Numerical Investigation of Melting-Freezing Cycle of Phase Change Material PCM Contained in Finned Cylindrical Heat Storage Systems Integrated with Nano-Particles Additives

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ABSTRACT: *Thermal energy storage systems containing phase change materials are widely used in industry. This investigation was done to improve the heat transfer performance of the charging and discharging processes (melting/freezing cycles) for heat exchangers containing phase change materials (Parafin wax) with Nano-particles (Al_2O_3), based on the total required time to complete the charging and discharging processes during the cycle. Using the enthalpy porosity technique to analyze the phase change phenomenon during the charging and discharging processes, a numerical model has been developed to study the heat transfer performance of the cycle In contrast, the influencing parameters, such as the geometric, thermophysical, and hydraulic parameters, are changed. The study was carried out in four arrangements: a base case, a reversed chamber, and each with two flow directions. For each arrangement, the effects of the volume fraction of the Nano-particles (0, 2, and 5%) on the melting/freezing average have been studied. The results show that by changing the above parameters, the total charge and discharge cycle time of the heat exchanger improves from 101 hours to 56 hours, which means 44.5% for the inversed chamber and the direction of flow, and 5% for Nano-particles.*

KEYWORDS: *Melting-freezing cycle; Phase change material; Finned cylindrical; Nano-particles; Heat storage system.*

INTRODUCTION

One of the energy-saving methods is using Phase Change Materials (PCM). The main disadvantage of PCMs is their low thermal conductivity. The use of fins and Nano-particles in energy storage systems may help to cover this weakness.

In a numerical study, *Bouhal et al*. [1] investigated the effect of fin shape in a rectangular chamber to integrate Phase Change Material (PCM) elements into passive solar buildings. They studied three types of chambers: those without a fin, those with a rectangular fin, and those with a triangular fin. The presence of a fin increases the melting rate, and a rectangular fin is more effective for this

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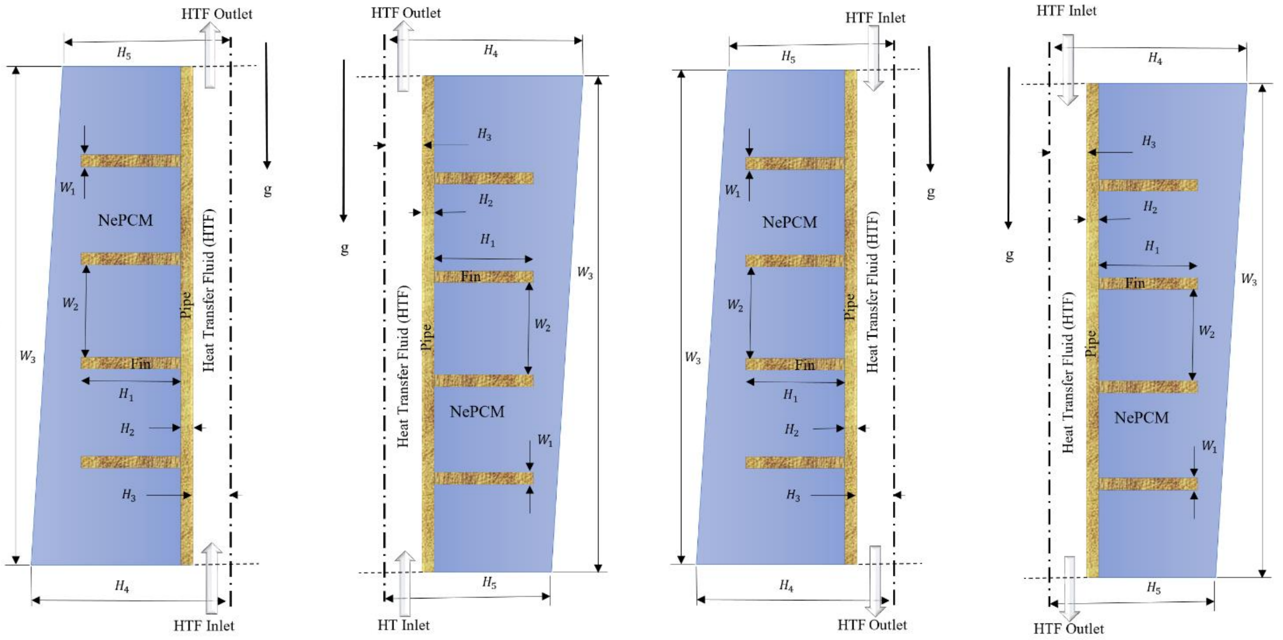
purpose, In contrast, a triangular fin creates a more uniform temperature inside the chamber. In the same regard, in another study, *Deng et al*. [2] studied and optimized finned pipes in energy storage systems. They have studied five different types of fin arranging and studied the impacts of fin number, dimensionless fin length, and outer tube material on the thermal performance of the set.

Sefidan et al. [3] filled the space between the two pipes with two layers of PCM and studied the melting phenomenon, melting time, and temperature distribution numerically. The effect of two-layer thickness and fin length on thermal performance has also been investigated. The results show that if two different types of PCM are used, the melting rate can be higher than if the same PCM is used in both parts. In the study of *Liang et al*. [4], a cylindrical heat reservoir has been studied. In this research, the impacts of parameters like the ratio of length to cylinder diameter, quiet or tangled air flow, and PCM thermal conductivity coefficient on the defined efficiency parameter have been studied. *Zhang et al*. [5] investigated variations in the melting efficiencies of heat storage chambers with different fins configurations. The results show that the use of a dual spiral fin has the most significant effect on vertical heat storage, and the use of a quadruple fin has the most significant effect on horizontal heat storage.

Some researchs have focused on the freezing phase. In Ref. [6], a chamber containing PCM in the freezing phase has been studied both numerically and experimentally. In this research, the number of fins, their thickness, and the wall temperature has been investigated, and their optimal value for the desired geometry has been reported. *Mehdi* and *Ensofor* [7] have numerically investigated the effect of the simultaneous addition of fin and Nano-particles to the chamber containing PCM. In this investigation, the impacts of varying fin lengths and volume fractions of Nano-particles on the melting front, temperature distribution, and changes in melt phase fraction at different times have been studied. In a research study, *Lee et al*. [8] studied a heat exchanger containing PCM under variable temperature conditions. In this research, the heat recovery of a single cycle has been discussed, for this purpose, a heat exchanger containing a phase change material has been modeled under the effect of fluid with temperature change. In line with the research that has been done on the heat exchanger under variable temperatures, we can also refer to the research of *Jimenez et al*. [9]. They have studied the capabilities of the heat exchanger containing the phase change material in order to recover the wasted heat. In this research, the focus is on the study of existing challenges and solutions. *Sarani et al*. [10] studied a cylindrical chamber with two types of continuous and discrete fins containing pure PCM, also PCM containing Nano-particles. The outcomes of this investigation show that the concurrent employment of Nano-particles and discrete fins can reduce the melting time by 77.8%. *Mousavi et al*. [11] have studied the effects of the presence of Nano-particles in PCM through numerical studies on the optimization of finned cylindrical chambers. The results show that the simultaneous use of aluminum Nano-particles (5%) and fin has the best effect on reducing the melting time by about 28%. The study of multi-layer cylindrical chambers with fins has also attracted the attention of researchers. In this regard, we can refer to *Zhou et al*.'s research [12]. In this article, eight types of multi-layer finned cylindrical enclosures containing phase change material have been investigated, and their optimal mode has been selected. The heat exchangers containing phase change material with non-uniform fins have been investigated in research [13]. In this research, variables such as pitch and location of the fin on the thermal performance of the converter have been studied. Numerical and experimental study of a heat exchanger containing PCM has been reported in [14]. In this research, helical fines have been used to increase the heat transfer between the flowing fluid and the PCM. In a study by *Y. Ju et al*. [15], a three-pipe vertical heat exchanger containing PCM has been studied. In this study, PCM is in the middle pipe and is surrounded by two pipes, cold water, and hot water. In this study, the effects of four states of water flow, for or against gravity acceleration, have been investigated.

The outcomes explain that the heat exchanger performs better when the direction of water flow is in the direction of gravity.

In the present study, ideas are studied with the aim to increase the rate of heat transfer in the charge phase (freezing), discharge phase (melting), and also the whole cycle of melting and freezing in a cylindrical chamber with fins containing Phase Change Material (PCM) and Nano-particles.



a b c d

Fig. 1: The studied thermal storage system (a) Base Case, (b) Reversed chamber, (c) Reversed flow direction, and (d) Reversed flow direction and chamber

Many researchers went in their articles to search for methods to improve the rate of heat transfer in the charging (melting) phase, and some of them went on to develop the heat transfer rate in the discharge (freezing) phase. There are some parameters that give better performance in the charging (melting) process. However, these same parameters may not give the best performance in the discharging (freezing) process and vice versa. The main reason is the reverse trend of natural convection in the melting and freezing processes.

Therefore, there is an urgent need for extensive studies to improve the performance of heat transfer rates in Thermal Energy Storage (TES) systems during the charging and discharging processes. Moreover, the literature lacks detailed studies on heat transfer improvements for a full charge and discharge cycles.

Therefore, we have to study the parameters affecting the melting-freezing cycle together. We might get the best case for the heat transfer rate of the whole cycle, which may not be the best case at the melting phase or the freezing phase. In the present work, the influence of main parameters: flow direction, geometric direction, and Nano-partical addition, are studied.

THEORETICAL SECTION

The mathematical model

The studied heat storage system is shown in Fig. 1 a. It is used as a base case, and the results of changes in geometry, boundary conditions, and thermophysical properties will be determined. The case of the current investigation is based on the results reported in refs., [16-18].

The walls and fins of the heat exchanger are made of copper; the passage of water is the pipe in the center; and the outer part is occupied by PCM. The running water is hot in the discharge phase, and its temperature is 325 K, but in the cold charge phase, it has a temperature of 300 K.

For the base case, the direction of water flow is opposite to gravity, with the larger base at the bottom and the smaller base at the top.

Accordingly, three other types of arrangements are studied: i, The chamber is reversed, i.e., the place of the large and small base is changed, but the water inlet is still from the bottom and the water outlet is at the top; ii, The same as the base case, but the water flow is in the gravity direction. iii, The chamber and the flow direction are reversed. In each case, PCM with a volume fraction of Nano-particles of 0%, 2%, and 5% are investigated.

Table 1: Dimensions of the storage system in mm

Dimension	W1	W2	W3	H1	H2	H3	H4	H5
Value	2	48	250	50	2	10	110	62.5

Governing equations and hypotheses

The assumptions introduced below are used in deriving the governing equations [11, 19]:

1. The Boussinesq approximation is used for buoyancy.
2. The fluid flow in HTF is laminar.
3. The Nano-particles are homogeneously dispersed in the PCM and do not precipitate.

A. Hydrodynamic equations

Accordingly, the equations of continuity, motion, and energy for an unsteady and smooth two-dimensional flow, including the displacement caused by the buoyancy force, are expressed as follows:

Continuity Eq.

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

$\frac{\partial \rho}{\partial t}$ is set to be zero due to the assumption of incompressibility flow after melting occurs.

Momentum Eq.

$$\frac{\partial}{\partial t}(\rho V) + \nabla \cdot (\rho V V) = -\nabla P + \rho g + \nabla \cdot \tau + F \quad (2)$$

Where τ is the stress tensor, P is the static pressure, ρg is the gravitational force, and F is the external body force.

Energy Equation.

$$\frac{\partial}{\partial t}(\rho H) + \nabla \cdot (\rho V H) = \nabla \cdot (k \nabla T) + S \quad (3)$$

Indicates H enthalpy of the phase change material and Nano-particale (Nano-PCM), ρ density of the NanoPCM, k conductive heat transfer coefficient of Nano-PCM, V velocity, and T temperature. S Here is the volumetric heat source term, considered zero in this investigated.

Total enthalpy H is calculated as the sum of sensible enthalpy h and melting enthalpy H_{mel} [19, 20]:

$$H = h + H_{mel} \quad (4)$$

Where the sum of sensible enthalpy, h, is defined as follows [19, 20]:

$$h = h_{ref} + \int_{T_{ref}}^{T} C_p dT \quad (5)$$

Here h_{ref} and T_{ref} mean the sensible reference enthalpy and the reference temperature, respectively, and C_p means the specific heat at constant pressure.

The latent heat, H_{mel} of melting, which varies between zero (solid) and L (liquid) in terms of the latent heat of the phase change material, is calculated as follows [19, 20]

$$H_{mel} = \alpha L \quad (6)$$

α is the liquid fraction dependent on PCM temperature. Its value ranges from 0 to 1, and it is given by Eq. (7) [19, 20]:

$$\alpha = \begin{cases} 0 & T < T_{sol} \\ \dfrac{T - T_{sol}}{T_{liq} - T_{sol}} & T_{sol} < T < T_{liq} \\ 1 & T < T_{liq} \end{cases} \quad (7)$$

It should be noted that the larger storage of latent heat compared to sensible heat for the same volume of phase change materials in thermal energy storage systems [21-23].

The energy Eq. (3) and the liquid fraction Eq. (7) are coupled. This necessitates an iterative algorithm between them to solve the temperature.

B. Thermo physical properties:

The thermos physical properties of the phase change material containing Nano-particles are calculated according to the following equations.

Density [24]:

$$\rho_{\text{NanoPCM}} = \varphi \rho_{\text{Nano}} + (1 - \varphi)\rho_{\text{PCM}} \quad (8)$$

Specific heat capacity [24]:

$$C_{\text{p.NanoPCM}} = \frac{\varphi(\rho C_p)_{\text{Nano}} + (1-\varphi)(\rho C_p)_{\text{PCM}}}{\rho_{\text{NanoPCM}}} \quad (9)$$

Latent melting heat [24]:

$$L_{\text{NanoPCM}} = \frac{(1 - \varphi)(\rho L)_{\text{PCM}}}{\rho_{\text{NanoPCM}}} \quad (10)$$

Dynamic viscosity[25]:

$$\mu_{\text{NanoPCM}} = 0.983 e^{12.959\varphi} \mu_{\text{PCM}} \quad (11)$$

In these relations, Nano and PCM subscripts refer to Nano-particles and phase change material, respectively, and φ the volume fraction of Nano-particles and the validity range is $0.01 \leq \varphi \leq 0.1$ for Al_2O_3 [26]. The thermal conductivity is given by Eq. (12), which is a combination of Maxwell's theory (first sentence to the right of the equation) and Brownian motion (second sentence

Table 2.:Thermophysical properties of PCM and Nano-particles [20]

Thermo-physical properties	**Paraffin wax**	AL_2O_3
Density(kg/m^3)	$750/(0.001(T-391.15)+1)$	3600
Specific heat(J/kgK)	2890	765
Thermal conductivity(W/mK)	0.21 if $T<T_{sol}$ 0.12 if $T>T_{liq}$	36
Viscosity(Ns/m^2)	$0.001\exp(-4.25+1790/T)$	———
Latent heat(J/kg)	173400	———
Solidus temperature (K)	319	———
Liquidus temperature (K)	321	———

to the right of the equation) [25]:

$$k_{NanoPCM}=\frac{k_{Nano}+2k_{PCM}-2(k_{PCM}-k_{Nano})\varphi}{k_{Nano}+2k_{PCM}+2(k_{PCM}-k_{Nano})\varphi}\,k_{PCM}+$$

$$5\times10^4\beta B\varphi\rho_{PCM}C_{p.NanoPCM}\sqrt{\frac{\kappa T}{\rho_{Nano}d_{Nano}}}f(T.\varphi) \quad (12)$$

The temperature range is: $293\,K\leq T\leq363\,K$ for Al_2O_3 [26], and the factor β represents the fraction of the liquid volume which travels with a particle, defined by Eq.(13) for Al_2O_3 as follows:

$$\beta=8.4407(100\varphi)^{-1.07304} \quad (13)$$

A correction factor B in a Brownian motion sentence is defined as follows:

$$B=\begin{cases}0 & T<T_{sol}\\ \dfrac{T-T_{sol}}{T_{liq}-T_{sol}} & T_{sol}<T<T_{liq}\\ 1 & T<T_{liq}\end{cases} \quad (14)$$

B is a correction factor in Brownian motion and for Nano-fluids, since there should be no Brownian motion in the solid phase. Its value is the same as for the liquid fraction, α, in eq. (7) [25].

The Boltzmann constant κ is 1.381×10^{-23} and $f(T.\varphi)$ the function is extracted from the experimental data as follows [27]:

$$f(T.\varphi)=(2.8217\times10^{-2}\varphi+3.917\times10^{-3})\frac{T}{T_0}+(-3.0669\times10^{-2}\varphi-3.91123\times10^{-3}) \quad (15)$$

That T_0 is equal to 273 Kelvin.

C. Boundary conditions

The fluid flowing in the tube (HTF) is water. The inlet water temperature is 325 K in the heating mode and 300 K in the cooling mode. The inlet water velocity is 0.02 m/s with a uniform profile, and the outlet boundary condition of the pressure is known. The acceleration of gravity is 9.81 meters per square second. Pipe walls can transfer heat through thermal conduction, so the energy equation for them and the fines have been solved to obtain the temperature distribution in them as well, but the side walls of thermal insulation (adiabatic) are assumed. The initial temperature in the whole geometry is 300 K in the heating mode and 325 K in the cooling mode.

Numerical simulation

A. Solve equations

ANSYS Fluent software will be used for numerical simulations [10] and [28]. According to the prevailing conditions of the problem, the three-dimensional solution can be replaced with the two-dimensional solution of the axial symmetry method, and appropriate solutions can be produced. A pressure-based method for solving the equations is proposed based on the reviewed articles [10, 28], and [29]. User-defined functions apply the dependency on the temperature and volume fraction of Nano-particles. The PISO method is used for speed-pressure combinations. Also, the PRESTO method for pressure relief and the second-order upstream method for momentum are proposed [30, 31].

The following coefficients of pressure relief, density, volumetric force, velocity, energy, and melt fraction were used: 0.3, 0.9, 1, 0.7, 1, and 0.9, respectively. Convergence accuracy is set equal for the momentum and mass survival equations and equal for the energy equation [30]. It should be noted that to introduce the properties of Nano-fluids, it is necessary to use the coding capabilities of Fluent software in most of the functions introduced by the user (UDF).

The properties of aluminum oxide (AL_2O_3) Nano-particles and phase change material (Paraffin wax) are given in Table 2.

B. Validation

The square cavity in Ref. [20] is adopted for validation in the present study. As shown in Fig. 2, the cavity is filled with a Phase Change Material (PCM) containing aluminum oxide Nano-particles. The hot and cold walls are located left and right, respectively, and the upper and lower walls are thermally insulated. The initial condition is a temperature of 300 K, so the phase change material in the initial state is excellent.

Figs. 3 and 4, the results of melt fraction and temperature distribution at $t = 3000\ sec$ for phase change material containing 2% aluminum oxide Al_2O_3. In order to evaluate the validation, the melt fraction contours and temperature distribution in 3000 s for the phase change material containing 2% aluminum oxide Al_2O_3 Nano-particles have been compared with the results of reference [19] and reference [20], which studied the same cavity.

C. Fruition grid independence and time step

To evaluate the appropriate time step, the results of the volume fraction of the modifier are measured concerning time. For this purpose, time steps of 0.1, 0.2, and 0.4 s were selected, and their results were compared. The results are shown in Fig. 5 a. Given of the slightly different results obtained for the time steps of 0.1 and 0.2 seconds, the time step of 0.2 seconds is selected to save solving time. To study the independence of the grid, grids with the numbers of cells 9296, 21431, 43775, and 85966 were produced, and the results of the melt volume fraction diagram were compared to time. As a result, the grid with the number of cells 43775 was selected. The results are shown in Fig. 5 b.

RESULTS AND DISCUSSION

In general, the chambers containing phase change materials are used to store thermal energy. Among the applications of the enclosure used in the present research, we can mention the storage of thermal energy in solar water heaters and air conditioning systems.

To find out what the effects of other parameters are on improving the performance of the melting-freezing cycle, a base case is considered, and the effect of each parameter on it is determined.

The mathematical model, geometry, and thermophysical conditions of the base case are described in Section 2. The aim is to find the arrangement with the fastest melting-freezing cycle rate. The arrangement may be fastest in the melting phase but not in the freezing phase, or vice versa. Therefore, it is necessary to study the whole cycle of melting-freezing and then describe the melting phase or freezing phase alone.

A. Effects of Nano-particles

The most significant weakness of Phase Change Materials (PCMs) is their low thermal conductivity. The use of Nano-particles that have a higher heat transfer coefficient is one way to overcome this weakness. One of the advantages of using Nano-particles is that they create a uniform distribution in the thermal conductivity coefficient.

The selection of appropriate Nano-composites in thermal energy storage systems and their effect on thermal conductivity depend on different criteria, such as the type and percentage of Nano-particles [21]. It should be noted that the addition of nanoparticles plays an important role in the dynamic viscosity during solidification and melting and thermal conductivity on the other hand [32, 22].

The balance technique between these two effects on the charging and discharging processes is one of the challenges facing researchers in thermal energy storage systems that contain PCM and nanoparticles.

In the present investigation, the effect of adding aluminum oxide Al_2O_3 to the phase change material (Paraffin Wax) was studied in order to improve the performance of the heat transfer rate. In Fig. 6, the time required for the melting-freezing cycle is shown for the 0%, 2%, and 5% volume fractions of Nano-particles.

During a melt-freeze cycle, according to Fig. 6, if Nano-particles are added to the phase change material by up to 5%, the time of one cycle can be reduced by 8% compared to the base case. If we focus on the melting process, by increasing the volume fraction of Nano-particles, the time required to melt the entire phase change material inside the chamber decreases.

It is evident that the higher the volume fraction of Nano-particles, the higher the melting rate at the beginning of the melting stages. In addition, if the goal is to melt the entire chamber, the total melting time will also decrease with the increase of Nano-particles. However, the difference between them will gradually decrease. By comparing the graphs, we can see the difference between the state where the volume

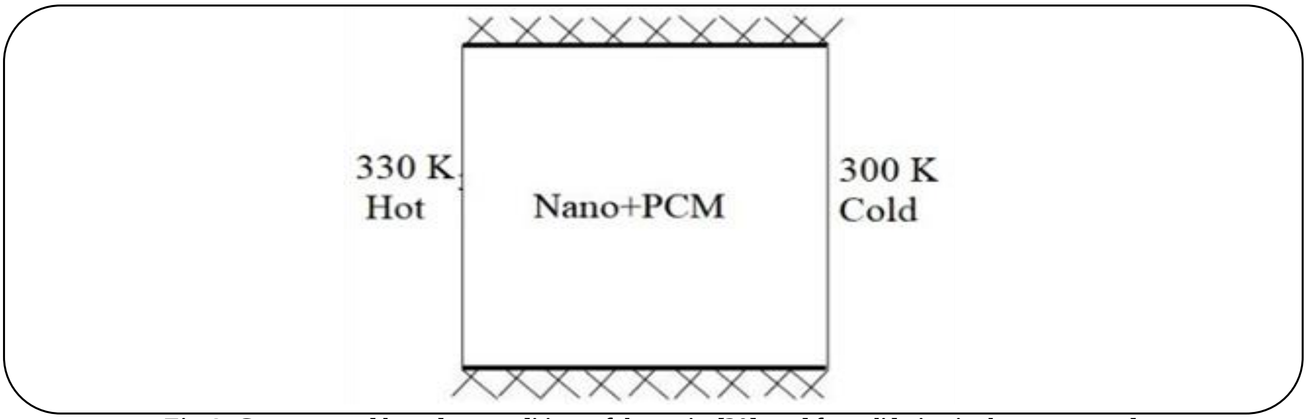


Fig. 2: Geometry and boundary conditions of the cavity [20] *used for validation in the present study*

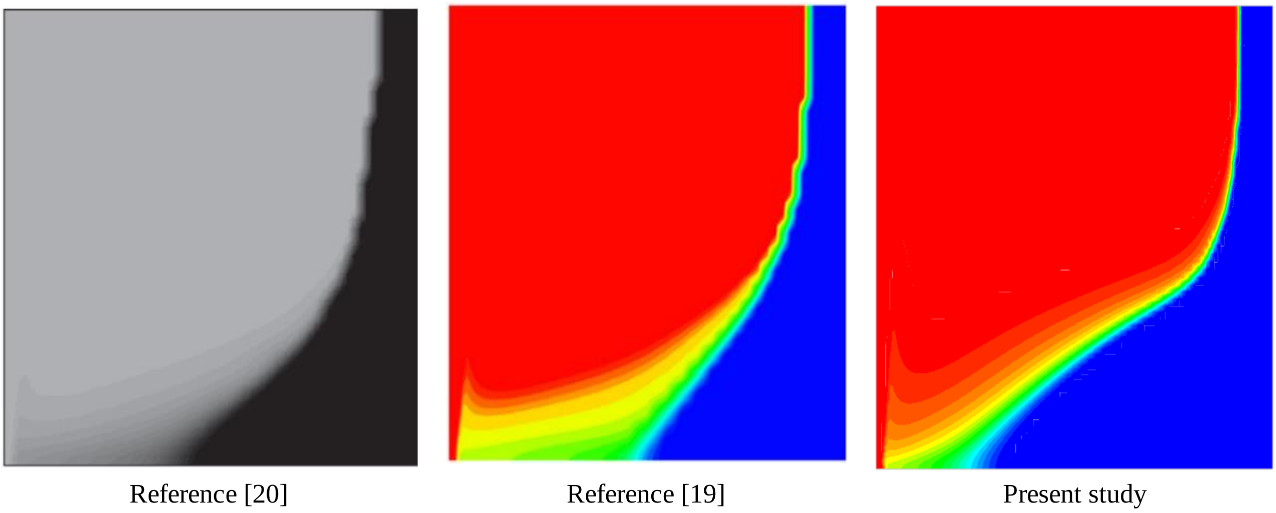


Fig. 3: Melt fraction in 3000 seconds for phase change material containing 20% aluminum oxide Nano-particles

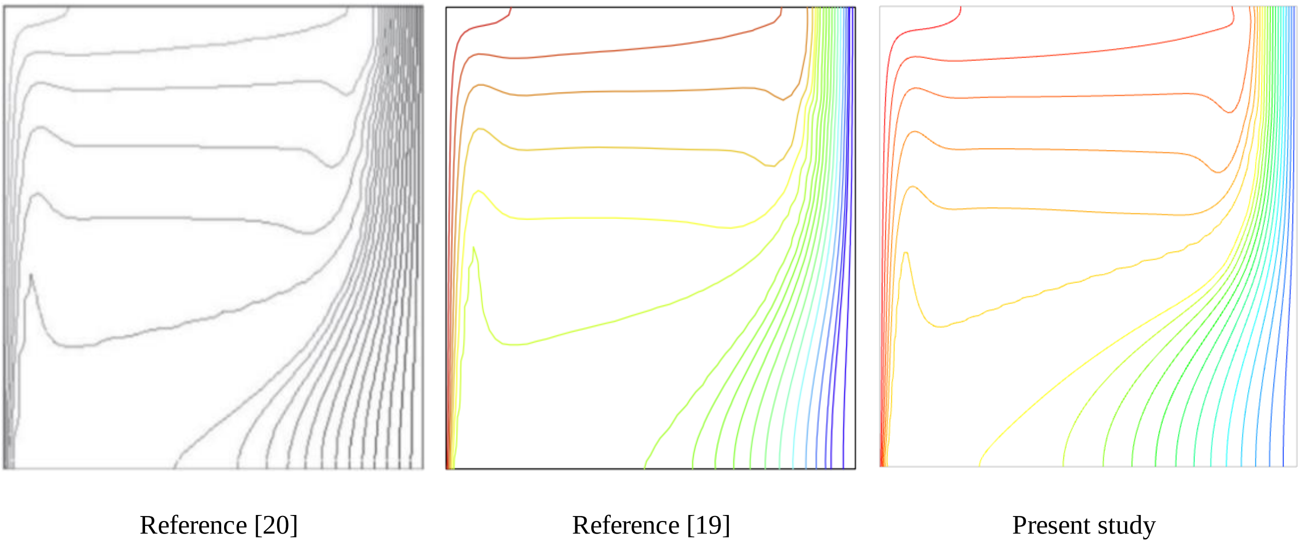


Fig. 4: Temperature distribution over 3000 s for phase change material containing 20% aluminum oxide Nano-particles

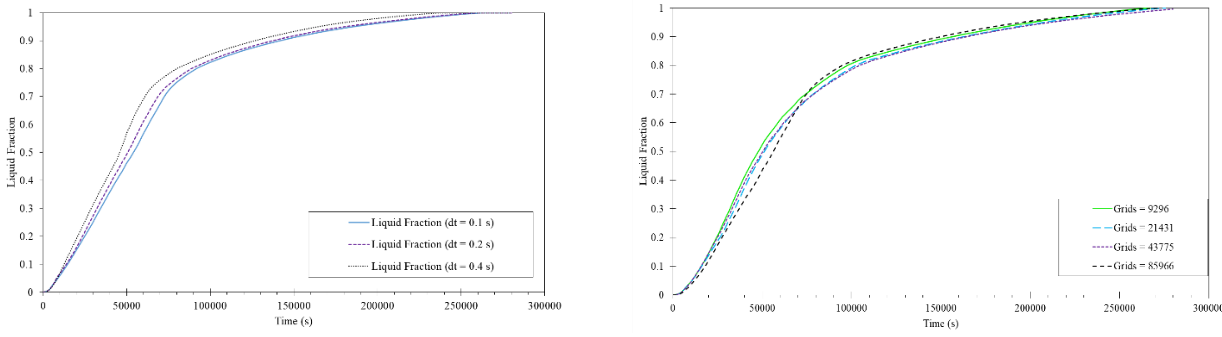


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Fig. 5: Changes in melt fraction over time at (a) different time steps and (b) different grids

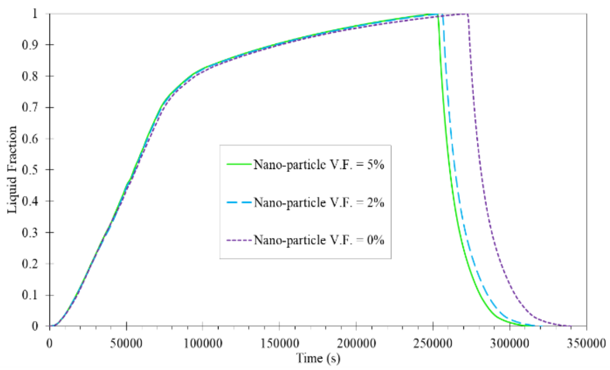

Fig. 6. Effects of Nano-particles on melting-freezing cycle

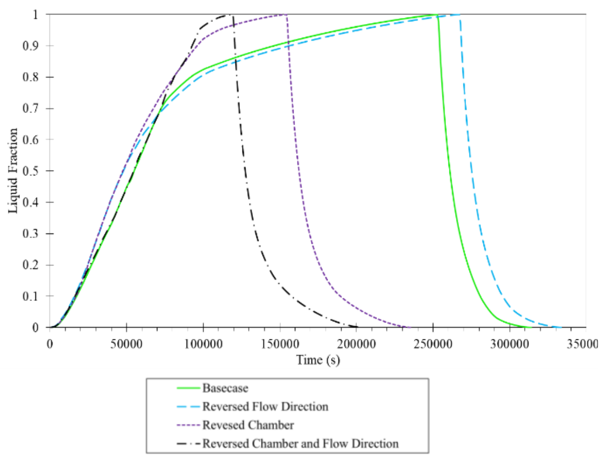

Fig. 7: Effects of flow direction and chamber orientation on the melting-freezing cycle with Nano-partical 5%.

fraction of Nano-particles is zero and the state where the volume fraction of Nano-particles is 2% is slight. However, when the volume fraction of Nano-particles is 5%, the difference becomes significant.

It the beginning, the phase change material is melted until 60 – 65% of the melting rate is faster, but as we get closer to the end of the melting process, the base case gets a better melting rate. However, in the process of freezing, as shown in Fig. 6, it can be seen that the freezing time of the chamber with the addition of Nano-particles did not change significantly and increased by 3%.

B. Effects of chamber orientation and flow direction

In this section, the effects of reversing the direction of water flow relative to the base case and including a 5% volume fraction of Nano-particles are investigated. Fig. 7 compares the time required for the melting-freezing cycle. If we compare the PCM with adding 5% of the Nano-particles in the same chamber as the base case, it shows that the cycle time has increased by up to 5.4% compared to the base case.

Therefore, reversing the water fluid inlet alone cannot be an excellent option to improve the system's performance in terms of energy release rate and storage compared to the base case.

However, in the case where the fluid flow inside the tube is reversed, the melting rate is faster at first until 65 to 70% of the PCM is melted, but the closer we get to the end of the melting process, the better the melting rate in the base case.

Also, in this part of the study, the direction of the chamber containing PCM is inverted relative to the base case (the larger base is higher), but the direction of water flow is the same as the base case (opposite to the direction of gravity), including a 5% volume fraction of Nano-particles.

According to Fig. 7, if we compare PCM with adding 5% Nano-particles in the inversed chamber with the base case, this action reduces the cycle time by up to 25%, which indicates an improvement in system performance in energy storage and release.

Table 3: Complete cycle time of the 12 cases studied, in hours

Arrangement / Nano-particle	Base Case	Reversed Flow Direction	Reversed Chamber	Reversed Flow Direction & Chamber
0%	94	101	74	63
2%	89	96	70	59
5%	87	92	65	56

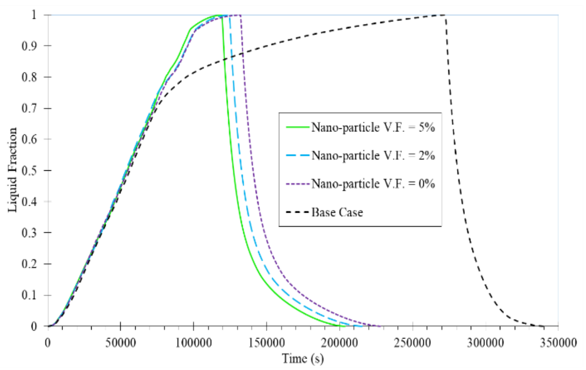

Fig. 8. Effects of proportionality between the Nano-particles concentration and the enhancement obtained in the performance on melting-freezing cycle

The reason for this is that during the freezing process, it is observed that the freezing time desired for the total solidification of the PCM inside the chamber is increases to the point that the difference is 14%.

The melting time of the chamber was significantly reduced compared to the base case. The time required to melt the entire PCM inside the chamber decreased by more than 39%.

Also, in this part of the study, the chamber containing the PCM was reversed relative to the base case (the larger base is located above), and the direction of water flow was reversed, including a 5% volume fraction of Nano-particles.

According to Fig. 7, if we compare the PCM diagram with adding 5% Nano-particles in the inverse chamber in the opposite direction of water flow with the base case, this action reduces the cycle time by up to 36%. The reason for this is that during the freezing process, it can be seen that the total PCM solidification time of the chamber with adding 5% Nano-particles was 23% longer than the base case.

Likewise, for the melting process, according to Fig. 7, it can be seen that the melting time of the chamber with the addition of Nano-particles was significantly reduced compared to the base case and improved by more than 59%. It can be seen that with the inversion of the chamber and the direction of water flow in the pipe, compared to the base case, the slope of the volume fraction chart is steeper over time, which means maintaining the initial velocity of the melting rate for a longer time.

In general, Fig. 7 shows that the addition of Nano-particles had a positive effect by reducing the melting and freezing cycle, while reversing the flow direction had a negative effect and inverting the geometric figure, had a positive effect.

As Fig. 8 indicates, the conductivity and viscosity increase when Nano-particles are added to the Phase Change Materials (PCM). Increase the conductivity has a positive effect on increase the heat transfer rates, while increase the viscosity has a negative effect on that as it weakens the impacts of the buoyancy force causing natural convection and thus on the charging (melting) and discharging (freezing) processes during the entire melting/freezing cycle, taking into consideration that the Nano-particles are homogeneously dispersed in the phase change material. The increase in thermal conductivity prevails over the increase in viscosity when increasing the percentage of Nano-particles from 0.2% to 0.5%, which gives an improvement to the melting process better than that given to the solidification process, and thus to the entire melting/freezing cycle.

The summary of using these parameters together means a positive effect much better than using any one of the above parameters separately. The required time to complete the cycle for the 12 simulated cases is given in Table 3.

CONCLUSIONS

The performance of a thermal storage system containing PCM and Nano-particles has been studied numerically. The whole time of the melting-freezing cycle was obtained for different arrangements and configurations. The results obtained from the present study can be summarized as follows:

1- By increasing the volume fraction of Nano-particles, the heat transfer rate is also increased, and the melting-freezing cycle time is decreased in all cases. The required time for a cycle is reduced by about 5±1% and 10±3% for Nano-particle mass fractions of 2% and 5%, respectively.

2- In all cases, the time required for melting is greater than the time required for freezing. Therefore, expediting the melting process is more significant for shortening the cycle time. In the longest cycle, the ratio of melting to freezing times is 80.9-20.4 h, and for the shortest cycle, it is 33.1-23.4 h.

3- The minimum time of the melting process is 33.1 h for the reversed chamber with the reversed flow including a 5% volume fraction of Nano-particle Al_2O_3 and the longest one is 75.36 h for the base case without Nano-particle.

4- For the whole melting-freezing cycle, the shortest time 56.3 h related to the reversed chamber with the reversed flow; this result was not far from expectation. Because of the optimal performance of heat exchange between HTF and the enclosure containing NanoPCM, caused by natural convection and the action of the buoyant in this case.

5- In order to achieve higher speed cycles, it is recommended to use 80% of the capacity of the system to avoid the slow part of the melting process.

6- The geometry plays a vital role in the distribution of the PCM mass in the chamber, and the verification of a unique geometry that ensures improved performance of the system is the future work.

Nomenclature

C_p	Specific heat at constant pressure (J/kg K)
F	External body forces $(\mathrm{N/m^3})$
g	Gravitational acceleration (m/s^2)
H	Enthalpy (J/kg)
h	Sensible enthalpy (J/kg)
k	Thermal conductivity (W/mK)
L	Latent heat (J/kg)
P	Static pressure $(\mathrm{N/m^2})$
S	Volumetric heat source $(\mathrm{W/m^3})$
T	Temperature (K)
t	Time (s)
V	Velocity (m/s)
Greek symbols	
α	Liquid fraction
β	Fraction of liquid volume traveling with a particle
B	Correction factor
κ	Boltzmann constant (J/K)
μ	Dynamic viscosity $(\mathrm{N\,s/m^2})$
ρ	Density $(\mathrm{kg/m^3})$
τ	The stress tensor $(\mathrm{N/m^3})$
φ	Volumetric fraction of Nano-particle
Subscripts	
liq	Liquid
mel	Melting
Nano	Nano-particle
Nano-PCM	Phase change material and Nano-particle
PCM	Phase change material
ref	Reference
sol	Solid

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