Alexandria Engineering Journal (2016) 55, 2065–2076

HOSTED BY

ELSEVIER

Alexandria University

Alexandria Engineering Journal

www.elsevier.com/locate/aej
www.sciencedirect.com

ORIGINAL ARTICLE

Response surface method optimization of V-shaped fin assisted latent heat thermal energy storage system during discharging process

Sina Lohrasbi, Mofid Gorji Bandpy, D.D. Ganji *

Department of Mechanical Engineering, Babol University of Technology, Babol, Iran

Received 26 April 2016; revised 30 June 2016; accepted 11 July 2016
Available online 27 July 2016

KEYWORDS

Finite Element Method;
LHTESS;
PCM;
RSM;
V-shaped fin

Abstract Latent Heat Thermal Energy Storage Systems (LHTESS) containing Phase Change Material (PCM) are used to establish balance between energy supply and demand. PCMs have high latent heat but low thermal conductivity, which affects their heat transfer performance. In this paper, a novel fin array has been optimized by multi-objective Response Surface Method (RSM) based on discharging process of PCM, and then this fin configuration is applied on LHTESS, and comparison between full discharging time by applying this fin array and LHTESS with other fin structures has been carried out. The employed numerical method in this paper is Standard Galerkin Finite Element Method. Adaptive grid refinement is used to solve the equations. Since the enhancement technique, which has been employed in the present study reduces the employed PCM mass, maximum energy storage capacity variations have been considered. Therefore phase change expedition and maximum energy storage capacity have been considered as the objectives of optimization and the importance of second objective is indicated which is proposed as the novelty here. Results indicate that considering maximum energy storage capacity as the objective of optimization procedure leads to efficient shape design of LHTESS. Also employing optimized V-shaped fin in LHTESS, expedites discharging process considerably in comparison with the LHTESS without fin.

1. Introduction

LHTESS containing PCMs are used to establish balance between thermal energy supply and demand. These systems store thermal energy during melting of PCM, and retrieve this energy during the solidification process. The amount of energy storage-retrieval density during phase change is higher in comparison with Sensible Heat Thermal Energy Storage System (SHTESS), which stores and retrieves energy during temperature change, not phase change [1]. Because of this feature, LHTESS have been widely used in several applications, such as solar systems [2], HVAC Systems [3] and Electronic Chip Cooling [4]. Since the ordinary materials used as PCMs have

* Corresponding author. Fax: +98 111 3234205.
E-mail address: ddg_davood@yahoo.com (D.D. Ganji).

Peer review under responsibility of Faculty of Engineering, Alexandria University.

http://dx.doi.org/10.1016/j.aej.2016.07.004
1110-0168

Nomenclature

C_p	heat capacity (m^2 kg/s^2 K)
D_2	outer tube diameter (mm)
K	thermal conductivity (m kg/s^3 K)
L	fin length (cm)
L_f	latent heat of fusion (m^2 s^{-2})
R_1	inner tube radius (mm)
S	solid fraction
Ste	Stefan number ($c_p(T_w - T_m)/L_f$)
T	time (s)
T_m	solid-liquid phase change temperature (K)
T_w	wall temperature (K)
w	fin thickness (mm)
α	thermal diffusivity (m^2/s)
β	fin branch direction (Rad)
ρ	density (kg/m^3)

Subscripts

f	fusion
m	melt
w	wall

the restriction of low thermal conductivity, heat transfer mechanisms in LHTESS are weak [1], and as a result, the rate of melting and solidification processes of PCMs, which are equivalent to charging and discharging processes of LHTESS respectively, are too low. Generally, heat transfer enhancement in the past few decades has evolved into an important component of heat transfer experimentation and theory. Heat transfer enhancement techniques can be divided into two groups, active and passive techniques. Where applying rough, treated and extended surfaces can be expressed as the examples of passive methods and using surface vibration, fluid vibration and electrostatic fields can be expressed as the examples of active methods. Much of these efforts, have been focused on microscale and nanoscale studies [5]. The enhancement methods that have been applied to LHTESS in order to overcome the restriction of low thermal conductivity of PCMs include using PCM dispersed with high conductivity particles [6–9], applying electric or magnetic field [10–18], surface waviness [19], finned tubes [20–26], insertion of a metal matrix into the PCM [28] and micro-encapsulation of the PCM [29]. Xuan and Lee [6] have experimentally investigated the effect of nanoparticle dispersion on heat transfer enhancement of nanofluids. The hotwire apparatus has been employed in order to measure the thermal conductivity of nanofuids. They have reported that the value of nanofuid thermal conductivity increases significantly with the increase in ultra-fine particle volume fraction, for example for Cu/water, the thermal conductivity ratio of the nanofuid to that of the base liquid varies from 1.24 to 1.78 when the ultra-fine particle volume fraction varies from 2.5% to 7.5%. Dhaidan et al. [7] studied melting phenomenon of Nano-Enhanced PCM (NEPCM) experimentally and numerically in a square container. They reported that heat transfer rate increases by adding nanoparticles because of the thermal conductivity enhancement. They reported a 9% reduction in full melting time by adding 5% CuO as nanoparticle to n-octadecane as PCM. Hosseinizadeh et al. [8] numerically investigated melting phenomenon in NEPCM in a spherical container. They used RT27 as PCM and Copper as nanoparticles and reported that since adding nanoparticles either enhances thermal conductivity or decreases latent heat, it enhances melting rate. Fan et al. [9] investigated solidification process of NEPCM in semi-finite region by similarity solution technique. They experimentally measured NEPCM properties and applied them in the similarity solution procedure. Their results indicate that by adding one percent Graphene as nanoparticles to Dodecanal as PCM, the solidification rate increases up to 34%. In the recent years, investigation of the effect of electric and magnetic field on hydrodynamics has been attractive topic [10–17]. Also the effect of electric and magnetic field on solid-liquid phase change phenomenon has been studied. Nakhla et al. [18] experimentally investigated solid extraction electrohydrodynamics on the performance of LHTESS during melting process. They have reported that by applying a (−8 kV) voltage potential across the storage module, the time needed for melting of 7 mm thickness of the PCM reduces up to 40%. Another enhancement method applied to LHTESS for increasing the melting and solidification rate is changing the geometry in order to increase the heat transfer area. Kousksou et al. [19] studied the effect of surface waviness on melting rate of PCM in rectangular cavity. They reported that varying the number of undulations, doesn't have a significant effect on melting rate but increasing the amplitude of the wavy surface, has a remarkable effect on melting rate. The other enhancement method applied to these systems is to immerse high thermal conductivity fin into PCM containers. The reason of fin employment desirability as an enhancement technique of LHTESS is due to the simplicity, ease in fabrication and low cost of construction [20]. Immersing fin into the LHTESS increases thermal penetration depth, but it should be noticed that by implementing fin into LHTESS, it occupies a considerable part of the storage tank volume and as a result the PCM mass decreases and the maximum energy storage capacity decreases subsequently [21,22]. Therefore, in fin design during solidification process, either expedition of the process or maximum energy storage capacity has to be considered. Lamberg and Siren [23] provided an analytical model based on a quasi-linear, transient, thin-fin equation in order to predict solid–liquid interface location and temperature distribution of the fin in a melting process in a semi-infinite PCM storage. They have reported that this model is not suitable for the solidification process because in solidification process, the predominant heat transfer is conduction. Ismaeil et al. [24] numerically and experimentally investigated the effect of adding fins to LHTESS in solidification phenomenon. They reported that the increase in fin thickness doesn't have considerable effect on solidification rate, but the increase in fin length increases the rate of the process significantly, but the change in the value of energy storage capacity by adding fins to the system has not been mentioned. Kamkari and Shokouhmand [25] experimentally investigated the effect of adding fins to the cavity containing PCM during melting process. Their results indicated that by adding one and three fins to the system, melting rate increases 18% and 37% respectively. But energy storage capacity variation by adding fins to the system did not have been mentioned in this work either. Al-Abidi et al. [26] numerically investigated heat transfer enhancement of a triplex tube heat exchanger during melting process by applying internal and external fin to the system. They reported that by using this technique, melting time reduces up to 34.7%. Lorenzini et al. [27] focused on geometric optimization of Y-shaped fins. They have indicated that the global thermal resistance of Y-shaped assembly of fins can be minimized by geometric optimization. They defined a parameter, which is a criterion to introduce Y-shaped fin cross section. If the value of this parameter is low, the first branch of optimized Y-shaped fin will be equal to zero; therefore, Y-shaped fin becomes V-shaped. In present study, fin thickness is selected in a range that the value of this parameter is in the desired range; therefore, fin configuration in present work is V-shaped. Tiari et al. [28] numerically investigated finned heat pipe assisted LHTESS during charging process. They have reported that ignoring natural convection heat transfer in melting leads to approximately 30% error. The insertion of a metal matrix into the PCM has been used in several works in order to enhance heat transfer during charging and discharging of PCM. Trelles and Duffy [29] numerically investigated a porous LHTESS for thermoelectric cooling, in which the PCM was in a porous aluminum matrix. They reported that the metal matrix in the PCM greatly improves performance. PCM microencapsulation is another method of heat transfer enhancement of LHTESS. By encapsulating PCM in a solid material of small diameter to be suspended in a liquid, partially melting and solidifying slurries and heat transfer enhancement can be achieved [30].

In this paper, solidification process has been simulated by Standard Galerkin Finite Element Method. Adaptive grid refinement strategy is used in the solution procedure of the equations. An Innovative fin configuration has been optimized by Response Surface Method and then been employed in order to enhance LHTESS performance during discharging process. Optimized configuration of fin has been obtained by investigating the interaction between solidification expedition and maximum energy storage capacity as the two objectives of optimization procedure. Unlike the previous studies, energy storage capacity is investigated in LHTESS, and also it has been indicated that considering this parameter as one of the objectives of optimization, leads to more efficient optimization and proper results. This is proposed as the novelty here. In the last section of this paper, this optimized fin configuration is applied to LHTESS to compare the results with the LHTESS with simple longitudinal fin and without fin.

2. Problem statement

2.1. Geometry and boundary conditions

The main geometry of the present study is a V-shaped fin assisted LHTESS, which has been illustrated in Fig. 1. The space between Heat Transfer Fluid (HTF) and storage tank shell, is filled with water as PCM, which is solidified during discharging process of LHTESS. The V-shaped fin is

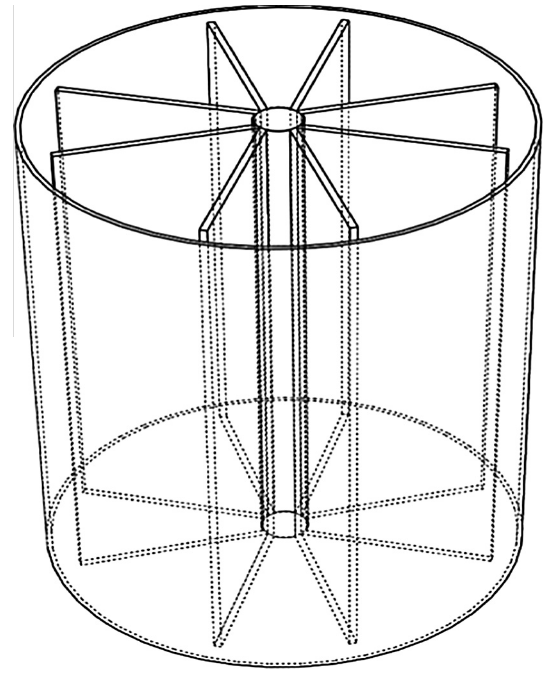

Figure 1 Three-dimensional view of V-shaped fin assisted LHTESS.

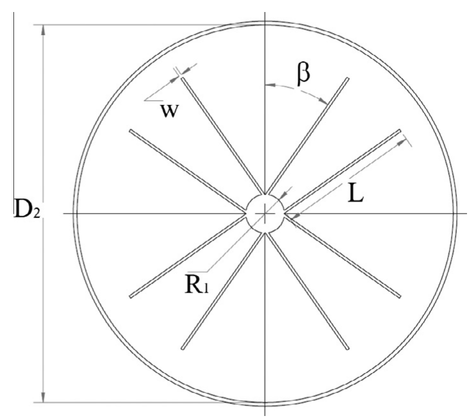

Figure 2 Two dimensional solution domain.

connected to the internal pipe containing HTF in order to enhance thermal penetration depth into the PCM.

This paper deals with two steps in the investigation of LHTESS performance enhancement. First, two dimensional simulation, by Finite Element Method and optimization by Response Surface Method is carried out in order to find the optimum longitudinal V-shaped fin configuration. In this step, the solution domain, which can be observed in Fig. 2, is a horizontal plane. The purpose of applying fin in this system was to increase penetration depth into the PCM. In the second step, this optimized V-shaped fin configuration will be applied in LHTESS and will be compared with the other common fin structures during discharging process of LHTESS, such as radial fin, simple longitudinal fin and also LHTESS without fin, to indicate the efficiency of V-shaped fin array in comparison with the other cases, and also indicating the efficiency of

Table 1 Geometry parameters of V-shaped fins.

Parameter	Range
β	[$1\pi/16$, $4\pi/16$]
L	[2.5, 4 cm]
w	[0.5, 1.2 mm]

Table 2 The physical properties of water as PCM and aluminum fin.

Property	PCM	Fin
ρ(kg/m^3)	997	2700
C_p(j/kg K)	4181	902
k(w/m K)	0.6	200
L_f(j/kg)	335,000	–

considering maximum energy storage capacity as one of the objectives of RSM optimization procedure.

The boundary condition, for the internal wall, containing HTF, is assumed constant and equal to 240 K and the other walls are assumed adiabatic. Initial temperature of the domain is assumed equal to 285 K.

In Table 1, geometry parameters and their ranges, which have been used in optimization procedure are listed.

Physical properties of PCM and fin are listed in Table 2.

2.2. Governing equations

General governing equations of solidification process can be expressed as below:

Continuity equation:

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

Momentum equation:

$$\frac{\partial u_i}{\partial t} + u_j\frac{\partial u_i}{\partial x_j} = \frac{1}{\rho}\left(\mu_{eff}\nabla^2 u_i - \frac{\partial P}{\partial x_i} + \rho\beta(T - T_{ref})g_i\right) \tag{2}$$

Energy equation:

$$\frac{\partial T}{\partial t} + u_i\frac{\partial T}{\partial x_i} = \frac{\partial}{\partial x_i}\left(\frac{k}{\rho C_p}\frac{\partial T}{\partial x_i}\right) + \frac{L_f}{\rho C_p}\frac{\partial s}{\partial t} \tag{3}$$

Solid fraction equation:

$$\begin{aligned} &S = 1 \quad T < T_m - T_0 \\ &S = 0 \quad T > T_m + T_0 \\ &S = \frac{(T_m + T_0/2 - T)}{T_0} \quad T_m - T_0 < T < T_m + T_0 \end{aligned} \tag{4}$$

Ettouney et al. [31] investigated the phase change process of Paraffin/Wax in vertical PCM double-pipe container. They have indicated that in solidification process, conduction heat transfer is the predominant heat transfer mechanism but in melting process, natural convection is predominant. Therefore, in solidification simulation, natural convection heat transfer can be ignored. Stritih et al. [32] investigated the conduction-dominated solidification process of PCM by analytical methods and compared the obtained results with experimental results to study the error of ignoring natural convection heat transfer mechanism in solidification. They reported good agreement between experimental and numerical results obtained by ignoring natural convection heat transfer in solidification process. They also showed that natural convection in solidification, has the power ten times lower than in melting. In the present work, the numerical investigation of solidification process is based on conduction-dominated assumption. Therefore, in solidification simulation, velocity variables and the natural convection heat transfer can be ignored and the governing equations of conduction-dominated solidification process can be presented as follows:

Energy equation in PCM region:

$$\rho C_p\frac{dT}{dt} = \nabla(k\nabla T) + L_f\frac{dS}{dt} \tag{5}$$

Energy equation in the fin region:

$$\rho C_p\frac{dT}{dt} = \nabla(k\nabla T) \tag{6}$$

Solid fraction equation is the same as presented before.

Total energy released during discharging process, which is sum of latent and sensible heat, is calculated using the following equation:

$$E_{total} = \rho\int\left(c_pT + (1-s)L_f\right)dV \tag{7}$$

3. Numerical method and validation

Standard Galerkin Finite Element Method with cubic interpolation over triangles is implemented to solve the present phase change problem. Nodal values are placed on the corners and sides of the mesh cells. The Galerkin equations are formed by symbolic analysis, which substitutes definitions, segregates dependencies on variables, applies integration by parts, integrates over cells, and ultimately differentiates the resulting system with respect to system variables to form the coupling matrix. The equations are solved simultaneously by an iterative method. For nonlinear systems Newton-Raphson iteration process with back-tracking is used. For time dependent problems, such as solidification problem, an implicit Backward Difference Method for integration in time is used. Variables are approximated by quadratic polynomials in time, and the time step is controlled to keep the cubic term smaller than the required value of error. The residual Galerkin integral over a patch of cells surrounding each mesh node is minimized by the Finite Element Equations. Then the residuals in each cell independently are analyzed as a measure of compliance, and subdivide each cell in which the required error tolerance is exceeded. Any cell, thus splits can be re-merged whenever the cell error drops two of the splitting tolerance.

In Adaptive Grid Refinement Method, when the initial mesh generation is carried out, code estimates the error and refines mesh in order to achieve the desired accuracy. In unsteady problems, this procedure also has to be applied to the initial values of the variables in order to refine the mesh where rapid change in variables occurs. In solid-liquid phase change problem, the position of phase change front, where the gradients are so high, is unknown; therefore, employing Adaptive Grid Refinement in these problems seems the most

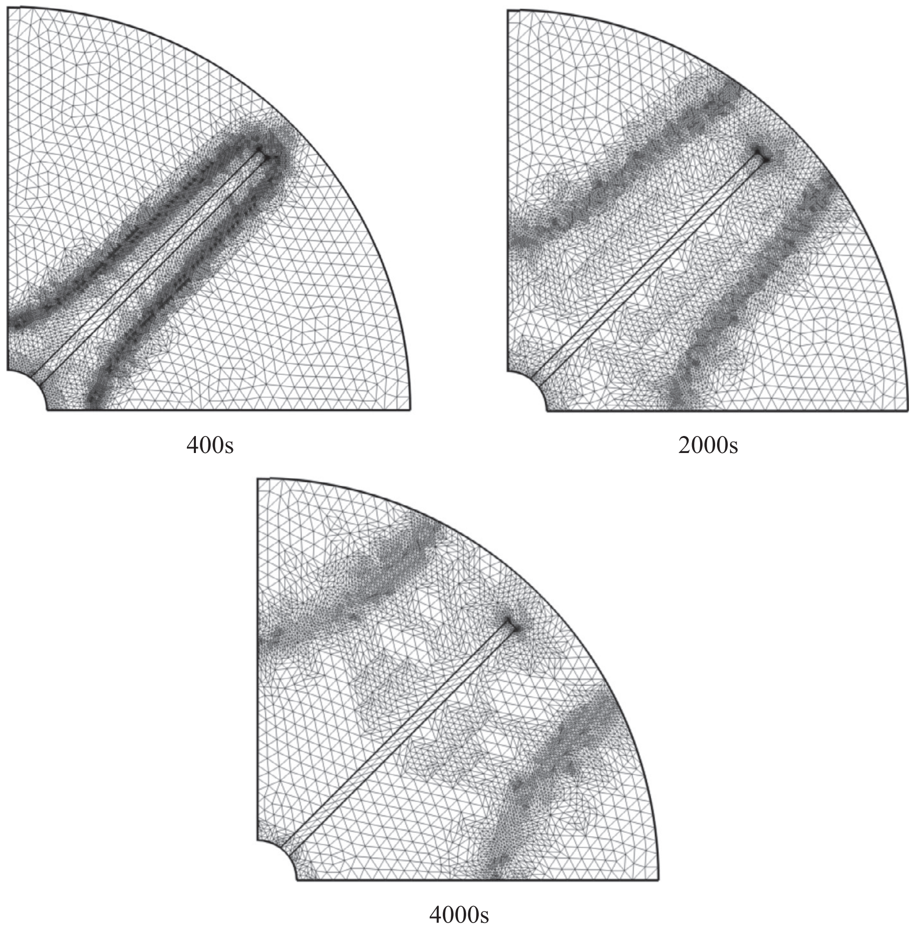

Figure 3 Adaptive grid refinement in three time steps.

reasonable, hence in present work, this method is used to simulate the phase-change procedure as illustrated in Fig. 3.

Comparison between the solid-liquid phase change front, at various time steps during solidification process, obtained by present code based on Galerkin Finite Element Method and experimental results obtained by Ismaeil et al. [24] indicates good agreement, which validates the present code as illustrated in Fig. 4. Moreover it proves that ignoring natural convection in numerical simulation of solidification phenomenon leads to results close to reality.

4. Response surface method optimization

In present work, the optimization procedure of V-shaped fin configuration has been carried out by employing CFD analysis and Response Surface Method (RSM). RSM consisted of mathematical methods, and it is applicable for the problems in which several variables, control the system response. The main procedure in this approach is to characterize the response based on suitable experiments [33]. In this research, fin configuration optimization is carried out based on 40 experiments, for 3 geometry parameters and 2 responses during solid-liquid phase change.

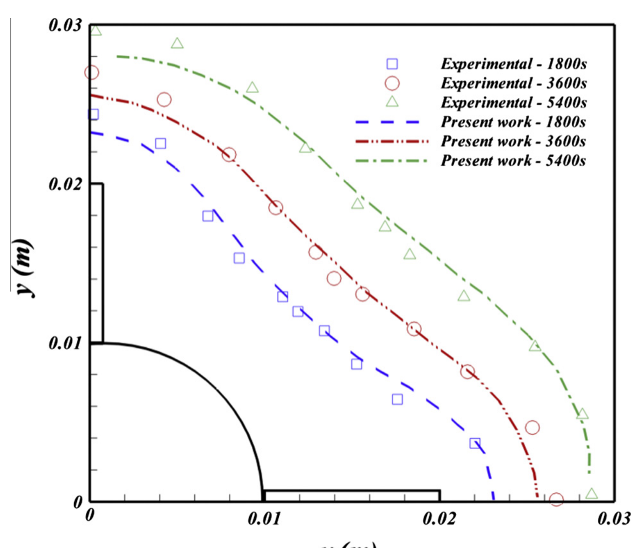

Figure 4 Calculated solid-liquid phase change fronts in present study and experimental results obtained by Ismaeil et al. [24] at various times.

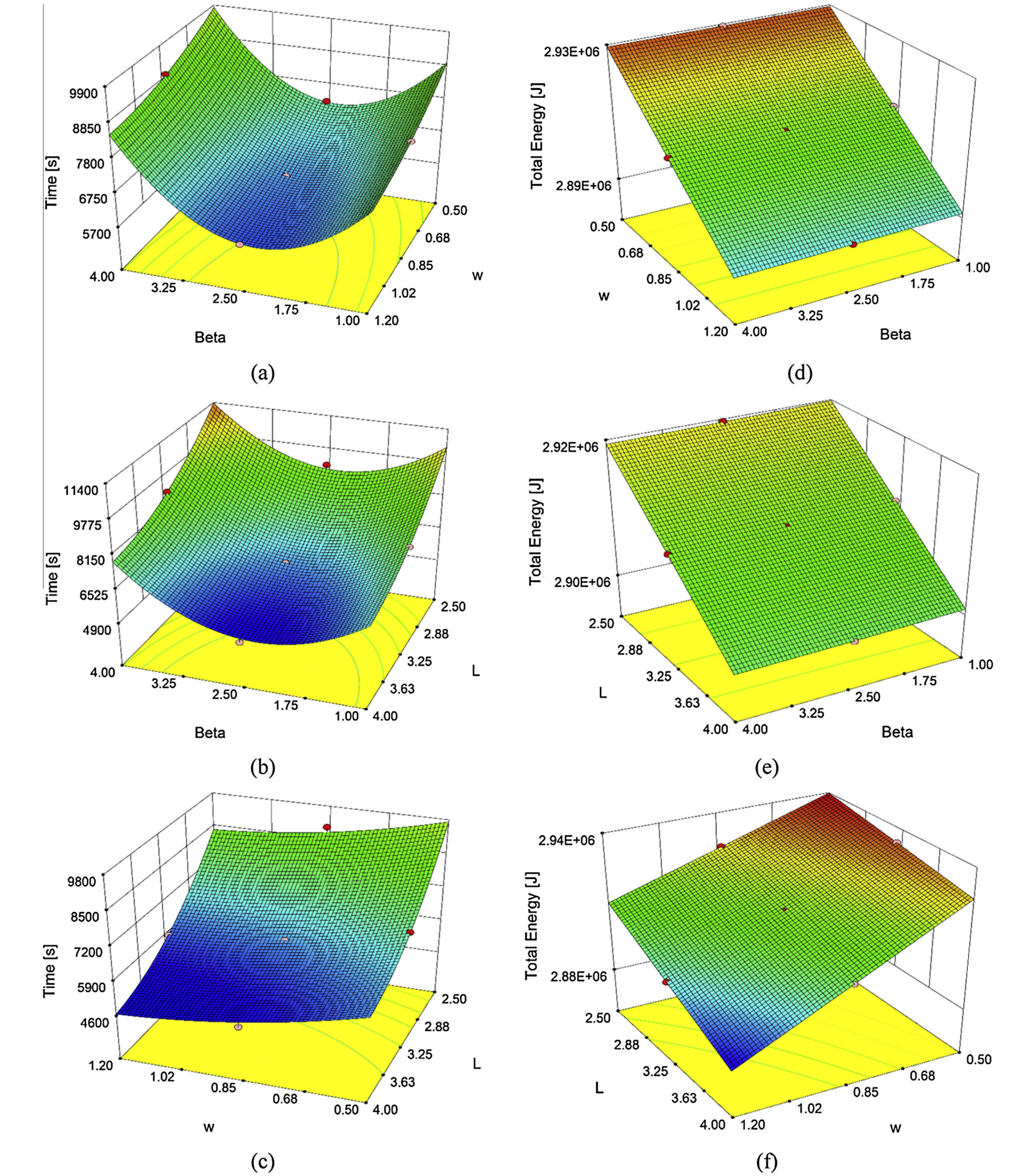

Figure 5 Full solidification time and total energy storage capacity response surfaces for geometry parameters (w [mm], L [cm] and β ($\times\pi/16$) [Rad]).

5. Results and discussion

5.1. Optimization of V-shaped fin configuration

In this section, first the V-shaped fin array will be optimized using RSM during solidification process in fin-assisted LHTESS. Geometry parameters, which will be studied during optimization process are β, L and w, where β is the angle between the branches and axes, L is the fin length and w is the fin thickness, as illustrated in Fig. 5. Range of changes in these parameters is [$1\pi/16$, $4\pi/16$] for β, [2.5, 4 cm] for L, [0.5, 1.2 mm] for w. The responses in the optimization proce-

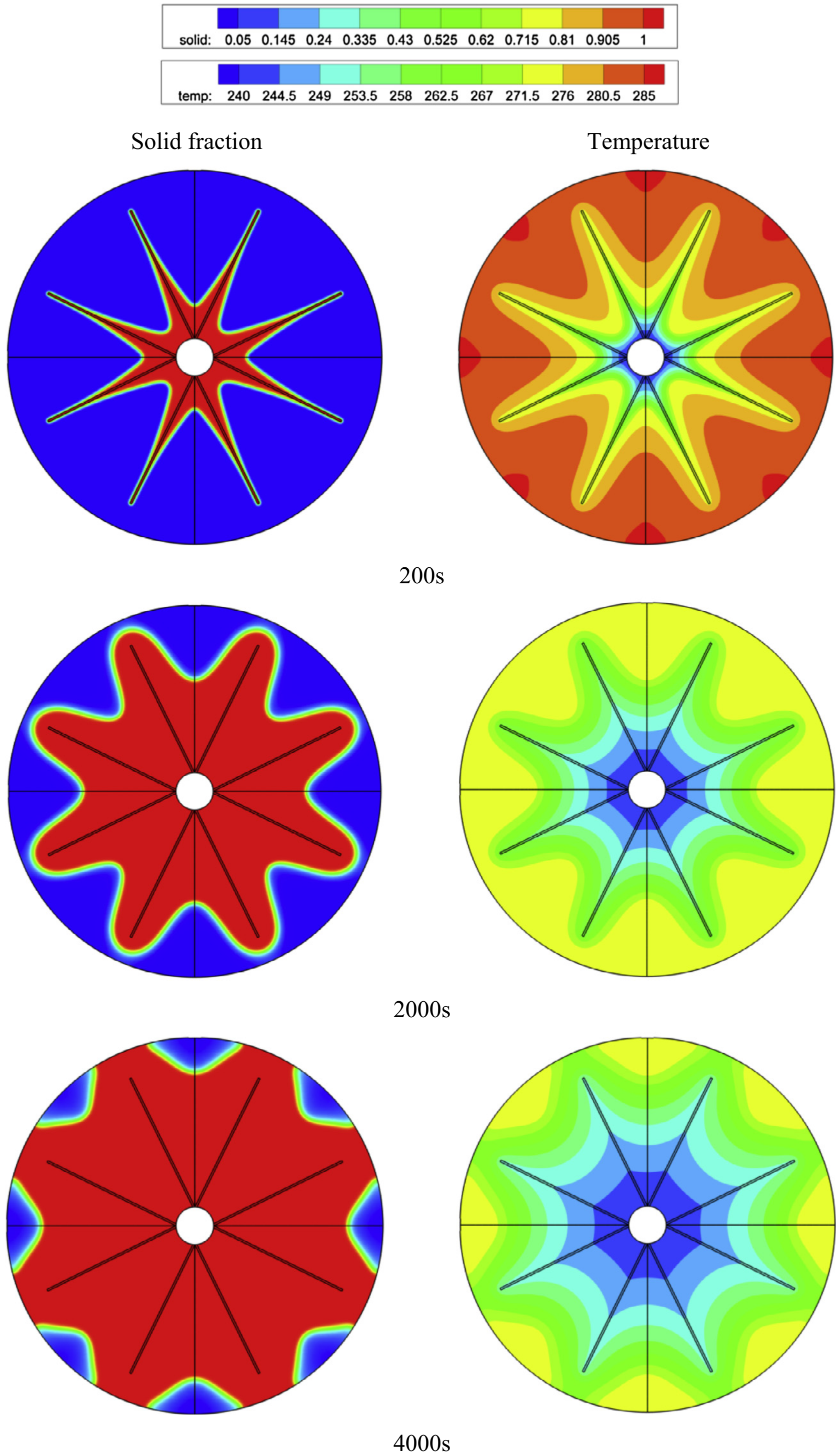

Figure 6 Temperature and solid fraction contours in three different time steps during solidification process in the optimized V-shaped fin array which is $\beta = 2.33\pi/16$, $L = 3.8$ mm, $w = 0.4$ mm.

dure are full solidification time and maximum energy storage capacity, where the time response is desired to be minimized, and energy storage capacity is desired to be maximized, in order to expedite the phase change process without lowering the maximum energy storage capacity too much. To study the maximum energy storage capacity quantitatively, this parameter is defined as the sum of sensible and latent heat over the entire domain at the beginning of the process for solidification.

As illustrated in the surface related to full solidification time, in Fig. 5, the effect of branches direction and length on phase change acceleration is significant but the effect of fin thickness is insignificant. The reasons for the significance of branches direction effect, are that when the branches are too

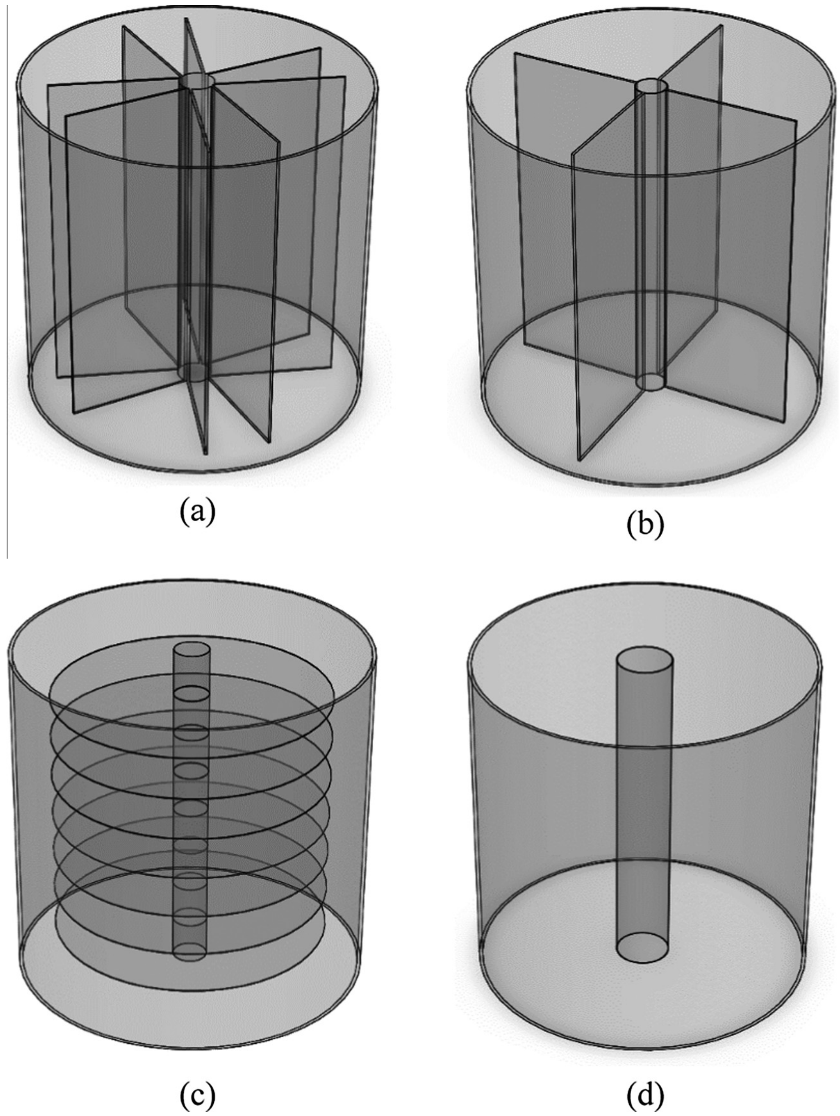

Figure 7 Three dimensional view of LHTESS with optimized V-shaped fin (a), with simple longitudinal fin (b), with radial fin (c) and without fin (d).

close to the axes, for the PCM in the space between each V-shaped branches, thermal resistance decreases considerably, but for the space between the four V-shaped fins, thermal resistance will be so high that the PCM mass in this space solidifies too slow, which slows down the full solidification rate. Therefore, it is important to find the optimized branch direction to achieve uniform PCM mass distribution.

As can be observed in Fig. 5, increasing in the value of fin thickness, increase heat transfer area, and therefore expedites phase change process slightly. On the other hand, with the increase in fin thickness, the employed amount of PCM will be less and as a result, maximum energy storage capacity will decrease. Since maximum energy storage decrement because of fin thickness augmentation, is more significant than phase change acceleration, it is desired to employ fin systems with the minimum value of thickness.

In Fig. 5, the effect of fin length on solidification rate and maximum energy storage capacity is illustrated. Increasing in fin length, increases thermal penetration depth into the PCM, and because of low thermal conductivity of PCM, immersing a high thermal conductivity fin system into PCM, results in significant enhancement in solidification rate. Although increasing fin length, results in maximum energy storage capacity decrement, but since the solidification rate enhancement is much more significant, the interaction between these two parameters makes the optimized value of fin length approximately equal to its maximum value.

In Fig. 6, Temperature and solid fraction contour plots for the optimized V-shaped fin configuration, which is $\beta = 2.33\pi/16$, $L = 3.8$ mm, $w = 0.4$ mm, are illustrated in three different time steps during solidification process, which are 200, 2000 and 4000 s. In these figures, it is desired to achieve more uniform temperature and mass distribution over the domain. From Fig. 6, it can be observed that applying V-shaped fin with optimized configuration in LHTESS, fulfills these purposes during discharging process.

Also, by comparing the value of solidified PCM in the same time steps between LHTESS with snowflake shaped fin and other fin configurations, it can be observed that, besides the uniform solidification process of snowflake shaped fin assisted

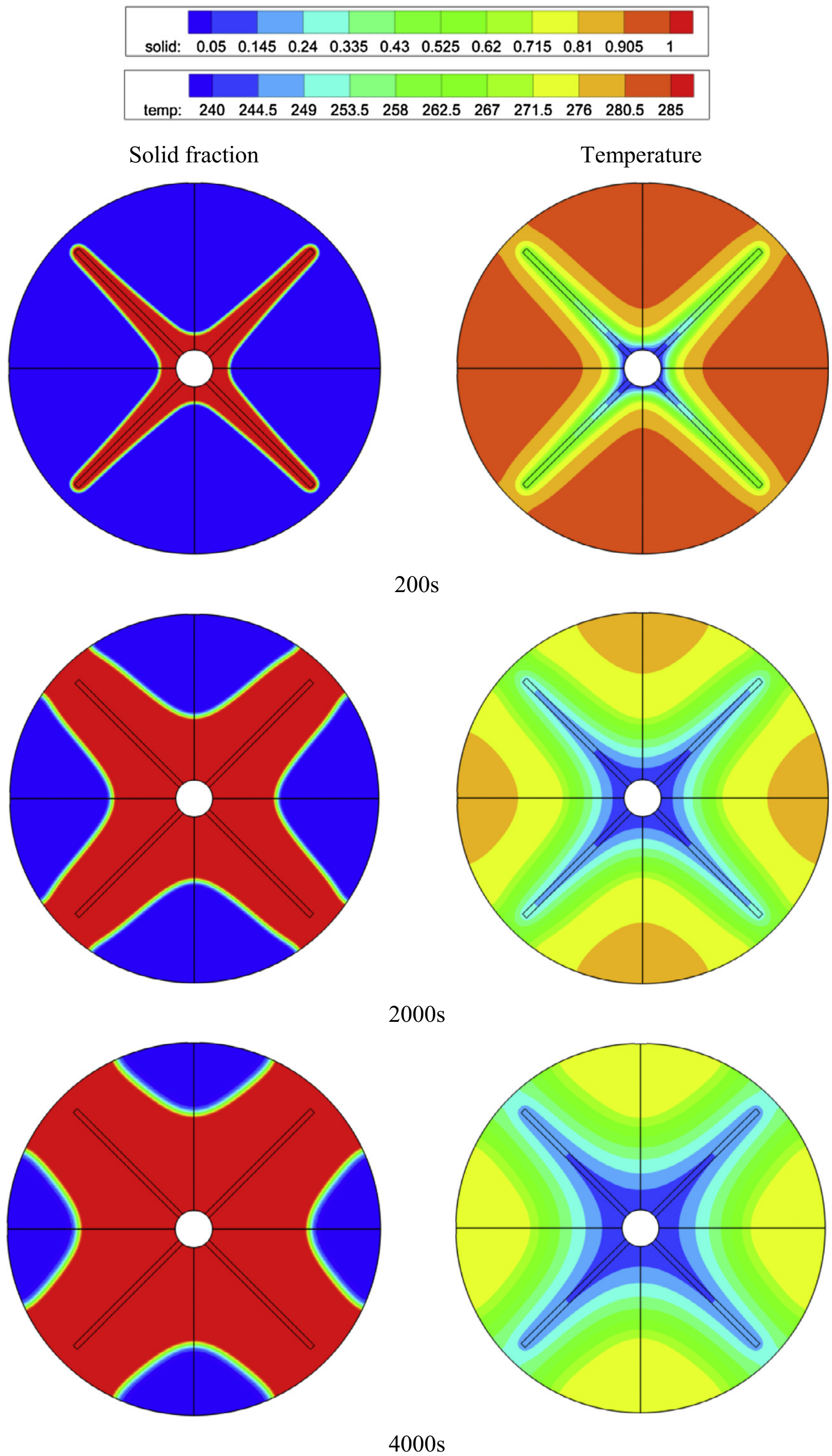

Figure 8 Temperature (left side) and solid fraction (right side) contour plots for LHTESS with simple longitudinal fin.

LHTESS, the fastest solidification is achieved by employing this structure.

In the following sections, by comparing these contour plots with LHTESS with simple longitudinal and radial fin arrays, with the same PCM mass, the efficiency of V-shaped fin array as an enhancement technique for LHTESS will be investigated.

5.2. Comparison between the optimized case and other common cases

In this section, comparison between performance of optimized V-shaped fin assisted LHTESS and LHTESS with simple longitudinal fin, with radial fin and without fin will be carried out.

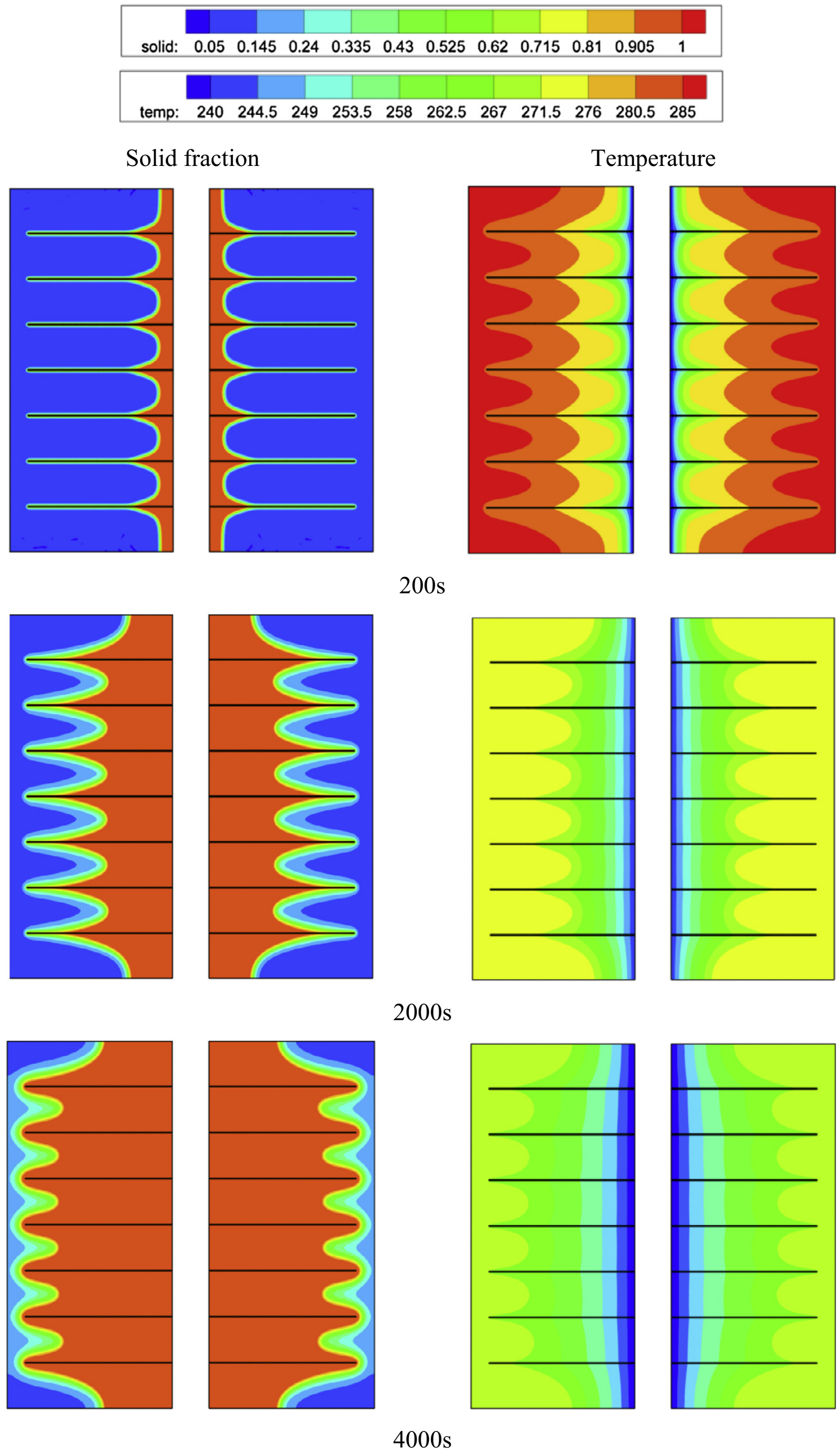

Figure 9 Temperature (left side) and solid fraction (right side) contour plots for LHTESS with radial fin.

The schematic of these cases is illustrated in Fig. 7. In these figures, the space between the inner and outer tube is filled with PCM and the abovementioned fin configurations are attached to the inner tube in order to enhance thermal penetration depth into the PCM. In all of these cases, the volume of employed fin and PCM mass is kept constant-equal to the case of optimized V-shaped fin- to compare solidification rate at the same value of maximum energy storage capacity.

In Figs. 8 and 9, temperature and solid fraction contour plots for LHTESS with simple longitudinal and radial fin are illustrated in three time steps during discharging process.

According to Figs. 8 and 9, it can be observed that the value of solid fraction increment rate of the optimized V-shaped fin assisted LHTESS, as illustrated in Fig. 6 is significantly higher in comparison with the other cases at the same value of PCM mass and maximum energy storage capacity. Also the

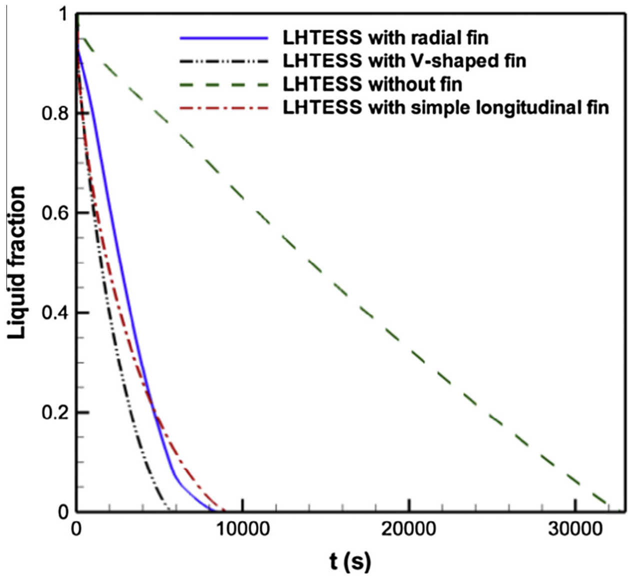

Figure 10 Liquid fraction over the domain.

temperature distribution of V-shaped fin assisted LHTESS is more uniform in comparison with the case of longitudinal and radial fins.

It should be noted that adding simple longitudinal or radial fins to LHTESS enhances conductive heat transfer, but by increasing the number of fins, natural convection heat transfer will be suppressed, because there will not be enough space for the vortexes to grow. In the solidification investigation, as mentioned before, natural convection heat transfer mechanism is negligible, but in melting process, which is equivalent to charging process of LHTESS, natural convection plays significant rule; therefore, immersing longitudinal or radial fin system with large number of fins, can have destructive effects during charging process, although it expedites discharging process.

Therefore first of all it should be mentioned that the main motivation of choosing V-shaped fin in this paper is that it has the capability of increasing thermal penetration depth into the PCM and achieving uniform mass distribution, also the space between the branches is not too low to suppress vortexes motion in natural convection heat transfer phenomenon during charging process, unlike the case of LHTESS with radial or simple longitudinal fins.

It should be mentioned that, in order to investigate heat transfer in radial fin assisted LHTESS, simulation has to be carried out in (r, z) coordinates, because of the axisymmetric geometry, unlike the cases of longitudinal fin systems, calculations cannot be carried out in (r, θ) coordinates.

In Fig. 10, liquid fraction variations over the domain during solidification process are illustrated. In this figure, the slope of solidification diagrams, represents the discharging rate, and the end of the diagrams represents the full discharging time of each case. From this figure, it can be inferred that since the solidification rate of PCM by adding fin of any kind to LHTESS is significantly higher than the case of LHTESS without fin, this enhancement technique is an efficient method in solid-liquid phase change acceleration. Among the investigated fin configurations, the optimized V-shaped fin has the highest solidification rate, radial and simple longitudinal fin has almost the same rate. The main difference between solid fraction variations behavior of LHTESS with radial fin and with simple longitudinal fin, is the lower solidification rate of radial finned system at the beginning of the process. This is because in present study, the number of radial fins in the system is small, and as it has been mentioned in Tiari et al. work [26], the efficiency of radial fins will be highest when more number of fins are employed, because this decreases thermal resistance, and leads to high enhancement rate in conduction dominated mechanism, including discharging process. But as mentioned before, more number of fins lead to natural convection suppression during charging process. In Table 3, the amount of solidification rate enhancement in indicated.

Table 3 Comparison between full solidification time and acceleration rate of LHTESS with simple longitudinal fin, with radial fin and with the optimized V-shaped fin with respect to LHTESS without fin.

Method	Full solidification time (s)	Acceleration enhancement (n-times faster)
LHTESS without fin	33,272	–
LHTESS with simple longitudinal	9131	3.64
LHTESS radial fin	8483	3.92
LHTESS optimized V-shaped fin	5888	5.65

6. Conclusions

In present study, innovative fin configuration has been optimized by Response Surface Method during discharging process of LHTESS and then this optimized fin array has been employed in LHTESS as a performance enhancement technique. The optimized fin structure has been obtained by investigating the interaction between solidification expedition and maximum energy storage capacity as the two objectives of optimization procedure, unlike the previous studies, where the parameter of maximum energy storage capacity hasn't been considered in the study of LHTESS performance. Then this optimized fin configuration is compared with the other cases to indicate its efficiency. It was found that:

- With the increase in fin thickness, heat transfer area increases and solidification expedition is achieved. But since the increase in fin thickness, increases cross-sectional area and results in less amount of PCM mass, it lowers maximum energy storage capacity, therefore because this expedition is not significant in comparison with the disadvantage of energy storage capacity reduction, the optimized value for fin thickness is the lowest value in the considered range.
- With the increase in fin length, although maximum energy storage capacity decreases, the enhancement in phase-change acceleration because of thermal penetration depth augmentation is so high that the disadvantage of energy storage capacity reduction can be neglected. Therefore the optimized value of fin length is approximately equal to the maximum value in the considered range.
- Fin branches direction, has significant effect on solidification rate; therefore, in the optimization process it is tried

to find the best direction, which is determined in a way that uniform mass distribution be achieved.

- Applying V-shaped fin array with optimized configuration is an efficient enhancement technique for LHTESS and results in uniform solidification and expedites the process.
- Applying optimized V-shaped, simple longitudinal and radial fins to LHTESS indicates 5.65, 3.64, and 3.92 times faster solidification process in comparison with LHTESS without fin.
- Considering maximum energy storage capacity as an objective of optimization procedure, leads to reasonable results. It can be claimed that neglecting this parameter in the design of LHTESS doesn't lead to acceptable results.
- Longitudinal fin configuration with simple or V-shaped fin structure is more efficient in the enhancement of discharging process in LHTESS in comparison with radial fin structure.
- The significant difference between the enhancement of discharging acceleration of LHTESS without fin and with fin, indicates the efficiency of fin, as an enhancement technique of LHTESS.

References

[1] S. Jegadheeswaran, S.D. Pohekar, Performance enhancement in latent heat thermal storage system: a review, Renew. Sustain. Energy Rev. 13 (9) (2009) 2225–2244.

[2] S. Shalaby, M. Bek, Experimental investigation of a novel indirect solar dryer implementing PCM as energy storage medium, Energy Convers. Manage. 83 (2014) 1–8.

[3] K. Azzouz, D. Leducq, D. Gobin, Performance enhancement of a household refrigerator by addition of latent heat storage, Int. J. Refrig. 31 (5) (2008) 892–901.

[4] F. Tan, C. Tso, Cooling of mobile electronic devices using phase change materials, Appl. Therm. Eng. 24 (2) (2004) 159–169.

[5] A.E. Bergles, Recent developments in enhanced heat transfer, Heat Mass Transf. 47 (8) (2011) 1001–1008.

[6] Y. Xuan, Q. Li, Heat transfer enhancement of nanofluids, Int. J. Heat Fluid Flow 21 (1) (2000) 58–64.

[7] N.S. Dhaidan, J. Khodadadi, T.A. Al-Hattab, S.M. Al-Mashat, Experimental and numerical investigation of melting of phase change material/nanoparticle suspensions in a square container subjected to a constant heat flux, Int. J. Heat Mass Transf. 66 (2013) 672–683.

[8] S. Hosseinizadeh, A.R. Darzi, F. Tan, Numerical investigations of unconstrained melting of nano-enhanced phase change material (NEPCM) inside a spherical container, Int. J. Therm. Sci. 51 (2012) 77–83.

[9] L.-W. Fan, Z.-Q. Zhu, M.-J. Liu, A similarity solution to unidirectional solidification of nano-enhanced phase change materials (NePCM) considering the mushy region effect, Int. J. Heat Mass Transf. 86 (2015) 478–481.

[10] M. Sheikholeslami, M. Rashidi, T. Hayat, D. Ganji, Free convection of magnetic nanofluid considering MFD viscosity effect, J. Mol. Liq. 218 (2016) 393–399.

[11] M. Sheikholeslami, T. Hayat, A. Alsaedi, MHD free convection of Al_2O_3–water nanofluid considering thermal radiation: a numerical study, Int. J. Heat Mass Transf. 96 (2016) 513–524.

[12] M. Sheikholeslami, M. Rashidi, Non-uniform magnetic field effect on nanofluid hydrothermal treatment considering Brownian motion and thermophoresis effects, J. Braz. Soc. Mech. Sci. Eng. (2016) 1–14.

[13] M. Sheikholeslami, K. Vajravelu, M.M. Rashidi, Forced convection heat transfer in a semi annulus under the influence of a variable magnetic field, Int. J. Heat Mass Transf. 92 (2016) 339–348.

[14] M. Sheikholeslami, M. Rashidi, D. Ganji, Effect of non-uniform magnetic field on forced convection heat transfer of-water nanofluid, Comput. Methods Appl. Mech. Eng. 294 (2015) 299–312.

[15] M. Sheikholeslami, M.M. Rashidi, Effect of space dependent magnetic field on free convection of Fe_3O_4–water nanofluid, J. Taiwan Inst. Chem. Eng. 56 (2015) 6–15.

[16] M.S. Kandelousi, Effect of spatially variable magnetic field on ferrofluid flow and heat transfer considering constant heat flux boundary condition, Eur. Phys. J. Plus 129 (11) (2014) 1–12.

[17] M. Sheikholeslami, D.D. Ganji, Ferrohydrodynamic and magnetohydrodynamic effects on ferrofluid flow and convective heat transfer, Energy 75 (2014) 400–410.

[18] D. Nakhla, H. Sadek, J.S. Cotton, Melting performance enhancement in latent heat storage module using solid extraction electrohydrodynamics (EHD), Int. J. Heat Mass Transf. 81 (2015) 695–704.

[19] T. Kousksou, M. Mahdaoui, A. Ahmed, J. Batina, Numerical simulation of PCM melting over a wavy surface, Int. J. Numer. Meth. Heat Fluid Flow 24 (8) (2014) 1660–1669.

[20] 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.

[21] S. Lohrasbi, M. Sheikholeslami, D.D. Ganji, Discharging process expedition of NEPCM in fin-assisted latent heat thermal energy storage system, J. Mol. Liq. 221 (2016) 833–841.

[22] M. Sheikholeslami, S. Lohrasbi, D.D. Ganji, Numerical analysis of discharging process acceleration in LHTESS by immersing innovative fin configuration using finite element method, Appl. Therm. Eng. 107 (2016) 154–166.

[23] Piia Lamberg, Kai Siren, Analytical model for melting in a semi-infinite PCM storage with an internal fin, Heat Mass Transf. 39 (2) (2003) 167–176.

[24] K. Ismail, C. Alves, M. Modesto, Numerical and experimental study on the solidification of PCM around a vertical axially finned isothermal cylinder, Appl. Therm. Eng. 21 (1) (2001) 53–77.

[25] B. Kamkari, H. Shokouhmand, Experimental investigation of phase change material melting in rectangular enclosures with horizontal partial fins, Int. J. Heat Mass Transf. 78 (2014) 839–851.

[26] A.A. Al-Abidi, S. Mat, K. Sopian, M.Y. Sulaiman, A.T. 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.

[27] G. Lorenzini, L.A.O. Rocha, Constructal design of Y-shaped assembly of fins, Int. J. Heat Mass Transf. 49 (23) (2006) 4552–4557.

[28] S. Tiari, S. Qiu, M. Mahdavi, Numerical study of finned heat pipe-assisted thermal energy storage system with high temperature phase change material, Energy Convers. Manage. 89 (2015) 833–842.

[29] J.P. Trelles, J.J. Dufly, Numerical simulation of porous latent heat thermal energy storage for thermoelectric cooling, Appl. Therm. Eng. 23 (13) (2003) 1647–1664.

[30] P.W. Griffiths, P.C. Eames, Performance of chilled ceiling panels using phase change material slurries as the heat transport medium, Appl. Therm. Eng. 27 (10) (2007) 1756–1760.

[31] H. Ettouney, H. El-Dessouky, E. Al-Kandari, Heat transfer characteristics during melting and solidification of phase change energy storage process, Ind. Eng. Chem. Res. 43 (17) (2004) 5350–5357.

[32] U. Stritih, An experimental study of enhanced heat transfer in rectangular PCM thermal storage, Int. J. Heat Mass Transf. 47 (12) (2004) 2841–2847.

[33] A.I. Khuri, J.A. Cornell, Response Surfaces: Designs and Analyses, CRC Press, 1996.