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Review article

Improvement of heat transfer within phase change materials using V-shaped rods

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ABSTRACT

This study numerically investigated the improvement of heat transmission to phase change material (PCM) paraffin wax in a triangular cell with and without fins. The enthalpy–porosity combination was quantitatively evaluated using the ANSYS/FLUENT 20 program. Materials with the phase shifts of paraffin wax were used in this study (RT42). According to the study findings, fins significantly accelerate the melting process and decrease the time required to finish it. The time difference between melting with and without fins is 125%. Moreover, the inclusion of v-shaped fins contributed to a 200% reduction in the melting process time. Thus, the use of v-shaped fins facilitates faster heat transfer to and from the applications wherein the phase change materials are used.

1. Introduction

Being so reliant on her and intertwined with human daily existence, the energy she carries has a tremendous impact on the development of modern civilization. Others are known to run out in the future, while certain energy sources are known to have substantial negative effects on the environment. As a result, researchers working around the world are looking into renewable energy alternatives. The long-term economic feasibility and lack of negative environmental effects of renewable energy are just two of their many advantages. The major disadvantage is the lack of regular access to sources like wind and sun, even though it has the potential to be utilized anywhere [1–3]. Keeping thermal energy stored is one solution to this issue, PCMs are the primary types of materials utilized in the storage of thermal energy [4]. Among these materials, paraffin wax material stands out because it is one of the widely available materials, as well as being an inexpensive material that accepts a wide range of temperatures, which has a large range of engineering and thermal applications in particular. Where the use of these materials has increased in many applications, including the storage of renewable energy and its use in the event that it is not available, and within a wide range of sustainable energy applications [5–7], Utilization of PCM thermal energy storage to lessen building energy consumption [8,9], also with buildings but for heating/cooling load reduction [10–12].

Many additions were added to phase change materials in order to improve their efficiency, most notably nanomaterials, Zeng et al.

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Nomenclature

c	specifics heat (J/kg K^{-1})
β	melting fraction
h	average heat transfers coefficient (W m^{-2} K^{-1})
k	thermal of conductivity (W m^{-1} K^{-1})
L	latent heat melting (kJ/kg)
t_e	elapsed time of each test run (s)
T	temperatures (K)
Greek symbols	
α	thermal of diffusivity (m^2 s^{-1})
β_f	liquid thermal of expansion coefficient (K^{-1})
ρ	density, (kg m^{-3})
ν	kinematic of viscosity (m^2 s^{-1})
Subscripts	
H	hot water
l	liquid PCM
m	melting
PCM	phase change material
s	solid PCM

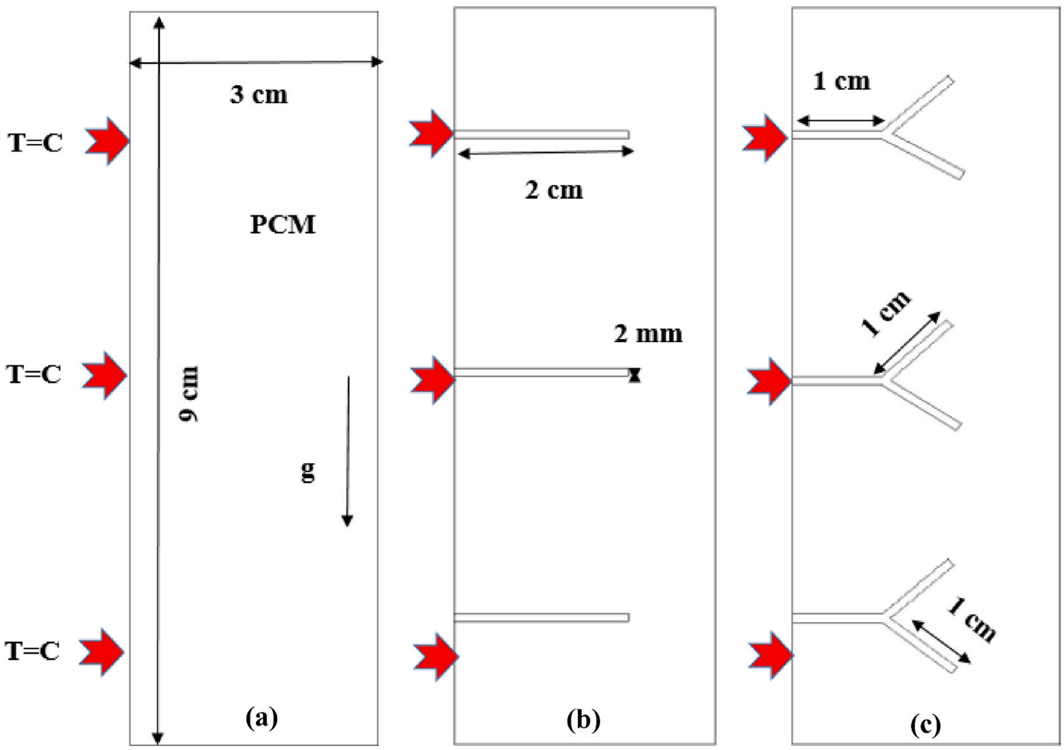


Fig. (1). Configuration of the physical model.

[13] In this research, organic phase change materials (PCM) composite materials including silver nanoparticles were synthesized for the first time and described. An investigation was carried out to determine how the presence of Ag nanoparticles will affect the thermal conductivity of PCM. While Frusteri et al. [14] using carbon fibers with PCM, it was discovered that there is a linear connection between the amount of carbon fiber loading and the rising thermal conductivity throughout a broad range of carbon loading. Then Mahdi et al. [15] study the enhancement of Solidification of PCM and thermal energy storage by using nanoparticles and fins inside a triplex-tube, according to the findings, the use of fins alone demonstrates superior enhancement compared to either the utilization of

Table 1
Boundary condition.

No.	B.C.	Mathematically
1	Rectangular cell to be studied "in three walls side"	Q = 0 (W)
2	Temperature of left side of the container "wall"	$T_w = 77\ ^\circ C$
3	Other rode the heat passed to the phase change materials	Convection

Table 2
Thermal properties of paraffin (RT42).

Density	kg/m^3	760
Specific heat	C_p (J/kg.K)	2000
Thermal conductivity	W/m.K	0.2
Heat of the fusion	J/kg	165000
Dynamic viscosity	kg/m.s	0.02351
Thermal expansion coefficient	1/K	0.0005
Solid temperature	K	311
Liquid temperature	K	315

nanoparticles alone or the combination of fins and nanoparticles.

Maher et al. [16] This study looks at ways to improve heat transfer in PCM thermal storage systems. These methods include using fins, fin materials and shapes, filling materials, nanofluids, nanoparticles, microencapsulation, and increasing thermal conductivity. While Amin et al. tries to find the optimization of PCM thermal storage devices for the highest possible efficiency in energy storage. Then Pássaro et al. study the influence of fins and nanoparticles on the discharge performance of a PCM thermal storage system equipped with a multi-pass finned tube heat exchanger. Other numerical study done by Mosaffa et al. [17] where the model is simplified form for the solidification of PCM in shell and tube finned storage. In the presence of a heat thermal fluid on the walls, they create an equation relating to energy, and evaluate the difference in the amount of time it takes for PCM to solidify in cylindrical shell and rectangular storages.

By reviewing previous research, the current study came up to find the effect of added V- shaped with a half-cylinder filled with a phase change material (PCM) which presents a new idea for shape form and the container. Also, studying the extent of improving heat transfer in the case of adding more than one fin indoors and comparing the results with case of copper rods.

2. Numerical procedure

2.1. Physics models

A 9 cm × 3 cm rectangular container filled with phase-changing materials is studied. In the first part (a), no rods were used, in the second part (b), longitudinal rods with a length of 2 cm were used with copper material, and in the third part (c), rods with a length of 1 cm were used, which branched out in the shape of a v with angle is equal to (30°) and a length of 1 cm "copper rods material" with thickness of the fin equal (2 mm), as shown in (Fig. 1(.

2.2. Computational procedure

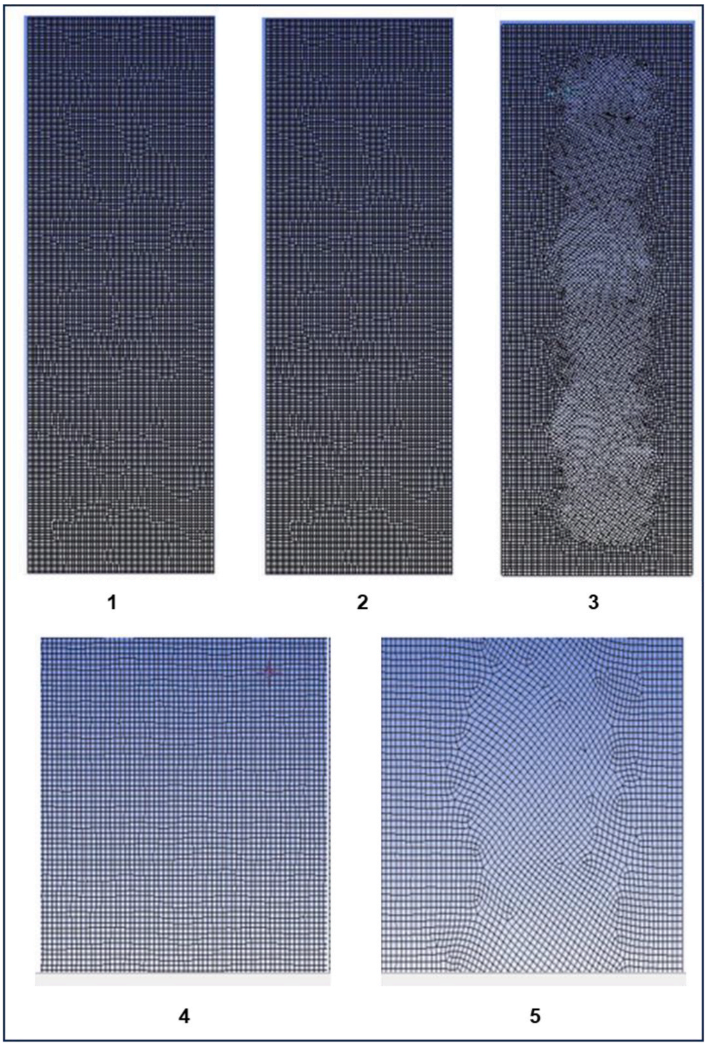
The capacity to forecast the specifics of the melting processes that occur in a rectangular cell was demonstrated by numerical analysis. The flow was discovered to be laminar, unstable, incompressible, and two-dimensional. To simulate the melting process, it was assumed that the liquid and solid phases were homogeneous, isotropic, and maintained a thermal equilibrium at their interface. The phase change area of the PCM was chosen to follow the enthalpy-porosity route. The melting processes of PCMs are regarded as collective original sins because of their nonlinearity, temporal conduction, and constant mobility at the solid-liquid interface. Further, the simultaneous continuity, momentum, and energy-governing partial differential equations are used to simulate the melting processes of PCMs (1), (2), and (3), respectively [4,18,19].

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

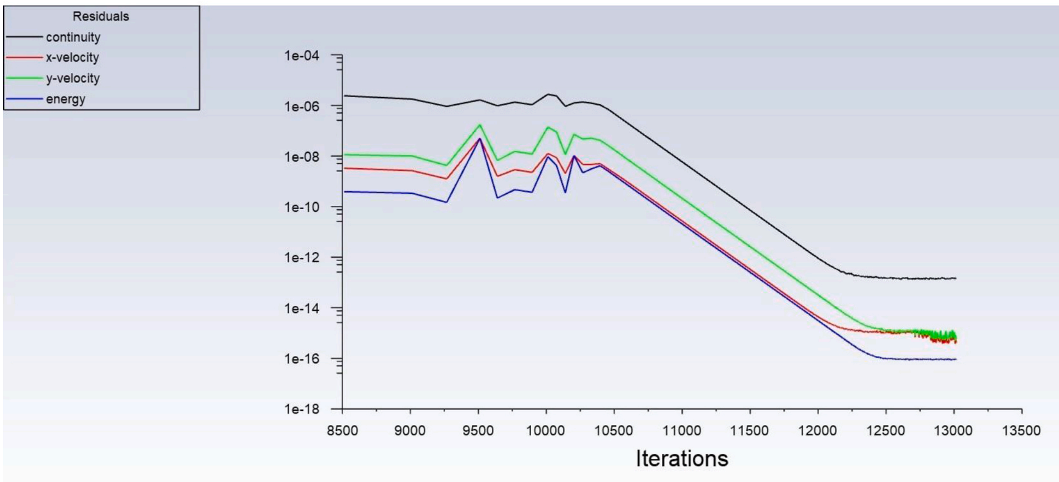
$$\frac{\partial (\rho v)}{\partial \mathrm{t}} + \nabla.\ (\rho V) = -\nabla P + \mu \nabla^2 V + \rho g + S \tag{2}$$

$$\frac{\partial}{\partial t}(\rho H) + \nabla.(\rho V H) = \nabla.(K \nabla T) \tag{3}$$

The specific enthalpy H is the sum of the sensible enthalpy (h) and the latent heat (ΔH) [20],



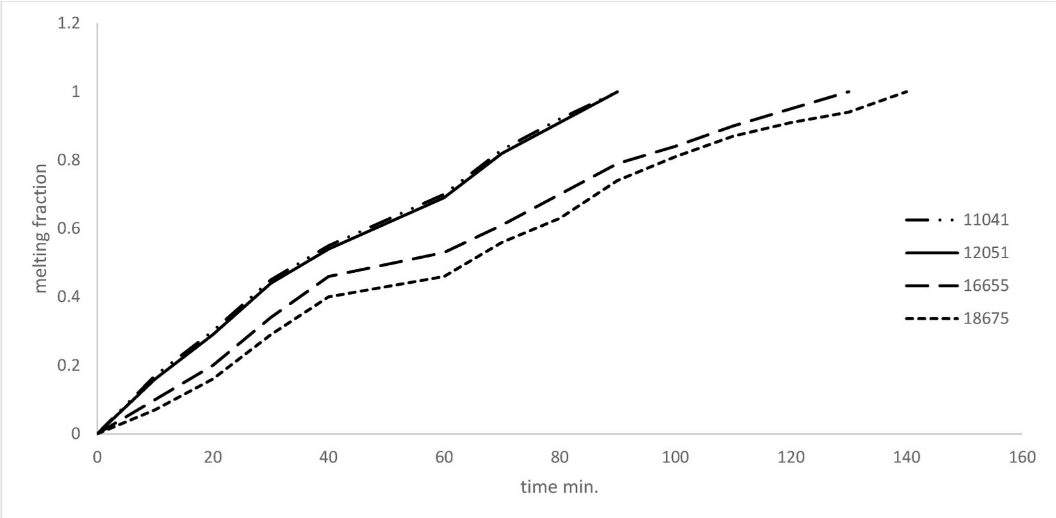
a



b

(caption on next page)

Fig. (2-a). Configuration of mush model.
Fig. (2-b) convergence history for simulation equations.



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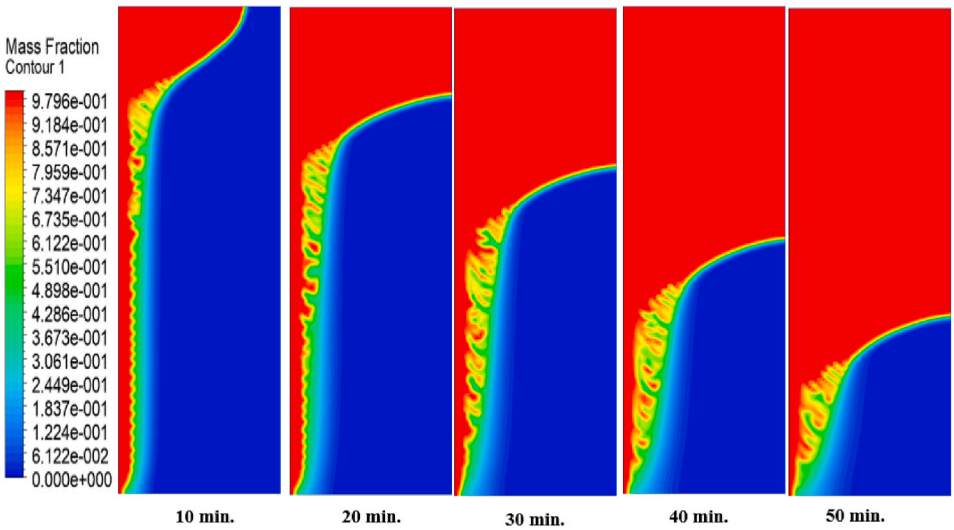

b

Fig. (3). Predicted evolution of the melting process without fins
Fig. (3-a) mesh independence.

$$H = h + \Delta \mathrm{H} \tag{4}$$

Where,

$$h = h_{ref} + \int_{T_{ref}}^{T} C_p \, dT \tag{5}$$

$$\Delta H = \beta L_f \tag{6}$$

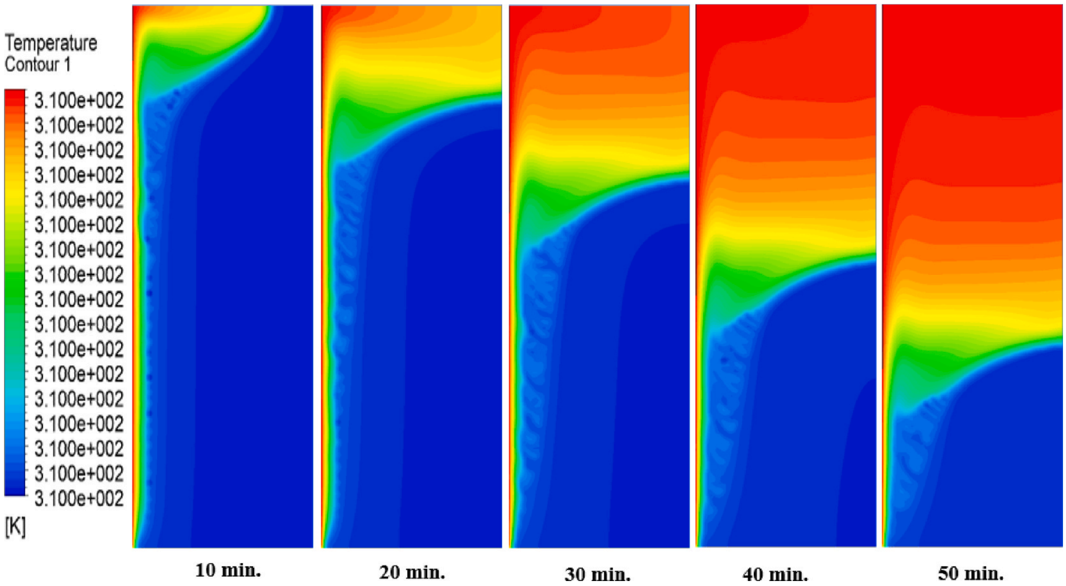

Fig. (4). Temperature distributions without fins.

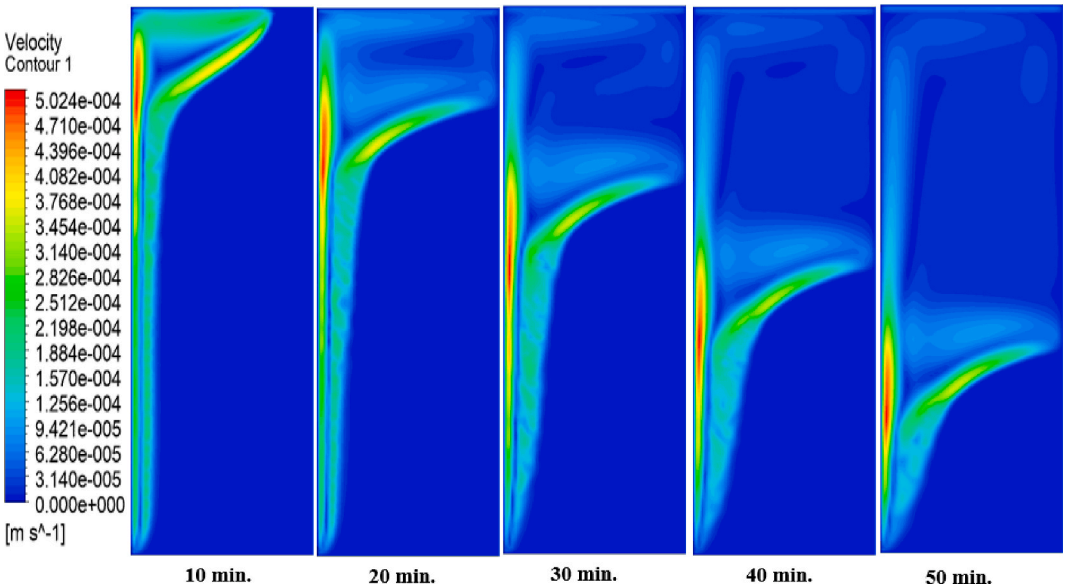

Fig. (5). Velocity distributions without fins.

Table 3
Convergence criterion equations.

No.	Residual equation	Absolute criteria
1	Continuity	1e-10
2	x-velocity	1e-10
3	y-velocity	1e-10
4	energy	1e-10

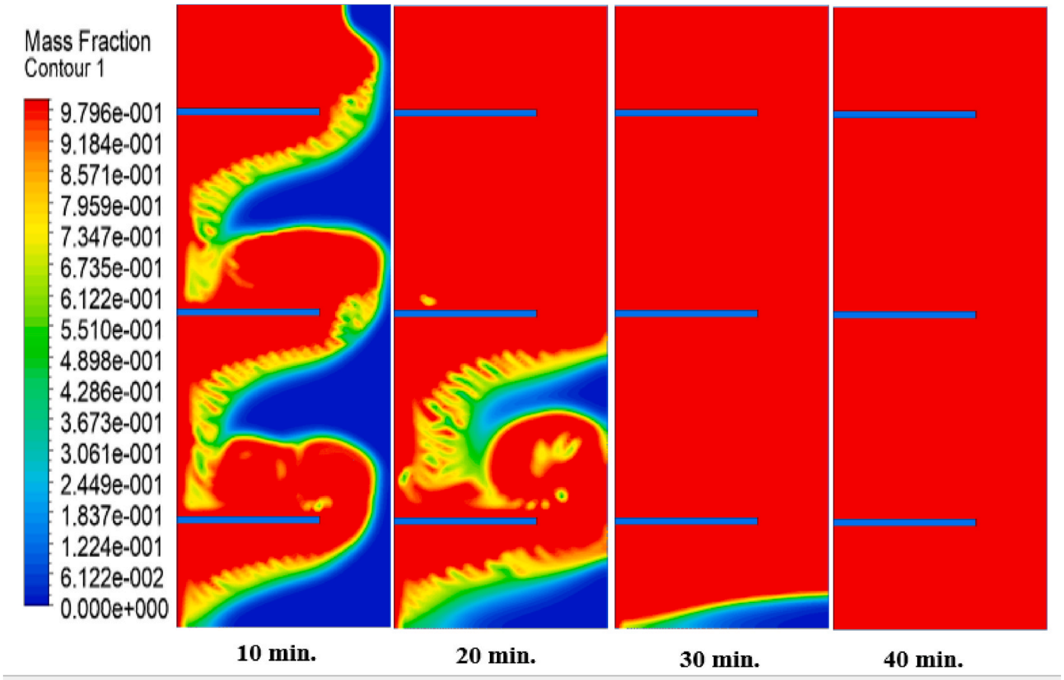

Fig. (6). Predicted evolution of the melting process with three fins.

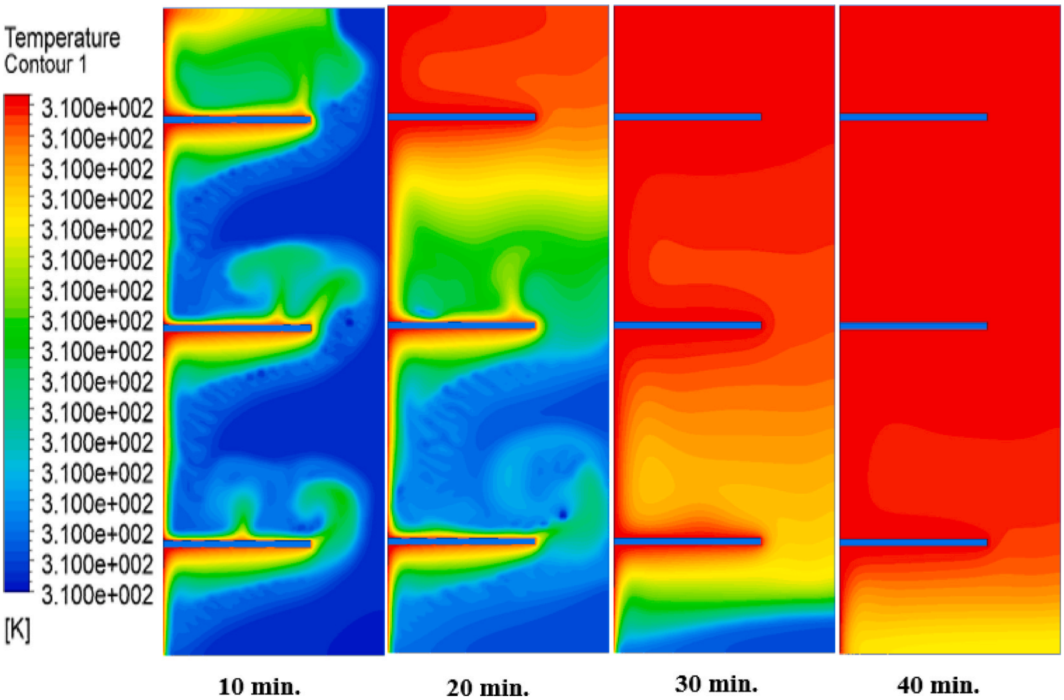

Fig. (7). Temperature distributions with three fins.

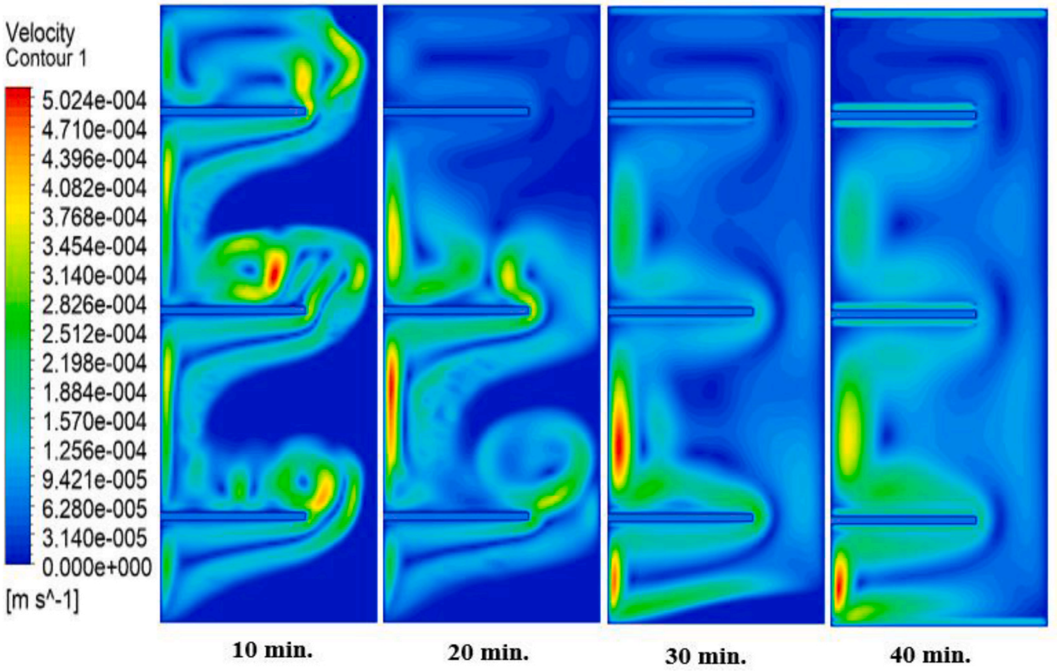

Fig. (8). Velocity distributions with three fins.

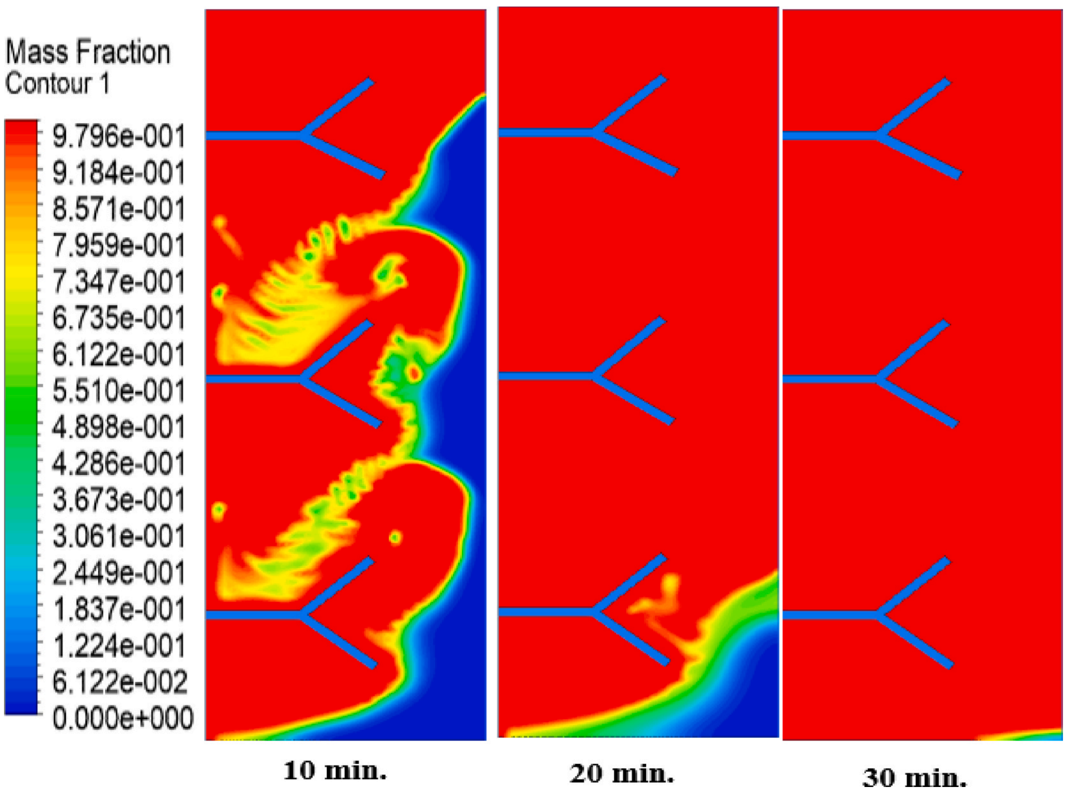

Fig. (9). Predicted evolution of the melting process with three v-shaped fins.

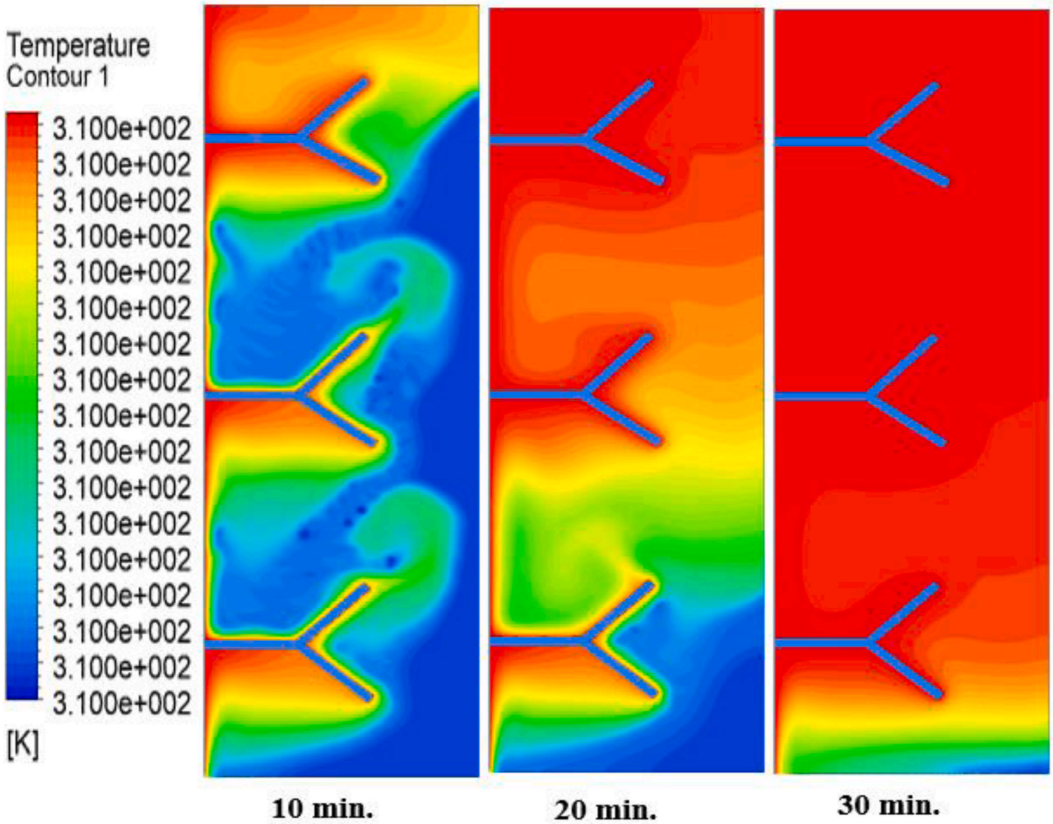

Fig. (10). Temperature distributions with three v-shaped fins.

The latent heat capability varies between zero (for a solid) and one (for a liquid), and the liquid fraction (β) can be expressed as [21, 22].

$$\beta = \begin{cases} 0 & solidus\ if\ \ T < \ Ts \\ 0 & solidus\ if\ \ T < \ Ts \end{cases}$$

$\frac{T-T_s}{T_l-T_s}$ if $T_s \leq T \leq \ T_l$.

The source term S in the momentum equation is a Darcy's law damping term, which is added to the momentum equation owing to the phase change effect on convection. The source term in the momentum equation is expressed as [23]:

$$S = \frac{C(1-\beta)^2}{\beta^3} V \tag{8}$$

where the coefficient (C) is the mushy zone constant that reflects the morphology of the melting region [24,25]. This fixed number is large, usually (10^4–$10^{7)}$. In the current study, (C) is assumed to be constant and set to (10^5).

2.3. Boundary conditions

The rectangular-shaped container contains a phase-changing material and is surrounded by a constant temperature from one direction, with the boundary condition specified in Table 1.

Paraffin wax (RT42) was used as a phase change material (see Table 2). The thermal properties of paraffin are listed in Table (2) [26,27].

2.4. Assumptions

When creating a mathematical formula to describe the melting processes inside a rectangular cell, the following assumptions are considered. The melting was modeled in two dimensions. The flow was unsteady, laminar, and incompressible. Further, the viscous dissipation term was negligible; the effects of the volume change associated with the solid-liquid phase change were neglected; and there was no heat gain or loss from the environment. The thermal properties of the PCM were assumed to be fixed in both solid and

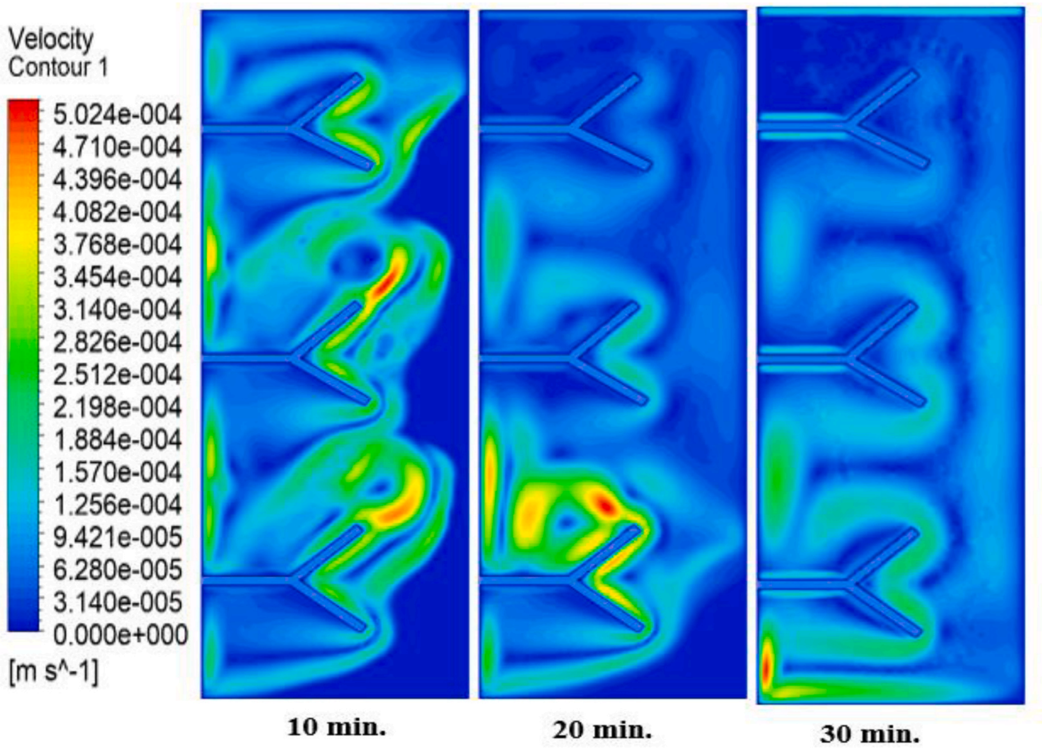

Fig. (11). Velocity distributions with three v-shaped fins.

liquid phases. Figure (2-a) presents the mesh distribution of the proposed model. figure (3-a) is a mesh shapes and distribution of rectangular container filled with phase-changing materials is studied without rode, while in figure (3-a), longitudinal rods mesh, and figure (3-a), rods of v shape [26,28,29].

2.5. *Stability analysis and convergence of the numerical solution*

To verify the simulation process, a validation table was created by adopting a numerical value for optimal results, totaling 11,041 cells as illustrated in Figure (3-a). The simulation of the dissolution of a phase-changed material using the Fluent equations showed that the solution converged and remained stable after 13,000 and 0.01 iterations and time step; respectively shown in figure (3-b). This means that the results of the simulation are accurate and reliable. The large number of iterations also shows that the simulation was thoroughly analyzed. This gives us confidence that the results of the simulation can be used to make informed decisions about the dissolution process.

The convergence criterion for the following simulation equations is given by the following Table (3)

3. Results and discussion

In this study, three cases were studied to clarify the effect of the presence of a v-fin inside the PCM. its effect on the melting process and heat transfer to the PCM, and thus, the effect on the time required to complete the melting process.

3.1. *Case one (without fins)*

In this study, we investigated a rectangular cell without fins. Notably, the melting process at the beginning of the heat transfer near the wall depends on the conduction load, as evident from the speed of the melting process owing to rapid heat transfer. Therefore, the melting process depended on natural convection, which reduced the rate of melting. Figure (3) shows that the melting process requires a long time to adopt most of the melting time, depending on natural convection. The melting process is the result of the acceleration and density of the liquid part of the phase change materials. Figure (4) shows the heat transfer through the wall and to the phase-changing materials. As evident, the heat transfer decreases as we move away from the wall. Figure (5) shows that the speed and movement of the melting process start from the wall and then move into the phase change materials.

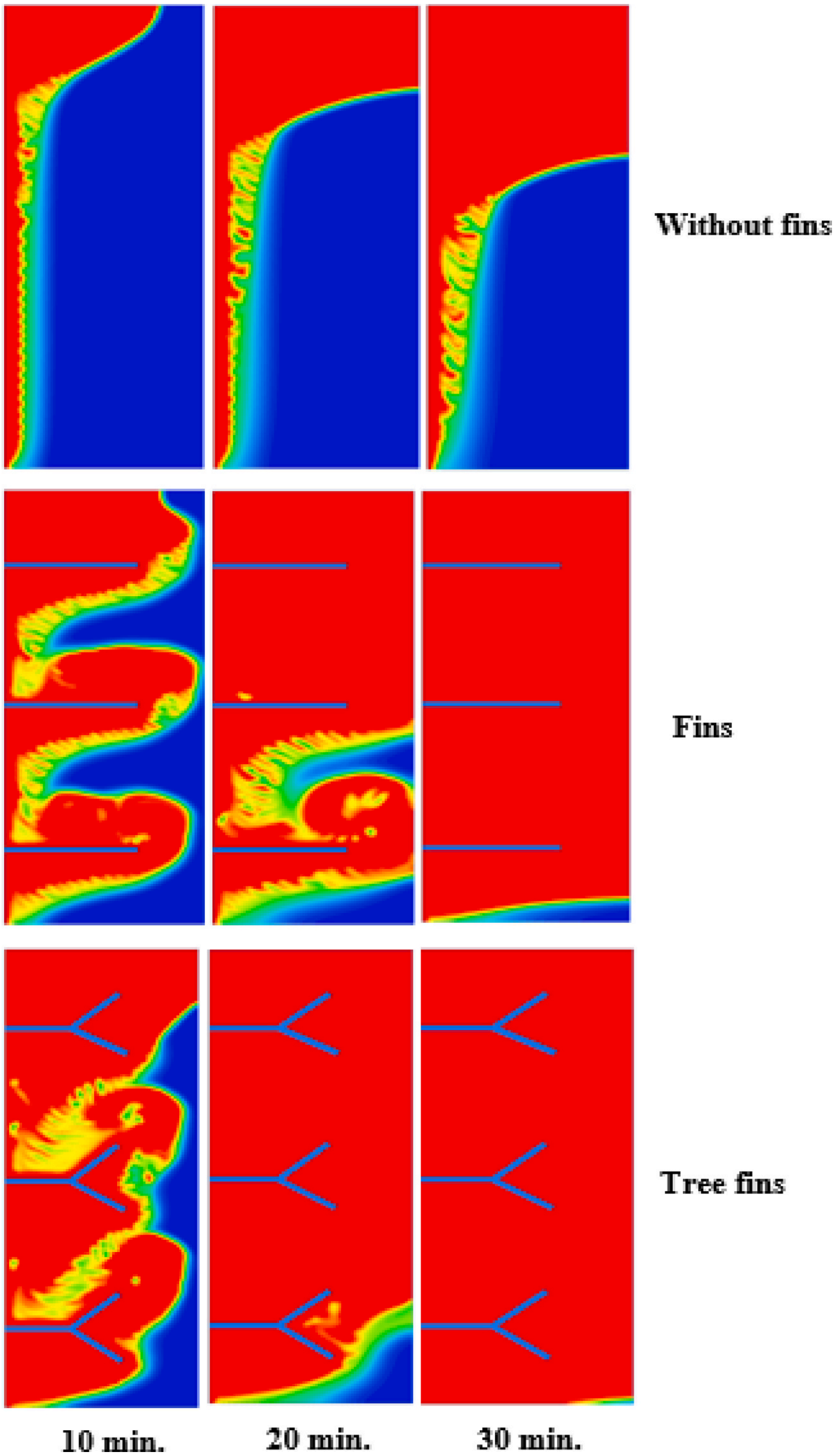

Fig. (12). Comparison of the melting process between all cases.

3.2. Case two (with three fins)

In this study, a rectangular cell with fins was used. The melting process at the beginning of the heat transfer near the wall depends on the conduction load, and the speed of the melting process owing to the speed of heat transfer was obtained. Thus, the melting process is dependent on natural convection, which reduced the rate of melting, and the presence of fins helps to accelerate the melting

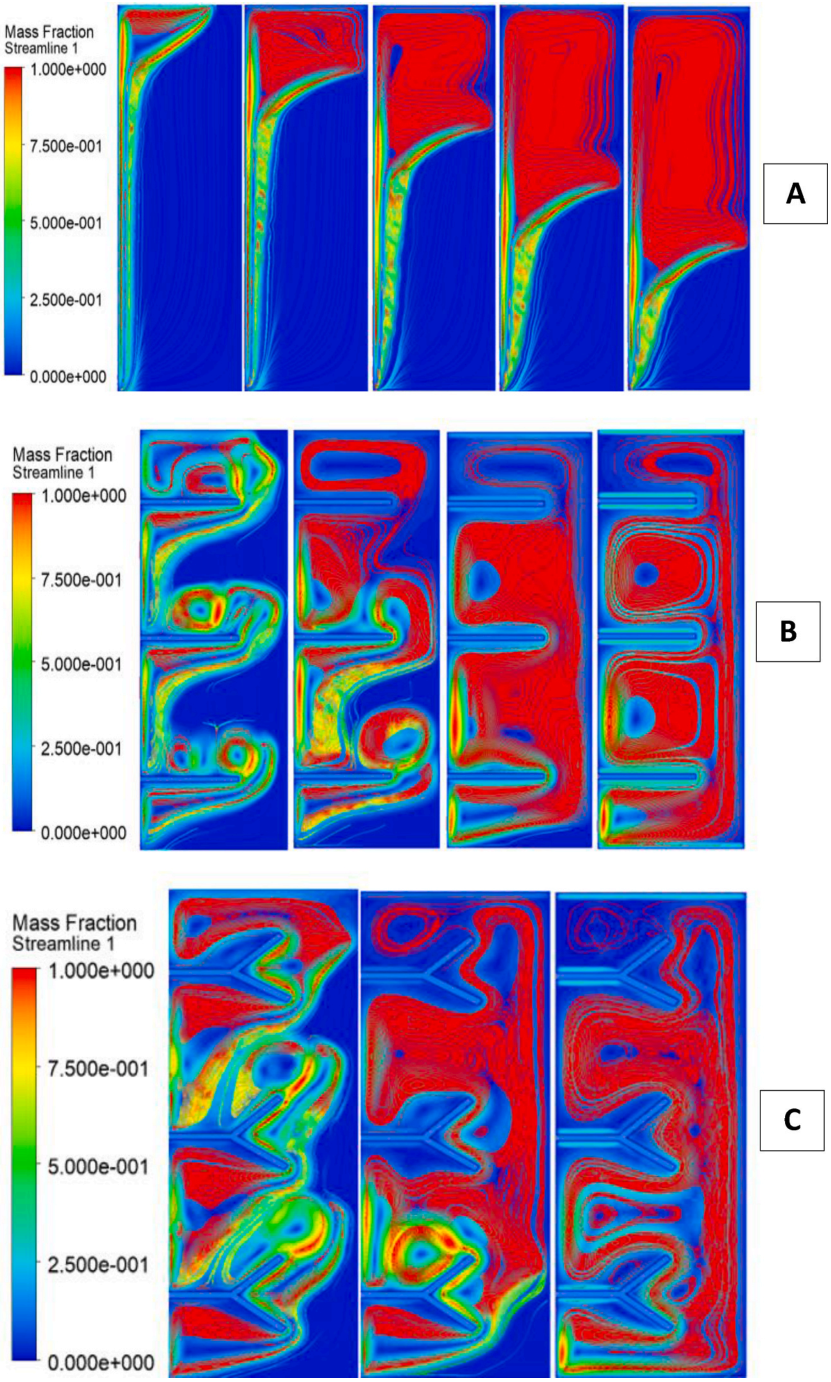

Fig. (13). Comparison of stream lines between all cases.

process. Figure (6) shows that the melting process requires less time because the fins are under natural convection. This melting process is owing to the effect of the acceleration and density of the liquid portion of the phase change materials. Figure (7) shows the heat transfer through the wall and to the phase-changing materials. As evident, the heat transfer slows down as we move away from the wall, and the presence of fins aids the heat transfer in a wider range. Figure (8) shows that the speed and movement of the melting process start from the wall and proceed to the phase change materials.

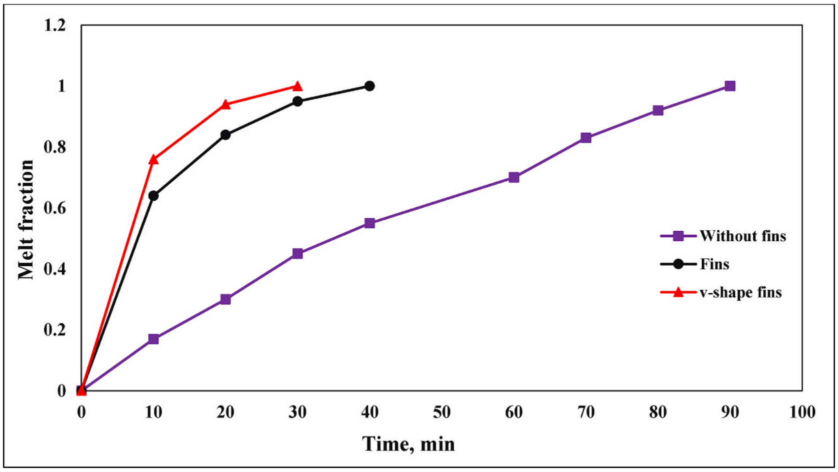

Fig. (14). Variation of melt fraction.

Table 4
Comparison with previous research.

Authors (Reference)	Type of enhancement of heat transfer	Melt fraction improvement	Temperature distributions improvement
A Basem et al. [23]	Copper rods	14.6 %	21.8 %
AF Khalaf et al. [30]	Air bubbles	31.69%	28.1%

3.3. Case three (with three v-shaped fins)

In this study, a rectangular cell with v-shaped fins was investigated. The melting process at the beginning of the heat transfer near the wall is dependent on the conduction load. Further, the speed of the melting process owing to the speed of heat transfer was obtained. Thus, the melting process is based on natural convection, which reduces the rate of the melting process, and the presence of v-shaped fins accelerates the melting process. Figure (9) shows that the melting process requires less time owing to the presence of v-shaped fins. Melting occurs in this manner owing to the effect of the acceleration and density of the liquid portion of the phase change materials. Figure (10) shows the transfer of heat through the wall to the phase-changing materials. As evident, the heat transfer decreases as we move away from the wall, and the presence of fins aids in transferring heat over wider ranges. Figure (11) shows that the speed and movement of the melting process start from the wall and proceed to the stage of changing the materials.

4. Compression of three cases

When comparing the cases studied, the melting process without fins required 90 min, that in the presence of longitudinal fins required 40 min, and that in the presence of v-shaped fins required 30 min. The significant difference in the time required to complete the process was owing to the presence of fins, which helped transfer heat to the phase change materials. Figure (12), shows that the melting process required less time in the presence of fins, particularly V-shaped fins.

Flow stream lines and the movement of the liquid material become evident in Fig. 13(A and B.C), where turbulence increases whenever there is an obstacle. This becomes apparent when using Fig. 13C. In the beginning of the dissolution process, the intensity of vortices resulting from phase changes becomes evident at the edges of the fins, given their significant role in the mixing operation.

Figure (14) indicates the importance of the presence of fins on heat transfer and the time required to complete the melting process.

5. Validation

A comparison of the findings of the present study and previous relevant research are present in table (4). Which shows the extent of the effect of the difference in shape with other shapes, and in other research it shows the effect of the shape of the content with the content used (see Table 4)

6. Conclusions

This study numerically investigated the enhancement of heat transmission to (PCM) in a triangular cell with and without fins. The enthalpy-porosity combination was quantitatively investigated using ANSYS/FLUENT 20 software. In this study, materials with the phase shifts of paraffin wax were used (RT42). From the results of this study, we found that the presence of fins significantly affected the melting process, reducing the time required to complete the melting process. The difference in the time required to complete the melting process with and without fins was 125%. Further, the presence of v-shaped fins reduced the time required to complete the melting process by 200%. Thus, the use of v-shaped fins facilitates faster heat transfer to and from the applications wherein phase change materials are used.

CRediT authorship contribution statement

Ali Basem: Conceptualization, Data curation, Project administration, Resources, Software, Writing – original draft, Writing – review & editing. **Ammar M. Al-Tajer:** Software, Validation. **Ihab Omar:** Conceptualization, Data curation, Formal analysis, Visualization, Writing – review & editing. **Hayder A. Dhahad:** Supervision. **Wissam H. Alawee:** Project administration, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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