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Numerical Study of Performance Enhancement of Phase Change Material (PCM) Thermal Energy Storage (TES) System by Using Nanoparticles

Ebtehal S. Hussain [1], Ihsan Y. Hussain[2]

Authors affiliations:
1) Mechanical Engineering Department, University of Baghdad-Iraq.
Ebtehalsalman99@gmail.com

2) Mechanical Engineering Department, University of Baghdad- Iraq.
drihsan@uobaghdad.edu.iq

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Abstract

Improvements in the thermo-physical properties of Phase Change Materials (PCM) caused by nanoparticle dissipation are critical for a wide range of technologies. The current study describes numerically the investigation of the charging and discharging process of paraffin wax dispersed with different concentrations (1%, 3%, 5%, 7%, and 10%) of Alumina nanoparticles (Al_2O_3), in a Single Thermal Energy Storage (STES) system. For this study, a time-dependent, two-dimensional simulation of the solidification and melting process was performed numerically for different velocities. The study is realized using the CFD ANSYS FLUENT software package (Version 18) that employs the phase-change phenomenon using the enthalpy technique. The results show that adding alumina nanoparticles to paraffin wax reduces the melting and solidification process, and raising nanoparticle concentration accelerated the melting and solidification process even more when compared to pure paraffin wax. The greatest improvement was obtained with the maximum concentration of nanoparticles with total time saving between (12% - 11.76%) in the charging process and between (15.71% - 19.60%) in the discharging process depending on velocity. Furthermore, other important findings were that the presence of nanoparticles makes a little effect in the early stages of the solidification and melting processes, but as time passes, the rate of solidification and melting rises. Comparison with previous works gave good agreement of about 34%.

Keywords: Thermal Energy Storage, Paraffin Wax with Al_2O_3, Charging and Discharging Processes, Nanoparticles

دراسة عددية لتحسين أداء مادة متغيرة الطور (PCM) لنظام تخزين الطاقة الحرارية (TES) باستخدام جزيئات نانوية

ابتهال سلمان حسين ، احسان يحيى حسين

الخلاصة:

تعتبر التحسينات في الخصائص الحرارية الفيزيائية لمواد تغيير الطور (PCM) الناتجة عن تبديد الجسيمات النانوية ضرورية لمجموعة واسعة من التقنيات. تصف الدراسة الحالية عدديًا التحقيق في عملية الشحن والتفريغ لشمع البارافين المشتت بتركيزات مختلفة (1٪ ، 3٪ ، 5٪ ، 7٪ ، و 10٪) من جزيئات الألومينا النانوية (Al2O3)، في نظام تخزين مفرد متكون من نوع واحد فقط من مادة متغيرة الطور (STES). في هذه الدراسة ، تم إجراء محاكاة ثنائية الأبعاد تعتمد على الوقت لعملية التصلب والذوبان عدديًا لسرعات مختلفة. تم تنفيذ الدراسة باستخدام حزمة برامج CFD ANSYS FLUENT (الإصدار 18) التي تستخدم ظاهرة تغيير الطور باستخدام تقنية المحتوى الحراري. أظهرت النتائج أن إضافة جزيئات الألومينا النانوية إلى شمع البارافين يقلل من عملية الذوبان والتصلب ، كما أن زيادة تركيز الجسيمات النانوية يسرع عملية الذوبان والتصلب بشكل أكبر مقارنة بشمع البرافين النقي. تم الحصول على أكبر تحسن مع أقصى تركيز للجسيمات النانوية مع توفير إجمالي للوقت بين (12٪ - 11.76٪) في عملية الشحن وبين (15.71٪ - 19.60٪) في عملية التفريغ حسب السرعة. علاوة على ذلك ، كانت النتائج المهمة الأخرى هي أن وجود الجسيمات النانوية له تأثير ضئيل في المراحل الأولى من عمليات التصلب

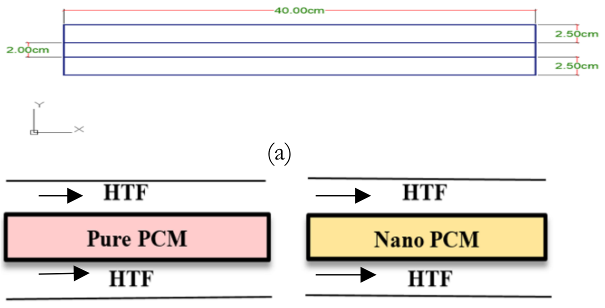
والذوبان ، ولكن مع مرور الوقت ، يرتفع معدل التصلب والذوبان. أعطت المقارنة مع الأعمال السابقة اتفاق جيد و بنسبة 34%.

1. Introduction

Renewable and clean energy sources, such as thermal energy are very important to meet the rising demand for energy while simultaneously controlling environmental pollution [1]. Thermal Energy Storage (TES) is one possible solution for storing excess energy as heat and releasing it when power generation is insufficient [2]. Usually, thermal energy can be stored in various forms such as latent heat storage, sensible heat storage, and thermochemical heat storage [3]. The energy in a thermal energy storage system can store by using, base materials, such as Phase-Change Material (PCM) that can release and absorb thermal energy [4]. The most promising material has been thought to be paraffin wax, as a result of its desirable properties; such as low melting pressure, high chemical stability, it doesn't have supercooling, it is 100% recyclable, and it involves considerable latent heat of fusion [5]. However, they require more time to store and release energy because, of their low thermal conductivity. So the researchers developed some methods for increasing it [6]. Porous media, encapsulation of PCM, extended surface/fins inside the PCM domain, and nanomaterial additives are significant contributors to influencing PCM thermal conductivity in the LHS system [3]. Arasu et al. [7]studied theoretically the effect of concentration of nanoparticle on the melting-solidification process of PCM distributed with (0%, 1%, 3%, and 5%) of both copper oxide (CuO) and alumina (Al_2O_3), the results showed that nanoPCM melted faster by (4.8% and 2.9%) for 1% alumina and copper oxide, compared to pure paraffin wax, respectively. Buonomo et al.[4] studied numerically the influence of putting metal foam and, nanoparticles into PCM on the Latent Heat Thermal Energy System (LHTES). The volume content of alumina (Al_2O_3) was 1%. The obtained results revealed that the charging time for pure PCM, nano-PCM, and nano-PCM with metal foam was (40301, 39781, and 1321 sec), respectively. Mahdavi et al. [8] used ANSYS-FLUENT 18.1 commercial CFD program to investigate the impact of the number of heat pipes, different concentrations of nanoparticles, and the type of nanoparticles (Cu, CuO, Al_2O_3, and Ag) on the melting and solidification processes. The results showed that adding 5% of nanoparticles leads to a 16% reduction in discharging time in all situations. Hiba [9] simulated numerically the effect of using Al_2O_3 with different concentrations (1%, 4 %, 7%, and 10%) on increasing the low thermal conductivity of paraffin wax. According to the findings, increasing the concentration of nanoparticles hastened the melting process even further. The biggest increase was obtained with the highest used concentration of 10%, with a 33% improvement in thermal conductivity and a 10% reduction in melting time, respectively. Teng and Yu [10] added silica, alumina, titania, and zinc oxide to paraffin wax at different concentrations (1%, 2%, 3%) to investigate the impacts of different nano-additives concentrations on the performance of heat conduction and thermal energy storage, The results of the experiments revealed that titania was more efficient than other additions in enhancing of heat conduction. Chaichan et.al [11] studied experimentally the improvement of paraffin wax's thermal conductivity with (1%, 2%, 3%, 4%, and 5%) mass fraction of alumina (Al_2O_3) and (TiO_2) during the discharging and charging process, The findings indicated that adding Al_2O_3 improved the thermal conductivity even at low concentrations as 1%, the same effect can be seen when nano TiO_2 was added, except that the relative increase was less than that of nano-Al_2O_3. Pradeep et al. [12] investigated experimentally the impact of adding silver nanoparticles on the charging/discharging characteristics of paraffin wax, The results revealed that very small quantities of silver nanoparticles reduced the charging/discharging temperatures of paraffin wax. Hiba and Ihsan [13, 14, 15, and 16] investigated experimentally and numerically the performance enhancement of CTESS. The results showed that adding metal foam to both STES and, Cascade Thermal Energy Storage (CTES) System reduced the time of the melting /solidification process compared to using pure PCM. Previous researchers conducted numerical and experimental investigations to improve the thermal characteristics of Phase Change Material (PCM), The current study provides a numerical analysis of the changes in thermophysical properties of paraffin wax caused by nanoparticle dispersion, in which charging and discharging processes were studied for paraffine wax with and without the addition of nanoparticles in different concentrations.

2. Physical Model and Mathematical Formulation

The physical model of the TES system was numerically implemented in 2D. The two cases for which a numerical analysis of melting and solidification was performed and compared are as follows: pure paraffin wax and nanoparaffin wax spread with (1%, 3%, 5%,7%, and 10%) by volume of Al_2O_3 as shown in figure (1). The Heat Transfer Fluid (HTF) is air passing through the lower and upper of air passages, at different HTF velocities (1, 3, 5, 7, and 10 m/s) and exchanging heat with PCM along its flow path.



(a)

(b) (c)

Figure (1): (a) Dimensions of model, (b) Model 1 (pure PCM), (c) Model 2 (Nano PCM)

»Assumptions

The following assumptions were made to solve the governing equations by ANSYS FLUENT [9]:

- The melted PCM was considered Newtonian and incompressible,
- A fluid motion was considered to be laminar, and unsteady with negligible viscous dissipation, while the HTF was considered a turbulent flow.
- Volume change of PCM was negligible, also the volume difference between nanoparticles and pure paraffin wax was neglected because NanoPCM was regarded as a homogenous material.
- The thermophysical properties of HTF and PCM were independent of temperature (except the density of PCM),
- The Natural convection is simulated by using the Boussinesq approximation, and gravitational acceleration would be along the y-axis;

$$\rho = \rho_0\,[(1-\gamma(T-T_0)] \qquad .....(1)$$

Where γ is the thermal expansion coefficient, ρ is the local PCM density,ρ_0 is the operating density T_0 is the operating temperature.

»The governing equations

The governing equations for the Nano-PCM can be formulated using the above assumptions as [17] ;

Continuity equation ;

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho\,\vec{V}\,) \qquad .....\ (2)$$

Momentum equation;

$$\rho\frac{\partial \vec{V}}{\partial t} + \rho\,(\vec{V}.\nabla)\vec{V} = -\nabla P + \mu\,\nabla^2\vec{V} + \rho\vec{g}\,(T - T_0) + \vec{S} \qquad .....\ (3)$$

Energy equation;

$$\frac{\partial}{\partial t}(\rho h) + \nabla.(\rho\,\vec{V}\,h) = \nabla.(k\,\nabla T) + S \ .....\ (4)$$

Where $\vec{V}$ is the velocity of the liquid PCM, ρ is the density, P is the pressure, μ is the dynamic viscosity, ,$\gamma$is the thermal expansion coefficient, $\vec{g}$ is the gravity vector, $\vec{S}$ is the momentum source term, S is the term of the volumetric heat source, and T_0 is the reference temperature. The enthalpy h in equation (4) can be expressed as;

$$h = h_{ref} + \int_{T_{ref}}^{T} C_p\,dT + \beta L \qquad .....\ (5)$$

Where T_{ref} is the reference temperature, while the enthalpy at the reference temperature is indicated by h_{ref} , L is the latent heat and C_p is the specific heat of the liquid PCM. The liquid fraction is indicated by β and it is defined as ;

$$\beta = 0 \qquad \text{if} \qquad T < T_{solidus}$$

$$\beta = 1 \qquad \text{if} \qquad T > T_{liquidus} \qquad .....\ (6)$$

$$\beta = \frac{T - T_{solidus}}{T_{liquidus} - T_{solidus}} \ \text{if}\ T_{solidus} < T < T_{liquidus}$$

The momentum source term in the enthalpy–porosity formulation is used to treat different phases as porous media, and it is given by the following equation;

$$\vec{S} = \frac{(1-\beta)2}{(\beta^3+\varepsilon)}\,A_{mushy}\,\vec{V} \qquad .....\ (7)$$

Where ε is a tiny number, often around 10^3, that is used to prevent division by zero. and A_{mushy} is called the mushy zone constant defines how sharply the velocity is reduced to zero when the substance solidifies and its amount varies from 10^4 to 10^8 kg/(m^{3}s), (10^5 was pointed for the present study). S is the volumetric heat source, given by the following equation [18];

$$S = \frac{\partial(\rho\,\nabla\,h)}{\partial t} + \nabla.(\rho\,\vec{V}h) \qquad .....\ (8)$$

»Thermophysical Properties

The thermophysical properties of the nano-PCM were simulated using a single-phase model, thus the nano-PCM is treated as a homogeneous fluid with no dynamic difference between the paraffin wax and nanoparticles. The nano-PCM volume concentration is the ratio of the volume of the alumina nanoparticles to the volume of the full domain [4];

$$\emptyset = \frac{Vol_{nano}}{Vol_{total}} \qquad .....\ (9)$$

The thermophysical properties of nanoparticles and paraffine wax were listed in Table 1. The density, the heat capacity, and the latent heat of the nanocomposite phase change material are defined by the following equations [19];

$$\rho_{npcm} = \emptyset\,\rho_{np} + (1-\emptyset)\rho_{pcm} \qquad .....\ (10)$$

$$C_{P,nano} = \frac{\emptyset\,(\rho\,C_p)_{np} + (1-\emptyset)\,(\rho C_p)_{pcm}}{\rho_{npcm}} \qquad .....\ (11)$$

$$L_{npcm} = \frac{(1-\emptyset)(\rho L)_{pcm}}{\rho_{npcm}} \qquad .....\ (12)$$

The dynamic viscosity and Boussinesq term of the nanoPCM, are determined in the following manner [20] ;

$$\mu_{npcm} = \frac{\mu_{pcm}}{(1-\emptyset)^{2.5}} \qquad .....\ (13)$$

$$\rho\gamma_{npcm} = (1-\emptyset)\big(\rho\gamma_{pcm}\big) \qquad .....(14)$$

And the Maxwell equation is used to compute thermal conductivity;

$$K_{npcm} = K_{pcm}\,\frac{K_{np} + 2K_{pcm} - 2\emptyset\,(K_{pcm} - K_{np})}{K_{np} + 2K_{pcm} + \emptyset(K_{pcm} - K_{np})} \qquad .....(15)$$

Where pcm, np, and npcm are indicated the physical properties of paraffin wax, nanoparticles, and Nano-PCM, respectively. $\emptyset$ is the nanoparticle volume fraction.

Table (1): Thermal properties of used PCM and Al2O3.

Properties	PCM	Al_2O_3
Melting temperature [K]	334	/
Solidus density [kg/m^3]	852.14	3600
Liquidus density[kg/m^3]	766.11	/
Specific heat [J/kg K]	2900	765
Thermal conductivity[W / m K]	0.265	36
Dynamic viscosity [kg/m s]	0.0121	/
Thermal expansion coefficient [1/K]	0.000305	/
Latent heat [J / kg]	270715	/
Solidus temperature [K]	324	/
Liquidus temperature [K]	338	/

3. Computational Methodology

The geometry and mesh of the present problem were originated by the GAMBIT 2.4.6 program, then exported to fluent for analysis after achieving a successful mesh. For mesh-independent solutions, seven different grids with spacing 0.1, 0.5, 1, 2, 4, 6, and 8mm were tested, and the compared results show that spacing 1mm was appropriate, because they provide the best trade-off between solution accuracy and computing cost, as shown in figure (2). The transient analysis was carried out using a time step size of 1 sec. HTF flow is turbulent, thus an appropriated turbulence is required, the standard k-epsilon model is adopted. The pressure based method was utilized for solving the governing equations For modeling the melting and solidification process, FLUENT employs an enthalpy-porosity method. In each iteration of this technique, the liquid melt fraction in each cell is calculated using enthalpy balance. The mushy zone (defined in the temperature range between Tliquidus and Tsolidus), is the region where the porosity of the PCM grows from 0 to 1 when it melts. A zone's porosity and flow velocity are both equal to zero when it is entirely solid, which also signifies that region.

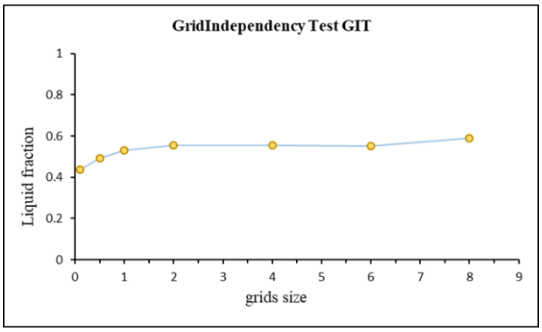


Figure (2): GridIndependency Test GIT

» Boundary Condition

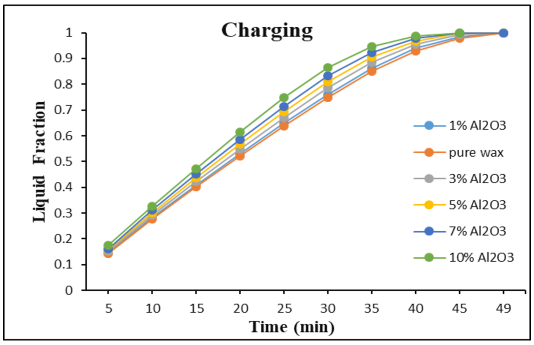
Inlet: inlet temperature was (373K, 294K) for the charging and discharging processes, respectively. For HTF at both entrances, a velocity inlet boundary condition type was chosen.

Outlet: The pressure outlet type was selected as the boundary condition type for HTF at both outlets. Wall: except for the walls that were between HTF and PCM, all walls were assumed to be insulated.

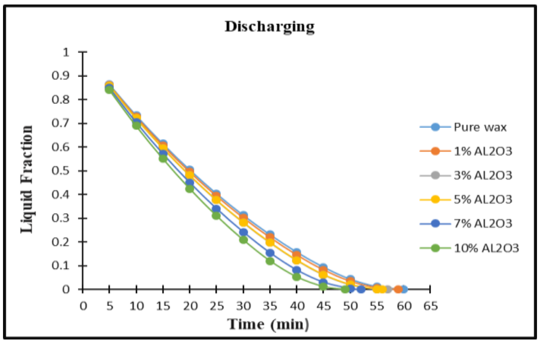
4. Results and Discussion

»Effect of the Nanoparticles on the Melting and Solidification Process

To understand the influence of dispersing the nanoparticles on the performance of the PCM, the charging and discharging rates of paraffin wax with and without alumina particles are examined. Figure (3) shows that when the concentration of nanoparticles increases, the liquid fraction tends to grow faster. and the greatest improvement was obtained with the highest concentration of (10%) and this is very agreed with the results of Hiba [9]. The comparison between the present study and the data that was investigated by (Hiba) was shown in Figure(4). and this comparison was taken at the same time and velocity (3 m/sec) for the charging process. Increasing the concentration of nanoparticles leads to a decrease in melting rate since at the beginning of the process conduction is the major heat transfer method because of the thin melt layer, which made buoyancy force very weak, so when conduction heat transfer is prominent, the addition of nanoparticles to the PCM increases the effective thermal conductivity of the nanoPCM, which reduces the melting time significantly. also, latent heat reduces the melting time and speeds up the heat transfer process since, The PCM's latent heat of fusion is decreased by the nanoparticles' presence., indicating that less energy is required for melting. As time passes, a layer of melt PCMs forms in contact with the air, and gravity causes the solid PCMs with higher density to sink to the bottom, while the less dense liquid PCMs rise to the top, resulting in natural convection. Unlike the melting process shown in figure (3), The time necessary for discharging process is projected to be longer than that required for the charging process. Adding alumina nanoparticles by different volume fractions in the case assisted with velocity 3 m/sec needs about (50-44) minutes to melt completely depending on concentration, and needs about (60-49) minutes to solidify completely. Because, the solidification process, contrary to the charging process, is controlled by conduction.



(a)



(b)

Figure (3): Average liquid fraction for Nanopcm with different concentrations for (a) Charging (b)Discharging.

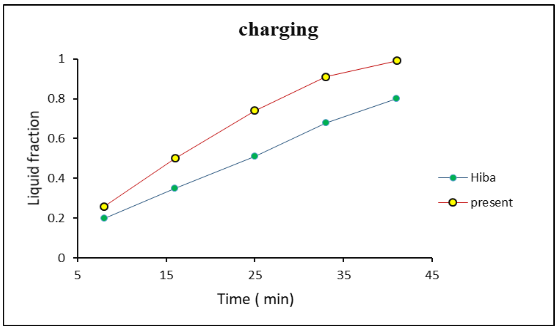
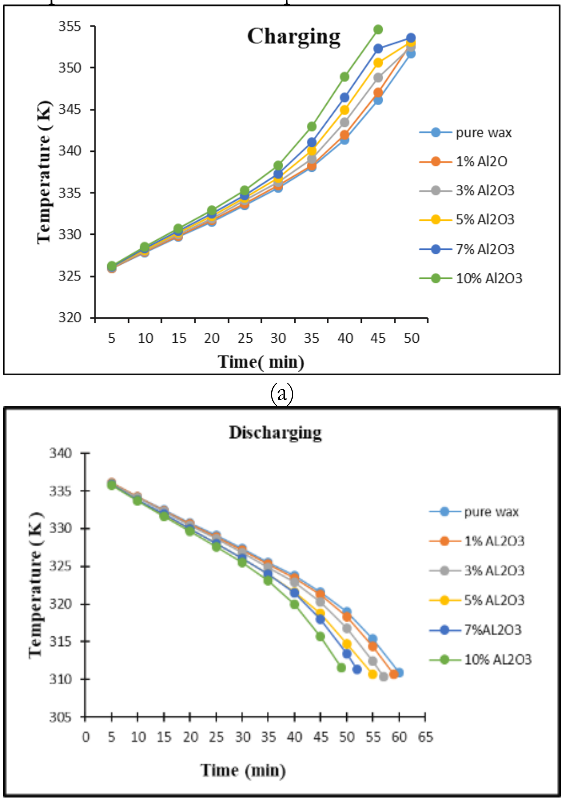


Figure (4): Comparision between the present work and Hiba [13] for the charging process.

The thermal conductivity of paraffin wax increases when nanoparticles are dissipated in it, As a result, more heat is transferred from the PCM to the heat transfer fluid, which speeds the discharging process. The result also shows that for both the melting and solidification process the inclusion of nanoparticles does not make a significant difference in the early phases of the charging and discharging process, but the percentage of solidification and melting increases as time passes. When heat transmission from the air to PCM stopped, the charging and discharging process was complete. The temperature distribution of the charging and discharging process for PCM and nanoPCM with a velocity of 3 m/sec is shown in figure(5). For the melting process, it was noted that paraffin wax with the highest used concentration of (10%) melted quickly compared to other concentrations, the same effect can be seen for discharging process, where the temperature continuously reduced during discharging until it reached the separation temperature between melting and solidification point.

»Effect of Velocity and Heat Transfer Enhancement for Charging and Discharging Process

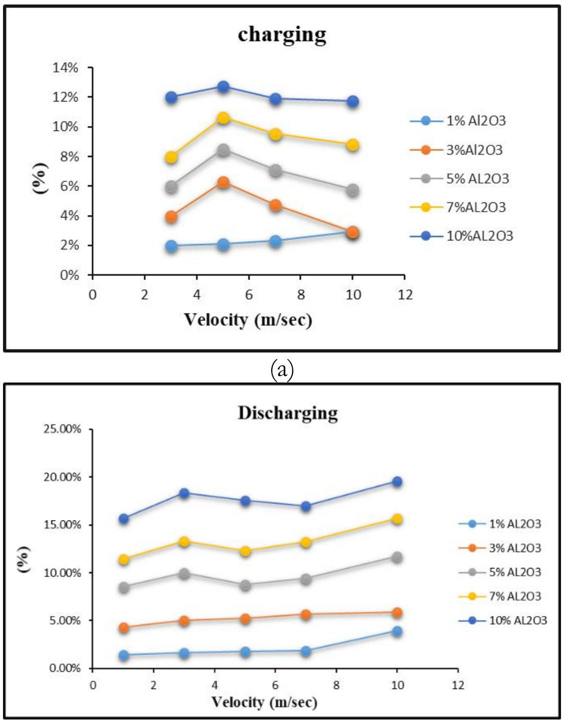
The velocity of HTF has a major role in the charging and discharging processes. From figure (6) it is noted that raising nanoparticles concentration to (10%) leads to an improvement in melting time by (12%, 12.76%, 11.904%, and 11.764%) for (3, 5, 7, and 10 m/sec), respectively. It is also obvious from the figure that we couldn't determine the percentage of improvement with a velocity of (1 m/s) because the melting isn't complete at that velocity for pure wax and the time isn't known, where the velocity of (5 m/sec) gave the highest improvement that is (6.3 %, 8.5%, 10.63%, and 12.76%) for (3%, 5%, 7%, and 10%) concentration, respectively compared with the single paraffine wax at the same velocity, this is observed for all concentrations of nanoparticles except at first concentration, where the highest improvement was achieved with the velocity at (10 m/sec). From the same figure, which is at the solidification process with the same velocity and the same concentrations, it displayed that dispersing Al_2O_3 nanoparticles of volumetric concentrations of (1% - 10%) results in a total saving time between (1.34% to 19.61%), where a velocity at (10 m/sec) with the different concentration of nanoparticles are more effective in enhancement solidification time than other cases. Influences of the different HTF inlet velocities on solidification and melting rates are presented in figure (7), the charging and discharging rates decrease with the flow velocity increase when the HTF inlet temperature is constant, and under different concentrations of nanoparticle, in the case of (10%) concentration, the charging time is (56, 44, 41, 37, and 30 min) corresponding HTF inlet velocity of (1, 3, 5, 7, and 10 m/sec), respectively. This is similar to what was observed in discharging process, where it is noted in the case of (10%) concentration, the solidification time is (59 min) at (1 m/ sec), while at the same concentration and at the different HTF inlet velocity the paraffin wax needs less time to complete the solidification process.



(a)

(b)

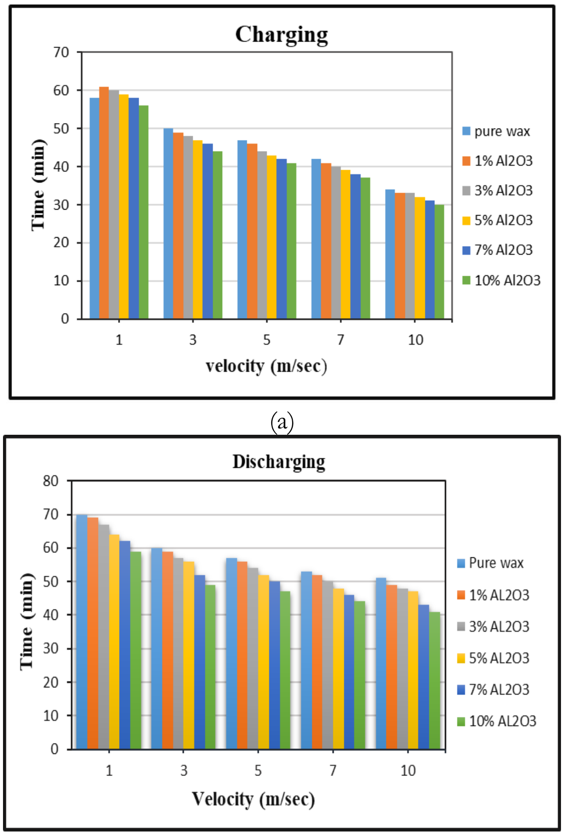
Figure (5): Average temperature for Nanopcm with different concentrations for (a)Charging (b)Discharging



(a)

(b)

Figure (6): The percentage enhancement for (a) Charging (b)Discharging

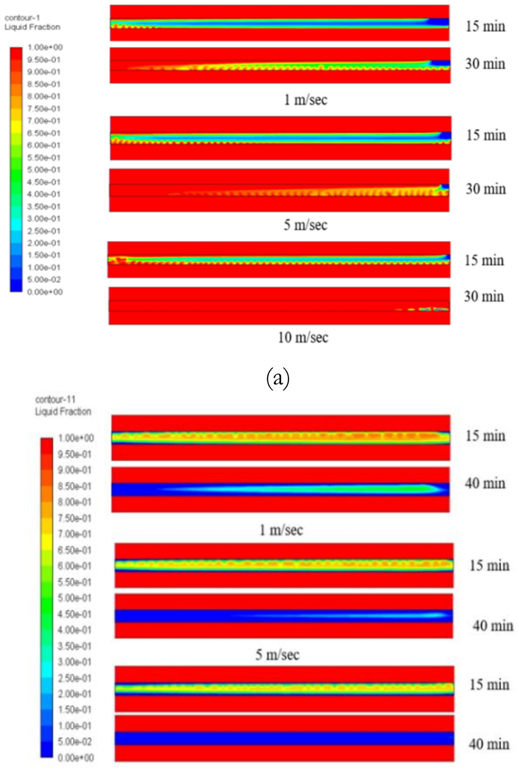


(a)

(b)

Figure (7): (a) Comparison of time for charging process (b) Comparison of time for discharging process

The liquid fraction contoured has been displayed in figure (8), at (10%) volumetric concentrations. In general, it can be noticed that increasing the velocity decreases the time required to complete the solidification and melting process. The temperature contours of melting paraffin wax dispersed with nano alumina particles and at (1, 5, 10 m/sec) of HTF velocity, are represented in figure (9), which is show that the temperature distribution in PCMs is much faster with an increased HTF inlet velocity, especially at (10%) volumetric concentrations, and the same thing for discharging process.



(a)

(b)

Figure (8): Liquid fraction contours of Nanopcm at (10%) concentrations for (a) Charging process, (b) Discharging process.

5. Conclusions

In this work, transient simulations have been carried out for the charging and discharging process of paraffin wax dispersed with different concentrations (1%, 3%, 5%, 7%, and 10%) of Alumina nanoparticles (AL_2O_3). The results show that raising nanoparticles concentration to (10%) leads to an improvement in the ending of melting time by (12%, 12.76%, 11.904%, and 11.764%) corresponding to HTF inlet velocity of (3, 5, 7, and 10 m/sec), respectively. While in discharging process dispersing Al_2O_3 nanoparticles of volumetric concentrations (1% - 10%) results in the total saving time between (1.34% to 19.61%), where a velocity at (10 m/sec) with the different concentration of nanoparticles are more effective in enhancement solidification time than other cases.

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Nomenclature

STES = Single Thermal Energy Etorage
TES = Thermal Energy Storagr
LTHES = Latent Heat Thermal Energy System
CTES = Cascade Thermal Energy Storage
PCM = Phase Change Material
HTF = Heat Transfer Fluid

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