Northumbria Research Link

Citation: Erfanian Nakhchi Toosi, Mahdi and Esfahani, J.A. (2020) Improving the melting performance of PCM thermal energy storage with novel stepped fins. Journal of Energy Storage, 30. p. 101424. ISSN 2352-152X

Published by: Elsevier

URL: https://doi.org/10.1016/j.est.2020.101424 <https://doi.org/10.1016/j.est.2020.101424>

This version was downloaded from Northumbria Research Link: http://nrl.northumbria.ac.uk/id/eprint/43475/

Northumbria University has developed Northumbria Research Link (NRL) to enable users to access the University's research output. Copyright © and moral rights for items on NRL are retained by the individual author(s) and/or other copyright owners. Single copies of full items can be reproduced, displayed or performed, and given to third parties in any format or medium for personal research or study, educational, or not-for-profit purposes without prior permission or charge, provided the authors, title and full bibliographic details are given, as well as a hyperlink and/or URL to the original metadata page. The content must not be changed in any way. Full items must not be sold commercially in any format or medium without formal permission of the copyright holder. The full policy is available online: http://nrl.northumbria.ac.uk/policies.html

This document may differ from the final, published version of the research and has been made available online in accordance with publisher policies. To read and/or cite from the published version of the research, please visit the publisher's website (a subscription may be required.)

Northumbria University NEWCASTLE

CUSTOMER SERVICE EXCELLENCE CSE UniversityLibrary

Improving the melting performance of PCM thermal energy storage with novel stepped fins

M. E. Nakhchi[a], **J. A. Esfahani**[a,1]

[a] Department of Mechanical Engineering, Ferdowsi University of Mashhad, Mashhad 91775-1111, Iran

Abstract

Numerical investigation on latent heat thermal energy storage (LHTES) systems with phase change materials (PCMs) vertically heated from one side with novel stepped fins is presented. Transient numerical simulation by using the enthalpy-porosity method is performed to investigate the heat transfer rate and melting behaviors, while the natural convection is considered. To improve the PCM melting process, different upward and downward stepped fins with the step ratios (b/c) of 0.66, 1, 1.5, 2.33 and 4 are employed. The melt fraction and temperature contours by consideration the natural convection effects are presented. The results show that at the beginning of the melting process, the fins in the downward direction with b/c=0.66 improve the PCM melting rate than the other cases, as the part of the heat is well transferred to the bottom of container along the fins and heat is trapped between the heated wall and the fins. The results show that the melting process in all of the tested stepped fins is faster than the conventional horizontal fins. The results show that by using downward stepped fins (b/c=0.4) instead of conventional horizontal fins, the melting process could be enhanced up to 56.3% at t=800sec and 65.5% at t=3600sec.

Keywords: phase change materials; thermal energy storage; stepped fins; liquid fraction; melting process

---

[1] Corresponding author (abolfazl@um.ac.ir)

1. Introduction

In the past years, the latent heat thermal energy storage (LHTES) systems using phase change materials (PCMs) have been numerically and experimentally investigated by several researchers in different thermal systems such as shell and tube energy storage units [1], heat recovery systems [2], thermal transport [3] and solar energy systems [4, 5]. Using PCMs in thermal systems have many benefits, such as high storage capacity, excellent heat transfer performance, and constant operating temperature. The primary defect of PCMs is their low conduction heat transfer coefficient, which increases the melting time and reduces the efficiency of the energy storage system. Accordingly, performance enhancement methods such as using different types of fins [6], using metal foams in PCMs [7], coil inserts [8] and using nanoparticles with high thermal conductivity [9-11] are developed to improve the efficiency of the thermal energy storage systems.

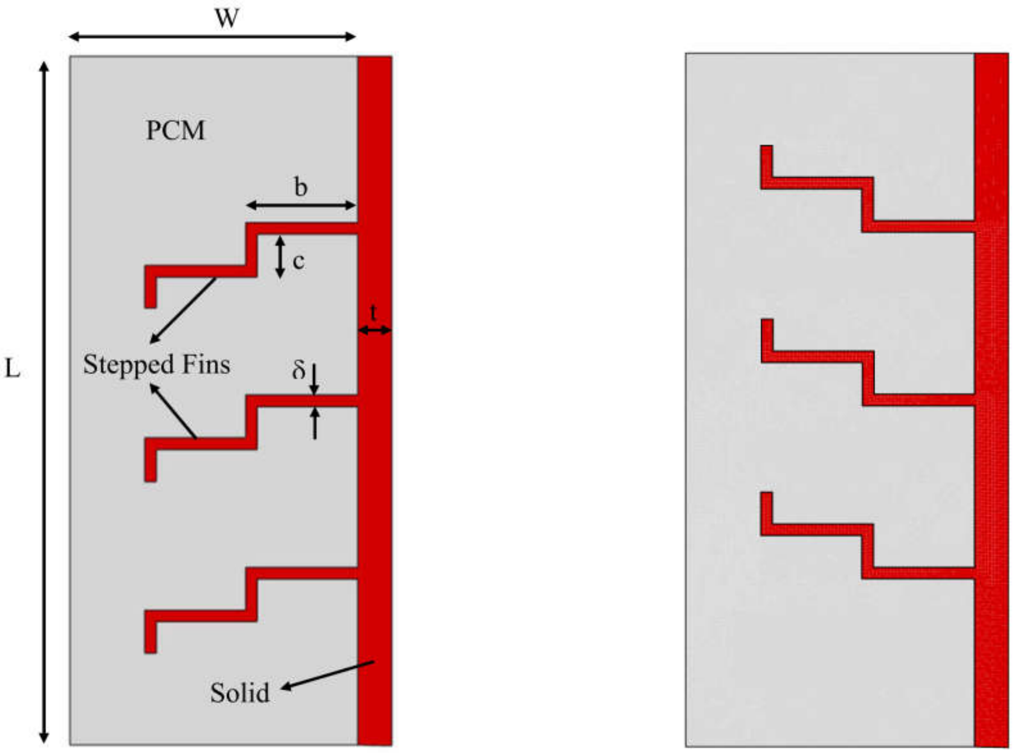
Using different types of fins as thermal performance enhancers are very popular in design of the LHTES units due to low cost, simple installation and high thermal conductivity [12]. Several investigations are conducted to investigate the effect of straight fins on the overall PCM melting process. Bhagat et al. [13] numerically investigated the thermal performance of multi tube latent heat thermal energy storage units fitted with straight fins. It was observed that using larger fins doesn't have considerable effect on PCM heat transfer augmentation. They also performed geometrical optimization to improve the performance of thermal energy storage units. Abdi et al. [14] numerically investigated the impact of straight vertical fins, on the heat transfer rate and energy storage capacity of a latent heat thermal energy storage system. They concluded that extending the length of the fins has better effects on the melting process than increasing the number of fins. Lacroix and Benmadda [15] performed a numerical analysis to examine the impact of the length and the number of horizontal fins in an enclosure with heated sidewall. It was concluded that the fin length is more effective on the melting performance rather than the number of fins. It means that using a small number of long fins had a better melting performance as compared to many of the small fins. Sheikholeslami et al. [16] analyzed the effects of nanoparticles and straight fins on the solidification performance of a heat storage unit. They observed that increasing the length of fins accelerates the solidification process. Sharifi et al. [17] numerically investigated the PCM melting in a square cavity with equipped with horizontal fins. It was concluded that using the straight horizontal fins initially enhanced the melting rate and then it slows down as the PCMs in the regions between the fins were melted. Kalbasi et al. [18] performed a numerical investigation to find the optimum number of fins in a PCM heat sink. They concluded that an increase in heat flux increases the number of optimal fins. Mahdi et al. [19] developed a novel configuration of fins ($L_1 = L_2 = L_3 = 25.3mm$, $L_3 = L_4 = 38mm$) with a constant width $(w = 1mm)$ in the triples-tube heat exchangers to enhance the PCM melting in energy storage systems.

Using inclined upward and downward enclosures and fins in LHTES systems become popular in recent years. Siyabi et al. [20] performed experimental and numerical investigation on the effects of inclination angle of PCM thermal energy storage unit. Their results revealed that the melting performance of PCMs in the energy storage is maximum for the inclination angle of 45°. Ji et al. [21] investigated the effects of upward and downward straight fins on the melting performance of the PCM filled thermal energy storage unit heated vertically from one side. They concluded that the inclined fins with a downward inclination angle of $-15°$give the best melting performance among tested geometries. Bondareva et al. [22] numerically investigated the heat transfer and thermal performance factor of nano-PCM materials inside an inclined finned enclosure. The effects of the inclination angle on the natural convection were also investigated. They observed that the nano enhanced PCM melts much faster for the slant angles higher than 90° at higher Rayleigh numbers. Avci et al. [23] experimentally studied the effects of inclination angle on the thermal performance of a flat type heat sink filled with PCM. Their results revealed that the melting time is increased about 5.5 times as the inclination angle increased from 0° to 90°. Karami and Kamkari [24] numerically investigated the melting process of PCM in inclined rectangular enclosures under the inclination angle varied from 0° to 180°. They also investigated the effect of natural convection on temperature and liquid fraction contours in inclined enclosures equipped with 1-3 straight fins. They concluded that that the maximum melting time reduction compared to the vertical enclosure without fins is about 72% obtained for the case of 3-fin enclosure with no inclination. This thermal behavior was also experimentally studied by Kamkari and Groulx [25]. They observed that decreasing the inclination is more efficient on melting process enhancement than adding more fins. The effect of other fin types, such as stepped fins on the melting process of PCM filled LHTES systems heated from side walls was not considered in previous numerical or experimental investigations.

Based on the literature review, using non-straight fin types to enhance the PCM melting performance and heat transfer rate in rectangular thermal energy storage units is shown to be lacking. In the present transient numerical study, upward and downward stepped fins with five different step ratios are employed to make heat transfer more uniform and enhance the melting process of PCM (lauric acid) in a rectangular enclosure which is isothermally heated from one side. Three fins are used in the energy storage unit to make comparisons with previous experimental and numerical investigations dealing with horizontal fins. The influences of conduction and buoyancy-driven convection mechanisms are considered in the numerical analysis based on the enthalpy porosity method. Finally, the effect of fin ratio on the wall heat flux and average temperature throughout the melting process is investigated to analyze the energy storage efficiency enhancement by using stepped fins.

2. Physical model

A schematic of the rectangular thermal storage system equipped with three stepped fins and filled with PCM is shown in Fig. 1. The enclosure has a height (L) of 120mm and a width (W) of 50 mm. The right wall of the rectangular enclosure is isothermally heated at 333 °K, while the other walls are insulated. The initial temperature of PCM was assumed to be equal to the ambient temperature (300 °K). 3-fin enclosure is studied by using stepped fins with different step ratios (b/c) ranging from 0.66 to 4. The thickness (δ) and total length of the stepped fins are 2 mm and 50 mm, respectively. The thickness of the heated aluminum plate is assumed to be 5mm. The details of the investigated test cases are presented in Table 1. Lauric acid with 99% purity is selected as the PCM due to appropriate properties such as high latent heat of fusion and excellent chemical stability. Table 2 shows the physical properties of lauric acid and aluminum used in the present study. As the fins are generally very thin, they can easily be folded by sheet metal folding tools, which is an inexpensive process and common for similar works. The attachment of the fins to the surface needs some care to reduce the thermal resistance on the base of the fin. To do this, the film layer of PCM material can be used as the filling of the gap between the fin and the wall. A more expensive way is integrating the fin with the wall to decrease thermal resistance, which can be done by casting. A traditional casting, not expensive method is not accurate and cannot produce the thin fin. Thus, an option of eternal mold such as slush molding can be incorporated.



a) Downward stepped fins b) Upward stepped fins

Fig. 1 Schematic view of the finned thermal storage unit

Table 1 Specifications of different fin configurations

Cases	b (mm)	c (mm)	Step ratio (b/c)	Step direction	Aluminum volume fraction (%)
Horizontal	25 $(\delta = 4mm)$	-	-	-	5
1	10	15	0.66	downward	5
2	12.5	12.5	1	downward	5
3	15	10	1.5	downward	5
4	17.5	7.5	2.33	downward	5
5	20	5	4	downward	5
6	10	15	0.66	upward	5
7	12.5	12.5	1	upward	5
8	15	10	1.5	upward	5
9	17.5	7.5	2.33	upward	5
10	20	5	4	upward	5

Table 2 Thermo-physical properties of lauric acid and aluminum [26, 27]

Properties	Lauric acid	Aluminum
Melting temperature range (°C)	43.5 (Solidus) – 48.2 (Liquidus)	-
Specific heat capacity (kJ/(kg·K))	2.18 – 2.39	0.87
Latent heat of fusion (J/kg)	187200	-
Density (kg/m^3)	940 – 885	2719
Thermal conductivity (W/(m·K))	0.16 – 0.14	202.4
Thermal expansion coefficient (1/K)	0.0008	-
Viscosity (μ)	$\mu = \exp\left(-4.25 + 1968/\left(T + 273.15\right)\right)$	-

3. Mathematical model and numerical simulation

The enthalpy-porosity method is utilized for modeling the melting process of PCM in the LHTES system [28]. The technique for this methodology considers different phases as a porous media through which porosity is equivalent to the fluid portion in that domain. Consequently, the porosity differs from zero to one as the PCM changes from solid to fluid. The Boussinesq approximation is utilized to simulate the buoyancy force term. Based on the above assumptions, the mathematical model for the 2D, laminar, unsteady and incompressible flow is as follows:

- Continuity:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{1}$$

- x- and y- momentum

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \frac{\mu}{\rho}\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) + \frac{1}{\rho}S_x \tag{2}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -\frac{1}{\rho}\frac{\partial p}{\partial y} + \frac{\mu}{\rho}\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) + \frac{(\rho\beta)}{\rho}g\left(T - T_m\right) + \frac{1}{\rho}S_y \tag{3}$$

Where u and v are the velocity components in x and y directions and β is coefficient of thermal expansion. The terms S_x and S_y on the right sides of Eqs. (2) and (3) are source terms added to the momentum equations to consider the effects of phase change in the mushy zone. This source term is defined as:

$$S_i = -\frac{(1-\lambda)^2}{\left(\lambda^3+\varepsilon\right)} A_{mushy} V_i \tag{4}$$

where i denotes x, y and A_{mushy} is mushy zone constant and $\varepsilon = 0.001$ is a small number to avoid division by zero. As discussed by Karami and Kamkari [24], $A_{mushy} = 5\times10^6$ gives the best results as compared with the experimental investigations. Therefore, $A_{mushy} = 5\times10^6$ is employed for further numerical simulations.

- Energy [29]

$$\frac{\partial(\rho H)}{\partial t} + \frac{\partial(\rho u H)}{\partial x} + \frac{\partial(\rho v H)}{\partial y} = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) \tag{5}$$

where H is defined as the total enthalpy of PCM and it is calculated as the sum of the sensible enthalpy (h) and the latent heat (L).

$$H = h + \Delta H = h + \lambda L \tag{6}$$

where the liquid fraction (λ) is defined as

$$\lambda = \begin{cases} 0 \ \text{ if } T < T_{solidus} \\ \dfrac{T - T_{solidus}}{T_{liquidus} - T_{solidus}} \ \text{ if } T_{solidus} < T < T_{liquidus} \\ 1 \ \text{ if } T > T_{liquidus} \end{cases} \tag{7}$$

The sensible enthalpy is defined as [14]:

$$h = h_{ref} + \int_{T_{ref}}^{T} C_p dT \tag{8}$$

The SIMPLE algorithm is used for the numerical simulations. The PRESTO! scheme is utilized for the pressure correlation equation. This scheme is recommended for simulation of natural convection heat transfer. The second-order upwind scheme is used for discretization of the momentum and energy equations and the first-order implicit scheme is employed for time discretization. The under-relaxation factors for pressure, density, body force, velocity, energy, and liquid fraction are 0.3, 0.9, 1, 0.7, 1, and 0.9, respectively. The convergence conditions are set as 10^{-5} for the momentum and continuity equations and 10^{-9} for the energy equation. The maximum number of iterations in every time step is 70. The computational domain used in the present study is shown in Fig. 2.

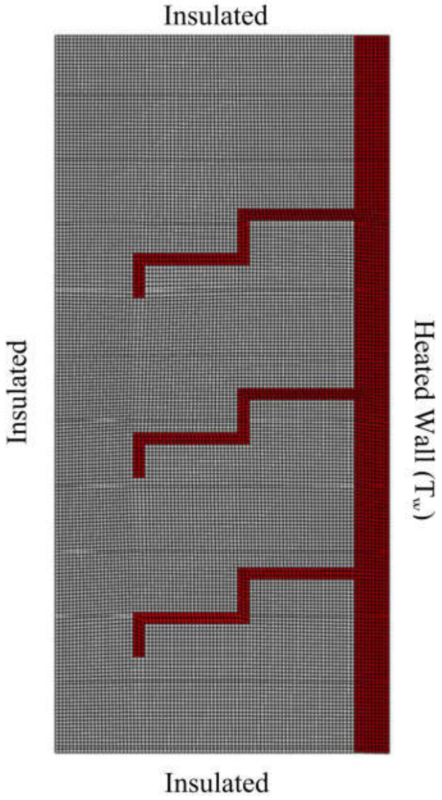


Fig. 2 Mesh generation for the PCM thermal energy storage unit with stepped fins

As shown in Fig. 3, three different grid sizes with 0.7mm, 0.5mm and 0.4mm element size are used to perform the grid independence study for melting in an enclosure fitted with the 3-straight horizontal fins. The maximum difference of the melt fraction between grid sizes of 0.5mm and 0.4mm is 0.7%. Therefore, a 0.5 mm grid size is selected for the numerical investigation. By using the same method, a time step of 0.07sec is used for time discretization.

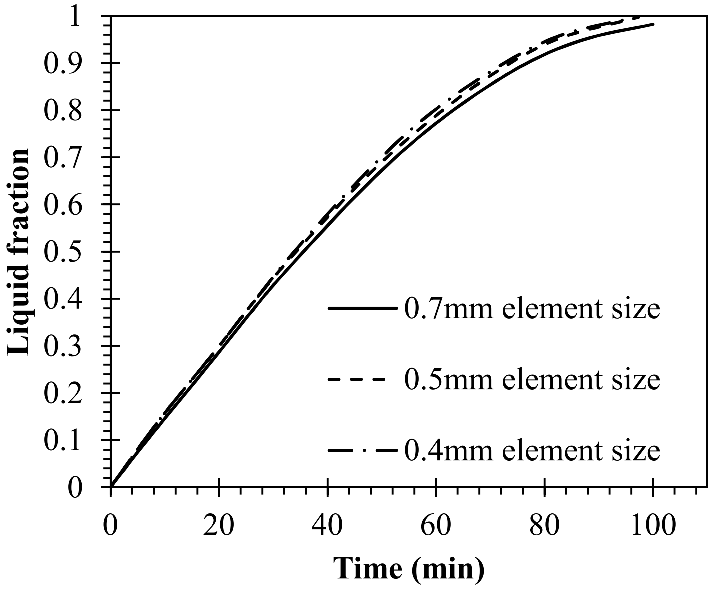
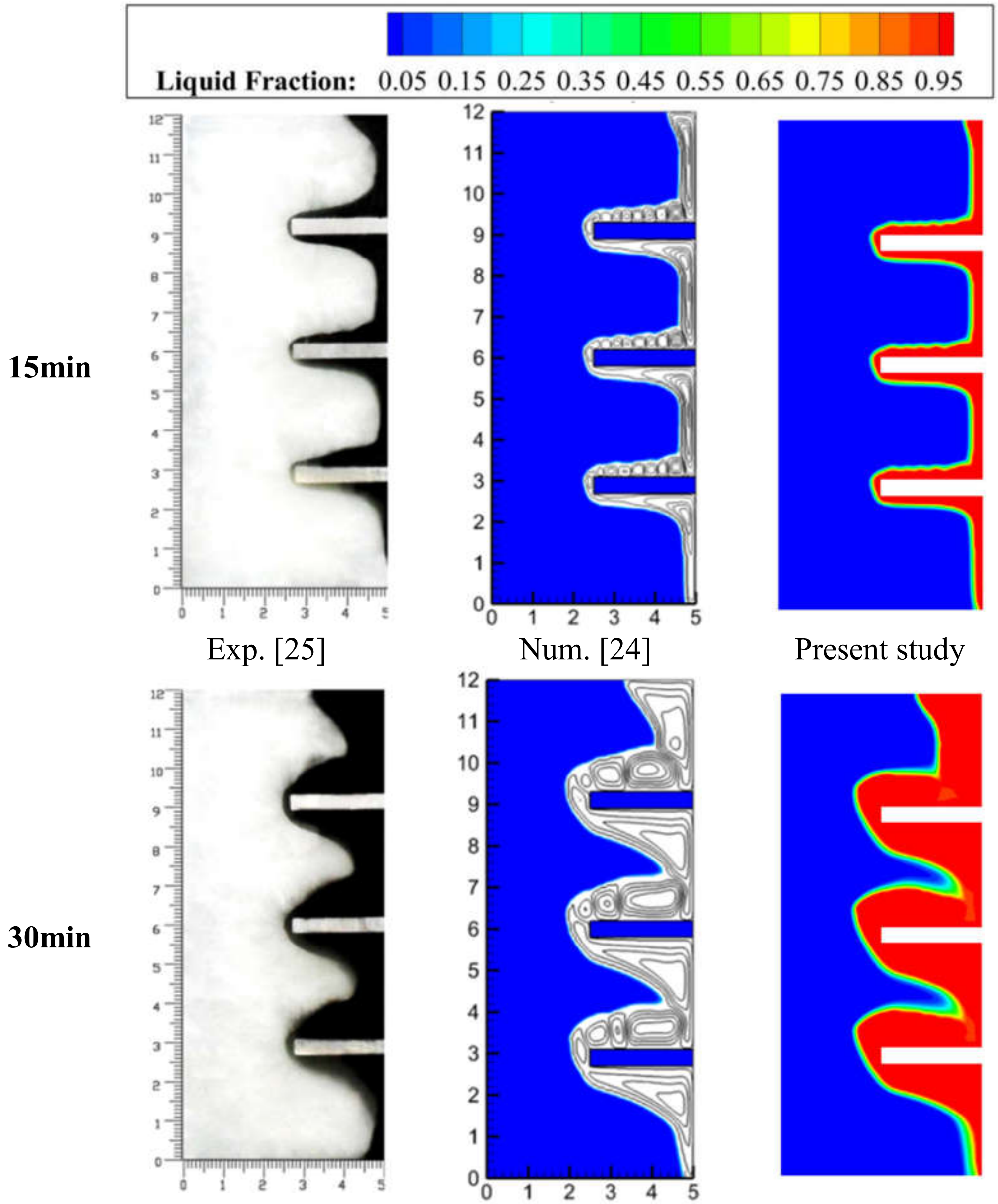


Fig. 3 grid independency test

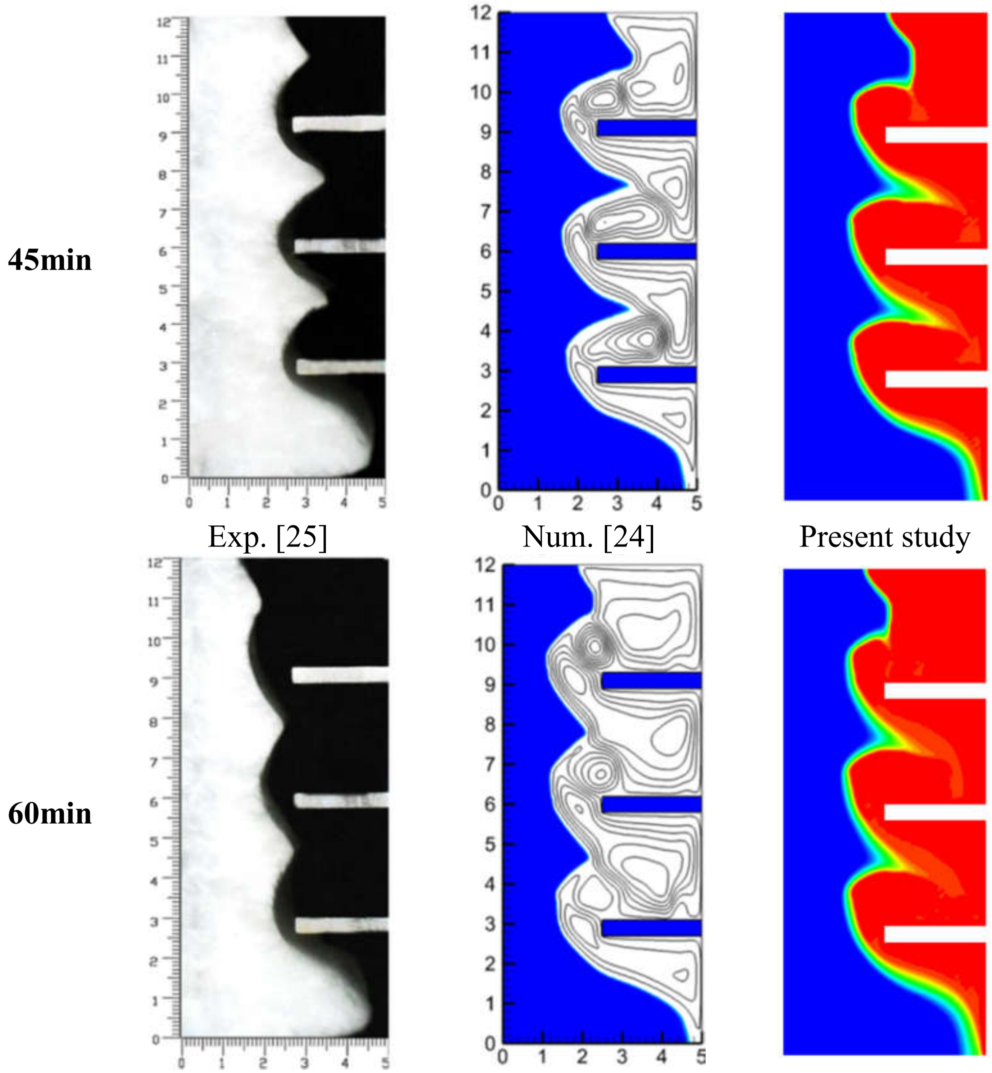
4. Results and discussion

Fig. 4 shows a comparison between present numerical results and previous experimental and numerical investigations for PCM melting in an enclosure enhanced with three horizontal fins. The results show that the numerical simulations are in agreement with previous experimental and numerical investigations for the PCM melting process in PCM filled rectangular enclosure vertically heated from a sidewall. The curved lines of the interface show that the natural convection flow is affected by the horizontal fins.



Exp. [25] Num. [24] Present study

Exp. [25] Num. [24] Present study

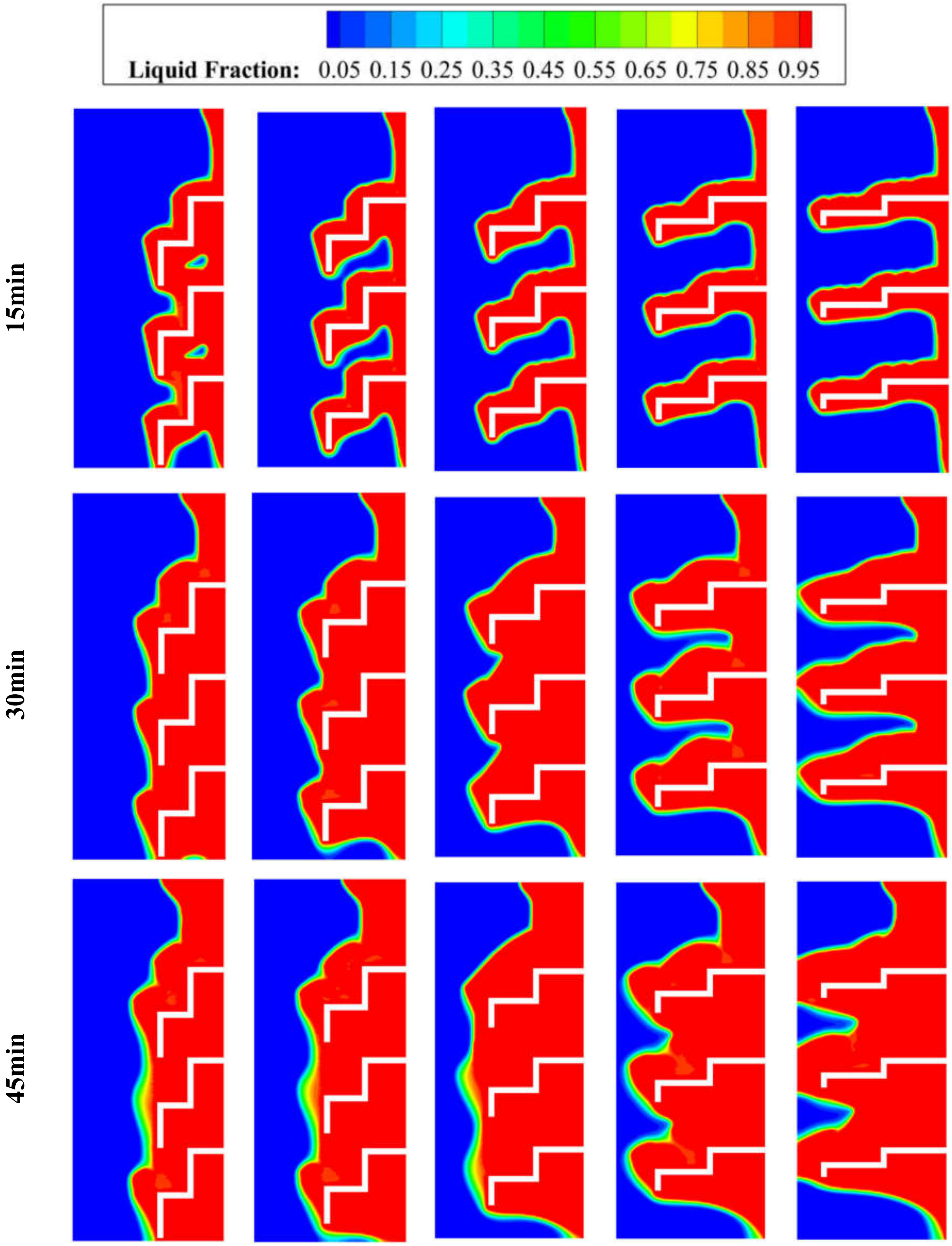


Exp. [25] Num. [24] Present study

Exp. [25] Num. [24] Present study

Fig. 4 Validation of liquid fraction contours with previous experimental and numerical investigations [24, 25] in the three-fin enclosure at different times

The melt fraction contours for downward stepped fins are presented in Fig. 5. As can be seen, the PCM melting process for b/c=0.66 is speedy at the beginning (t=15min), but it becomes slower than the other cases for t>30min. This is mainly due to the higher amount of heat trapped between the heated wall and the downward stepped fins with smaller step ratios in the presence of natural convection. It can be observed that with increasing the step ratio from 1 to 4, the non-uniform melting is reduced and the PCM melting performance enhances significantly. Between the tested geometries, the downward stepped fins with b/c=4 have the best influence on PCM melting enhancement (especially at t>45min).



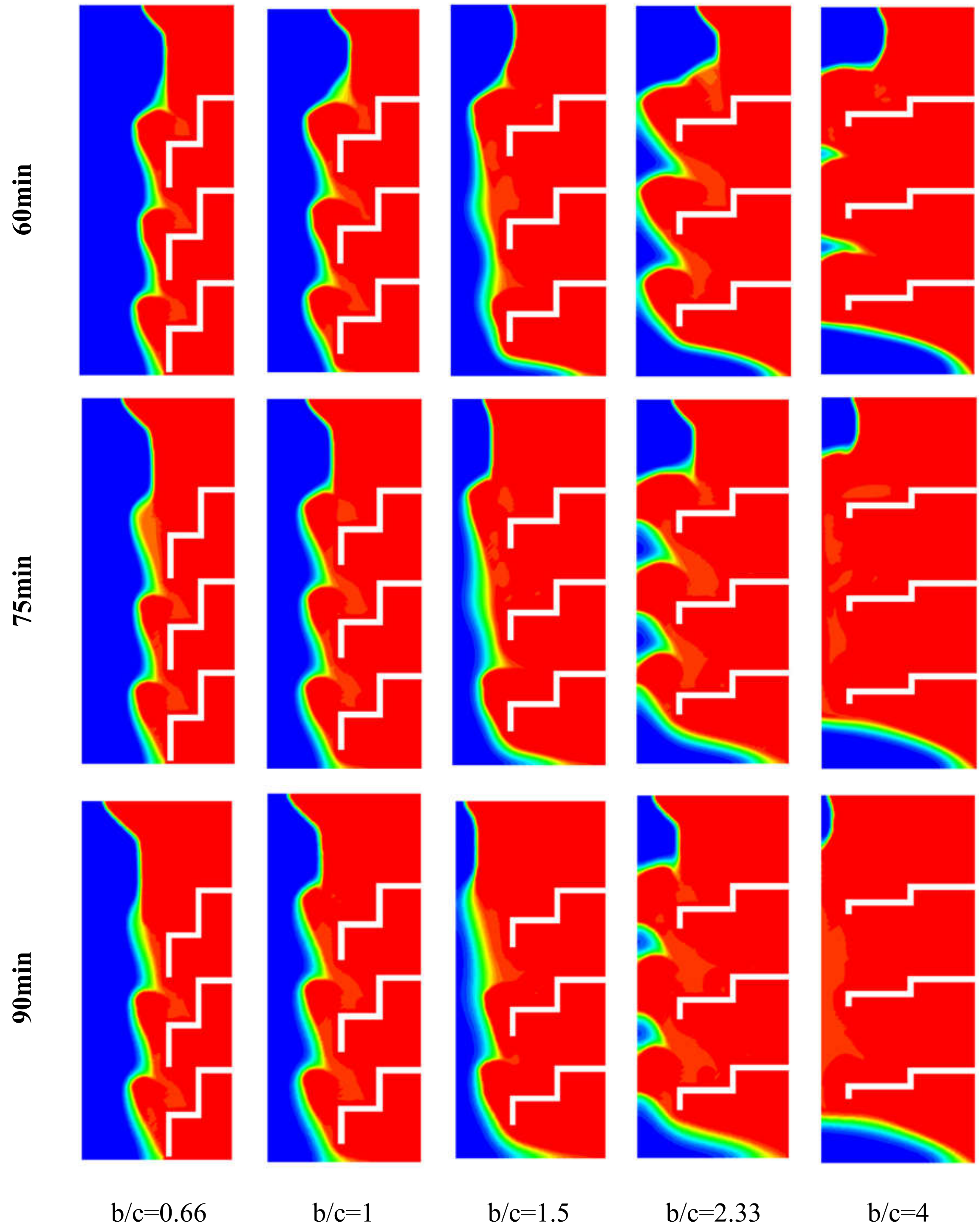
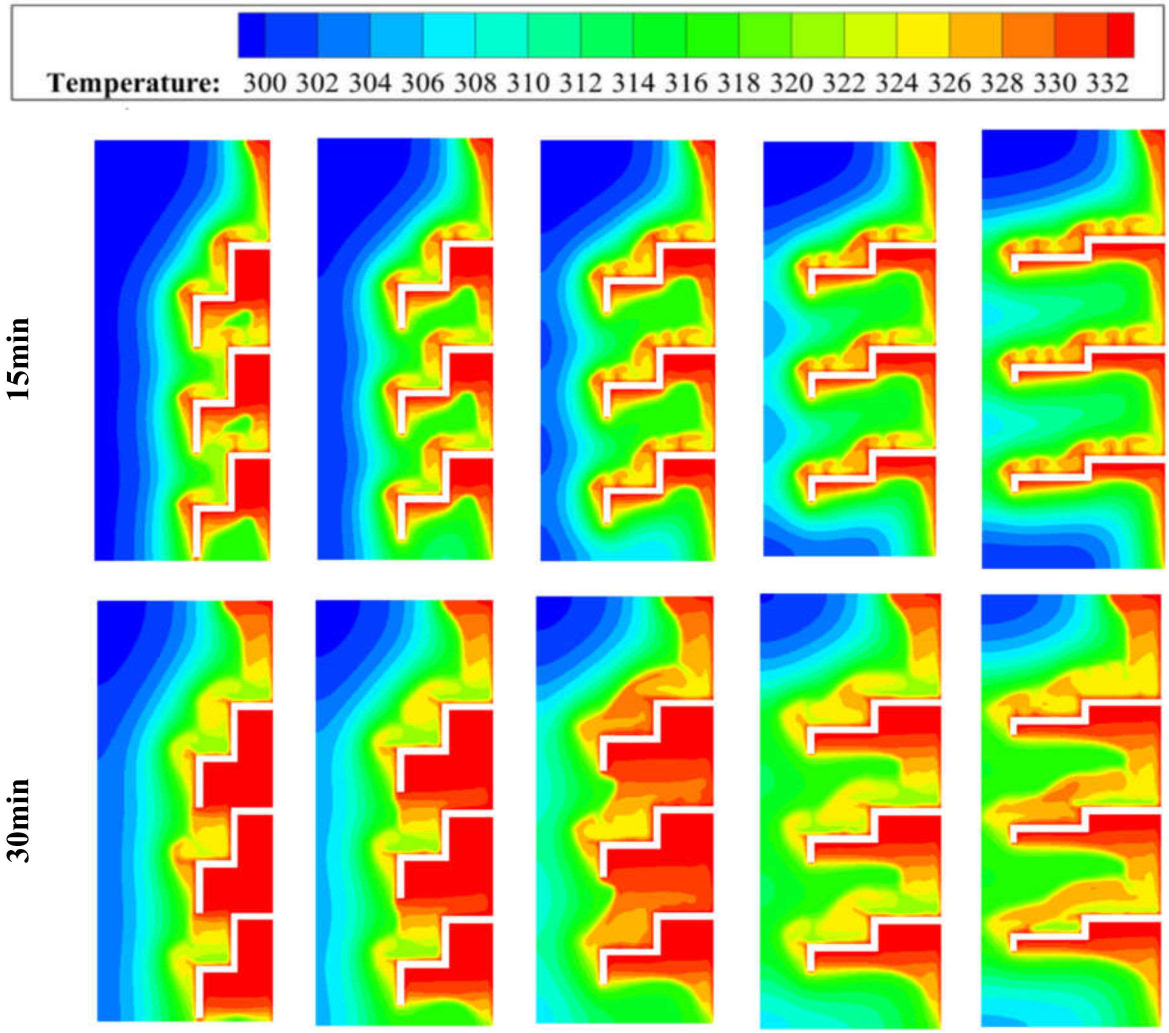
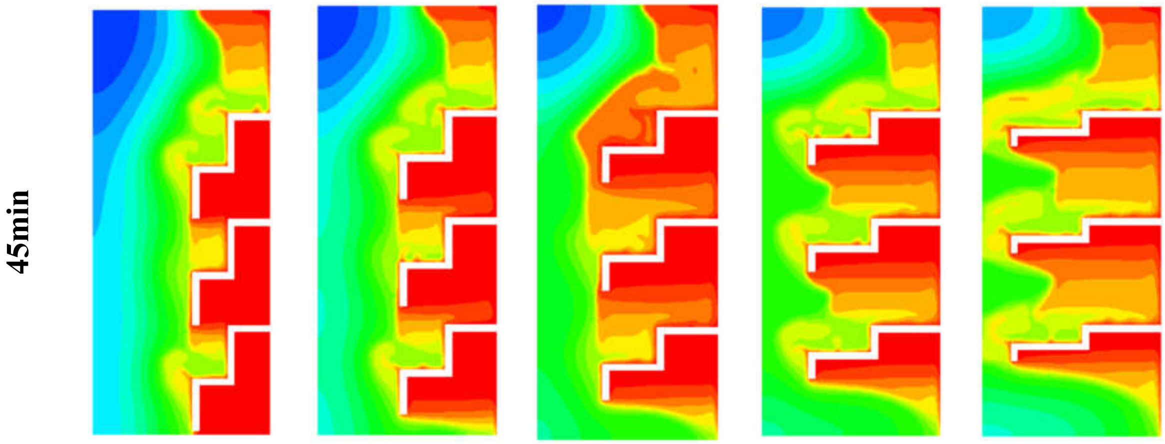


Fig. 5 Contours of the melt fraction with natural convection driven flow for the downward stepped fins

Fig. 6 shows the temperature contours of the melting process in a thermal energy storage system enhanced with downward stepped fins with different step ratios. It can be seen that the temperature contours are much more uniform for the case of b/c=4. The results show that heat is trapped between the stepped fin with b/c=0.66 and the heated wall due to the natural convection. This causes the melting process to be fast at the beginning (t=15min), but later, due to the lack of heat in the other areas, the melting rate is significantly reduced compared to the other tested cases. Due to the heat trap at the beginning of the melting process, Heat transfer in the enclosure with stepped fins with b/c<1 is non-uniform.

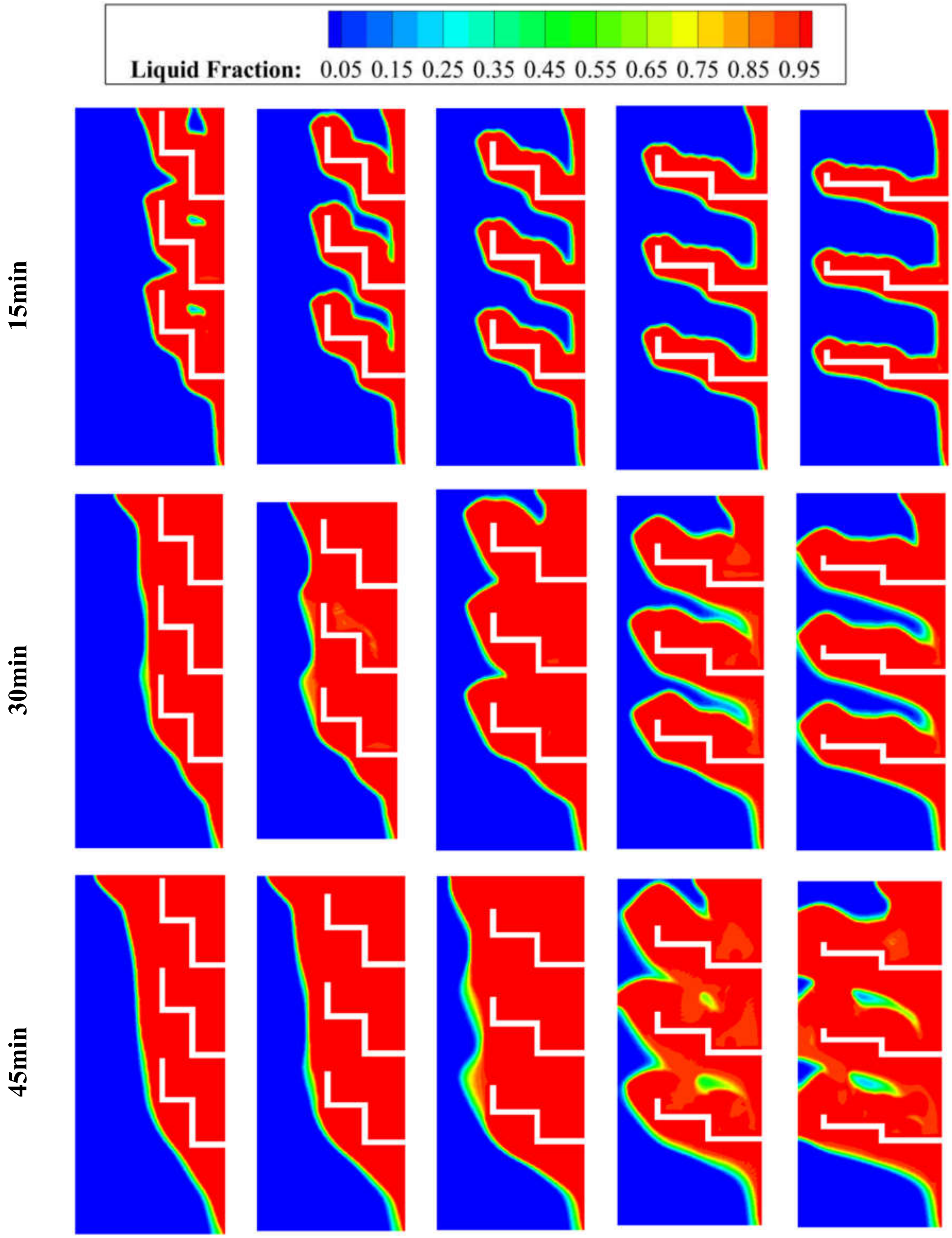




b/c=0.66 b/c=1 b/c=1.5 b/c=2.33 b/c=4

Fig. 6 Temperature contours for PCM filled thermal energy storage unit with the downward stepped fins

Figs. 7 and 8 show the liquid fraction and temperature contours of PCM melting in an enclosure enhanced with upward stepped fines with different step ratios. It can be observed that the melting rate in the upside direction is faster than the downside one. The main physical reason is that the melted PCM with higher temperature moves to the upside, under the influence of natural convection. In contrast, PCM at the bottom of the enclosure is still cold and solid. The non-uniform temperature contours lead to overheating of the upper part of the enclosure. Therefore, the non-uniform temperature distribution arising from the natural convection slows down the melting process in the enclosure. It also can be observed that the conduction heat transfer in the solid PCM near the fin edge increases the temperature of solid PCM.


Liquid Fraction: 0.05 0.15 0.25 0.35 0.45 0.55 0.65 0.75 0.85 0.95
15min
30min
45min

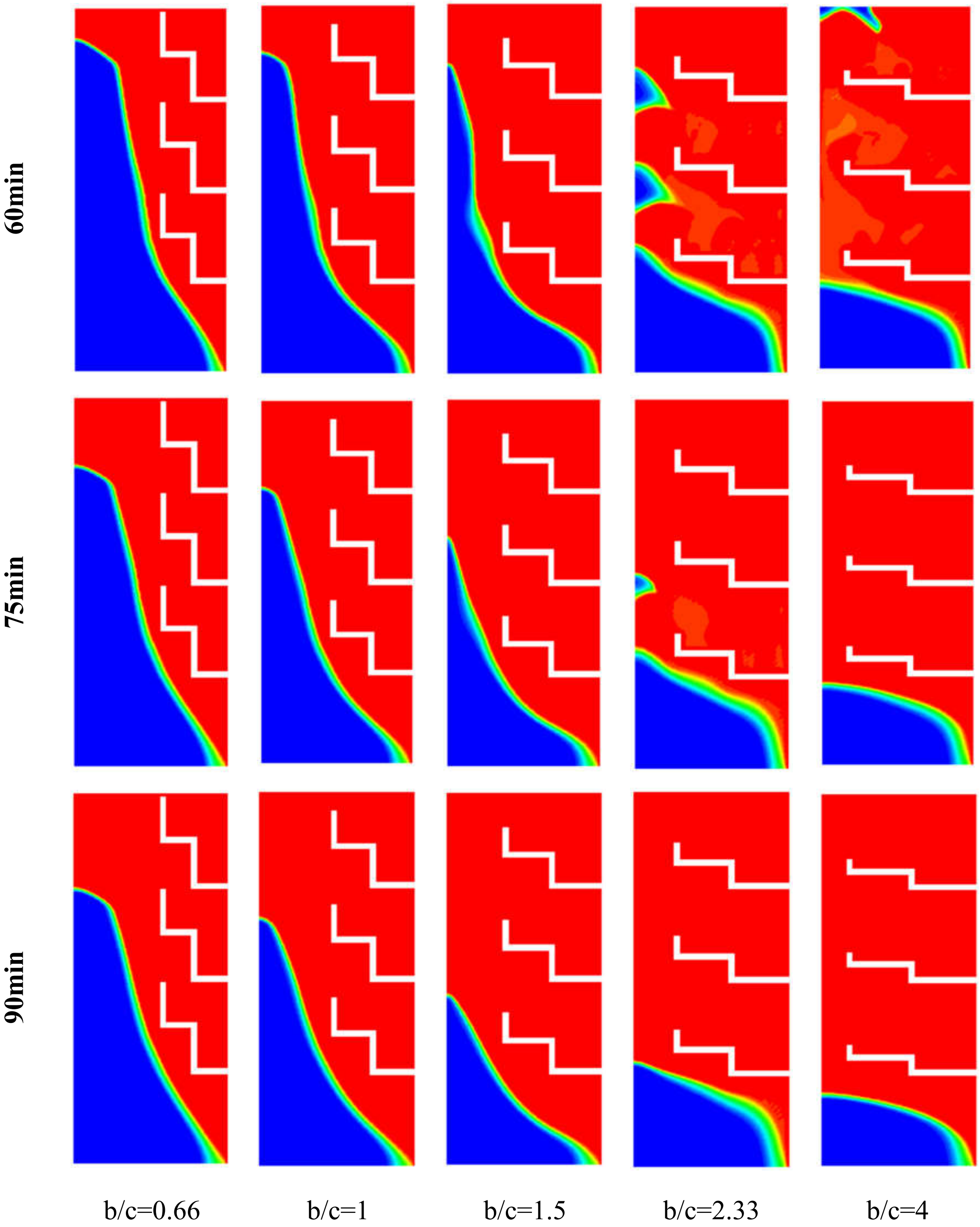


Fig. 7 Contours of the melt fraction with natural convection driven flow for the upward stepped fins

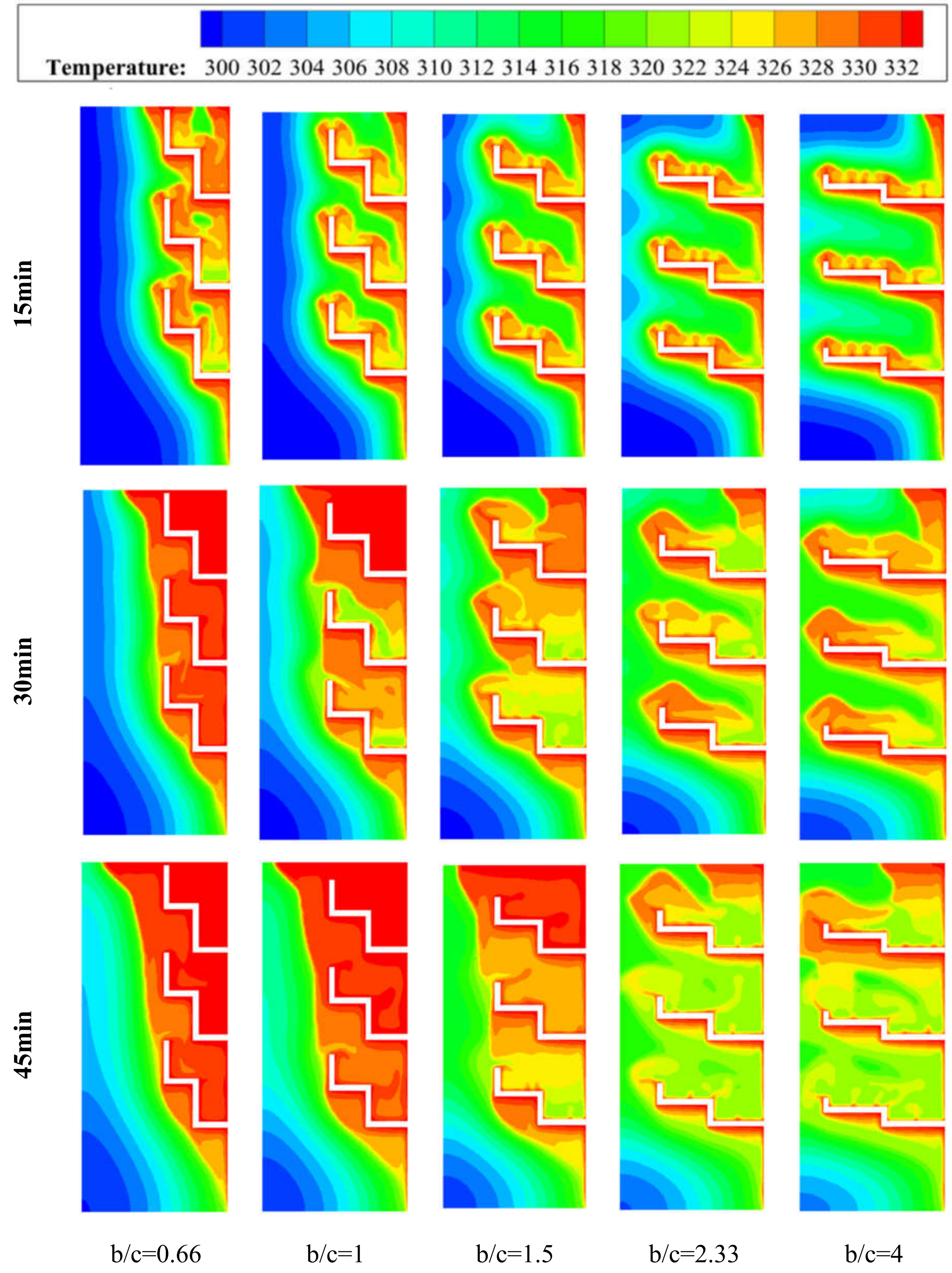
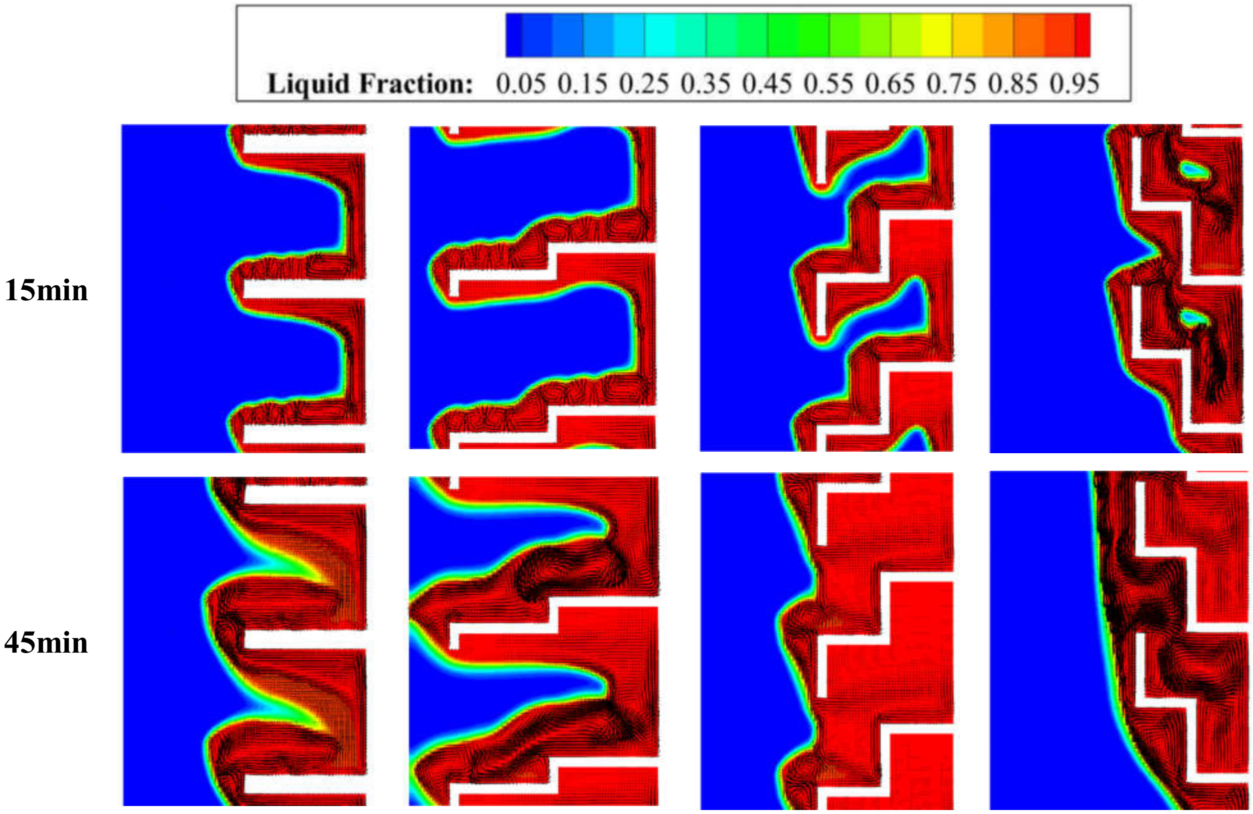


Fig. 8 Temperature contours for PCM filled thermal energy storage unit with the upward stepped fins

Fig. 9 shows the velocity vectors of melted PCM together with liquid fraction contours in an enclosure enhanced with different stepped fins. It can be seen that at the early times (t=15min), some vortex flows are generated near regions of the hot wall. These vortices receive heat from the heated wall and collide with a solid-liquid interface, which results in a curved interface. Besides, on the upper surface of the stepped fins, many small vortices and liquid PCM loops are formed, which melt at a later time as the thickness of the liquid layer increases. The fast PCM melting in the upper area of the cavity with upward fins with b / c = 0.66 is explained by the storage of heat in the upper side of the thermal storage unit.



Horizontal (validation case) b/c=4 (Downward) b/c=1 (Downward) b/c=0.66 (Upward)

Fig. 9 Velocity vectors and detailed view of the liquid fraction contours for different upward and downward fins

Fig. 10 shows the temporal variation of liquid fractions in the enclosure enhanced with upward and downward stepped finned with different step ratios ranging from 0.66 to 4. The liquid fraction of PCM in the vertical cavity with three horizontal fins is also plotted for analyzing the effects of the upward and downward stepped fins on the melting rate. It is seen that the melting rate accelerates by increasing the step ratio or changing the fin positions from upward to the downward direction. It is interesting to note that, initially the melting rate in the enclosure with small fins (b/c=0.66) is higher than the other tested geometries (t<1000sec) and then it reduces as the liquid fraction increases. Such melting performance can be described by measuring the effect of natural convection currents in different geometries. At the beginning of the melting process, heat is trapped between the heated wall and stepped fins with more towering vertical walls. This area with high temperature enhances the melting process of PCM in this area. Subsequently, the melting process slows down due to the inhomogeneous heat transfer area in the enclosure. The melting process of PCM energy storage unit enhanced with downward stepped fins is generally higher than the upward ones. This is mainly due to the effect of natural convection. The transition time from fast to slow melting occurs when the PCM in the upper half of the cavity is completely melted. This shows that the downward fins more effectively melt solid PCM above fin's surface due to the natural convection effects. The results show that by using downward stepped fins with b/c=4 instead of conventional horizontal fins, the melting process could be enhanced up to 56.3% at t=800sec and 65.5% at t=3600sec.

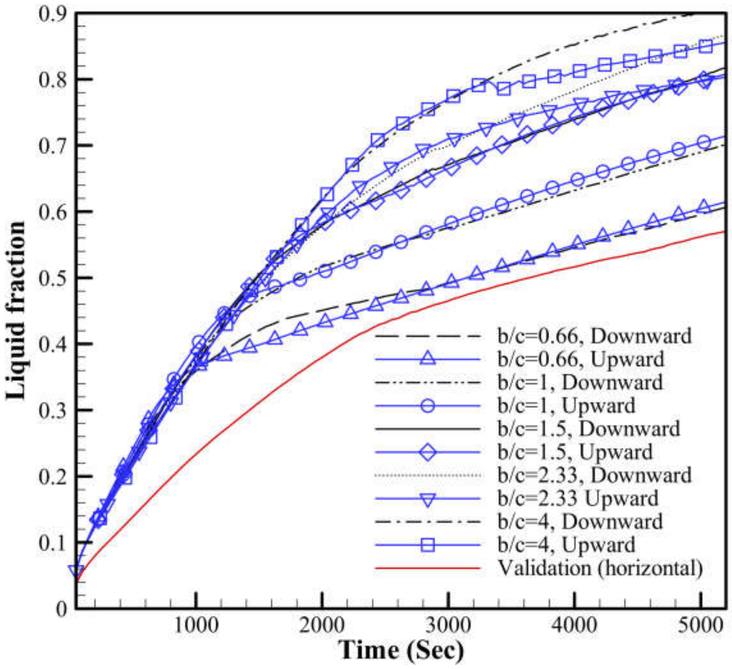
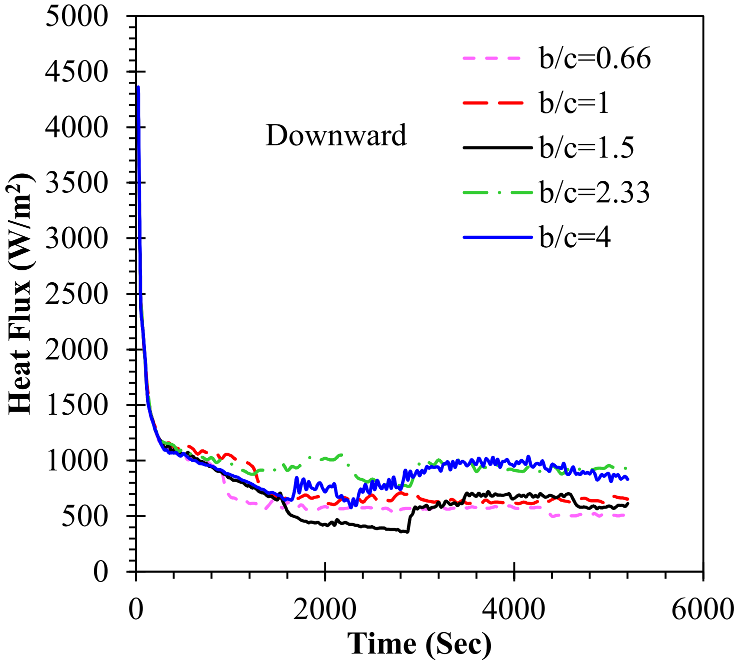
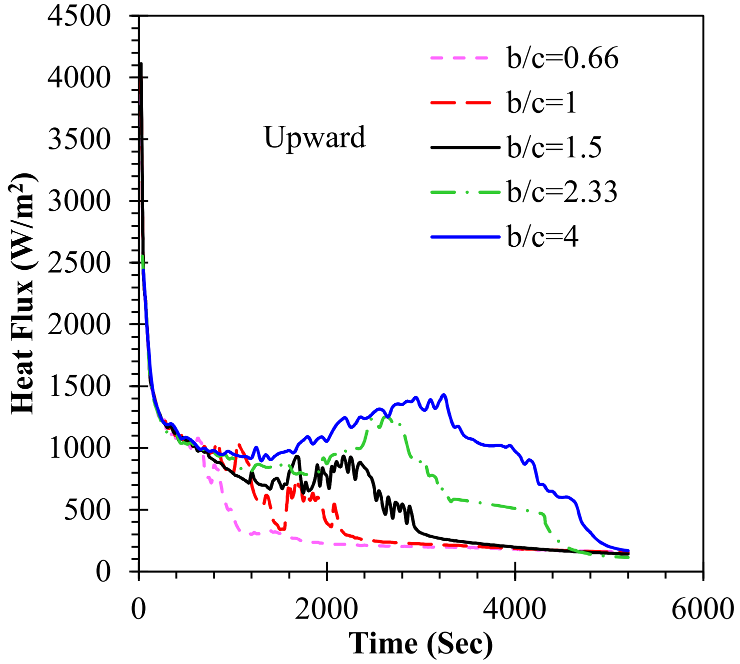


Fig. 10 Melt fraction as a function of time for all cases

The instant heat flux at different melting times is shown in Fig. 11. The heat flux is defined as $q''(t) = \dot{Q}(t)/A$ where $\dot{Q}(t)$ is the instantaneous total heat transfer rate to the phase change material and A is the total heat transfer surface including base and fins. After a significant decrease in the heat flux at the early stage of melting in all cases, the heat flux is further reduced for cases with b / s = 0.66 at the highest times. Also, the heat flux is more reduced when the fins are in the upward direction. During the PCM melting process, there is another time duration in which the heat flux enhances and makes its second maximum and then decreases again. When the heat flux is high, natural convection and total heat transfer rate reach their maximum values. During this period, the local eddies merge (see Fig. 9), and the fins disturb the PCM flow direction. The maximum heat flux of 1430 W / m2 is achieved for the case of ascending stepped ribs with b / c = 4 at t = 3151 sec.



(a) Downward stepped fins



(b) Upward stepped fins

Fig. 11 Heat flux over the time, (a) downward stepped fins and (b) upward stepped fins

The average PCM temperature with different fin geometries is presented in Fig. 12. It is observed that for the initial melting time (t = 800 s), the average PCM temperature increases with increasing b/c. In other words, increasing b/c increases heat storage capacity. It is seen that with increasing time, temperature changes decrease. The real reason for this is a more uniform distribution of temperature inside the enclosure with increasing the melting time. Besides, there is no significant difference in the average temperature for b/c = 1.5, 2.33 and 4 at t = 3600 s. This means that with increasing melting time, the influence of the fins geometry on the improvement of heat transfer decreases. The results show that when replacing conventional horizontal fins with stepped fins with b/c = 4, the average temperature of the latent heat energy storage unit increases by 1.94% at t=800s. The temperature enhancement reduces with increasing the melting time to 3600sec. This is mainly due to smaller heat flux values at higher melting times.

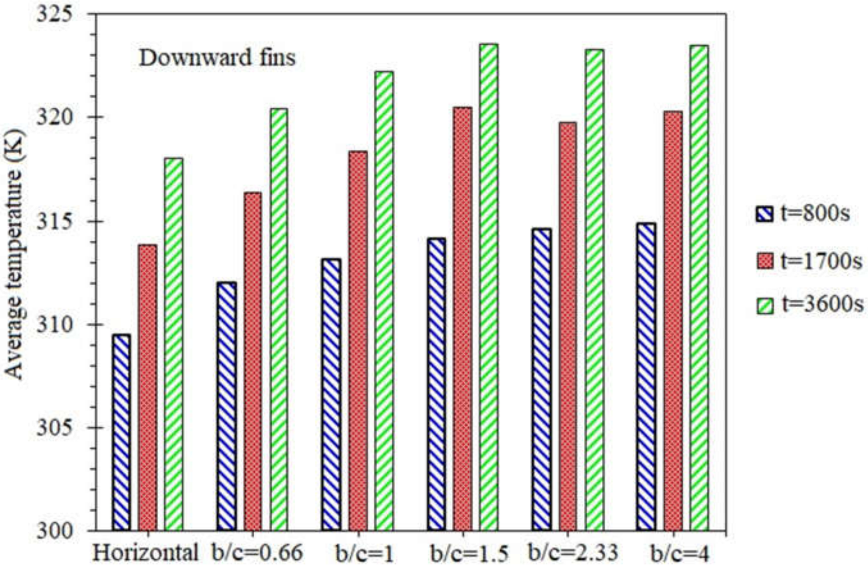


Fig. 12 Effects of the stepped fin geometry on average temperature

Fig. 13 shows the Accumulative stored energy inside PCM filled enclosure as function of melting time for different downward stepped fins. It can be seen that the required time to store the energy is considerably reduced with increasing b/c from 0.66 to 4. As discussed earlier, stepped fins with larger step ratios have more uniform temperature distribution in the enclosure and as a result, the melting process would be intensified. The results illustrate that the accumulative stored energy for all of the test cases is equal, due to the fact the volume of the fins is kept constant for all of the test cases. However, the required time to store that amount of energy (179.8 KJ) is completely dependent on the step ratio.

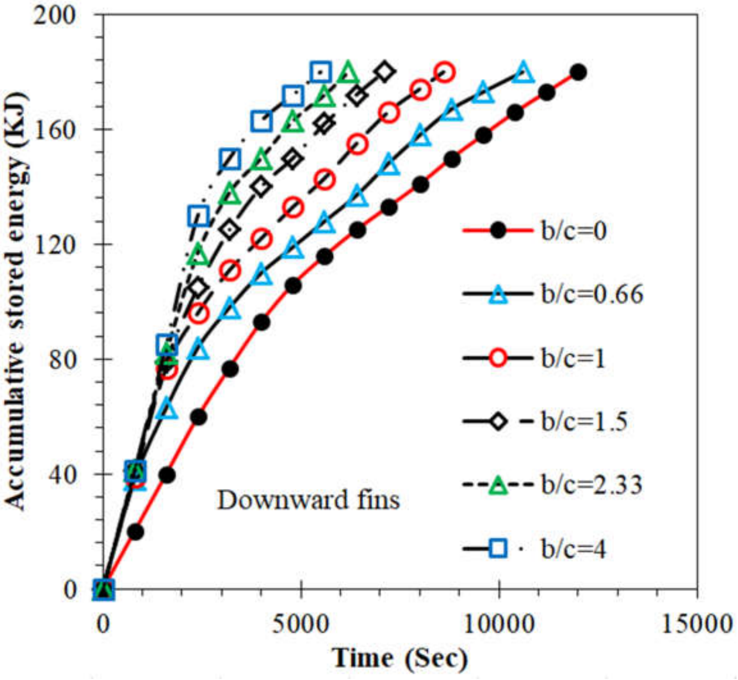


Fig. 13 Accumulative energy as function of time for different stepped fins

Reducing the melting time is only one of the important aspects in design of PCM energy storage units. Economic analysis is also important in the design of this equipment. Another critical parameter that should be evaluated is the total mean power of the system as function of the fin geometry. The mean power is defined as the ratio of the total accumulated energy at the end of melting to the total melting time [14]. Fig. 14 shows the effects of the fins geometry (b/c) on the mean power of the latent heat thermal energy storage unit. It can be seen that the mean power considerably increases with increasing the step ratio. Physically speaking, by raising the step ratio, hot melted PCM is trapped at the upper part of the storage unit due to the natural convection heat transfer effects. As discussed in Figs. 6 and 8, large amount of heat would trapped between the stepped fins with larger step ratios and the vertical heated walls. As a result, the melting process would be delayed and the mean power would be reduced. As expected, the mean power of the system equipped by upward stepped fins is relatively smaller than that for downward ones.

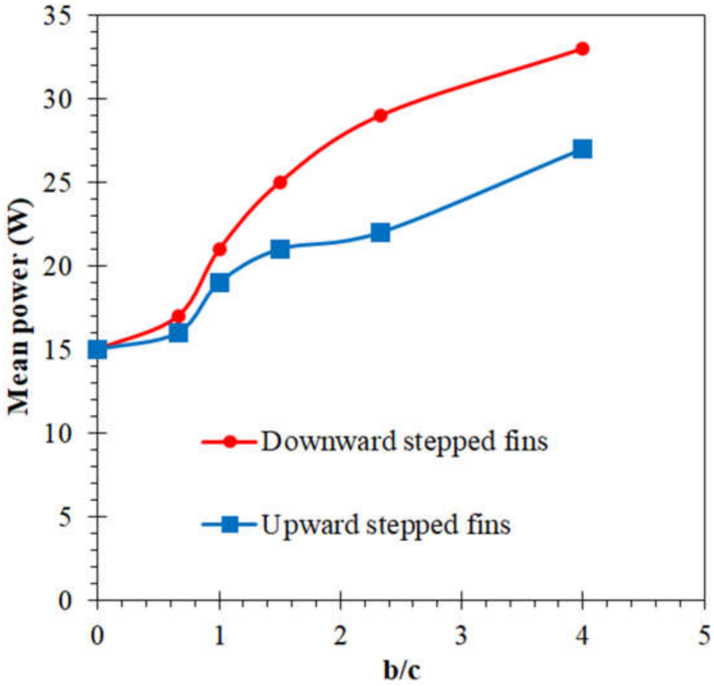


Fig. 14 Mean power as function of the fin step ratio for upward and downward stepped fins

5. Conclusion

In this work, numerical investigations of heat transfer with a phase change in a rectangular PCM-based LHTES system is carried out by using the enthalpy-porosity method. Lauric acid is selected as the PCM. The heat is transferred to the PCM from a side heating wall. In order to improve PCM melting performance for the accumulation of thermal energy, three parallel stepped fins with five different step ratios are proposed. A two-dimensional transient numerical model is used based on the Navier-Stokes equations considering the natural convection effects. After validation of the accuracy of the numerical results with previous experimental data, a model is developed for the numerical simulation of thermal behavior of the PCM filled enclosure with downward and upward stepped fins. The main findings are as follows:

- As can be seen, the PCM melting process for b/c=0.66 is slightly faster at the beginning (t=15min), but it becomes slower than the other cases for t>30min. This is mainly due to the higher amount of heat trapped between the heated wall and the downward stepped fins with smaller step ratios in the presence of natural convection.
- Between the tested geometries, the downward stepped fins with b/c=4 have the best influence on PCM melting enhancement. The melting process could be enhanced up to 56.3% at t=800sec and 65.5% at t=3600sec.
- The melting process accelerates by increasing the step ratio or changing the fin positions from upward to downward. At the beginning of the melting process, the melting rates in the enclosure with small fin ratios (b/c=0.66) is slightly higher than the other tested geometries (t<1000sec), and then it decelerates as the liquid fraction increases.
- There is a period during the PCM melting, in which the heat flux increases and reaches its second maximum value. When heat flux is high, natural convection and overall heat transfer rate reach their maximum values. The maximum heat flux of 1430 W / m2 was achieved for the case of ascending stepped ribs with b/c =4 at t=3151 sec.
- Replacing the conventional horizontal fins with stepped fins with b/c= 4 enhances the average temperature of the thermal energy storage unit up to 1.94% at t=800sec. The

temperature enhancement reduces with increasing the melting time to 3600sec. This is mainly due to smaller heat flux values at higher melting times.

Acknowledgment

This research was supported by the Office of the Vice Chancellor for Research, Ferdowsi University of Mashhad, under Grant No. 48898.

References

[1] J.M. Mahdi, E.C. Nsofor, Multiple-segment metal foam application in the shell-and-tube PCM thermal energy storage system, Journal of Energy Storage, 20 (2018) 529-541.

[2] Z. Gu, H. Liu, Y. Li, Thermal energy recovery of air conditioning system—heat recovery system calculation and phase change materials development, Applied Thermal Engineering, 24 (2004) 2511-2526.

[3] M. Krašna, E. Klemenčič, Z. Kutnjak, S. Kralj, Phase-changing materials for thermal stabilization and thermal transport, Energy, 162 (2018) 554-563.

[4] S. Kahwaji, M.B. Johnson, A.C. Kheirabadi, D. Groulx, M.A. White, A comprehensive study of properties of paraffin phase change materials for solar thermal energy storage and thermal management applications, Energy, 162 (2018) 1169-1182.

[5] G. Kumaresan, V. Vigneswaran, S. Esakkimuthu, R. Velraj, Performance assessment of a solar domestic cooking unit integrated with thermal energy storage system, Journal of Energy Storage, 6 (2016) 70-79.

[6] K.A. Aly, A.R. El-Lathy, M.A. Fouad, Enhancement of solidification rate of latent heat thermal energy storage using corrugated fins, Journal of Energy Storage, 24 (2019) 100785.

[7] B.V.S. Dinesh, A. Bhattacharya, Effect of foam geometry on heat absorption characteristics of PCM-metal foam composite thermal energy storage systems, International Journal of Heat and Mass Transfer, 134 (2019) 866-883.

[8] A.I.N. Korti, F.Z. Tlemsani, Experimental investigation of latent heat storage in a coil in PCM storage unit, Journal of Energy Storage, 5 (2016) 177-186.

[9] M. Bashar, K. Siddiqui, Experimental investigation of transient melting and heat transfer behavior of nanoparticle-enriched PCM in a rectangular enclosure, Journal of Energy Storage, 18 (2018) 485-497.

[10] I. Daou, L. El-Kaddadi, O. Zegaoui, M. Asbik, N. Zari, Structural, morphological and thermal properties of novel hybrid-microencapsulated phase change materials based on Fe2O3, ZnO and TiO2 nanoparticles for latent heat thermal energy storage applications, Journal of Energy Storage, 17 (2018) 84-92.

[11] N.S. Bondareva, B. Buonomo, O. Manca, M.A. Sheremet, Heat transfer inside cooling system based on phase change material with alumina nanoparticles, Applied Thermal Engineering, 144 (2018) 972-981.

[12] A. Campos-Celador, G. Diarce, I. González-Pino, J. Sala, Development and comparative analysis of the modeling of an innovative finned-plate latent heat thermal energy storage system, Energy, 58 (2013) 438-447.

[13] K. Bhagat, M. Prabhakar, S.K. Saha, Estimation of thermal performance and design optimization of finned multitube latent heat thermal energy storage, Journal of Energy Storage, 19 (2018) 135-144.

[14] A. Abdi, V. Martin, J.N. Chiu, Numerical investigation of melting in a cavity with vertically oriented fins, Applied energy, 235 (2019) 1027-1040.

[15] M. Lacroix, M. Benmadda, Numerical simulation of natural convection-dominated melting and solidification from a finned vertical wall, Numerical Heat Transfer, Part A Applications, 31 (1997) 71-86.

[16] M. Sheikholeslami, R.-u. Haq, A. Shafee, Z. Li, Y.G. Elaraki, I. Tlili, Heat transfer simulation of heat storage unit with nanoparticles and fins through a heat exchanger, International Journal of Heat and Mass Transfer, 135 (2019) 470-478.

[17] N. Sharifi, T.L. Bergman, A. Faghri, Enhancement of PCM melting in enclosures with horizontally-finned internal surfaces, International journal of heat and mass transfer, 54 (2011) 4182-4192.

[18] R. Kalbasi, M. Afrand, J. Alsarraf, M.-D. Tran, Studies on optimum fins number in PCM-based heat sinks, Energy, 171 (2019) 1088-1099.

[19] J.M. Mahdi, S. Lohrasbi, D.D. Ganji, E.C. Nsofor, Accelerated melting of PCM in energy storage systems via novel configuration of fins in the triplex-tube heat exchanger, International Journal of Heat and Mass Transfer, 124 (2018) 663-676.

[20] I. Al Siyabi, S. Khanna, T. Mallick, S. Sundaram, An experimental and numerical study on the effect of inclination angle of phase change materials thermal energy storage system, Journal of Energy Storage, 23 (2019) 57-68.

[21] C. Ji, Z. Qin, Z. Low, S. Dubey, F.H. Choo, F. Duan, Non-uniform heat transfer suppression to enhance PCM melting by angled fins, Applied Thermal Engineering, 129 (2018) 269-279.

[22] N.S. Bondareva, B. Buonomo, O. Manca, M.A. Sheremet, Heat transfer performance of the finned nano-enhanced phase change material system under the inclination influence, International Journal of Heat and Mass Transfer, 135 (2019) 1063-1072.

[23] M. Avci, M.Y. Yazici, An experimental study on effect of inclination angle on the performance of a PCM-based flat-type heat sink, Applied Thermal Engineering, 131 (2018) 806-814.

[24] R. Karami, B. Kamkari, Investigation of the effect of inclination angle on the melting enhancement of phase change material in finned latent heat thermal storage units, Applied Thermal Engineering, 146 (2019) 45-60.

[25] B. Kamkari, D. Groulx, Experimental investigation of melting behaviour of phase change material in finned rectangular enclosures under different inclination angles, Experimental Thermal and Fluid Science, 97 (2018) 94-108.

[26] H. Shokouhmand, B. Kamkari, Experimental investigation on melting heat transfer characteristics of lauric acid in a rectangular thermal storage unit, Experimental Thermal and Fluid Science, 50 (2013) 201-212.

[27] A.C. Kheirabadi, D. Groulx, The effect of the mushy-zone constant on simulated phase change heat transfer, in: ICHMT Digital Library Online, Begel House Inc., 2015.

[28] A. Brent, V. Voller, K. Reid, Enthalpy-porosity technique for modeling convection-diffusion phase change: application to the melting of a pure metal, Numerical Heat Transfer, Part A Applications, 13 (1988) 297-318.

[29] S. Deng, C. Nie, G. Wei, W.-B. Ye, Improving the melting performance of a horizontal shell-tube latent-heat thermal energy storage unit using local enhanced finned tube, Energy and Buildings, 183 (2019) 161-173.