J. Appl. Comput. Mech., 9(2) (2023) 475-486
DOI: 10.22055/jacm.2022.41867.3829
ISSN: 2383-4536
jacm.scu.ac.ir

Shahid Chamran University of Ahvaz

Journal of Applied and Computational Mechanics

Research Paper

Heat Transfer Improvement in a Thermal Energy Storage System using Auxiliary Fluid Instead of Nano-PCM in an Inclined Enclosure: A Comparative Study

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Received September 12 2022; Revised October 23 2022; Accepted for publication October 23 2022.
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Abstract. Modern thermal energy storage (TES) systems rely laboriously on finding a low-cost method to improve heat transfer. In the present analysis, adding CuO nanoparticles and tilting the enclosure simultaneously is compared with a novel approach that employed water as a supplemental fluid to improve the melting process using the density difference between PCM and supplemental fluid. Oleic acid is selected as an immiscible PCM in water, which causes PCM and auxiliary fluid utterly separate at the end of the melting process to be usable in more additional TES cycles. By placing water as a heavier material directly on top of oleic acid, the melted oleic acid is replaced by water at the bottom of the enclosure when it melts because water has a heavier density than oleic acid. At first, adding 1% and 2% of CuO nanoparticles in an enclosure with different inclinations of 0°, 45°, and 90° is studied to identify the energy storage rate. Continuity, momentum, and energy equations are used to formulate a mathematical model of the TES system. In the next step, the melting process of the combined system is analyzed to determine the energy storage rate of the combined system compared to the system, including CuO nanoparticles in the inclined enclosure. Comparing the combined system with the optimal case of nano-PCM in the inclined enclosure, it was found that the energy storage rate in the system using auxiliary fluid is 1.396 times higher.

Keywords: Energy storage rate, Phase change materials (PCMs), Melting process, Supplemental fluid.

1. Introduction

The growing demand for energy, the limited supply of fossil fuels, and the emission of greenhouse gases make renewable energy sources more vital than ever. However, a critical limitation of some renewable sources, including solar power, is their restricted accessibility, and the energy demand consistently exceeds the supply. It is possible to mitigate the contradiction between society's needs and supply for a short or long period by storing thermal energy in phase change materials (PCMs), which have the exceptional capacity to store heat within a limited phase change temperature. PCMs are widely used in a variety of thermal energy storage (TES) applications, including building energy saving [1], photovoltaic thermal systems [2], food industries [3], batteries thermal management [4], and electronic cooling [5].

Even though PCMs enjoy numerous advantages, such as low prices, high TES density, and chemical structure endurance, almost all PCMs are not appropriate thermally conductive [6], which confine PCMs usage in TES devices. Accordingly, different amplification strategies, such as operating nanoparticles [7], fins [8], metal foams [9], and heat pipes [10], have been explored to overcome the inadequate conductivity of PCMs.

A possible method to enhance heat transfer is to employ nanoparticles within PCMs [11]. The dispersal of nanoparticle additives inside PCM can enrich its thermal conductivity. Chaichan and Kazem [12] dispersed Al_2O_3 nanoparticles in paraffin wax as a PCM to increment the thermal conductivity compared with pure PCM. The thermophysical characteristics of PCM, such as its density, thermal conductivity, and viscosity, tended to increase by adding nanoparticles while the specific heat capacity decreased. The results showed that adding Al_2O_3 to paraffin wax improved heat transfer up to 50.15%. Li et al. [13] filled window sections with a PCM to ameliorate the thermal efficiency; however, the low conductivity of PCM negatively influences thermal performance.

Published online: November 03 2022

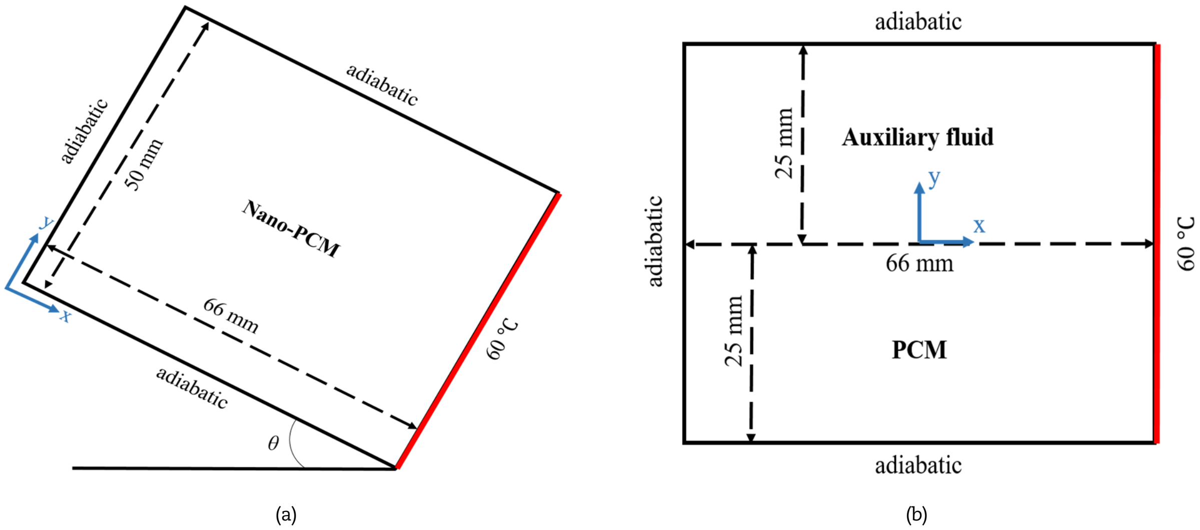

Fig. 1. The schematic of (a) nano-PCM with various enclosure inclinations and (b) auxiliary fluid and PCM composite in the TES system.

On the other hand, dispersing 1% volume fraction of CuO nanoparticles in PCM enhances the performance of windows. Jesumathy et al. [14] experimentally examined the effect of CuO nanoparticles with concentrations of 2, 5, and 10% on heat transfer in a heat exchanger. There is an increase of up to 1.3 in the thermal conductivity ratio of nano-PCM combinations. Additionally, the heat transfer coefficient increased by 78% during solidification. Mahdi and Nsofor [15] numerically modeled the effects of dispersing Al_2O_3 nanoparticles on the solidification process of a PCM in a triplex-tube TES system. Based on the study's outcomes, dispersing Al_2O_3 nanoparticles with volume fractions between 3% and 8% results in time savings up to 20%. It also indicates that nanoparticles have little impact in the initial phases of solidification, but it becomes more rapid by passing time or increasing the nanoparticles' volume fraction.

Furthermore, PCM melting was previously studied in which natural convection caused by enclosure inclination angle had a remarkable effect on the melting process. Bouzennada et al. [16] proposed the effect of adding a fin with various enclosure inclinations on the melting performance of a PCM. The results demonstrated accelerating the melting and energy storage rate by inclining the enclosure. Avci and Yazici [17] experimented to determine whether inclination angle affects heat source performance. Thermal proficiency is significantly influenced by inclination angles between 15° and 75°. Also, the melting time is changed more than 5.5 times when the inclination is adjusted. Kamkari and Groulx [18] experimentally examined fins' effect on PCM melting time under various inclination angles in a rectangular enclosure. PCM melts more quickly when the inclination angle changes in the enclosure with or without fins. Adjusting the inclination angle can increase the melting rate more effectively than adding fins.

Nevertheless, finding low-priced and accessible methods to enhance heat transfer is one of the important priorities in TES. Heat transfer rate is enhanced by positioning a supplemental fluid on top of PCM because of the buoyancy effect and density difference. In addition, auxiliary fluids improve the PCM melting rate by transporting heat through convection to regions far from heat sources. It is essential to overcome some constraints associated with auxiliary fluid usage, including that auxiliary fluid solidification temperature must be lower than PCM temperature to control auxiliary fluid solidification.

Favakeh et al. [19] initially attempted to improve the performance of a TES system by using two immiscible PCMs with different arrangements. Using one PCM with higher latent heat might be more practical than two PCMs. This way, an insoluble auxiliary fluid can replace a second PCM in a double PCMs system to improve the TES efficiency. The auxiliary fluid enhancement technique is based on a density difference between the auxiliary fluid and PCM. An auxiliary fluid with a higher density than PCM is initially placed above the chosen PCM in TES systems. Molten PCM moves upward during the melting process because of its lower density, and auxiliary fluid replaces it. To prove the improvement intensity of using auxiliary fluid compared with a simple PCM system, Mehrjardi et al. [20] studied the effects of spatial sinusoidal temperature on the melting process of various PCMs. However, no studies have examined the advantage of using auxiliary fluid in improving PCM melting compared to other enhancement methods. Additionally, investigating an enclosure exposed to a warm wall with a constant temperature is preferred over studying an enclosure with spatial sinusoidal temperature.

During the melting process of the PCM, since an auxiliary fluid with a heavier density is used on the PCM and in direct contact with it, displacement occurs between the two materials, which accelerates the convection heat transfer. Therefore, the melting rate is reduced, affecting energy storage. Thus, in the present research, the TES performance of a technique using an auxiliary fluid to enhance the melting process of a PCM based on the density difference between materials is evaluated, showing its advantages in comparison with a system containing nano-PCM in an inclined enclosure. It is shown that adding nanoparticles up to 2% by optimizing the enclosure inclination increases the energy storage rate less than the TES system with a composition of 50% auxiliary fluid and 50% PCM.

2. Physical Model

A rectangular enclosure containing nano-PCM in various inclinations and a developed TES system employing auxiliary fluid to enhance the melting of PCM are schematically exhibited in Fig. 1. The design criteria for the TES assembly and its component dimensions are defined based on Favakeh et al. [19, 21]. The right side wall is warmed at a constant temperature of 60 °C, while the others are well isolated. CuO nanoparticles are selected to enhance PCM conductivity and its thermal characteristics. Oleic acid and water, which are immiscible, are chosen as PCM and auxiliary fluid, respectively. First, a simple system that includes PCM with 0%, 1%, and 2% nanoparticles in the enclosure shown in Fig. 1a with 0°, 45°, and 90° inclinations is investigated. Meanwhile, a TES system, which is in direct contact, and includes the composition of 50% water and 50% oleic acid, is analyzed to evaluate its energy storage capability. Figure 1b illustrates how auxiliary fluid is positioned over PCM in the enclosure to capitalize on the displacement caused by density differences.

Table 1. The thermophysical properties of selected materials and nanoparticles.

Materials	$C_p\,(J/kg.K)$	$k\,(W/m.K)$	$\mu\,(kg/m.s)$	$L\,(kJ/kg)$	$\rho\,(kg/m^3)$	$T_m\,(^{\circ}C)$	References
oleic acid	2150	0.24	0.003	80.6	850	13-14	[23]
water	4182	0.6	0.001003	---	998.2	---	[24]
CuO	540	18	---	---	6510	---	[25]

The advantage of using water as an auxiliary fluid is that it is readily available and reasonably priced. Also, the designed TES system can run for more cycles if PCM is insoluble in the auxiliary fluid. Therefore, PCMs are a vital component of the invented TES system, so selecting the right one is crucial. Despite being insoluble in water, oleic acid has an inferior thermal conductivity and homological melting with high latent heat. The thermophysical properties of materials and CuO nanoparticles are depicted in Table 1. According to Khademi et al. [22], the water-oleic acid contact angle at side walls is calculated to be 30° for use in simulations with wall adhesion.

3. Mathematical Formulation

The molten PCM and water behave according to Newtonian principles and are assumed to as incompressible laminar flow. The volumetric changes are also modeled using Boussinesq approximations. It is important to note that thermophysical properties remain constant during the melting process, regardless of whether the system is solid or liquid. Additionally, the enthalpy-porosity relationship is used to model melting in the enclosure [26]. Based on the assumptions raised above, the melting equations can be written as follows:

Continuity [27]:

$$\frac{\partial(\alpha_k\rho_k)}{\partial t}+\frac{\partial(\alpha_k\rho_k u_k)}{\partial x}+\frac{\partial(\alpha_k\rho_k v_k)}{\partial y}=\Gamma_k \tag{1}$$

where,

$$\alpha_k=\frac{V_k}{V_{total}} \tag{2}$$

$$\sum_{k=1}^{2}\Gamma_k=0 \tag{3}$$

in the above equations, k is used as the phase indicator.

x-momentum [28]:

$$\frac{\partial(\rho u)}{\partial t}+\frac{\partial(\rho uu)}{\partial x}+\frac{\partial(\rho uv)}{\partial y}=-\frac{\partial P}{\partial x}+\frac{\partial}{\partial x}\left(\mu\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu\frac{\partial u}{\partial y}\right)+S_x u+\rho g\beta\cos\theta(T-T_m) \tag{4}$$

y-momentum [28]:

$$\frac{\partial(\rho v)}{\partial t}+\frac{\partial(\rho uv)}{\partial x}+\frac{\partial(\rho vv)}{\partial y}=-\frac{\partial P}{\partial y}+\frac{\partial}{\partial x}\left(\mu\frac{\partial v}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu\frac{\partial v}{\partial y}\right)+S_y v+\rho g\beta\sin\theta(T-T_m) \tag{5}$$

Energy [28]:

$$\frac{\partial(\rho C_p T)}{\partial t}+\frac{\partial(\rho u C_p T)}{\partial x}+\frac{\partial(\rho v C_p T)}{\partial y}=\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)-S_E \tag{6}$$

where,

$$S_E=\frac{\partial(\rho\Delta H)}{\partial t}+\frac{\partial(\rho u\Delta H)}{\partial x}+\frac{\partial(\rho v\Delta H)}{\partial y} \tag{7}$$

in which ΔH represents the instantaneous change in latent heat.

$$\Delta H=fL \tag{8}$$

The porosity function in the momentum equations is as follows [29]:

$$S_x=S_y=-C\frac{(1-f)^2}{f^3+\varepsilon} \tag{9}$$

The momentums and energy equations are solved simultaneously for oleic acid and water. In the meantime, for water, S_x, S_y, and S_T are not considered and are equal to zero.

Also, the definition of the liquid fraction is described [29]:

$$f=\begin{cases}0 & T\le T_{solidus}\\ \dfrac{T-T_{solidus}}{T_{liquidus}-T_{solidus}} & T_{solidus}<T<T_{liquidus}\\ 1 & T\ge T_{liquidus}\end{cases} \tag{10}$$

To estimate nano-PCM thermophysical properties such as density, specific heat, latent heat, thermal expansion, and dynamic viscosity, the following formulas are used [30]:

$$\rho_{nPCM} = \varphi_n \rho_n + (1-\varphi_n)\rho_{PCM} \tag{11}$$

$$\left(\rho C_p\right)_{nPCM} = \varphi_n \left(\rho C_p\right)_n + (1-\varphi_n)\left(\rho C_p\right)_{PCM} \tag{12}$$

$$(\rho L)_{nPCM} = (1-\varphi_n)(\rho L)_{PCM} \tag{13}$$

$$(\rho\beta)_{nPCM} = \varphi_n (\rho\beta)_n + (1-\varphi_n)(\rho\beta)_{PCM} \tag{14}$$

$$\mu_{nPCM} = 0.9197\mu_{PCM}\exp(22.8539\varphi_n) \tag{15}$$

To estimate the thermal conductivity of nano-PCM, a correlation incorporating the Brownian motion effect is used [30]:

$$k_{nPCM} = \frac{k_n + 2k_{PCM} - 2(k_{PCM}-k_n)\varphi_n}{k_n + 2k_{PCM} + (k_{PCM}-k_n)\varphi_n} k_{PCM} + fb\gamma\varphi_n\rho_{PCM}C_{p,PCM}\sqrt{\frac{\delta T}{\rho_n d_n}} f(T,\varphi_n) \tag{16}$$

$$\gamma = 9.881(100\varphi_n)^{-0.9446} \tag{17}$$

$$f(T,\varphi_n) = \left(28.217\times10^{-3}\varphi_n + 3.917\times10^{-3}\right)\frac{T}{298.15} - \left(30.669\times10^{-3}\varphi_n + 3.91123\times10^{-3}\right) \tag{18}$$

where b with the value of 5×10^4 is the Brownian motion constant, δ symbolizes the Boltzmann constant (1.381×10^{-23} J/K), and d_n is the CuO nanoparticles diameter (29×10^{-9} m). This is an assurance that Brownian motion in the solid phase does not influence the thermal conductivity factor for Brownian motion is defined in the thermal conductivity factor.

A finite volume method is used to discretize momentum equations using a second-order upwind scheme, while a first-order upwind scheme is used to discretize energy equations. In addition, momentum and continuity equations are coupled using the PISO algorithm. Iteratively solving the conservation equations, checking for convergence of velocity, pressure, and temperature fields in accordance with the convergence criterion of 10^{-6}, 10^{-6}, and 10^{-8} is carried out for each iteration.

3.1 Numerical validation

The 2D numerical model formulated in the current study is validated using the simulation results reported by Dhaidan et al. [31] for the melting fraction of n-octadecane paraffin possessing CuO nanoparticles. In the simulations, the geometry is a cubic chamber with dimensions of 25.4 mm, with the left wall having an electrical heater attached and the other walls having thermal insulations. Following the completion of the validation study for the above experimental work, it has been observed that the numerical results of the present study are reasonably in agreement with the experimental values.

Also, a new validation examination is accomplished to strengthen the credibility of the numerical model by using the results of an empirical study in an inclined enclosure. Sathe and Dhoble [32] investigated the study in a rectangular enclosure (5cm×10cm×10cm) with a warmed side wall, while the other sides of the enclosure were manufactured with insulated glass. Lauric acid with specific properties was used as PCM in the experiments. Inclinations of 30°, 60°, and 90° were tested to compare the heat transfer changes in the system, and the inclination of 60° was chosen for the comparison of the numerical model of the current research. Comparing the results showed that the error of the simulated model is less than 6%.

It is also possible to verify the validity of the numerical model by comparing its predictions for the liquid fraction with those of Khademi et al. [22] at some specific period of time. Similar to the current study, the experiment was conducted within a rectangular enclosure measuring 66 mm in width and 50 mm in height. A constant temperature of 60 °C was maintained along the right wall, while other walls were thermally insulated. An initial temperature of -8 °C was used for the PCM and 15 °C for the auxiliary fluid. It is evident from Table 2 that the results of the 2D simulation are reasonably accurate when compared to those of the experiment.

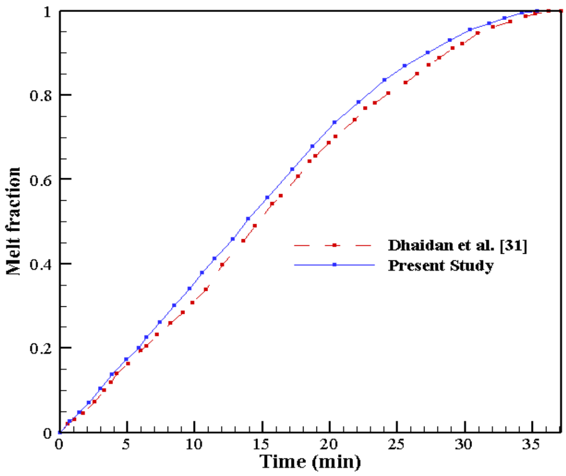

Fig. 2. Comparing the numerical model developed in the current study with the results of Dhaidan et al. [31].

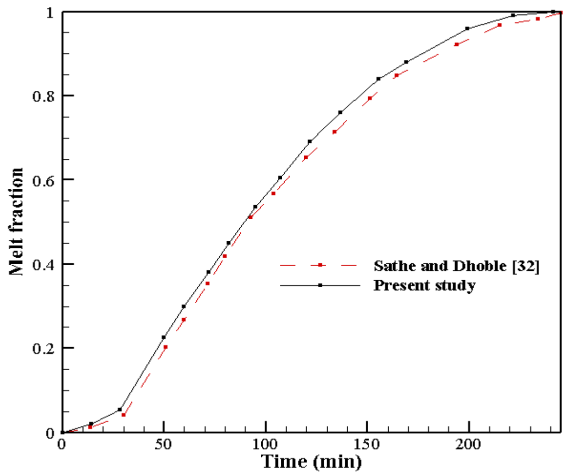

Fig. 3. Comparing the numerical model developed in the current study with the results of Sathe and Dhoble [32].

Table 2. Experimental results of Khademi et al. [22] in conjunction with melting fraction data of the numerical simulation generated in this study.

Time (min)	3	6	9	12	15
Present study	0.06	0.16	0.48	0.67	0.87
Khademi et al. [22]	0.06	0.15	0.45	0.62	0.81
Deviation (%)	0	6.25	6.25	7.46	6.89

4. Independence Analysis

4.1 Grid size

The effect of grid size compression on melting fraction is evaluated by using four different grid sizes, which include 25×20, 50×40, 66×50, and 75×60. The beginning temperature of the water and oleic acid are 10 °C, and the right side wall is constant at 60 °C. As shown in Fig. 4, melting fractions are calculated during melting for a variety of grid sizes. Therefore, the grid size of 66×50 is selected for further calculations based on the melting fractions of all four grid sizes due to the small changes when the grid sizes are compressed. This grid density is also suitable for the pure PCM and nanoparticles PCM system because of the fewer complexities than the hybrid system.

4.2 Time step

As shown in Fig. 5, three different time steps were used to analyze time step independence. For time steps of 0.01 and 0.005 seconds, melting fraction averages differ by less than 5%.

5. Results and Discussion

In the current research, the melting of oleic acid is investigated using different methods of increasing heat transfer. First, the melting of pure oleic acid in a rectangular enclosure is examined for better understanding. Then, the improvement of melting and energy storage in oleic acid is analyzed using common enhancement methods, including adding nanoparticles and enclosing the enclosure. Finally, the melting of oleic acid is examined using a denser auxiliary fluid, and the effect of its presence on the melting and energy storage of oleic acid is compared with other enhancement methods.

5.1 Pure PCM melting process

Figure 6 shows the melting process of oleic acid and the temperature distribution inside the enclosure in three different melt fractions, and its melting process is a good representation of the buoyancy force effect. Volumetric forces and density gradients coexist to produce buoyancy within each fluid. The melting process of pure oleic acid takes 1447 seconds, and different enhancement methods can be used to reduce the melting time. Also, stored energy in oleic acid is 170.76 kJ/kg during the melting process.

In the melting process of a 100% PCM system, compared to a combined system (50% water and 50% oleic acid), convection acts weaker due to less buoyancy and slower heat diffusion, which causes the melting process to be longer compared to other investigated systems. Figures 7a and 8a for pure PCM prove this issue and show that the melting process rate has decreased incrementally over time due to the dominance of advection over convection.

5.2 Nano-PCM in the inclined enclosure

This section examines the effect of adding nanoparticles to oleic acid along with tilting the enclosure. CuO nanoparticles with weight percentages of 1% and 2% are added to oleic acid at 0°, 45°, and 90° inclination angles. The effect of adding nanoparticles on melting at each inclination is compared in Fig. 7. The melting time of oleic acid decreases with the addition of nanoparticles by up to 2% in all three inclination angles, which shows the positive effect of adding nanoparticles. At the inclination angles of 0°, 45°, and 90°, the melting time decreases by 33.76%, 30.63%, and 32.77%, respectively. Also, the effect of inclination changing in different weight proportions of CuO nanoparticles is investigated, as shown in Fig. 8. The melting time reduces using pure oleic acid (0% CuO), 1% CuO, and 2% CuO by 39.43%, 37.27%, and 36.57%, respectively. As a result, the simultaneous use of nanoparticles and tilting enclosure reduces the melting time of oleic acid from 1447 seconds to 608 seconds. The best performance of the system is at the inclination angle of 45° and the weight percentage of 2% CuO nanoparticles.

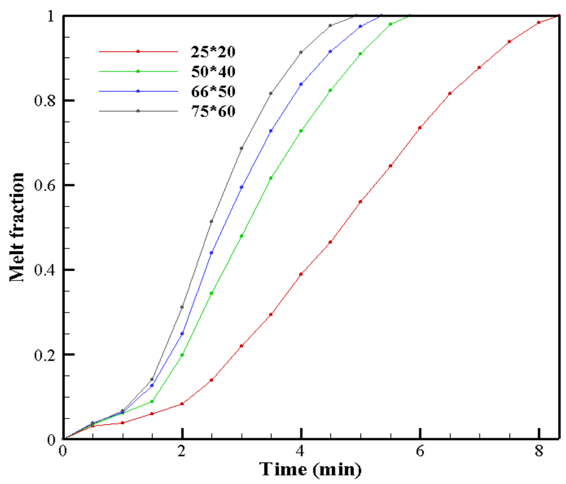

Fig. 4. The melting fraction of the system with 50% water and 50% oleic acid composition for different grid sizes.

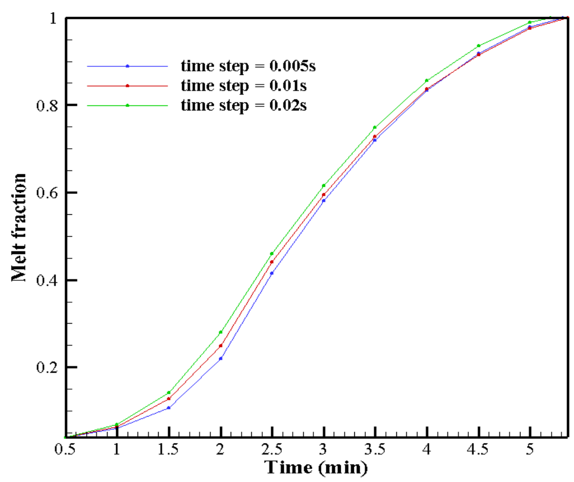

Fig. 5. The melting fraction of the system with 50% water and 50% oleic acid composition for different time steps.

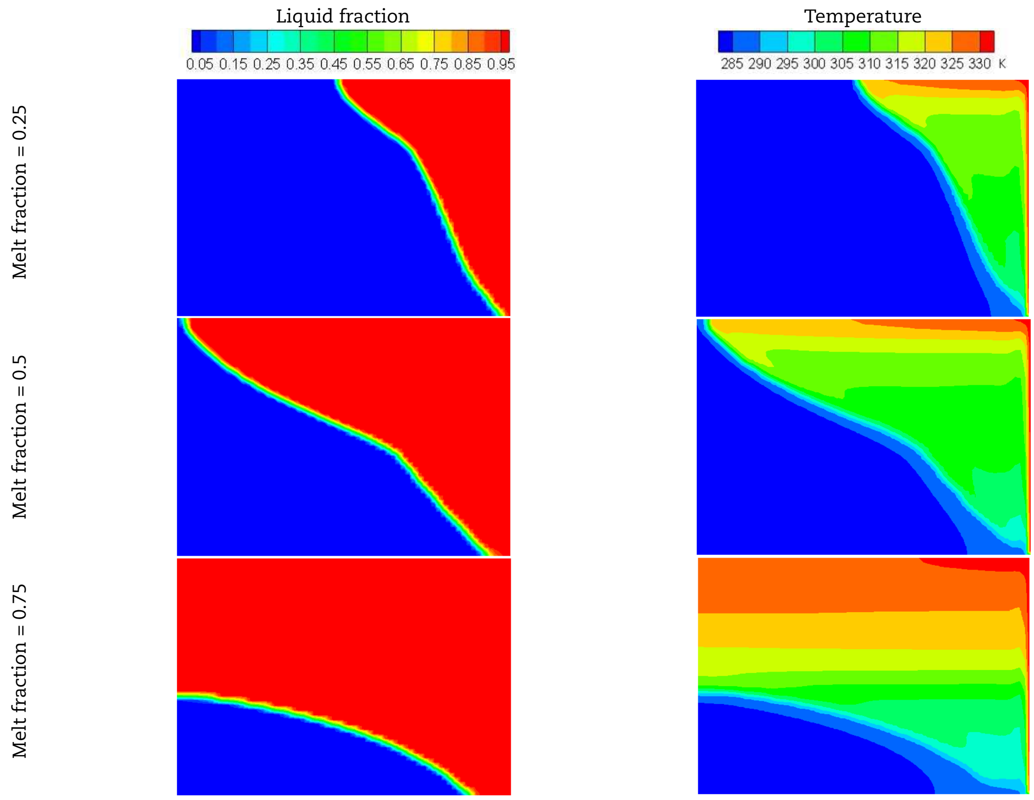

Fig. 6. The liquid fraction and temperature contours of pure oleic acid in the enclosure at different melt fractions.

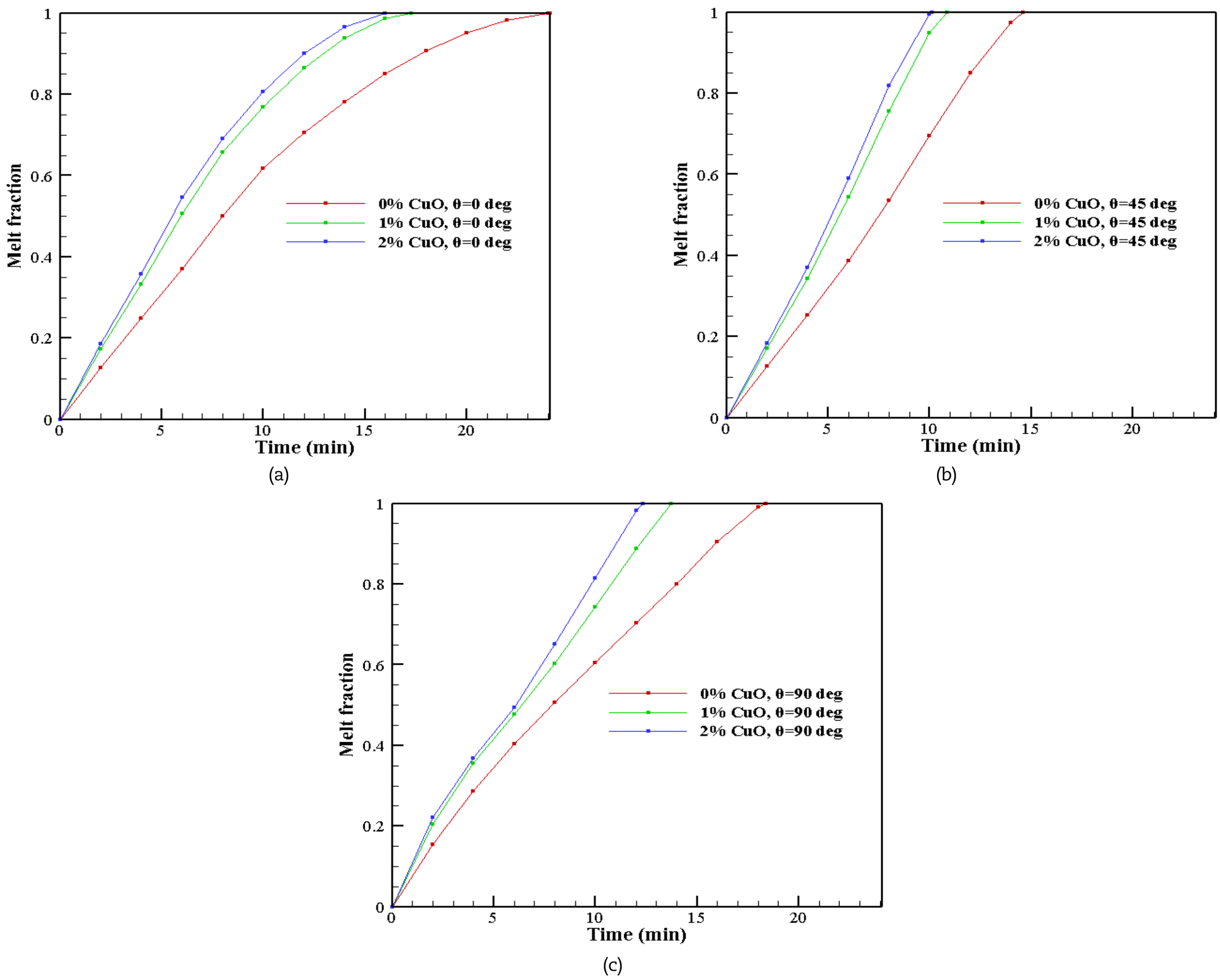

Fig. 7. The melt fraction of the system, including different weight percentages of CuO nanoparticles in the enclosure with the inclination of (a) 0°, (b) 45°, and (c) 90°.

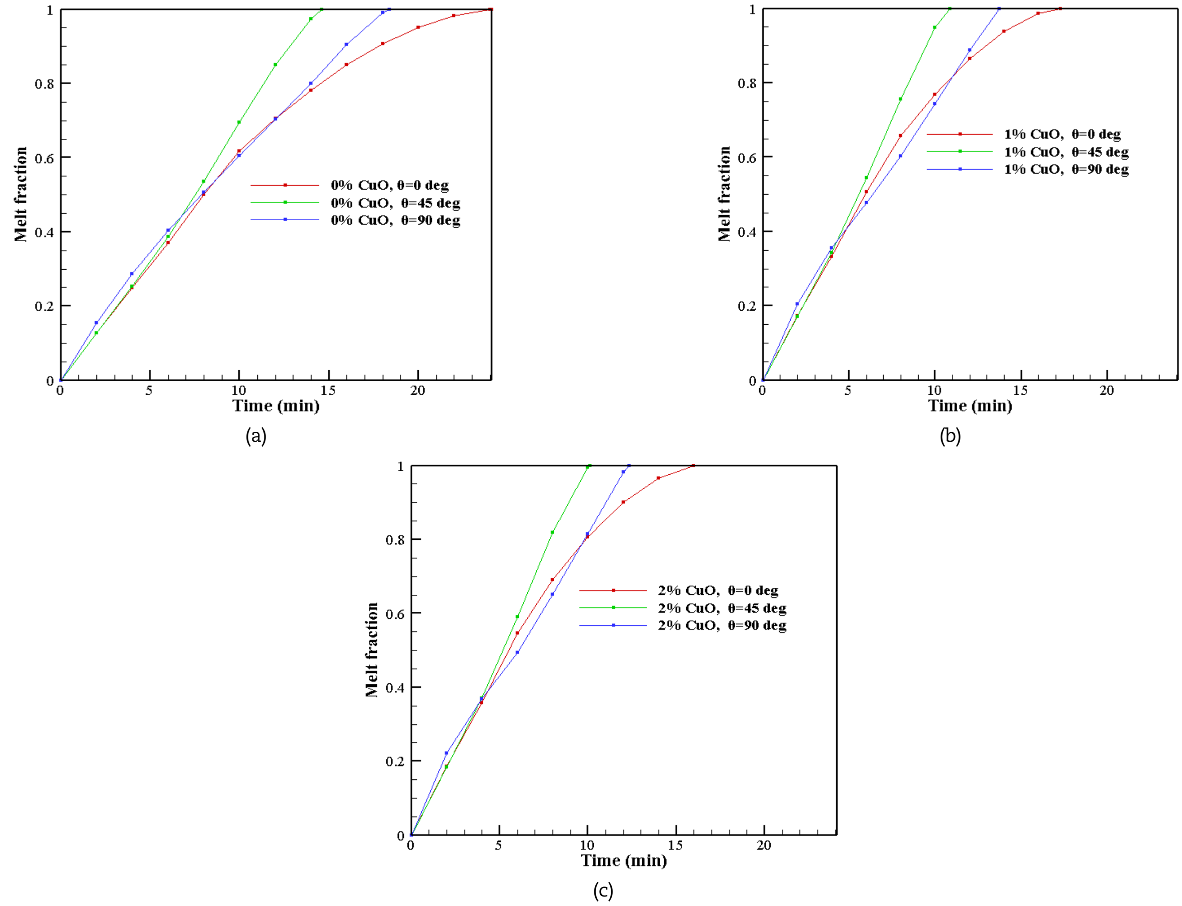

Fig. 8. The melt fraction of the system with different inclinations including (a) 0%, (b) 1%, and (c) 2% CuO nanoparticles.

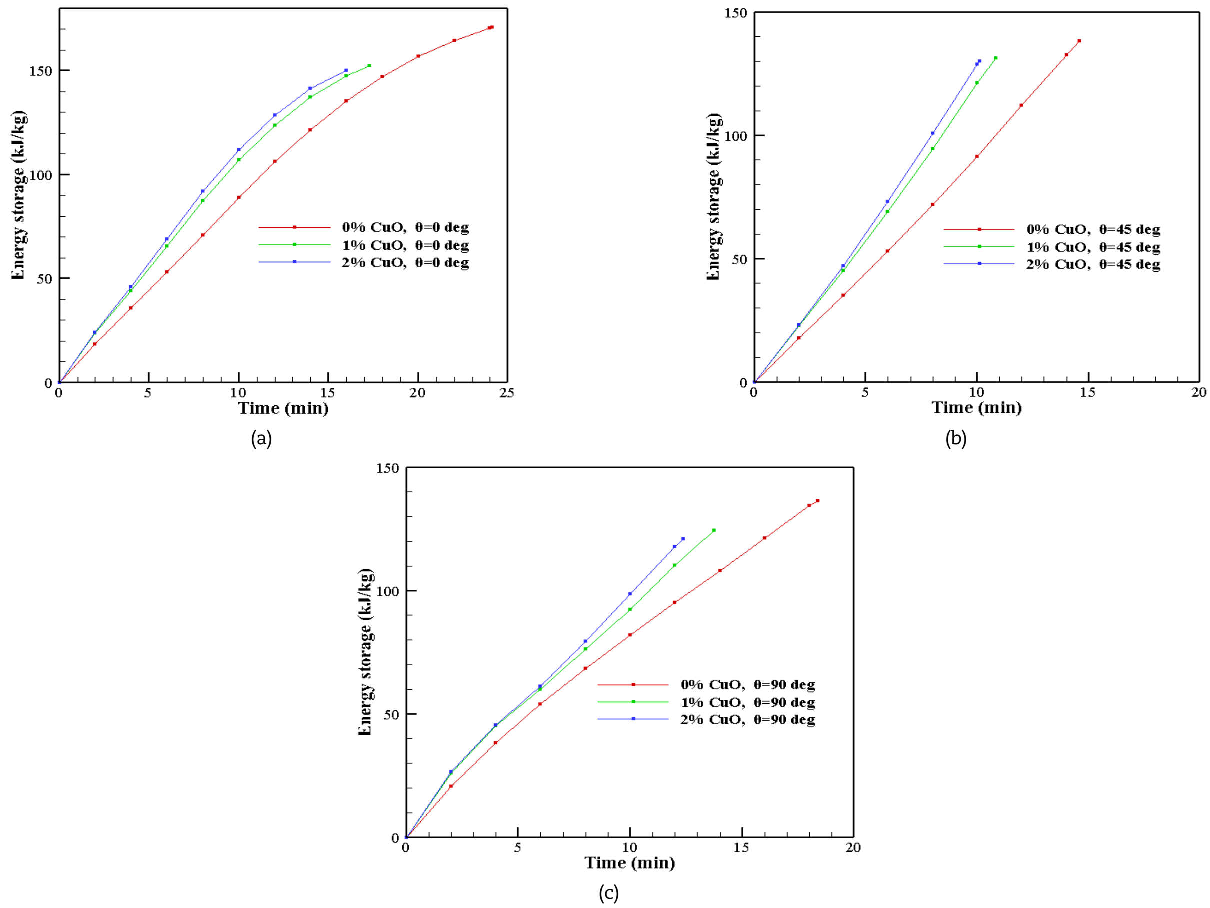

Fig. 9. The amount of energy storage of the system, including different weight percentages of CuO nanoparticles in the enclosure with the inclination of (a) 0°, (b) 45°, and (c) 90°.

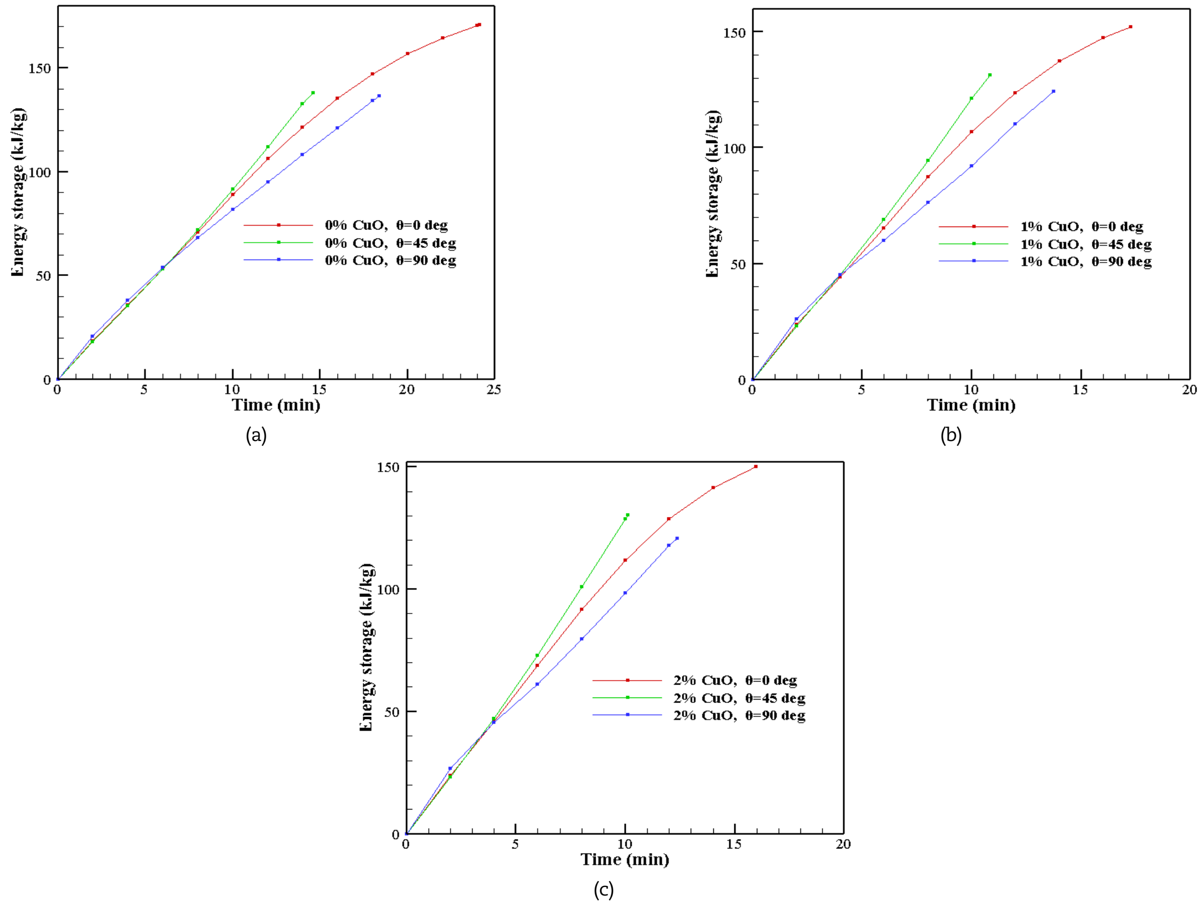

Fig. 10. The amount of energy storage of the system with different inclinations, including (a) 0%, (b) 1%, and (c) 2% CuO nanoparticles.

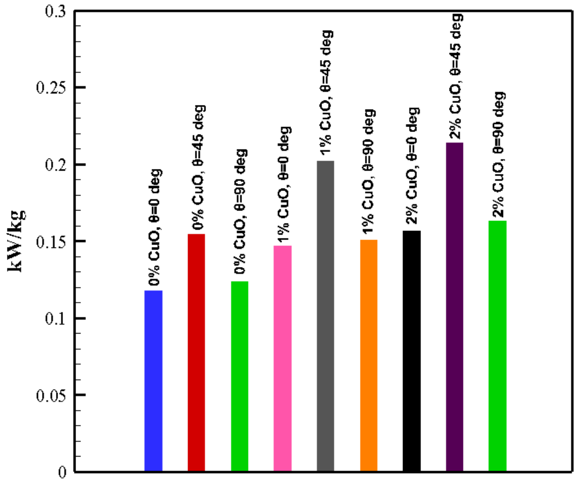

Fig. 11. The energy storage rate of the system with different inclinations and CuO nanoparticles concentrations.

The presence of nanoparticles accelerates the melting process due to strengthening the heat transfer properties of PCM. Nanoparticles do not change the melting process procedure, as is evident in Figs. 7 and 8 and only make the slope of the graphs steeper.

Tilting the enclosure according to the direction of tilting of the enclosure causes an increase in gravity towards the warmed wall. The gradual increase in the incline angle is initially due to better warming of melted PCMs with a local lower temperature from the wall (better convection), but at high inclination angles due to creating a melted PCM layer that acts as an insulator between the hot wall and the solid PCM causes the speed of the melting process to decrease again. Therefore, increasing the angle from 0° to 90° first accelerates and then reduces the rate of the melting process.

On the other hand, the effect of adding nanoparticles and inclining the enclosure on energy storage is also studied. Energy storage in oleic acid by adding nanoparticles with weight percentages of 1% and 2% at each inclination is demonstrated in Fig. 9. At constant inclination angles, adding nanoparticles reduces the duration of the melting process, which causes less energy storage in the system. However, when nanoparticles with weight percentages of 1% and 2% are added to the system, energy is stored at a higher rate. Also, in Fig. 10, the energy storage in different weight percentages of nanoparticles at different inclinations of the enclosure is investigated. The increased rate of energy storage for a 45° inclination angle is higher than inclinations of 0° and 90° because of the increase in convection heat transfer at this angle.

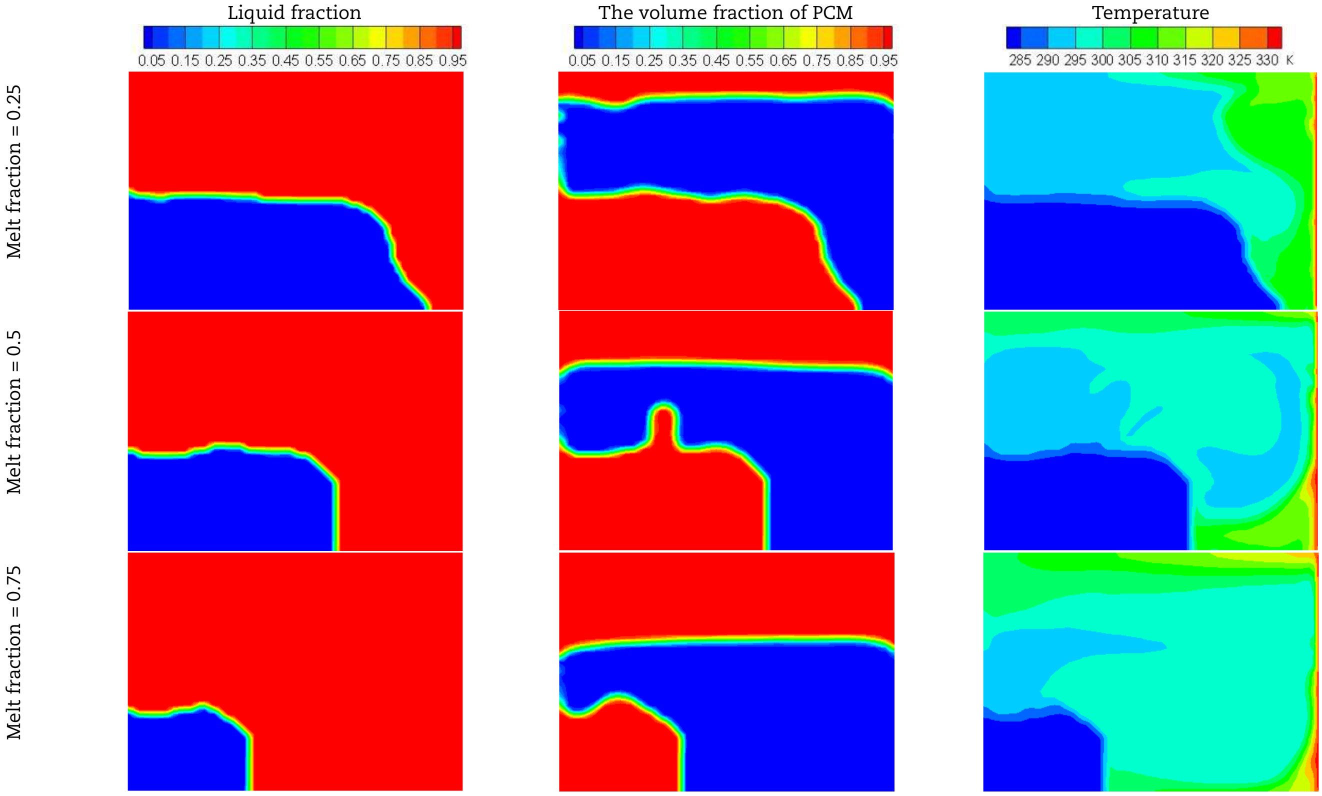

Fig. 12. The liquid fraction, the volume fraction of oleic acid, and temperature contours in the combined system (50% water and 50% oleic acid).

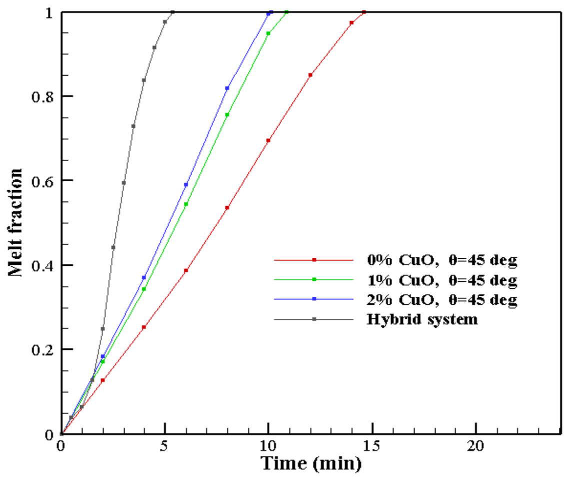

Fig. 13. The melt fraction of the combined system (50% water and 50% oleic acid) and inclined system, including different weight percentages of CuO nanoparticles.

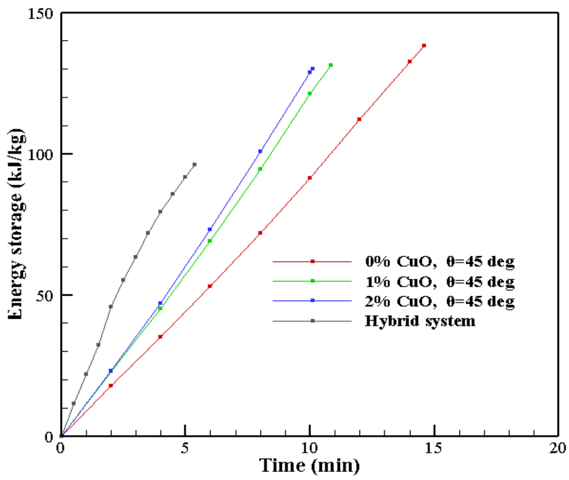

Fig. 14. The amount of energy storage in the combined system (50% water and 50% oleic acid) and inclined system, including different weight percentages of CuO nanoparticles.

The energy storage rate, which gives a better view for comparing different nanoparticle weight percentages and different inclination angles, is shown in Fig. 11. Without adding nanoparticles at the inclination of 0°, the energy storage rate is 0.118 kW/kg, while by adding 2% CuO nanoparticles at the inclination of 45°, the energy storage rate increases to 0.2142 kW/kg. It can also be seen that pure oleic acid (0% CuO) at a 45° inclination angle has almost the same energy storage rate as can be obtained by adding 2% nanoparticles at a 0° inclination angle.

5.3 Combined TES systems analysis

Utilization of improved heat transfer methods, such as adding nanoparticles or tilting the enclosure, has its own costs. Always finding enhancement methods that are less expensive in addition to improving heat transfer is one of the main research priorities in the field of renewable energy storage. In this research, the method of using auxiliary fluid is introduced, and its comparison with improvement methods, including adding nanoparticles and tilting the enclosure, is discussed.

The details in Fig. 12 show the melting process of oleic acid, as briefly discussed here. These snapshots illustrate the liquid fraction, the volume fraction of oleic acid, and temperature contours at three different melt fractions of oleic acid. Warm areas can be found in the upper and right sections of the enclosure due to natural convection in the liquid phase. The melted oleic acid is moved to the upper area of the enclosure, and this process continues until the melting is completed. The temperature gradient between oleic acid and the warmed wall initially causes melting to occur on the right side. Then, water replaces oleic acid during melting because it is denser than oleic acid. The melted oleic acid moves up continuously near the hot wall until the water completely covers the right side of the solid oleic acid. Thereafter the melted oleic acid droplets rise to the top of the enclosure as they melt.

Table 3. The price information of CuO nanoparticles [33].

Nanoparticles	Price (£ / g)	Preparation
CuO	0.2732	simple method
	2.42	purchased from Sigma Aldrich Company

Oleic acid takes a shorter melting time and melts in 321.62 seconds, as seen in Fig. 13, using the auxiliary fluid method. The amount of oleic acid mass used in the enclosure is indeed half of the regular state, but its melting time is reduced by more than half of the regular state melting time. Also, its melting rate is growing faster compared to the case where the chamber is located at an angle of 45°, and different weight percentages of CuO nanoparticles are dissolved. In the meanwhile, the amount of energy storage in the hybrid system, i.e., including oleic acid and water, with an enclosure with a 45° angle of inclination and the use of CuO nanoparticles with different weight percentages, is compared in Fig. 14. The energy storage during the melting process in the hybrid system is 96.21 kJ/kg. This amount of energy at the time of 321.62 seconds is significantly higher compared to other states of inclined systems with nanoparticles.

The energy storage rate in the hybrid system is 0.299 kW/kg, which is higher than the energy storage rate obtained by adding CuO nanoparticles to oleic acid in the enclosure with an inclination of 45°. Also, the energy storage rate in the simple system is 0.118 kW/kg, which concludes that using the auxiliary fluid method increases the energy storage rate in the system by 2.5 times.

There are different ways to improve the melting process of PCMs, each of which has costs. The cost of constructing CuO nanoparticles shown in Table 3 is between 0.2732 and 2.42 pounds per gram, which is a relatively high cost. On the other hand, tilting the enclosure is indeed a low-cost method, but heat transfer is not improved enough. As a result, using water as an available and economical fluid that improves heat transfer and energy storage in oleic acid by using the auxiliary fluid method is a practical method. Another advantage of using auxiliary fluid is that water is insoluble in oleic acid, which makes these two materials completely separate from each other at the end of the melting and energy storage process, and they can be reused in more cycles.

6. Conclusion

In this research, the method of using auxiliary fluid was compared with the methods of adding nanoparticles and tilting the enclosure. It was observed that using auxiliary fluid is a cost-effective method that significantly improves heat transfer in the system. In the following the main results obtained from this research are summarized:

- One of the ways to improve energy storage in renewable systems is by adding nanoparticles to PCM or making the enclosure inclined. Compared to the system where pure oleic acid is used in the enclosure with the inclination angle of 0°, adding 2% CuO nanoparticles in the enclosure with a 45° inclination increases the energy storage rate in the system up to 1.82 times.
- In addition to significantly reducing the melting time, the use of auxiliary fluid increases the energy storage rate in the system by 2.5 times, which is up to 1.396 times higher than the simultaneous use of adding nanoparticles and tilting the enclosure.
- Producing nanoparticles is usually an expensive method that is not cost-effective compared to using water as an auxiliary fluid due to its accessibility. Also, an auxiliary fluid such as water cannot be dissolved in oleic acid, which helps to carry out the energy storage process in industries with high cycles.
- One of the future challenges is to improve the performance of the auxiliary fluid method, which can be of great help to renewable energy storage systems. Adding nanoparticles to the auxiliary fluid instead of PCM, using metal foam, and installing fins in the enclosure along with the simultaneous use of the auxiliary fluid method can improve the energy storage rate in the system to a greater extent.

Author Contributions

A. Khademi and S.A. Abtahi Mehrjardi contributed equally to the final version of the article. They principally designed and generated this research paper. Also, they devised mathematical modeling, analyzed the theory validation, and provided the technical interpretation of numerical analysis results. The detailed review carried out by Z. Said and A.J. Chamkha, extensively improved the quality of the work. The manuscript was written through the contribution of all authors. All authors discussed the results, reviewed the methodology, and approved the final version of the manuscript.

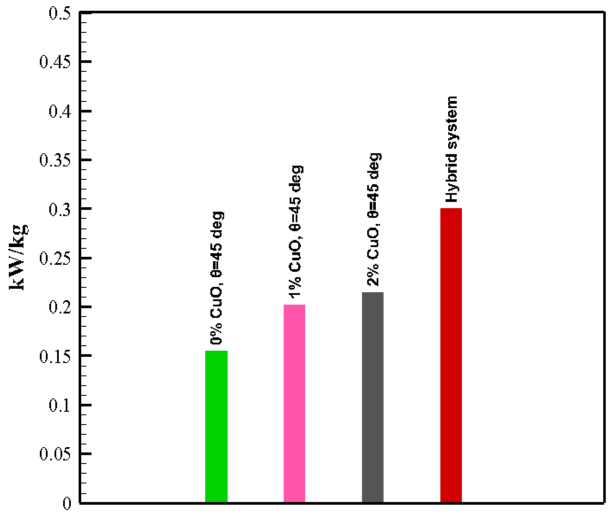

Fig. 15. The energy storage rate in the combined system (50% water and 50% oleic acid) and inclined system, including different weight percentages of CuO nanoparticles.

Acknowledgments

Not applicable.

Conflict of Interest

The authors declared no potential conflicts of interest concerning the research, authorship, and publication of this article.

Funding

The authors received no financial support for the research, authorship, and publication of this article.

Data Availability Statements

Not applicable.

Nomenclature

b	Brownian movement constant	x	Horizontal Cartesian coordinates [m]
C_p	Specific heat [kJ/kg.°C]	y	Vertical Cartesian coordinates [m]
d	Nanoparticles diameter [m]	α	Void fraction
f	Liquid fraction	β	Thermal expansion [1/°C]
g	Gravity [m/s^2]	Γ_k	Mass flux of each phase [kg/m^2.s]
ΔH	Instant latent heat [kJ/kg]	γ	Brownian movement parameter
k	Thermal conductivity [W/m.°C]	θ	Inclination angle [°]
L	Latent heat [kJ/kg]	κ	Boltzmann constant [J/°C]
P	Pressure [Pa]	μ	Dynamic viscosity [kg/m.s]
T	Temperature [°C]	ρ	Density [kg/m^3]
u	Horizontal velocity component [m/s]	φ_n	Nanoparticle void fraction
v	Vertical velocity component [m/s]		

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How to cite this article: Khademi A., Abtahi Mehrjardi S.A., Said Z., Chamkha A.J. Heat Transfer Improvement in a Thermal Energy Storage System using Auxiliary Fluid Instead of Nano-PCM in an Inclined Enclosure: A Comparative Study, *J. Appl. Comput. Mech.*, 9(2), 2023, 475–486. https://doi.org/10.22055/jacm.2022.41867.3829