min and 32 s. This difference means 12.6% reduction in melting time for this model. Though the improvement is less compared to Model #3 but the appropriateness of the change of the place of the eastern and the western fins are confirmed in the results obtained for Model #4.

3.2. Eccentric heat exchangers

Eccentric heat exchanger is another design for decreasing the melting time of the PCM material. This kind of design has not been used in triplex heat exchanger yet and here by using the results of Ref. [16] we consider its application.

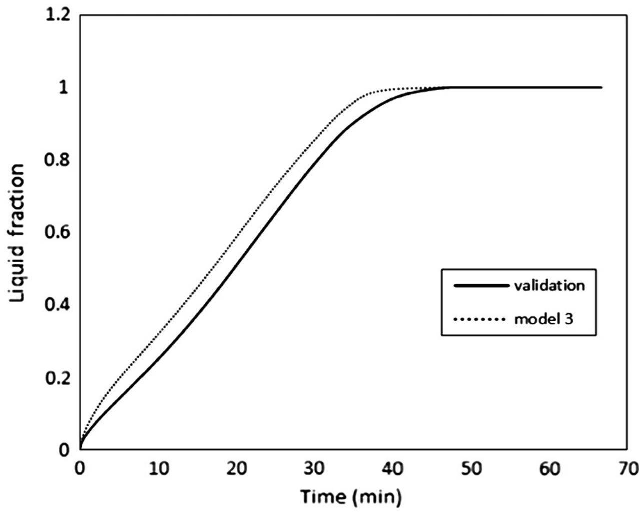

Fig. 14. Liquid fraction versus time for Model #3 along with the Ref. model [12] comparison.

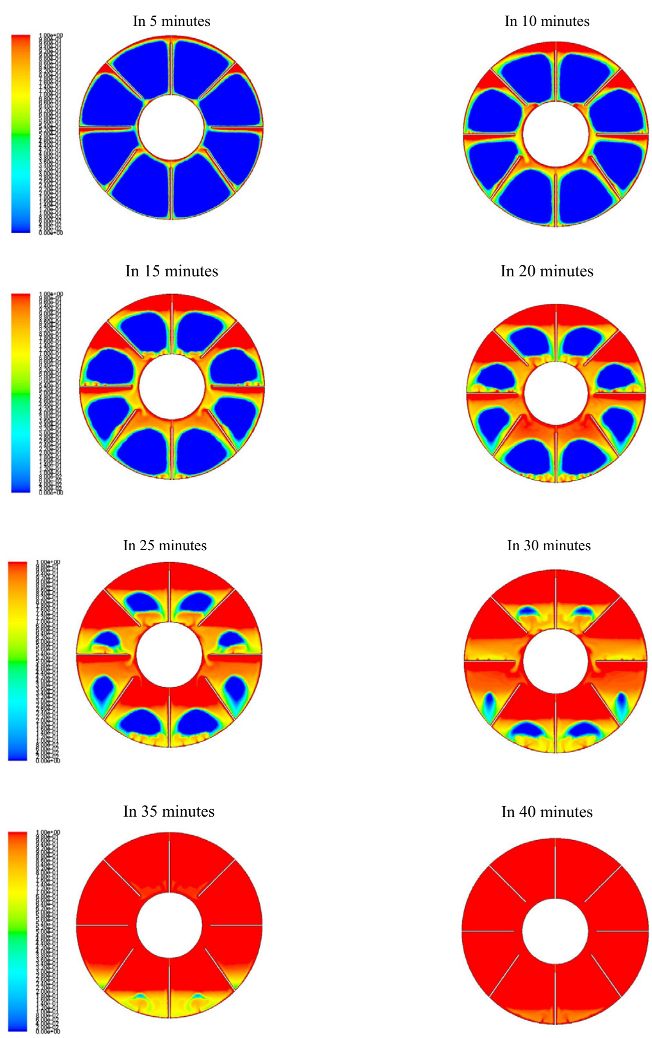

Fig. 15. Liquid fraction contours for Model #4 at selected intervals.

3.2.1. Model # 5

Here, Model #4 is used but in eccentric form. The middle tube is lowered as much as 5.4 mm and we call it Model #5 here which is shown in Fig. 6. The contours of liquid fraction for this model are shown below (see Fig. 17).

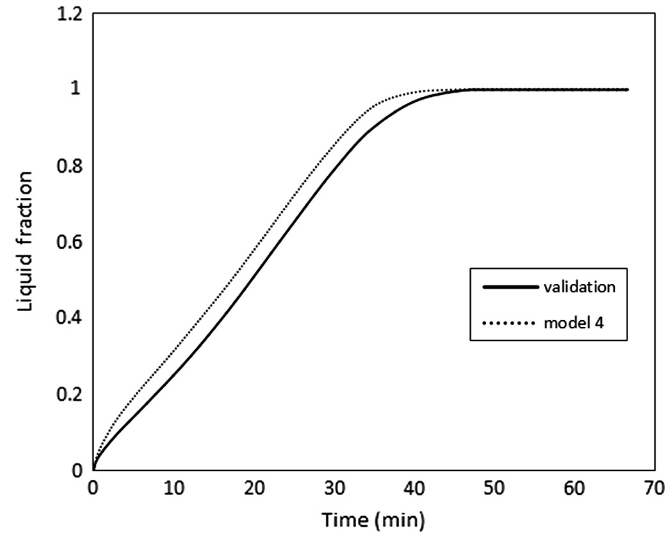

Fig. 16. Liquid fraction versus time for Model # 4 along with the Ref. model [12] comparison.

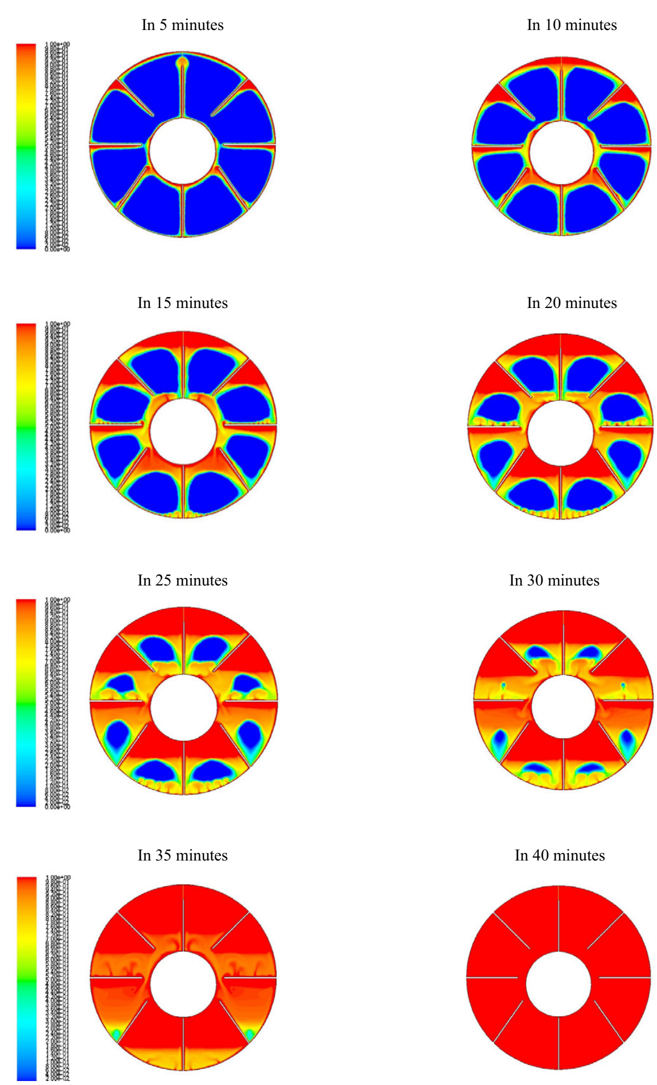

Fig. 17. Liquid fraction contours for Model # 5 at selected intervals.

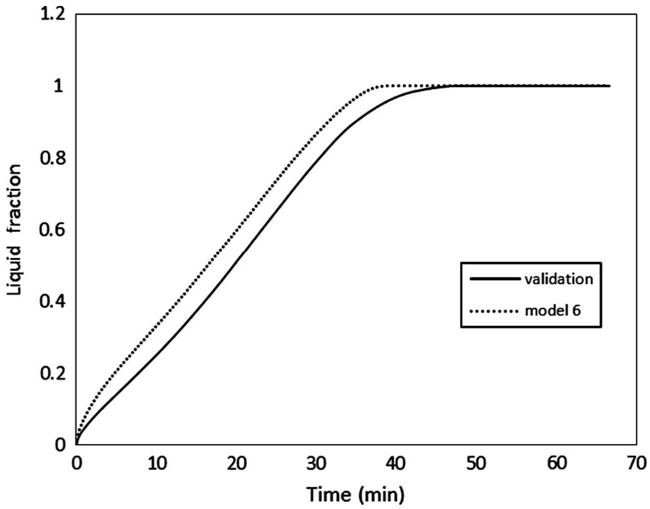

Fig. 18. Liquid fraction versus time for Model #5 along with the Ref. model [12] comparison.

Table 3
Comparison of melting time for all the considered models.

Model #5	Model#4	Model#3	Model#2	Model#1	Model, Ref. [12]	Model no.
82.1	87.4	84.3	94.7	89.5	100	Time in%

As it can be seen from these contours, the PCM material is completely melted at time interval of 40. This is because the heat can transfer upward more freely.

The accurate results show that complete melting for Model # 5 happens at 39 min and 1 s whereas this time for model Ref. [12] is 47 min and 32 s. This difference means 17.9% reduction in melting time for this model (see Fig. 18).

4. Conclusions

The major task in researches regarding use of PCM materials is to reduce the melting time of this material and we have been following the same path. As mentioned, the impact of fin location on melting of the phase-change material is very important in triplex type heat exchangers which the gravity and natural convection have important role in phase-change material melting. Different types of fin arrangements have been suggested in this undertaking. The general idea is to select a fin arrangement with less prevention or improvement of transfer of heat to go upwards. Fin arrangement in Model #1 has shown changes in the trend of melting and this idea has been the basis for proposing Models #2, #3 and #4. In all these models the contact area of fins and PCM material is the same and the only effect implemented here to bring about changes in the trend of melting is the fin arrangement. The results have proved that it is better for the fins in northern hemisphere to be like in Model #1 and the eastern and western fins to be attached to the outer tube and the south eastern and south western fins be inclined in certain ways and the southern fin to be attached to the outer tube in order to guide the heat to move upwards. By use of this experience and considering the fact that the PCM material in the lower part of the heat exchanger is the last part which melts, Model #5 has been introduced. This model has some eccentricity compared with Model #4 and has improved the melting time by 17.9%. This improvement has been shown in Table 3 along with comparison with other models.

References

[1] F. Agyenim, N. Hewitt, P. Eames, M. Smyth, A review of materials, heat transfer and phase change problem formulation for latent heat thermal energy storage systems (LHTESS), Renew. Sustain. Energy Rev. 14 (2) (2010) 615–628.
[2] H. Benli, Energetic performance analysis of a ground-source heat pump system with latent heat storage for a greenhouse heating, Energy Convers. Manage. 52 (1) (2011) 581–589.
[3] G. Çakmak, C. Yıldız, The drying kinetics of seeded grape in solar dryer with PCM-based solar integrated collector, Food Bioprod. Process. 89 (2) (2011) 103–108.
[4] E. Oró, L. Miró, M. Farid, L. Cabeza, Improving thermal performance of freezers using phase change materials, Int. J. Refrig. 35 (4) (2012) 984–991.
[5] M. Alkilani, K. Sopian, M. Alghoul, M. Sohif, M. Ruslan, Review of solar air collectors with thermal storage units, Renew. Sustain. Energy Rev. 15 (3) (2011) 1476–1490.
[6] S. Sharma, T. Iwata, H. Kitano, K. Sagara, Thermal performance of a solar cooker based on an evacuated tube solar collector with a PCM storage unit, Sol. Energy 78 (3) (2005) 416–426.
[7] K. Ermis, A. Erek, I. Dincer, Heat transfer analysis of phase change process in a finned-tube thermal energy storage system using artificial neural network, Int. J. Heat Mass Transf. 50 (15–16) (2007) 3163–3175.
[8] R. Velraj, R. Seeniraj, B. Hafner, C. Faber, K. Schwarzer, Experimental analysis and numerical modelling of inward solidification on a finned vertical tube for a latent heat storage unit, Sol. Energy 60 (5) (1997) 281–290.
[9] J. Trelles, J. Dufly, Numerical simulation of porous latent heat thermal energy storage for thermoelectric cooling, Appl. Therm. Eng. 23 (13) (2003) 1647–1664.
[10] E. Mettawee, G. Assassa, Thermal conductivity enhancement in a latent heat storage system, Sol. Energy 81 (7) (2007) 839–845.
[11] A. Al-Abidi, S. Mat, K. Sopian, M. Sulaiman, A. Mohammad, Numerical study of PCM solidification in a triplex tube heat exchanger with internal and external fins, Int. J. Heat Mass Transf. 61 (2013) 684–695.
[12] A. Al-Abidi, S. Mat, K. Sopian, M. Sulaiman, A. Mohammad, Internal and external fin heat transfer enhancement technique for latent heat thermal energy storage in triplex tube heat exchangers, Appl. Therm. Eng. 53 (1) (2013) 147–156.
[13] F. Agyenim, P. Eames, M. Smyth, A comparison of heat transfer enhancement in a medium temperature thermal energy storage heat exchanger using fins, Sol. Energy 83 (9) (2009) 1509–1520.
[14] M. Fang, G. Chen, Effects of different multiple PCMs on the performance of a latent thermal energy storage system, Appl. Therm. Eng. 27 (5–6) (2007) 994–1000.
[15] S. Jegadheeswaran, S. Pohekar, Exergy analysis of particle dispersed latent heat thermal storage system for solar water heaters, J. Renew. Sustain. Energy 2 (2) (2010) 023105.
[16] A. Darzi, M. Farhadi, K. Sedighi, Numerical study of melting inside concentric and eccentric horizontal annulus, Appl. Math. Model. 36 (9) (2012) 4080–4086.
[17] A. Al-Abidi, S. Mat, K. Sopian, M. Sulaiman, A. Mohammad, Experimental study of PCM melting in triplex tube thermal energy storage for liquid desiccant air conditioning system, Energy Build. 60 (2013) 270–279.
[18] A. Al-Abidi, S. Mat, K. Sopian, M. Sulaiman, A. Mohammad, Experimental study of melting and solidification of PCM in a triplex tube heat exchanger with fins, Energy Build. 68 (2014) 33–41.
[19] O. García-Valladares, Numerical simulation of triple concentric-tube heat exchangers, Int. J. Therm. Sci. 43 (10) (2004) 979–991.
[20] C. Swaminathan, V. Voller, On the enthalpy method, Int. J. Numer. Methods HFF 3 (3) (1993) 233–244.
[21] C.J. Ho, C.R. Siao, W.M. Yan, Thermal energy storage characteristics in an enclosure packed with MEPCM particles: an experimental and numerical study, Int. J. Heat Mass Transfer 73 (2014) 88–96.
[22] C.J. Ho, K.C. Liu, W.M. Yan, Simulation on melting processes in a vertical rectangular enclosure with a free-moving ceiling, Int. J. Heat Mass Transfer 83 (April) (2015) 222–228.
[23] Y.H. Siao, W.M. Yan, C.M. Lai, Transient characteristics of thermal energy storage in an enclosure packed with MEPCM particles, Appl. Therm. Eng. 88 (September) (2015) 47–53.
[24] A. Brent, V. Voller, K. Reid, Enthalpy-porosity technique for modeling convection-diffusion phase change: application to the melting of a pure metal, Numer. Heat Transfer 13 (3) (1988) 297–318.
[25] W. Ye, D. Zhu, N. Wang, Numerical simulation on phase-change thermal storage/release in a plate-fin unit, Appl. Therm. Eng. 31 (17–18) (2011) 3871–3884.