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Enhancing latent heat storage systems: The impact of PCM volumetric ratios on energy storage rates with auxiliary fluid assistance

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A R T I C L E I N F O

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Melting
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Numerical study

A B S T R A C T

The present study investigates the effect of different volume ratios of PCM on the melting process and energy storage in the improved thermal energy storage (TES) system using auxiliary fluid. The purpose of using the auxiliary fluid is to benefit from the density difference between the auxiliary fluid and the PCM, which improves the convection heat transfer in the auxiliary fluid and increases the melting speed of the PCM. The auxiliary fluid, which has a higher density, is placed on the solid PCM at the beginning of the melting process and takes the place of the melted PCM during the melting process. This displacement causes better heat transfer between auxiliary fluid, PCM, and hot wall. Five different PCM/auxiliary fluid volume ratios are studied, including 30, 40, 50, 60, and 70% of PCM. The rate of energy storage in the system increases to 0.341 kW/kg, the highest rate of energy stored in the system and in PCM, corresponding to a volume ratio of 30% of PCM. Although the total energy stored in the system increases with an increase in the PCM volume ratio, the energy storage rate in the system increases with a decrease in the PCM volume ratio. Therefore, the optimal use of the most appropriate volume ratio of PCM is of great importance.

1. Introduction

Renewable energy sources such as solar, hydro, biomass, and geothermal energy, which are environmentally friendly, abundant, and nontoxic, can solve several environmental issues [1]. Despite the benefits, it is hampered by two intrinsic disadvantages. As a lean energy source, it consumes significant quantities of land to generate an appreciable amount of energy. In addition, it is intermittent by nature, so a storage system is required to ensure a continuous supply of energy to meet user demands during periods when the energy source is unavailable. Investing in thermal energy storage (TES) to preserve existing energy and maximize its use is essential since TES can alleviate the inconsistency between energy supply and demand [2].

Thermal energy can be stored in three forms: sensibly, latently, or chemically [3]. A latent heat energy storage system (LHESS) can store energy during melting at a constant temperature, so the energy storage density of phase change materials (PCMs) is significantly higher than materials storing sensible energy [4]. Especially in applications that are limited in space, this advantage is of great importance. It should be noted, however, that the LHESS has many downsides, including low thermal conductivity [5]. Thermal energy is stored in PCMs during phase changes from solid to liquid when temperature rises and discharged when temperature decreases during the solidification process. Even though PCMs have low thermal conductivity, their thermal characteristics allow them to be useful in energy storage applications, such as photovoltaic systems [6], buildings [7,8], electronic devices [9], and food industry [10].

LHESSs suffer from weak heat conduction, resulting in substantial energy storage and retrieval delays. Therefore, various enhancement

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Nomenclature

C_p	specific heat capacity, kJ/kg.K
g	gravity, m/s^2
h_{sf}	latent heat, kJ/kg
ΔH	latent heat in an instant, kJ/kg
k	thermal conductivity, W/m.K
N	number of materials
P	pressure, Pa
T	temperature,°C
t	time, s
u	velocity component in the horizontal direction, m/s
v	velocity component in the vertical direction, m/s

Greek Symbols

ε	void fraction
β	thermal expansion, 1/K
Γ	mass flux, $kg/m^2.s$
γ	liquid fraction
μ	dynamic viscosity, kg/m.s
ρ	density, kg/m^3

Subscripts

k	indicator of materials
l	liquid
m	melting
s	solid

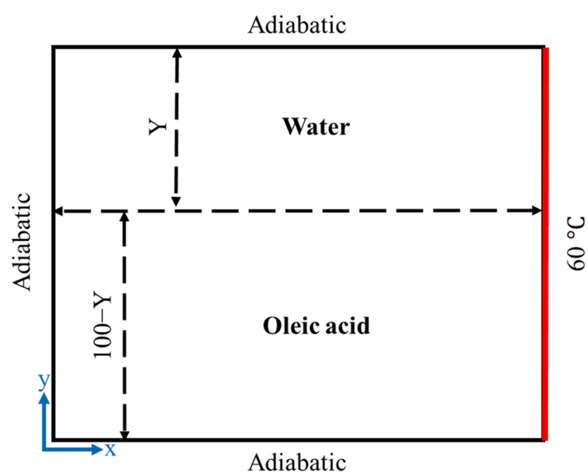

Fig. 1. The schematic of the designed TES system.

techniques, such as employing nanoparticles [11–13], fins [14,15], porous media [16,17], composite PCMs [18], and heat pipes [19,20], have been studied to overcome the low conductivity of PCMs. Motahar et al. [21] experimentally studied $MPSiO_2$ dispersed as nanoparticles in n-octadecane to manufacture a PCM-based composite. $MPSiO_2$ 3 wt.% enhanced thermal conductivity by 5% at 5°C, and 5 wt.% improved its thermal conductivity by 6% at 55°C. Additionally, PCM containing 5 wt.% $MPSiO_2$ nanoparticles exhibited a viscosity increase of up to 60% more than the liquid PCM without nanoparticles. Yao and Huang [22] suggested a developed triangular fin in a TES system. An optimized configuration of a triangular fin reduced the discharging time by approximately 31% compared to a rectangular fin. Sheikholeslami et al. [23] investigated a TES unit intending to decrease energy consumption in building applications. Porous media and nanoparticles are utilized to enhance heat transfer in PCM. Solidification duration was explored to evaluate the performance of the system, and results revealed that solidification completes 21.4% quicker by using porous foam than the pure system. Robak et al. [24] investigated an LHESS using heat pipes or fins in an experimental study. The usage of heat pipes raises PCM melting rates up to 60%. Fins, on the other hand, are not as practical for the operating conditions. In comparison to fin-assisted and simple arrangement, the heat pipe-assisted setup releases around twice the energy during the solidification process. Although these enhancement methods have shown good performance in TES systems, research to find less expensive methods is of great importance.

Khademi et al. [25] performed the first investigation on using an auxiliary fluid to improve the melting process of PCM. Auxiliary fluid and PCM should have different densities, which is the basis of this enhancement technique. Therefore, water as a low-cost auxiliary fluid was initially placed above oleic acid, chosen as PCM, due to its higher density to move downward during the melting and replace oleic acid. The displacement between water and molten oleic acid transfers the heat and energy faster than in a pure PCM system. In a recent study, Mehrjardi et al. [26] examined the auxiliary fluid enhancement method for a TES system exposed to a sinusoidal wall temperature with four different PCMs. Based on the heat storage rate analysis, the rate of absorbed energy in PCM increased up to 177%. In the previous literature, the favorable effect of using auxiliary fluid to improve the melting process of PCM was proven. Still, only the melting process in the 50% auxiliary fluid ratio has been studied, while the most effective volume ratio has not been investigated.

In this research, the method of melting and the energy stored in different volume ratios of PCM, and auxiliary fluid are investigated. This

Table 1
The thermophysical properties of water and oleic acid [28].

Materials	$C_p\left(\frac{kJ}{kg.K}\right)$	$k\left(\frac{W}{m.K}\right)$	$\mu\left(\frac{kg}{m.s}\right)$	$h_{sf}\left(\frac{kJ}{kg}\right)$	$\rho\left(\frac{kg}{m^3}\right)$	$T_m(^\circ C)$
Oleic acid	2.15	0.24	0.003	80.6	850	13-14
Water	4.182	0.6	0.001003	334	998.2	0

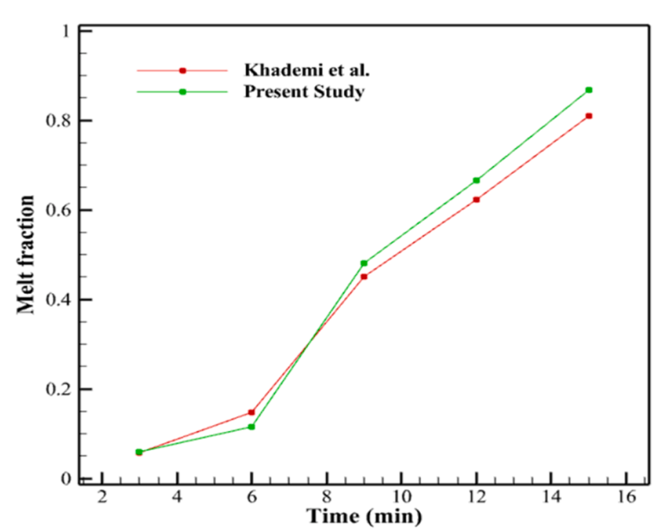

Fig. 2. An analysis of the numerical model developed in the present study and the results reported by Khademi et al. [27].

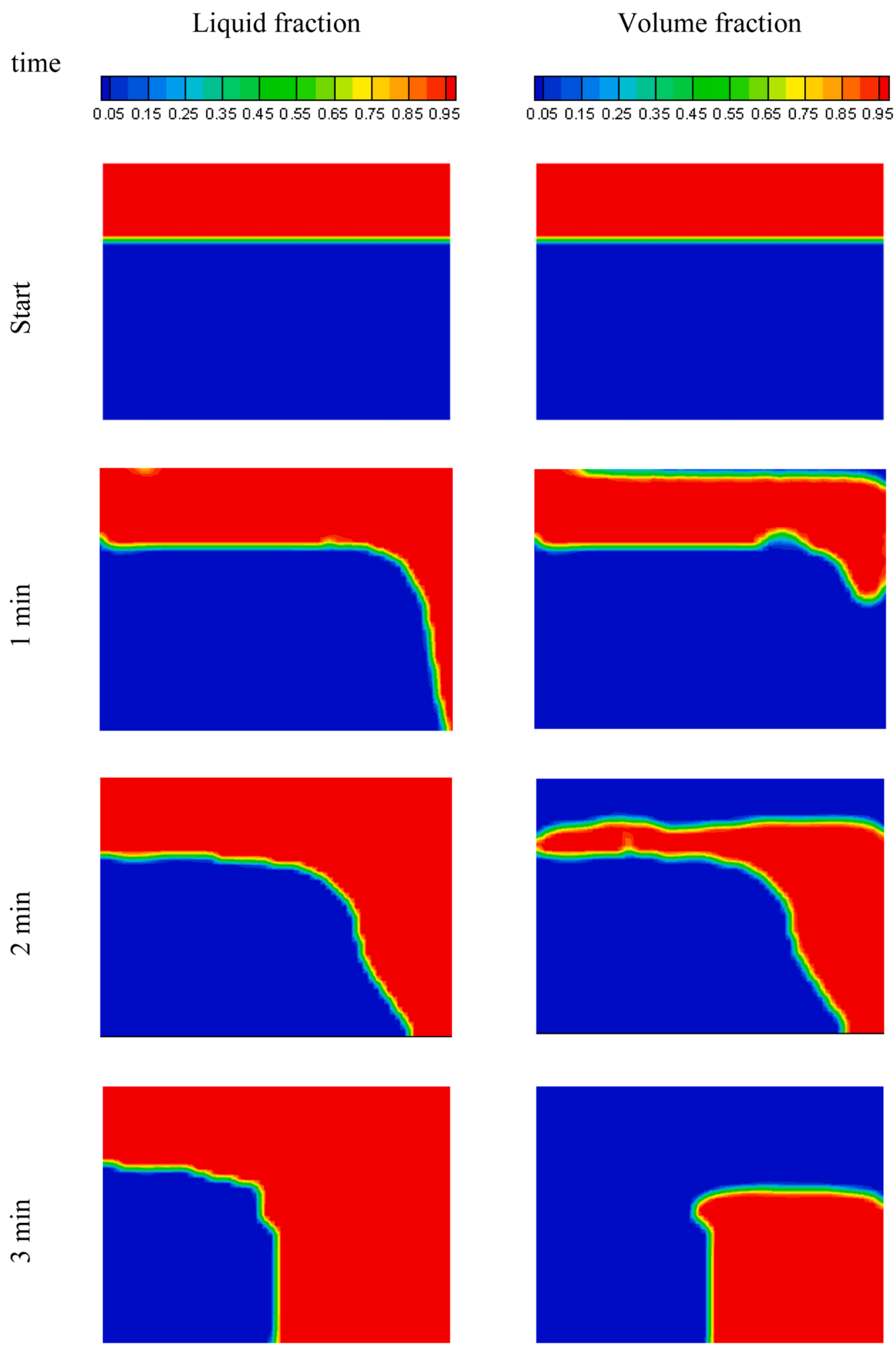

Fig. 3. The liquid and volume fraction of PCM for the volume fraction of 70% PCM at different times.

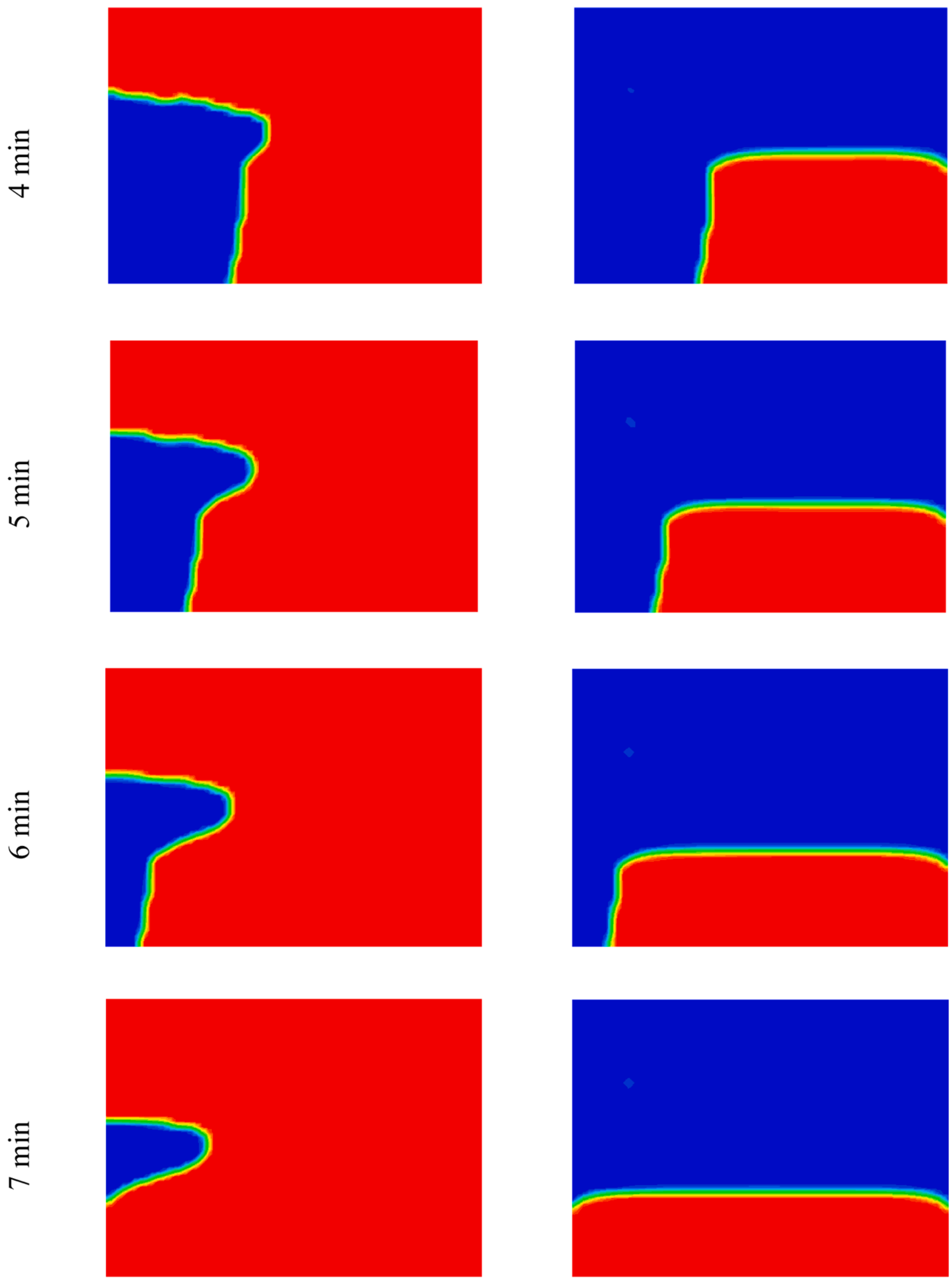

Fig. 3. (*continued*).

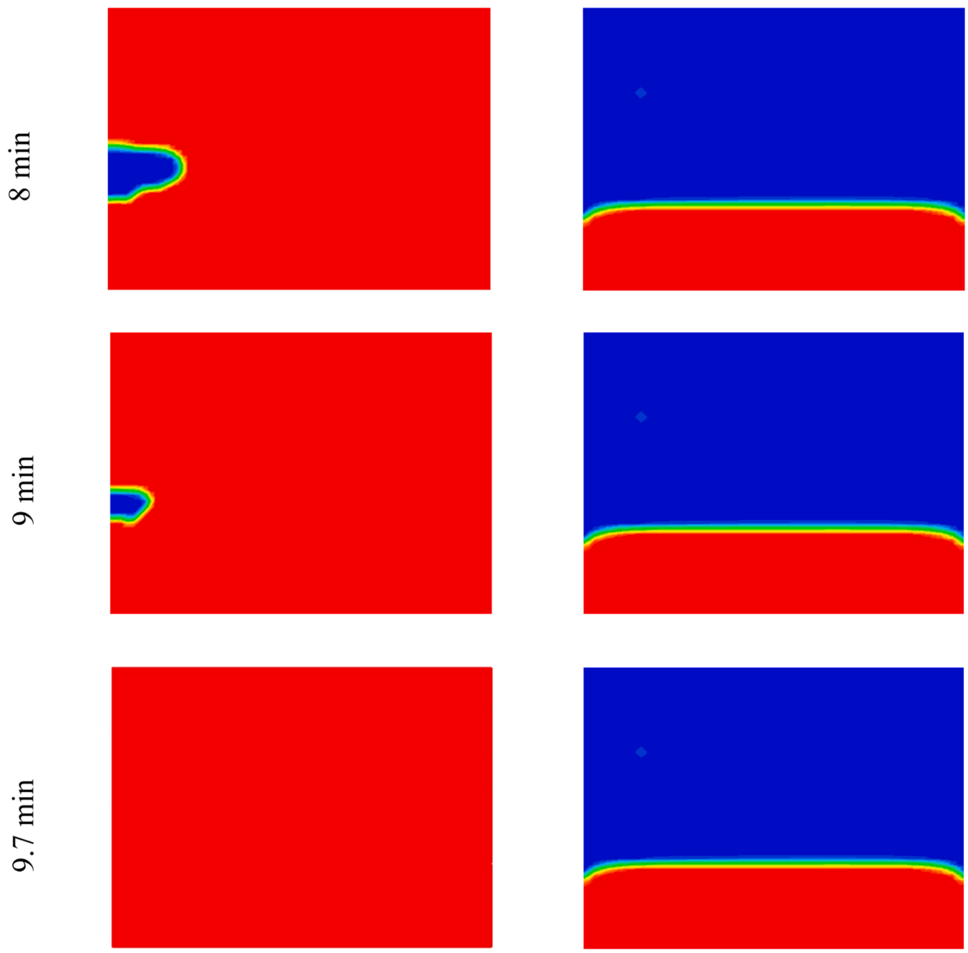

Fig. 3. (*continued*).

study is important from the aspect of the optimal use of PCM to achieve the highest heat transfer rate, which has not been discussed in past research. First, the melting process in volume ratios of 30, 40, 50, 60, and 70% of PCM is studied in detail, and then the energy stored in the system and PCM is analyzed.

2. Computational model description

2.1. Physical geometry

An enclosed rectangular container is schematically shown in Fig. 1, designed to simulate the melting process of PCM affected by auxiliary fluid presence. An enclosure wall is warmed isothermally at 60°C, while its other walls are adiabatic. A no-slip boundary condition is also imposed on the walls. The designed TES system consisting of Y% water and (100−Y)% oleic acid is examined, and Y is assigned various values, including 0, 30, 40, 50, 60, and 70.

Auxiliary fluid, like water, has many advantages since it is readily available and affordable. PCM must be insoluble in the chosen auxiliary fluid to ensure the designed TES system can be used in more cycles. In this regard, selecting a suitable PCM is one of the most crucial components of the TES system. The latent heat of fusion of oleic acid, an organic PCM insoluble in water, is high, while its thermal conductivity is low. Table 1 describes water and oleic acid thermophysical properties. To use wall adhesion in simulations, the contact angle between water and oleic acid at side walls is estimated at 30° [27].

2.2. Governing equations

A phase change model for PCM is developed using the enthalpy-porosity method [29]. This technique does not explicitly track the interface between liquid and solid. Using the liquid fraction (β) as a measure of the porousness of the liquid-solid mushy zone, a momentum sink term is included in the momentum equations to capture the pressure drop caused by solid PCM. Thermal buoyancy is modeled in the liquid's density variation by the Boussinesq approximation. This leads to the following equations governing PCM transient analysis during the melting process.

Transport equation [30]:

$$\frac{\partial(\varepsilon_n \rho_n)}{\partial t} + \nabla \cdot \left(\varepsilon_n \rho_n \cdot \vec{V}\right) = \Gamma_n \tag{1}$$

where ε_n is the ratio of each phase volume to the total enclosure volume. Also, it is required to satisfy the following condition in the transport equation,

$$\sum_{n=1}^{2} \Gamma_n = 0 \tag{2}$$

Momentum equation [31]:

$$\rho\left[\frac{\partial \vec{V}}{\partial t} + \left(\vec{V} \cdot \nabla\right)\vec{V}\right] = -\nabla P + \nabla \cdot \left(\mu \nabla \vec{V}\right) + \rho \vec{g} + S \tag{3}$$

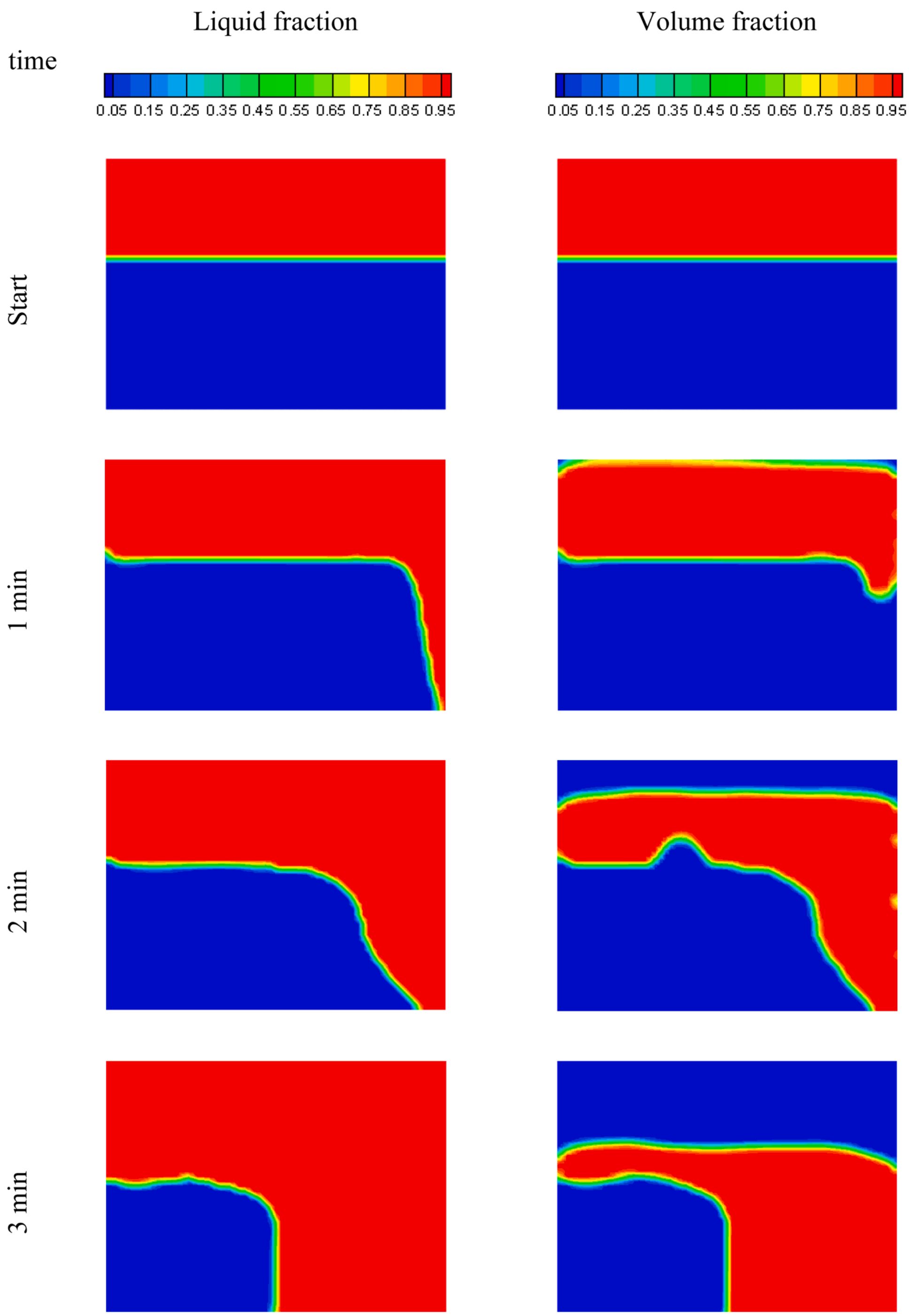

Fig. 4. The liquid and volume fraction of PCM for the volume fraction of 60% PCM at different time.

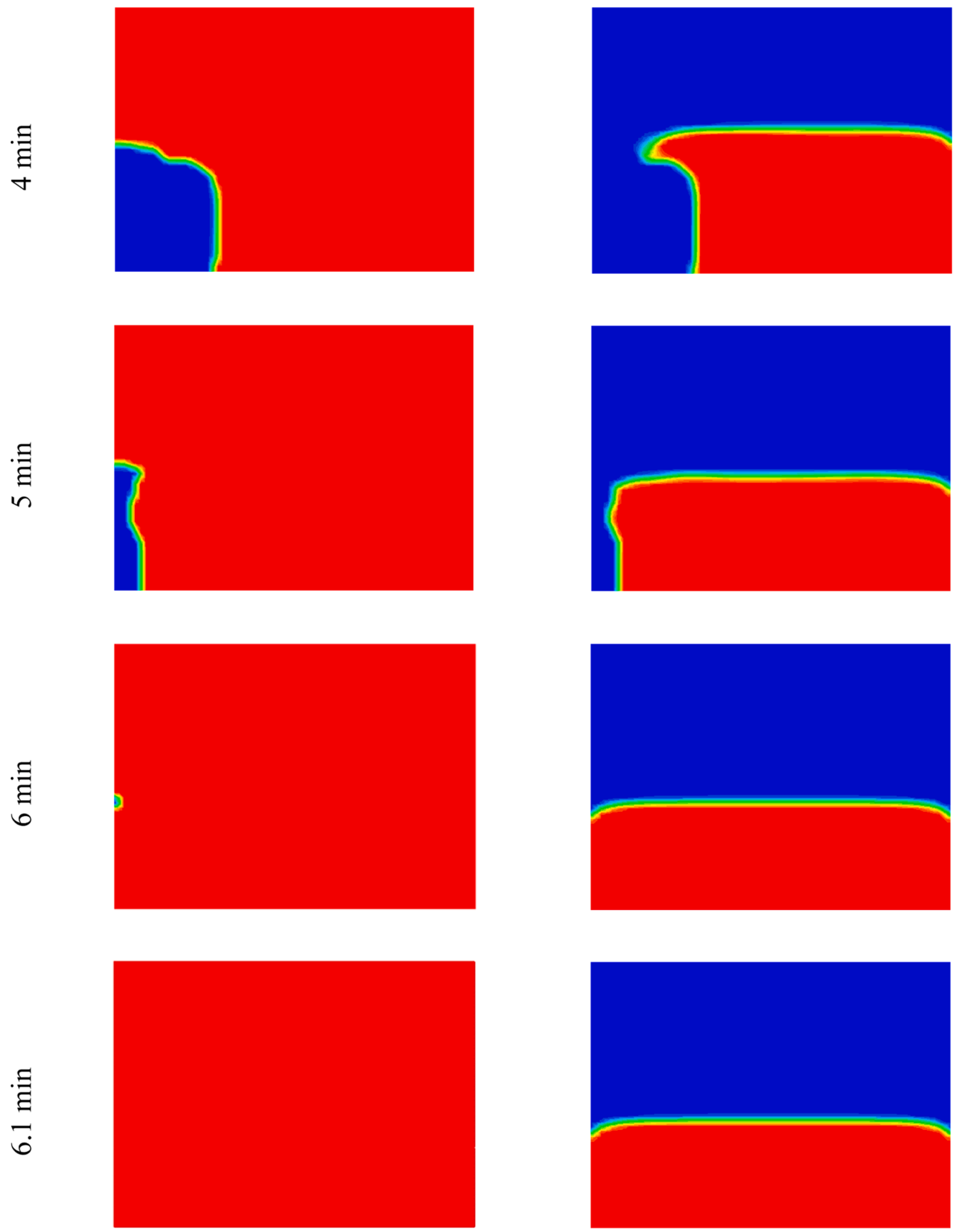

Fig. 4. (*continued*).

$$S = \frac{(1-\beta)^2}{\beta^3 + \varphi} A_{mush} \vec{V} \tag{4}$$

A_{mush}, equal to 10^6, is a mushy zone constant. As a slight number, φ is equal to 10^{-3} so as to avoid division by zero.

Energy equation [31]:

$$\frac{\partial(\rho H)}{\partial t} + \nabla\cdot\left(\rho \vec{V} H\right) = \nabla\cdot(k\nabla T) \tag{5}$$

$$H = h + \beta L \tag{6}$$

$$h = h_{ref} + \int_{T_{ref}}^{T} C_p dT \tag{7}$$

Liquid fraction (β) description is as follows [31],

$$\beta = \begin{cases} 0 & T \le T_{solidus} \\ \dfrac{T - T_{solidus}}{T_{liquidus} - T_{solidus}} & T_{solidus} < T < T_{liquidus} \\ 1 & T \ge T_{liquidus} \end{cases} \tag{8}$$

To account for momentum and heat exchange between two phases, specifically phase change material (PCM) and water, the Volume of Fluid (VOF) equations have been employed. These equations help in better understanding and quantification of the phenomena involved. For further details and clarification, you can refer to [32].

2.3. Simulation validation

The accuracy of the numerical simulation of the current research is validated by corresponding the results of Khademi et al. [27]. The

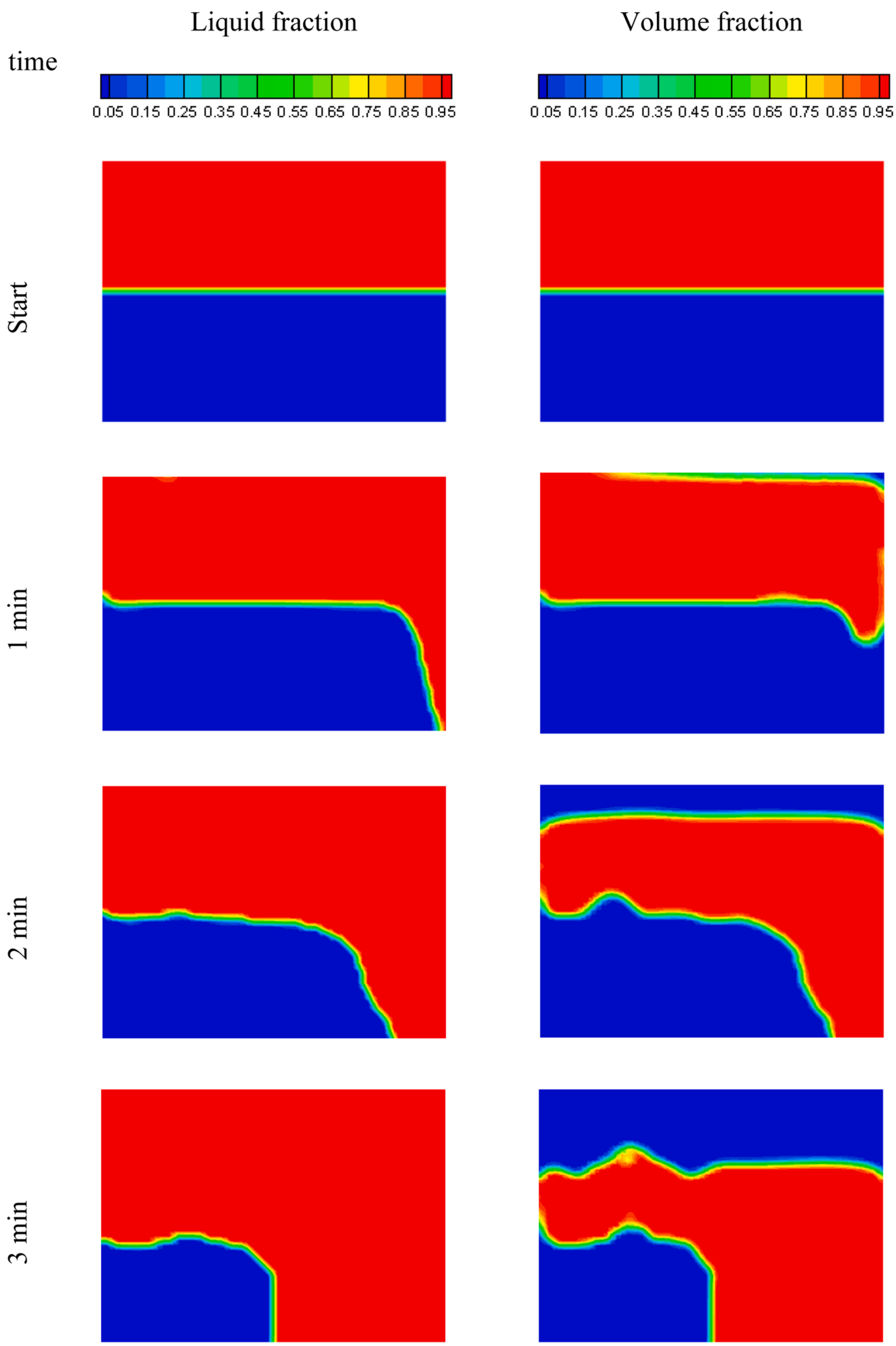

Fig. 5. The liquid and volume fraction of PCM for the volume fraction of 50% PCM at different time.

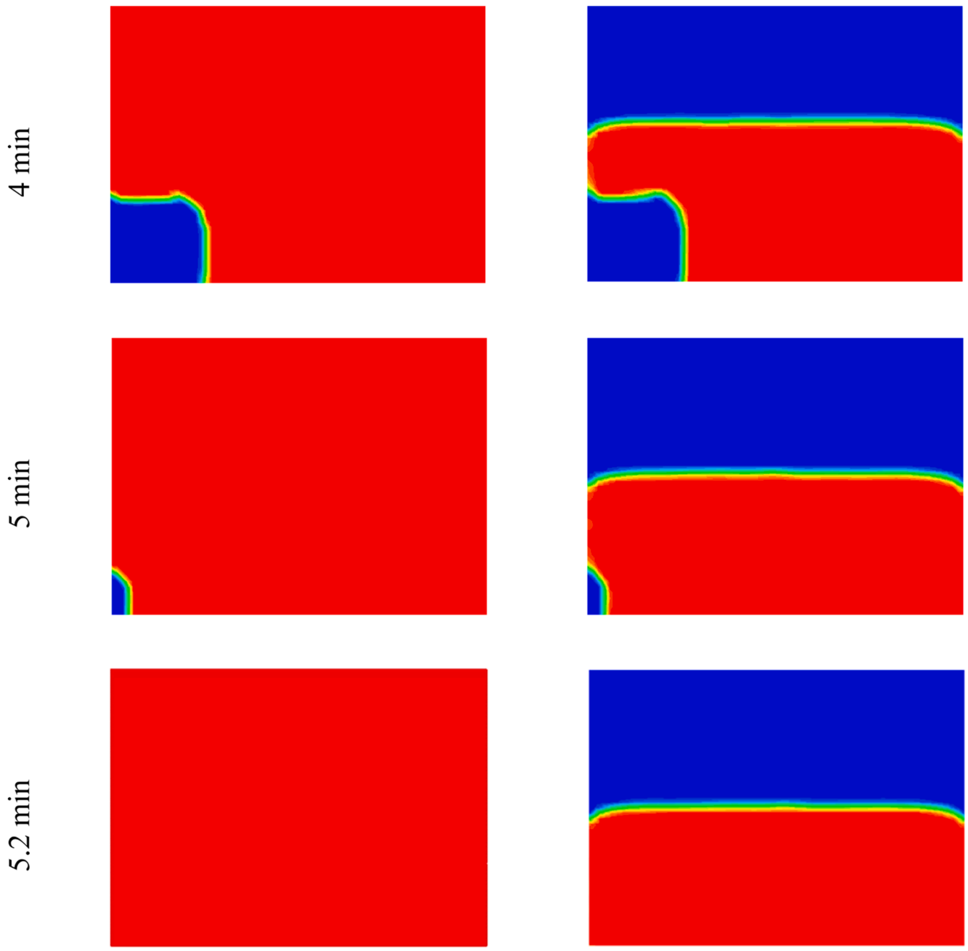

Fig. 5. (*continued*).

experimental results were achieved in a rectangular enclosure with a width of 66 mm and a height of 50 mm, similar to the enclosure size of the current research. Thermal insulation was applied to the other walls, while the right wall was kept at a constant temperature of 60°C. Both PCM and auxiliary fluid were initialized at -8°C and 15°C, respectively. As shown in Fig. 2, the 2D simulation results correspond reasonably well with the experimental results.

3. Results and discussion

Elective convection in PCMs dominates heat transfer after transitory conduction in a rectangular container. Heat is transferred primarily by conduction at this stage when a thin liquid PCM layer is formed. The thin liquid PCM layer makes the viscous effect more dominant than convection (buoyancy). Afterward, the thin layer expands upward in the fluid region, promoting natural convection. Therefore, water is used as an auxiliary fluid to improve the convection mode and increase the melting rate in oleic acid. Current research investigates the melting process of oleic acid with different volume ratios in the energy storage system using auxiliary fluid. First, the details of the melting process of varying volume ratios of oleic acid are discussed, and then the energy stored in the system is studied for each of these volume ratios.

Fig. 3 shows the melting process of oleic acid in the presence of water with a volume ratio of 30% at different times. Also, the melting process of oleic acid in the system with the combination of 70% oleic acid and 30% water lasted 9.7 minutes. At the start of the melting process, water with a volume percentage of 30%, which is in direct contact with the oleic acid and is on top of it, takes the place of the melted oleic acid near the hot wall. After all the water has replaced the molten oleic acid at the hot wall side, a significant portion of the heat is transferred through the water to the oleic acid. For this reason, from minute 3 onwards, the remaining oleic acid melts from the bottom. On the other hand, in this ratio, a volume of melted and solid oleic acid is in direct contact with each other for a certain time, which slows down the melting process due to the lower conductivity of oleic acid compared to water.

The melting process of oleic acid in the system containing 40% volume ratio of water is shown in Fig. 4. The melting time in this system (60% oleic acid and 40% water) is 6.1 minutes, which is about 3.3 minutes faster than the system with a combination of 70% oleic acid and 30% water, while only a 10% volume ratio of oleic acid has changed. In this volume percentage, the start of melting from the bottom occurs much later. Also, a smaller area of solid oleic acid is in contact with melted oleic acid, which is also a reason for accelerating the melting process.

The melting process of oleic acid shown in Fig. 5 takes 5.2 minutes at a volume ratio of 50%. The difference between the melting process in this volume ratio and systems with volume ratios greater than 50% of oleic acid is that melting does not happen from the bottom. Due to the volume ratio of water, at all times during the melting process, water completely surrounds the solid oleic acid. Therefore, the effect of the

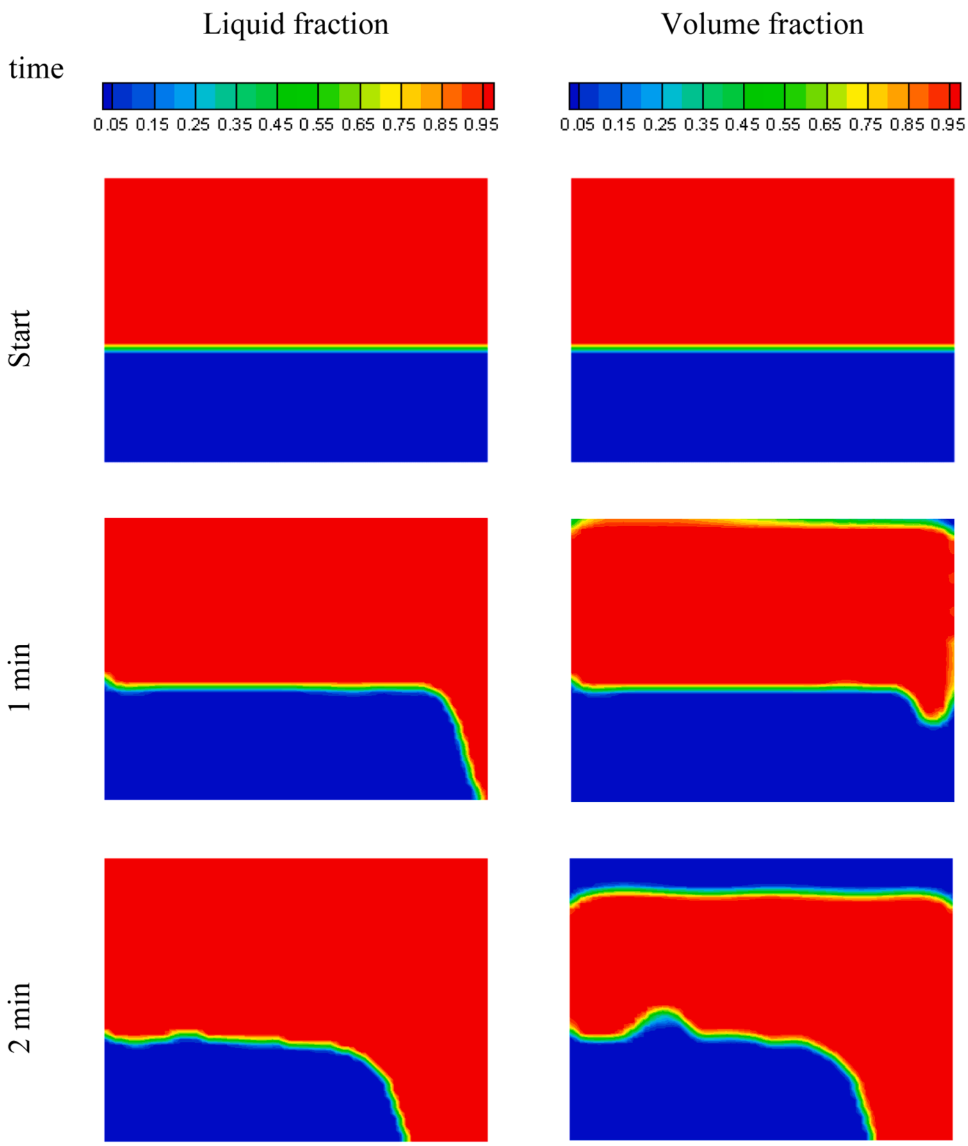

Fig. 6. The liquid and volume fraction of PCM for the volume fraction of 40% PCM at different times.

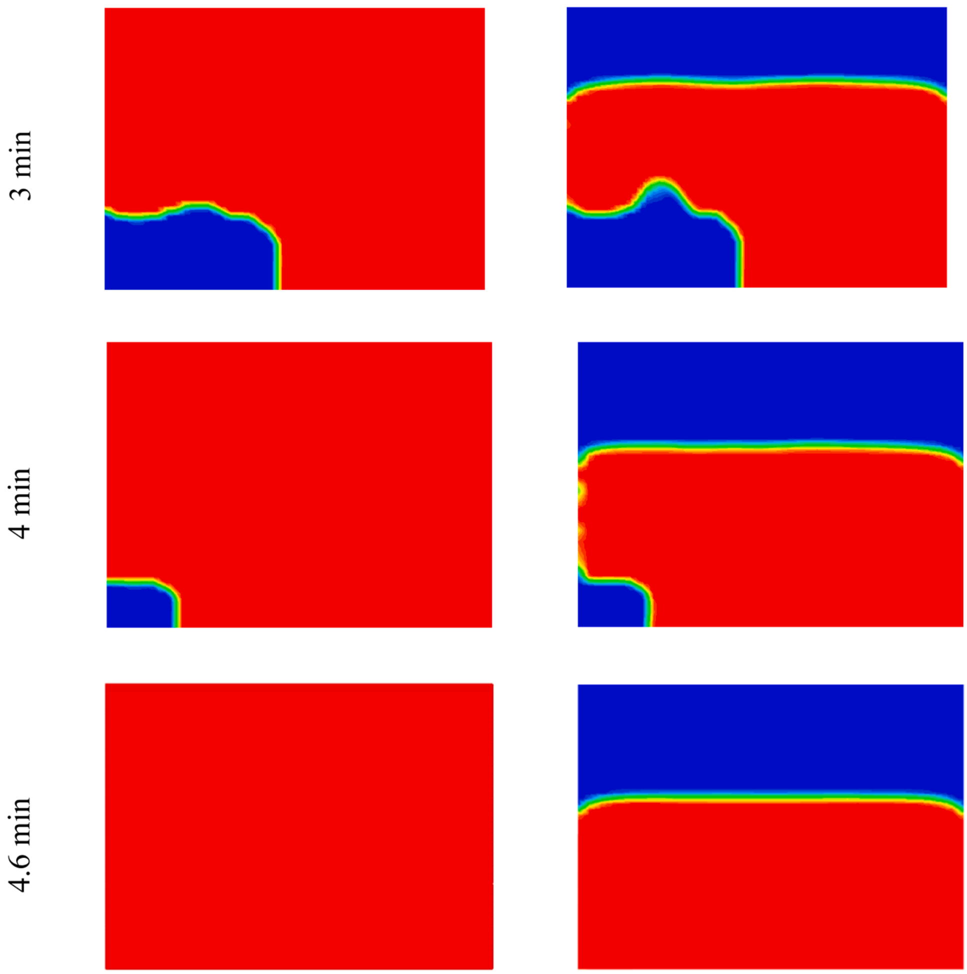

Fig. 6. (*continued*).

presence of auxiliary fluid on convection heat transfer is stronger in volume ratios less than 50% of oleic acid.

The melting process of oleic acid in the systems containing the volume ratios of 40% and 30% of oleic acid shown in Figs. 6 and 7, respectively, takes 4.6 and 3.7 minutes. The melting process in these two volume ratios is the same as the 50% volume ratio with the same trend. First, the oleic acid adjacent to the hot wall starts to melt. Then water, which has a higher density than the melted oleic acid, takes the place of the melted oleic acid due to the buoyancy force. The water then transfers heat from the hot wall to the solid oleic acid that is completely surrounded.

Fig. 8 shows the liquid fraction for PCM volume ratios, from which the duration of melting in each volume ratio can be seen. Volume ratios of 50, 60, and 70% PCM go through a similar melting process until minute 2, which is due to the dominance of conductive heat transfer over convective heat transfer. After minute 2, according to the volume of melted PCM, the system with a higher volume ratio of PCM takes longer to melt the remaining solid PCM in it. In systems with 30% and 40% PCM volume ratio, the melting process is almost the same until minute 2, and after that, the system with a 30% volume ratio of PCM, melts faster as convection heat transfer prevails. As can be seen, the duration of melting in each system is proportional to the volume ratio of PCM.

The energy stored in the system is latent and sensible, which is shown separately for each volume ratio in Figs. 9(a) and 9(b), respectively. Also, the total energy stored during the melting process, which is the summation of latent and sensible energy, can be seen in Fig. 9(c). The latent energy of melting is proportional to the amount of melted PCM. On the other hand, the sum of sensible energy in PCM and auxiliary fluid is important in sensible energy, which is almost equal for volume ratios of 30 to 50% of PCM. Nevertheless, in volume ratios of 60 and 70% of PCM, the amount of sensible energy increases significantly.

For a more detailed analysis of the energy stored in different volume ratios of PCM, the amount of energy storage rate in the system and PCM is summarized in Figs. 10 and 11, respectively. Unlike the stored energy, which is proportional to the volume ratio of PCM, the rate of stored energy is inverse, and in the volume ratio of 30% of PCM, the highest rate of stored energy is in the system and PCM. However, for other volume ratios (40, 50, and 60% of PCM), the rate of energy stored in the system has a different trend from the rate of energy stored in PCM. The rate of stored energy in the system for these volume ratios of PCM varies between 0.305 and 0.319 kW/kg, which is a very small difference, while the rate of energy stored for the volume ratio of 30 and 70% of PCM is equal to 0.341 and 0.246 kW/kg, respectively.

Therefore, the rate of stored energy in the system and PCM with a volume ratio of 30% of PCM, unlike the total stored energy, is the highest value compared to other volume ratios of PCM. In other words, using a system with a 30% volume ratio of PCM, more energy is stored in the system and PCM in a certain period. In energy storage systems, one

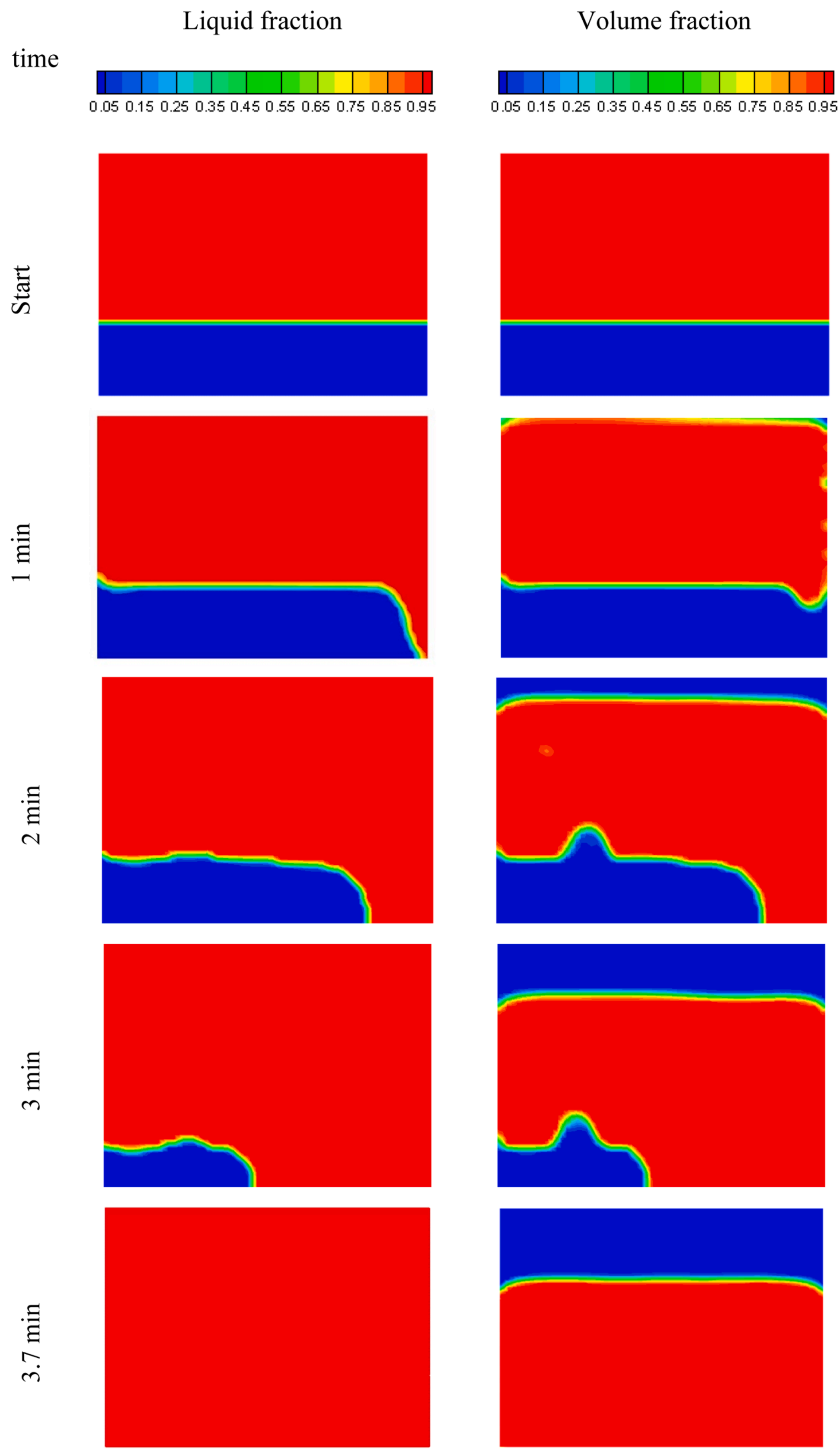

Fig. 7. The liquid and volume fraction of PCM for the volume fraction of 30% PCM at different times.

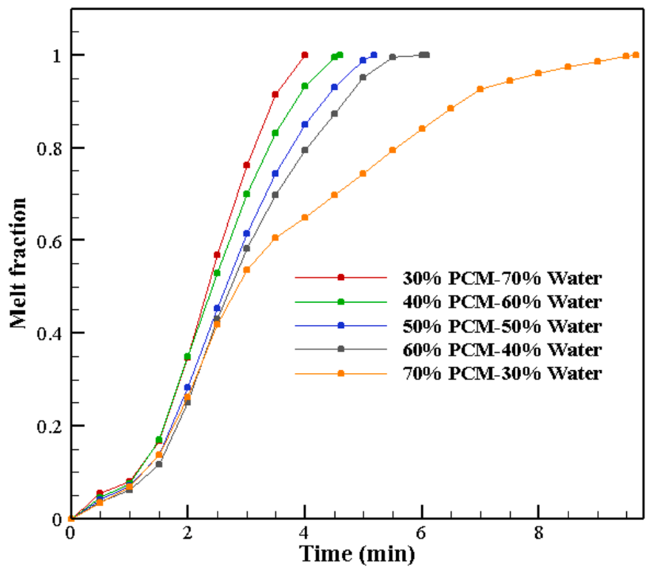

Fig. 8. The melting fraction of PCM with different water volume ratios.

cycle alone is not functional, and usually, the system is designed to operate in many cycles. Therefore, the stored energy rate in the 30% volume ratio of PCM is higher than for other volume ratios in a certain period. Then the system with this volume ratio can be used in many cycles.

4. Conclusions

The current research investigated the melting process and stored energy in a TES system with different PCM and auxiliary fluid volume ratios. Volume ratios of 30, 40, 50, 60, and 70% of PCM were studied, and then the energy storage rate in these volume ratios was compared. The following are the most important results of the research:

- Auxiliary fluid with a higher density than PCM takes its place during the melting of PCM, and the melted PCM goes to the top of the chamber. This displacement improves the convection heat transfer within the auxiliary fluid and accelerates the melting process.
- The duration of melting is reduced by decreasing the volume ratio of PCM. Also, the latent heat and the total energy stored in the system also decrease with the reduction of the volume ratio of PCM, while the stored sensible energy in volume ratios of 50, 40, and 30% is almost the same.
- The rate of energy stored in the system for a volume ratio of 30% PCM is 1.38 times the rate of energy stored in the system for a volume ratio of 70% PCM. Meanwhile, the energy rate stored in PCM with a volume ratio of 30% PCM is 1.87 times the energy rate stored in PCM with a volume ratio of 70% PCM. Also, the energy rate stored in the system for volume ratios of 40, 50 and 60% of PCM is almost the same and differs by less than 4%.
- PCM (oleic acid) and auxiliary fluid (water) are insoluble in each other, which makes this system a strong point since it can be solidified and rotated to return to the initial state after the melting process.

The further scope of the current study could contain examining the application of the improved TES system in practical applications, developing advanced numerical models and simulations to provide a deeper understanding of the complex heat transfer phenomena, and conducting experimental investigations to validate the findings of the study and verify the effectiveness of using the auxiliary fluid for

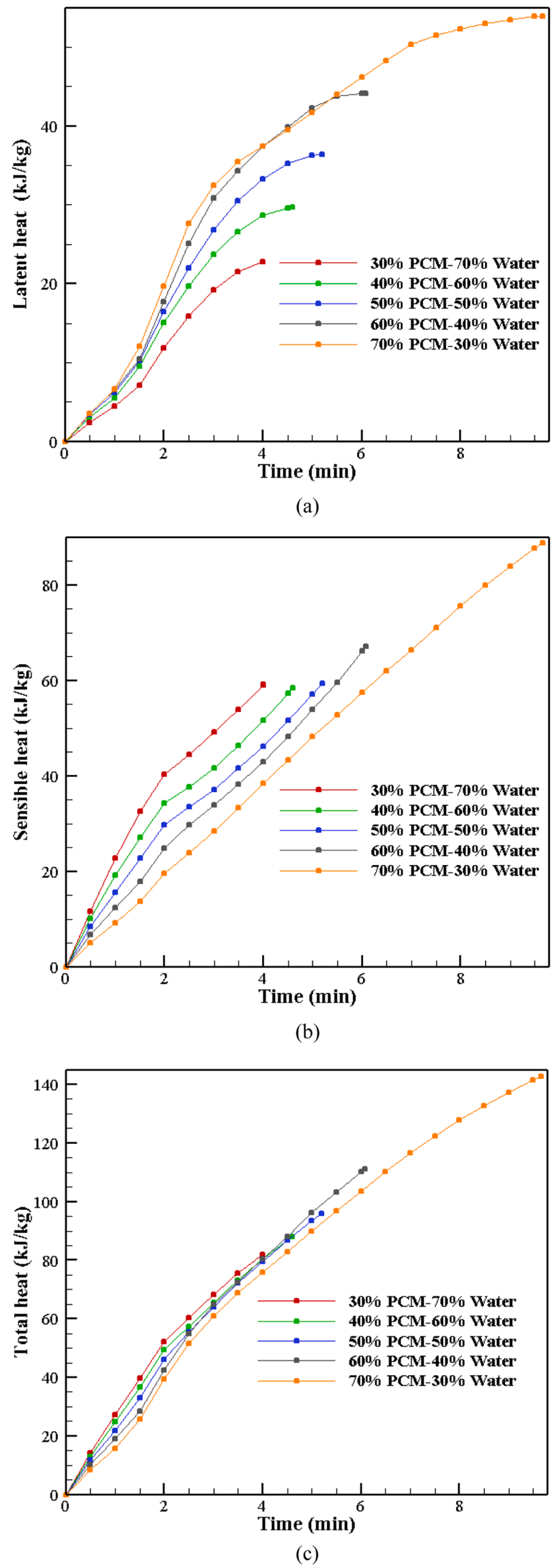

Fig. 9. (a) The latent heat, (b) sensible heat, and (c) total heat in the systems with different volume ratios of PCM.

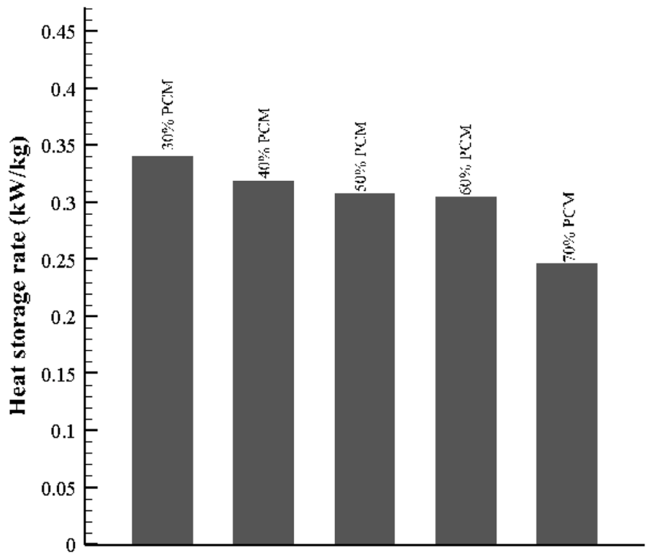

Fig. 10. The Heat storage rate of the system.

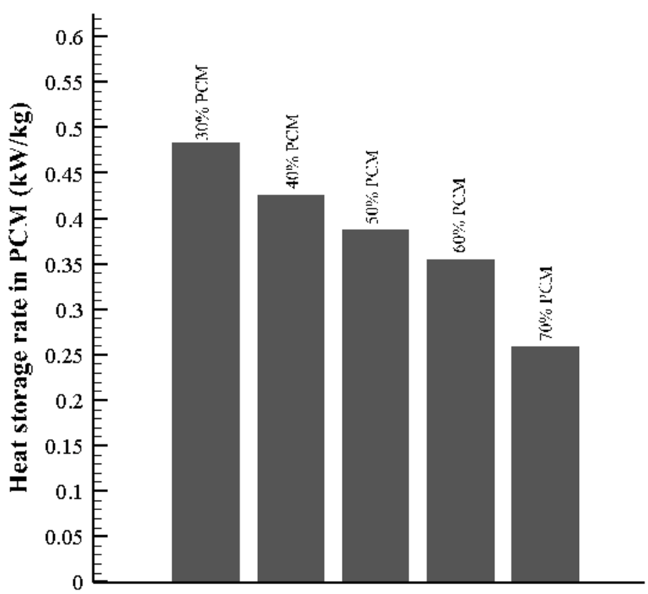

Fig. 11. The Heat storage rate of PCM.

enhanced convection heat transfer and increased melting speed of PCM. By pursuing these further areas of investigation, the present study can contribute to the development of improved thermal energy storage systems, facilitate their practical implementation, and address key challenges in energy storage and utilization.

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.

Data availability

No data was used for the research described in the article.

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