

Prediction of Behavior of Thermal Storage, PV-Thermal Solar Collector with Nanofluids and Phase Change Material

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Abstract

This study is intended to present a numerical model that was established after the energy conservation equations coupled with the heat transfer equations to predict the behavior of different phase change materials, paraffin under the effect of different operating conditions such as solar radiation, heat transfer fluid, using nanofluids; Al₂O₃, CuO, Fe₃O₄ and SiO₂, at different concentrations, and heat transfer fluid temperatures. Also, the effect of the aforementioned operating conditions on the thermal storage process and PV-Thermal hybrid system performance as well as the thermal energy conversion efficiency is presented and discussed. It has been observed during the phase charging process of the kinds of paraffin that the nanofluid Al₂O₃ used as heat transfer fluid exhibited the longest time compared to other nanofluids and water as base heat transfer fluid. Also, the results indicated that the nanofluid Fe₃O₄ had the shortest time consumed during the phase charging process under solar radiations; 500, 750, 1000 and 1200 w/m². Besides, it was found the higher the nanofluid concentration the longer the time to reach a liquid fraction of 100% compared to water as heat transfer fluid and less thermal load is needed to reach the threshold of phase change. Finally, the presented numerical model compared fairly with published experimental data.

Keywords — PV-Thermal; Thermal storage; Phase change materials; Nanofluids; Numerical modeling; model validation

I. INTRODUCTION

Recently, thermal energy storage (TES) is considered as a major player in practical and rational and policy and planning of energy usage. The key important factors to viable solar thermal energy storage are Phase change materials (PCMs) and Heat Transfer Fluid (HTF) [1] through [35]. Phase Change Materials (PCMs) can absorb and release a large amount of thermal energy as latent heat during the phase change at a reversible quasi-isothermal process. Paraffin as a PCM is widely used as thermal storage material due to its availability and performance at large temperatures

range [7-12]. Nanofluids exhibit superior heat transfer characteristics to conventional heat transfer fluids such as water. One of the main reasons is that the suspended particles remarkably increase the thermal conductivity of nanofluids. The thermal conductivity of nanofluid is strongly dependent on the nanoparticle volume fraction. Therefore, the use of nanofluids as a heat transfer fluid with the phase change material can significantly enhance the thermal energy storage process

Nanofluid is a heat transfer fluid which allows more heat to be absorbed from the solar system collector. The use of nanoparticles with the base fluids is intended to enhance the thermal conductivity which results in a higher heat transfer coefficient as well as higher thermal efficiency. Adding solid nano-size particles to base fluid such as water at small volume concentration has many advantages compared with water as heat transfer fluid other than the improved thermal and thermos-physical properties such as specific heat, density thermal diffusivity and thermal conductivity of the heat transfer fluid and heat transfer properties, which yields to higher solar receiver efficiency. Very recently, Nuria et al [12] reported on the thermal energy storage of solar salt (60% NaNO₃ - 40% KNO₃) that was improved by adding a phase change material composed of Al-Cu alloy nano capsulated with an aluminum oxide layer. He demonstrated that the total thermal energy storage was enhanced up to 17.8% at constant volume basis comparison. Besides, the thermal conductivity of the nanofluid was increased when adding the nanoparticles improving its heat transfer performance.

A novel class of nanofluid phase change materials (NFPCMs) has been presented by Kumaresan et al [13] on dispersing multiwalled carbon nanotubes (MWCNTs) in water with sodium dodecyl benzene sulfonate (SDBS) as the surfactant with volume fractions of 0.15, 0.3, 0.45, and 0.6 in water. Their work showed that an enhancement in thermal conductivity increased with MWCNT concentration and reduction in supercooling with the addition of MWCNTs in water.

Azwadi et al. [14] presented a complete review paper, on recent progress work on cold thermal storage, PCM-CTES and numerical and experimental studies on the heat transfer performance of different base fluid of PCMs. The paper Azwadi et al. also

discussed the different factors affecting thermophysical properties of PCMs, such as nanoparticles enhanced PCMs, shape of encapsulated PCM volume fraction and particle size.

A Ph D thesis dealt with problems of the modeling of nanophenomena has been presented by MacDevette, [15]. The thesis used the Heat Balance Integral Method (HBIM), as an approximate solution analytical method. The author discussed the analysis of the boundary layer flow of a nanofluid and showed that Brownian motion, thermophoresis of heat transfer mechanisms and heat transfer decreases with nanoparticle concentration, which is contrary to the results that have reported in the literature.

The review paper presented by Gopalakrishnan et al [16] provided an overall of the types of thermal energy storage systems, enhancement techniques of the thermal conductivity and a general assessment of the TES. It also discussed the main challenges for the use of nanofluids in TES, Brownian motion of nanoparticles and stability of nanofluids.

Addad, et al. [17] studied the thermal effects of using nanofluid as a heat transfer fluid (HTF) in a thermocline-type packed-bed energy storage tank filled with spherical phase-changing material (PCM) capsules. Fortran code has been developed and validated using existing experimental and numerical data. His work showed that use of a nanofluid as HTF was able to accelerate the charging and discharging periods, and positively impacted the thermal storage efficiency.

A paper presented by Pise et al [18], to study the enhancement of the performance of paraffin wax with nano alumina (Al_2O_3) particles in the mass fraction of 1, 3, and 5% in a Thermal Energy Storage (TES) System at a constant flow rate and variable temperature of heat transfer fluid (HTF). Reference [18] studied the effect of alumina nanoparticle on the total cyclic time of TES for a different mass fraction. Commercially available paraffin wax was used as a phase change material (PCM). The results illustrated that the suspended nanoparticles substantially increased the heat transfer rate and also the nanofluid heat transfer rate was increased at higher nanoparticles mass fractions.

Sami and Marin [19] recently developed a simulation model to predict the behavior of a hybrid system composed of PV-Thermal panel and thermoelectric generator using nanofluids; Al_2O_3 , CuO, Fe_3O_4 , and SiO_2 . The model has been based upon the energy and mass conservation equations for nanofluids flow, the dynamic behavior of the PV-Thermal solar panels, and thermoelectric generator. The model prediction fairly compared with existing data. Huijin and coworkers [30 through 35] presented significant results on PCM with and without a porous medium to show that the solid-liquid interface of pure PCM in the line area and the mushy area. Their

findings showed that the heat transfer by natural convection in the melting liquid was significant for a PCM without a porous medium. They have also reported that the porous medium weakened the heat transfer by natural convection, however, it made the profile of the temperature field, flow field and solid-liquid interface distribution more homogeneous. They also concluded that the metal foam can greatly improve the heat storage process and its rate of a PCM.

Our study is intended to present a numerical model to investigate the phase change material and the thermal storage process driven by a PV-Thermal solar hybrid system under different conditions including solar radiations. In the following, we present a mathematical model for predicting the behavior of the thermal storage process using phase change material (PCM) and nanofluids as the heat transfer fluid in an integrated PV-thermal solar panel loop. The model was established after the energy conservation coupled with the heat transfer equations. This model was intended to study the effect of different operating conditions such as solar radiation, working fluid flow rates, nanofluids, and paraffin wax temperatures on the thermal storage process and system performance as well as the thermal energy conversion efficiency. The practical application of this study is enhancing the heat transfer process and thermal storage in solar energy systems which are one of the most important and critical issues to achieve a better performance of these systems with compact designs and higher efficiency.

II. MATHEMATICAL MODEL

In this section, we present the mathematical model describing the behavior of the thermal storage process using PCM and nanofluids. As depicted in Figure.1. The system was composed of a PV-Thermal solar panel, thermal tank, paraffin wax as PCM and nanofluids heat transfer loop. The thermal tank with paraffin had a diameter of 0.49 meters and a length of 0.90 meters. The thermal tube inside the paraffin wax had 0.02 diameter and length of 7.6 meters. The volume of the paraffin wax was 0.0169 m³. The heat transfer fluid circulated in thin tubes that were welded to the backside of the PV solar panel to absorb the heat dissipated from the solar radiation energy conversion process in the PV panel. The phase change material PCM was paraffin wax. The paraffin wax was embedded in the thermal tank as shown in Figure.1. The proposed model was based on the following assumptions: PCM was a homogeneous and isotropic, the HTF with nanofluids was incompressible and it can be considered as a Newtonian fluid, inlet conditions were assumed constant. Initially, PCM was in the solid-state phase, thermophysical properties of the HTF with nanofluids and the PCM were also assumed constant.

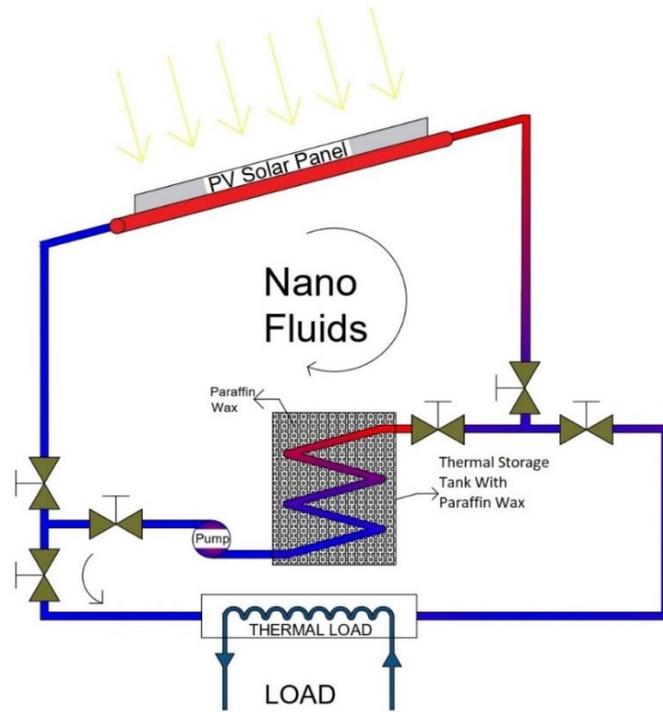


Figure 1. Thermal storage using nanofluids.

III. SOLAR PV MODEL

The PV solar panels' electric circuit was composed of a load controller, batteries, and inverter. The output voltage of the PV solar circuit was DC power and was converted into AC power using the inverter. The AC power of the inverter output $P(t)$ of the PV solar panels was calculated using the following equation (1) with the inverter efficiency η_{inv} , output voltage between phases, neutral V_{fn} , and for single-phase current, I_o and the power factor, $\cos\phi$ as follows;

$$P(t) = \sqrt{3}\eta_{inv}V_{fn}I_o\cos\phi \quad (1)$$

Interested readers in the calculation of the different terms of equation (1) are advised to consult Sami and Edwin [19] and references [20-21] for further details.

A. Thermal Energy Incident in a PV cell:

The thermal energy dissipated and transferred from the PV solar panels to the Heat Transfer Fluid (HTF) can be determined from the following heat balance in terms of heat transfer mechanisms; conduction, convection and radiation as follows [19-21].

$$Q_{conduction} = Q_{convection} - Q_{radiation} \quad (2)$$

Where,

$Q_{conduction}$: Thermal heat transferred by conduction

$Q_{convection}$: Thermal heat transferred by convection

$Q_{radiation}$: Thermal heat transferred by radiation

Interested readers in the calculations of the various terms in the heat balance equation (2) are advised to consult reference [19-21].

The finite-difference formulation has been implemented to determine the HTF flow rate and its temperatures at each element. Each element was considered in the finite element analysis as a finite control volume. The thermal energy dissipated from the back of the PV cell to the heat transfer fluid (HTF) was obtained by the following equation, [19].

$$Q_{Thermal} = \dot{m}_w \times C_{p_water} \times \Delta T (T_{fHx+1} - T_{f_In}) \quad (3)$$

Where. (1)

$Q_{Thermal}$: Heat from the thermal process

T_{fHx+1} : Fluid temperature at thermal element (f+1)

T_{f_in} : Fluid temperature at thermal element (1)

\dot{m}_w : mass flow rate of HTF

IV. THERMAL STORAGE AND PHASE CHANGE MATERIAL (PCM):

The phase change material experienced three phases: solid-state, liquid state and mushy state. The solid and liquid phases have sensible heat additions, however, the mushy phase has latent heat addition.

The heat released from the HTF to the Phase Change Material (PCM) can be written as follows, [10, 11],

$$\rho_{PCM} V_{PCM} C_{p_{PCM}} \frac{\Delta T_{PCM}}{\Delta t} = Q_{tub} = m_w C_{p_w} \Delta T_w \quad (4)$$

Where; ΔT_w : The heat transfer fluid temperature difference

ΔT_{PCM} : The phase change material temperature difference. And Q_{tub} : Heat transfer per tubes (kJ)

And ρ_{PCM} , V_{PCM} , Cp_{PCM} are the density, volume and specific heat of the phase change material (PCM), respectively.

m_w , Cp_w Are the mass flow rate of the HTF water-based and the specific heat of the HTF, respectively.

The heat balance for the heat exchanger tube in the thermal tank can be formulated as follows [10, 11].

$$(T_{in} - T_{out})Cp_w m_w = 2\pi Rlh(T_{in} - T_{sfc}) \quad (5)$$

Where, h Represents the heat transfer coefficient HTF and the phase change material and R , l are the tube radius and length of the tube, respectively.

Readers interested in the calculation of the heat transfer coefficient in Equation (5) are advised to consult references [10, 11] for further details.

A. Charging phase process:

During the charging phase of the phase change material PCM, the HTF mass flow rate can be calculated from the thermal heat released from PV-Thermal solar panel and absorbed by the PCM as per Equation (4). The phase change material in the thermal tank was divided into different elements. Each element was treated as a discrete control volume. During the phase change process, phase change material experienced a phase change from liquid to mushy and solid while storing the heat absorbed during the charging process. The finite-difference formulation was used to determine the different temperatures of the phase change material as per the following equations.

B. Solid-phase:

$$T_{PCM_{m+1}} = T_{PCM_m} + \frac{m_w Cp_w \Delta T_w}{\rho_s V_{PCM} Cp_s} \Delta t \quad (6)$$

Where, T_{PCM_m} , The temperature of PCM at m element ($^{\circ}C$)

Finite difference formulation can also be applied to determine the phase change material characteristics in the mushy and liquid phases as follows.

C. Mushy-phase:

$$\gamma_{m+1} = \gamma_m + \left(\frac{m_w Cp_w \Delta T_{w,mushy}}{\rho_L V_{PCM} h_L} \right) \Delta t \quad (7)$$

Where, γ_m , a Liquid fraction at m element(%), ΔT_w , the temperature difference in the mushy varied between 3-9 $^{\circ}C$ depending upon the melting point of the type of phase change materials displayed in Table -1

The heat transferred per tube to the phase change material is.

$$Qtub = \rho_L V_{PCM} h_L \gamma \Delta t \quad (8)$$

D. Liquid-phase:

The PCM liquid temperatures can be calculated as.

$$T_{PCM_{m+1}} = T_{PCM_m} + \frac{m_w Cp_w \Delta T_w}{\rho_L V_{PCM} Cp_L} \Delta t \quad (9)$$

E. Discharge phase process:

During the discharge process, phase change material experienced phase change from liquid to mushy and solid while yielding heat absorbed during the charging process. The water mass flow rate of heat transfer fluid during the discharge process can be calculated.

$$m_w = \frac{Q_{charging}}{Cp_w \cdot \Delta T_w \cdot n} \quad (10)$$

Therefore, the total heat absorbed $Q_{charging}$ during the charging process by the phase change material during solid, mushy and liquid phases can be given by;

$$Q_{charging} = m_{PCM} (Cp_s \Delta T_s + h_L + Cp_L \Delta T_L) \cdot n \quad (11)$$

Where:

m_{PCM} : The mass of PCM per finite different element
 n : represents the number of finite different elements of the phase change material

V. NANOFUID HEAT TRANSFER FLUID

The thermophysical, thermodynamic and heat transfer properties of the HTF with nanoparticles can be calculated as a function of the volumetric concentration of the nanoparticles flowing in the fluid flow as follows.

$$\alpha_{total} = \alpha_{particles} + \alpha_{base\ fluid} \quad (12)$$

Where α represents a particular thermophysical property of the nanofluid.

The nanofluid thermal and thermophysical properties can be evaluated in terms of the base fluid heat transfer as follows.

$$\alpha_{total} = \alpha_{base\ fluid} + \alpha_{particles}(\Phi) \quad (13)$$

Where Φ represents the nanoparticle's volumetric concentration.

The following relationship presented in Equation (14) was used to determine the specific heat of the nanofluids in terms of the thermal conductivity, thermal diffusivity and density of the nanofluids as per references [19, 22, and 23].

$$\lambda = \alpha \rho Cp \quad (14)$$

Where Cp is the specific heat, α is the thermal diffusivity, λ and ρ represent the thermal conductivity and density, respectively.

Interested readers in further details of the calculation of thermodynamic and thermophysical properties such as specific heat, density thermal diffusivity and thermal conductivity of nanofluids are advised to consult references [19, 22, 23, 29 through 35].

VI. NUMERICAL PROCEDURE

The model presented in equations (1) through (14) to describe the energy conversion process taking place during the charging and discharging of thermal storage in the PCM using a finite-difference element scheme was presented in Figure.2. Numerical calculation procedure started with the initiation of the dependent

and independent parameters of solar radiation, geometrical configuration, thermodynamic and thermophysical properties of the base fluid, nanofluids and phase change material paraffin as per Figure.2. This was followed by solving the mass and energy equations during charging and discharging processes written in finite-difference formulation under different boundary conditions for the base fluid water and different nanofluids under investigation. Iterations were performed using MATLAB iteration techniques until a converged solution was reached to an acceptable iteration error. Finally, the thermal energy stored in the phase change material was determined and the impact of nanofluids on the charging and discharging phase processes was also assessed.

VII. DISCUSSION AND ANALYSIS

Equations (1) through (14) have been numerically solved in finite-difference formulation for the energy conversion during the charging and discharge processes of phase change materials paraffin in the hybrid system of PV-Thermal solar collector under consideration. However, only the impact of nanofluids; Al₂O₃, CuO, Fe₃O₄ and SiO₂ on the phase charging process of the phase change materials of three kinds of paraffin as per Table.1 will be presented and discussed hereby at different nanofluids concentrations and water as base heat transfer fluid. The different phase change materials paraffin wax presented in Table [1] were considered in this study because of their commercial availability and the availability of their thermal and thermophysical properties [10, 11]. It is worthwhile noting that the temperature variation was taken into consideration in the calculation of the specific heat of the phase change material paraffin wax [8, 10, and 11] in the numerical simulations. In the following sections the predicted results were presented for different types of phase change materials, paraffin; under different inlet conditions such as solar insolation, heat transfer fluid flow rates circulating from the PV-Thermal solar collector, heat transfer fluid temperatures and various nanofluids at different volumetric concentrations. In the numerical simulation, 108 PV solar panels were assumed with 120 watts per each PV solar panel. Solar radiations were taken as 500 w/m², 750 w/m², 1000 w/m² and finally 1200 w/m².

A typical temporal thermal heating load during the charging process of the phase change process is presented in Figure.3 and Figure. 4 at solar radiation of 750 W/m² for phase change material paraffin 1, 2 and 3 using water as heat transfer fluid. Results displayed in these figures showed that the amount of heat transferred from the heat transfer fluid to the paraffin changed the material phase from solid phase to mushy phase and finally to a liquid phase where thermal energy was stored. This heat transfer transferred to the phase change material depended upon the condition of the paraffin wax initially, paraffin thermal properties, heat transfer temperature profile, the heat transfer fluid thermal properties, and the solar radiation. Also, it can

be seen from these figures that the time to complete each phase change depended upon the type of paraffin, and its thermal properties, as well as the thermal energy, absorbed. Furthermore, the comparison presented in Figure. 4 demonstrated that paraffin 1 absorbed a higher quantity of heat compared to the other kinds of paraffin under investigation. This comparison demonstrated that paraffin 1 has a higher thermal energy storage capacity more than the other kinds of paraffin. This is an important desired characteristic in the thermal energy storage process.

Table 1. Paraffin Wax Properties [10, 11].

Paraffin PCM 1	
Melting point	46.7 °C
Specific heat (Solid)	2.89 kJ/kg°K
Specific heat (Liquid)	2.89 kJ/kg°K
Density (Solid)	947 kg/m ³
Density (Liquid)	750 kg/m ³
Latent heat	209 kJ/kg
Paraffin PCM 2	
Melting point	41 °C
Specific heat (Solid)	2.48 kJ/kg°K
Specific heat (Liquid)	2.76 kJ/kg°K
Density (Solid)	29 kg/m ³
Density (Liquid)	765 kg/m ³
Latent heat	288 kJ/kg
Paraffin PCM 2	
Melting point	37 °C
Specific heat (Solid)	1.82 kJ/kg°K
Specific heat (Liquid)	2.17 kJ/kg°K
Density (Solid)	911 kg/m ³
Density (Liquid)	799 kg/m ³
Latent heat	201 kJ/kg

Values displayed in Table -1 of specific heat of and the latent heat of fusion for the different kinds of paraffin obtained from references [10, 11].were considered in the calculations.

To illustrate the impact of solar radiation on the thermal energy storage and phase change material process, Figure. 5, has been constructed where the thermal capacity of the paraffin 1 was displayed at different solar radiations; 500, 750, 100 and 1200 W/m². The results in this figure demonstrated that the higher the solar radiation the higher the thermal energy absorbed by the paraffin 1 and also the higher the thermal energy storage. This can be attributed to the fact that during the melting process, the higher solar radiation absorbed by the PV solar panels that resulted in higher heat transfer by convection to the heat transfer fluid circulating in the heat exchanger tubes soldered under the PV solar panels. This heat transfer by convection became very significant and resulted in an increase in heat transfer rate transferred to the PCM and caused a higher liquid fraction that accelerated the melting process of from the solid phase into latent/muchly phase to a liquid phase. It also can be

observed that the charging time was gradually reduced continued and the molten PCM region was transformed during the phase change process because the heating rapidly.

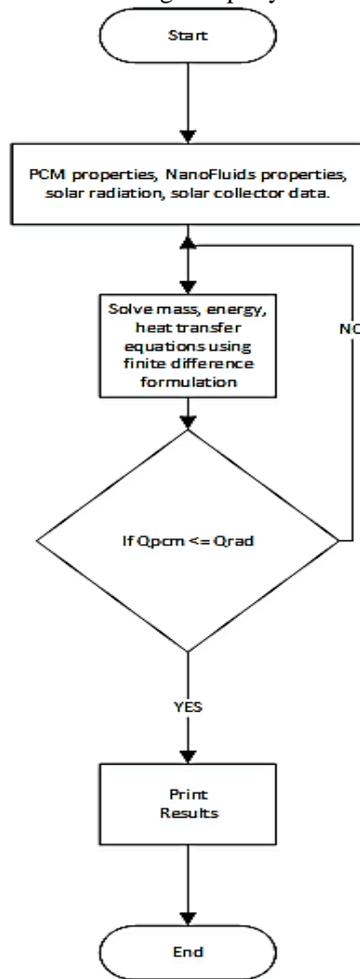


Figure 2. Numerical procedure for finite difference scheme.

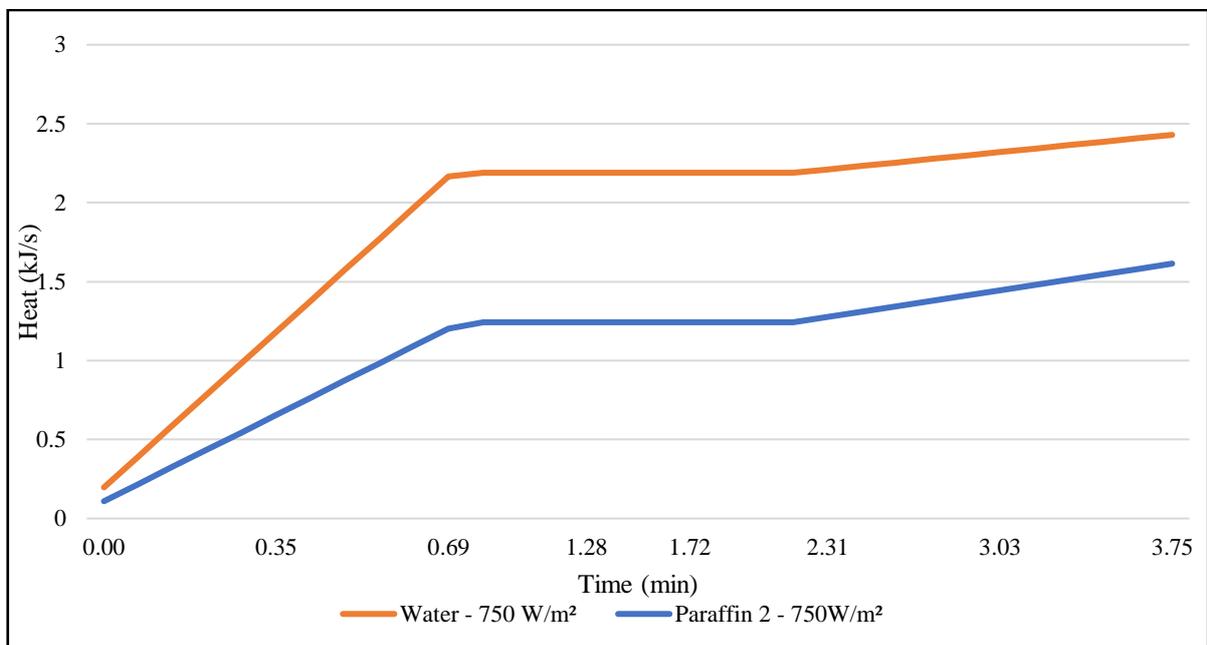


Figure 3. Heat load during phase change process at 750 W/m².

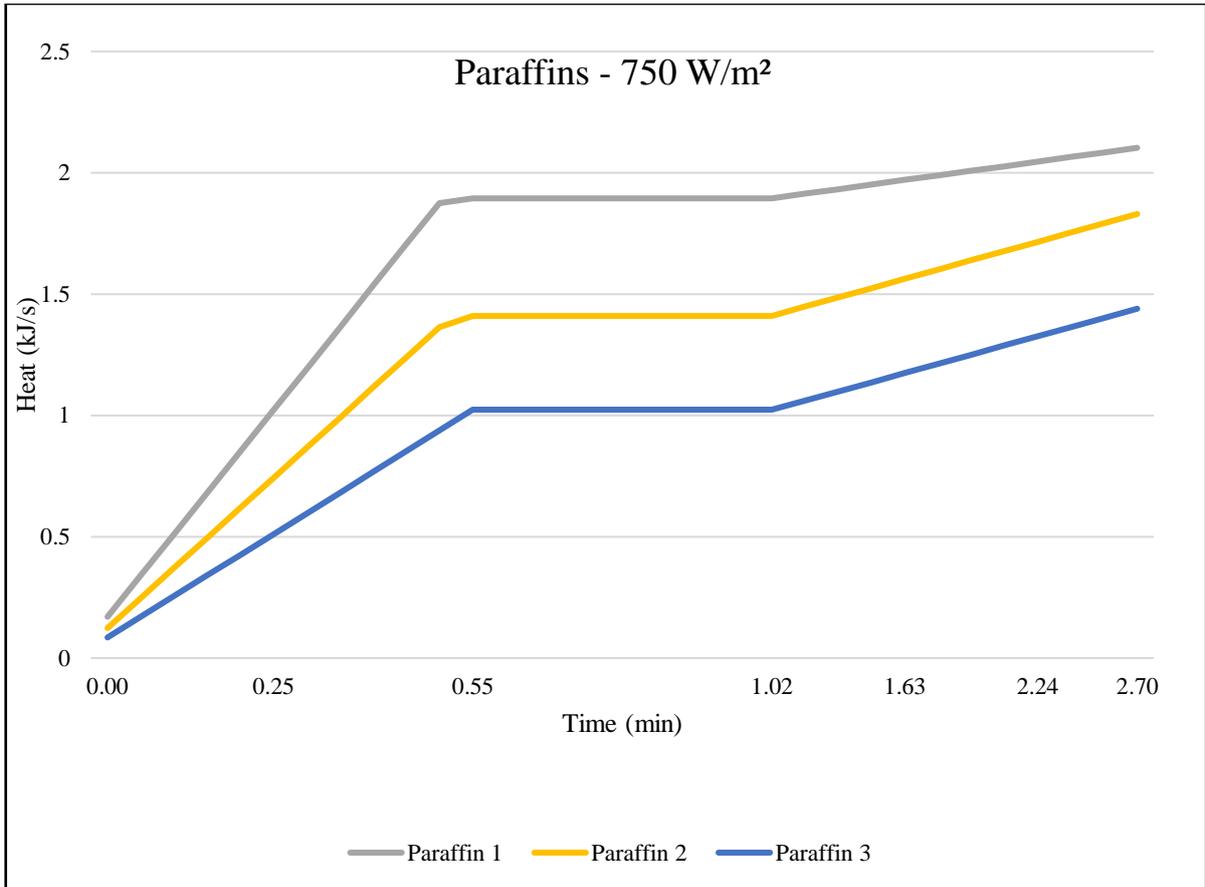


Figure 4. Heat load during phase change process at different paraffins.

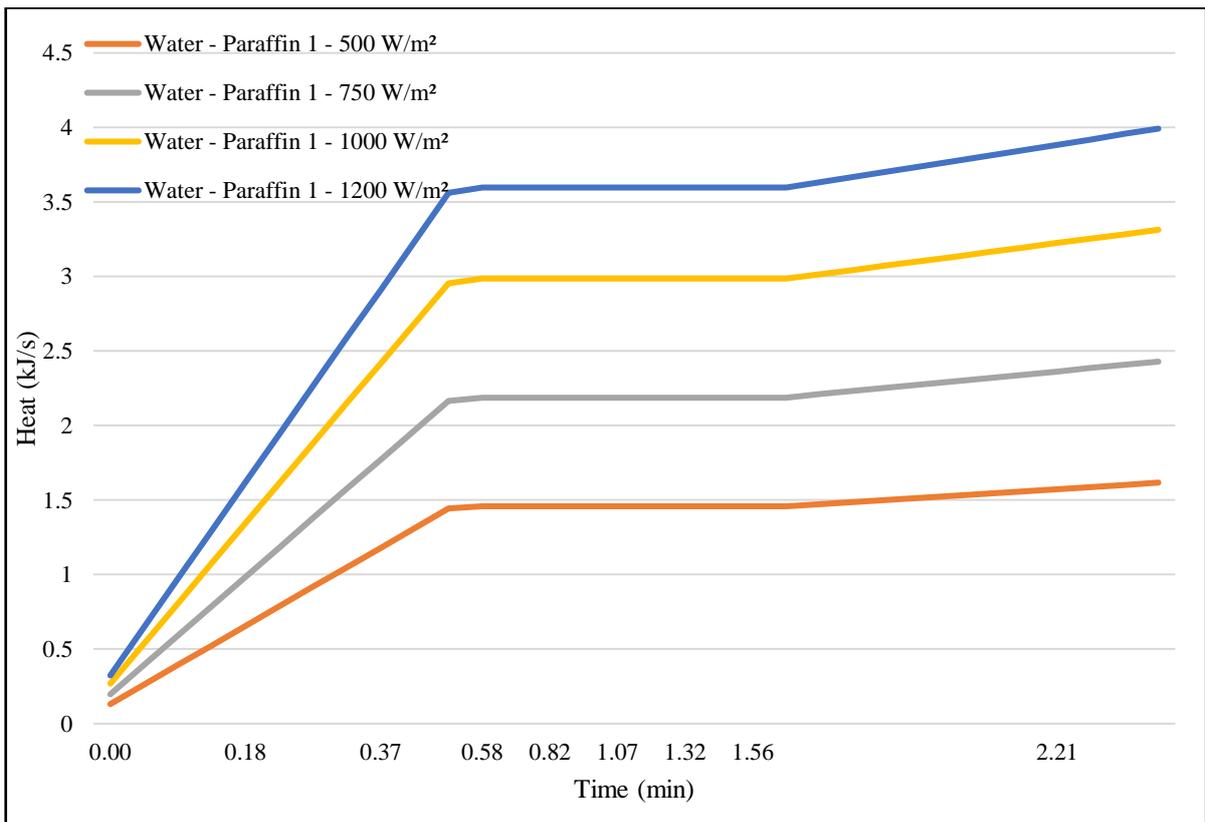


Figure 5. Comparison of Heat loads during the phase change process.

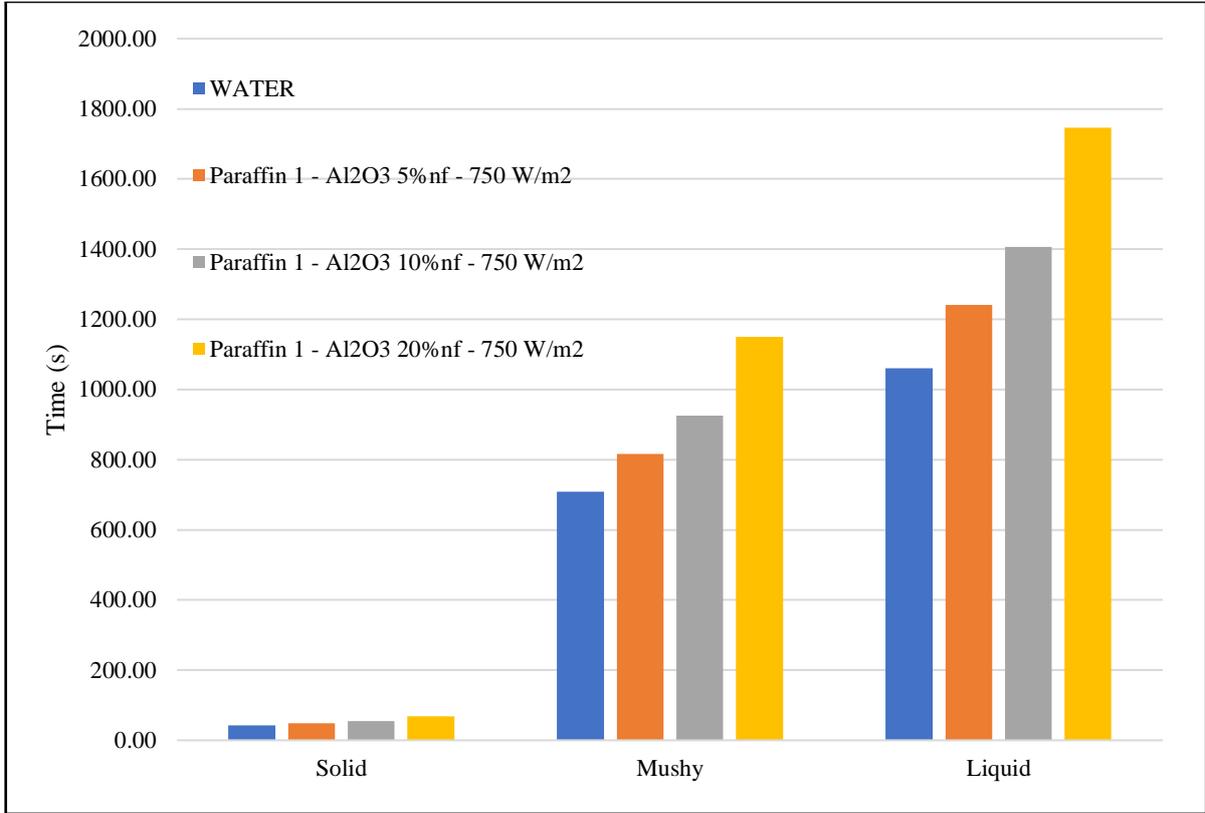


Figure 6. Comparison of time during the phase change material process with Al₂O₃.

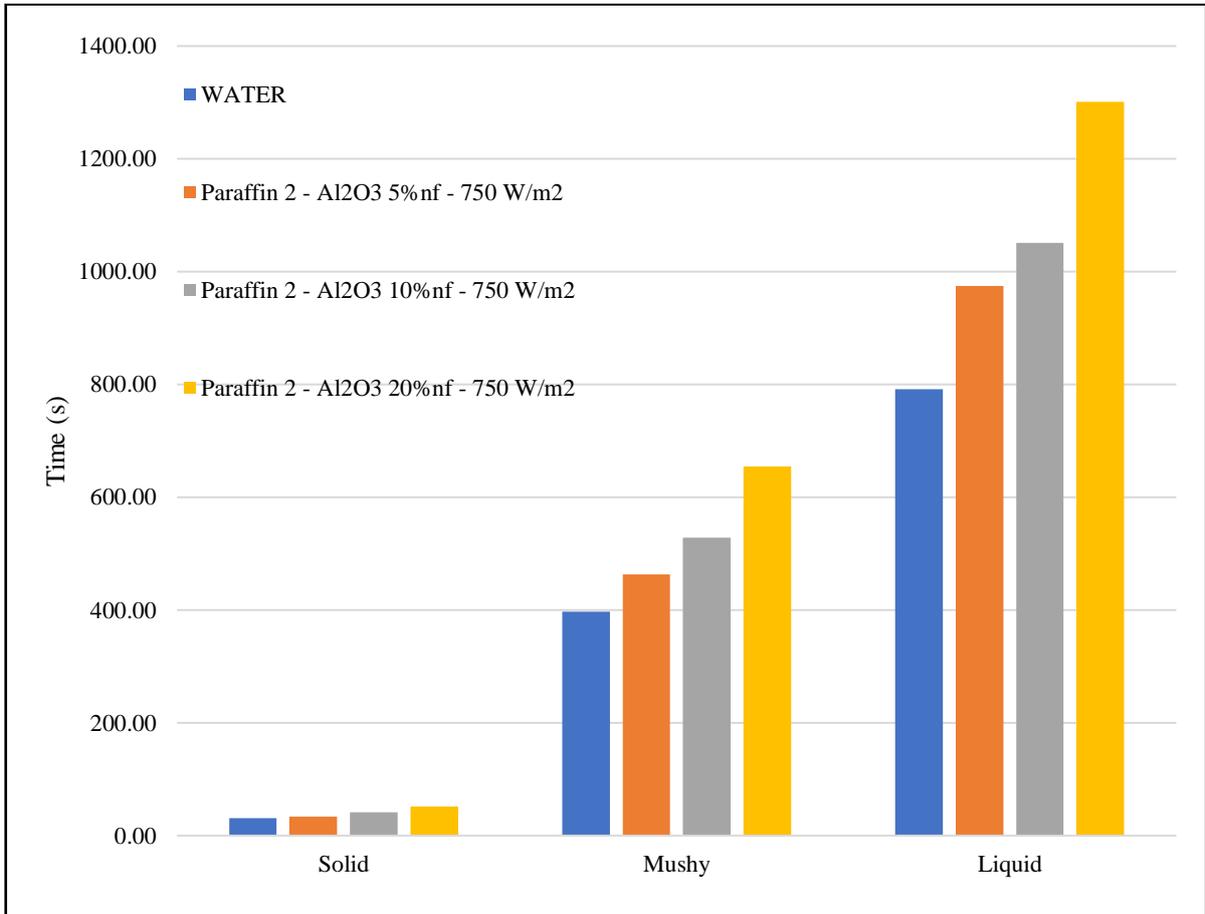


Figure 7. Comparison of time during the phase change material process with Al₂O₃.

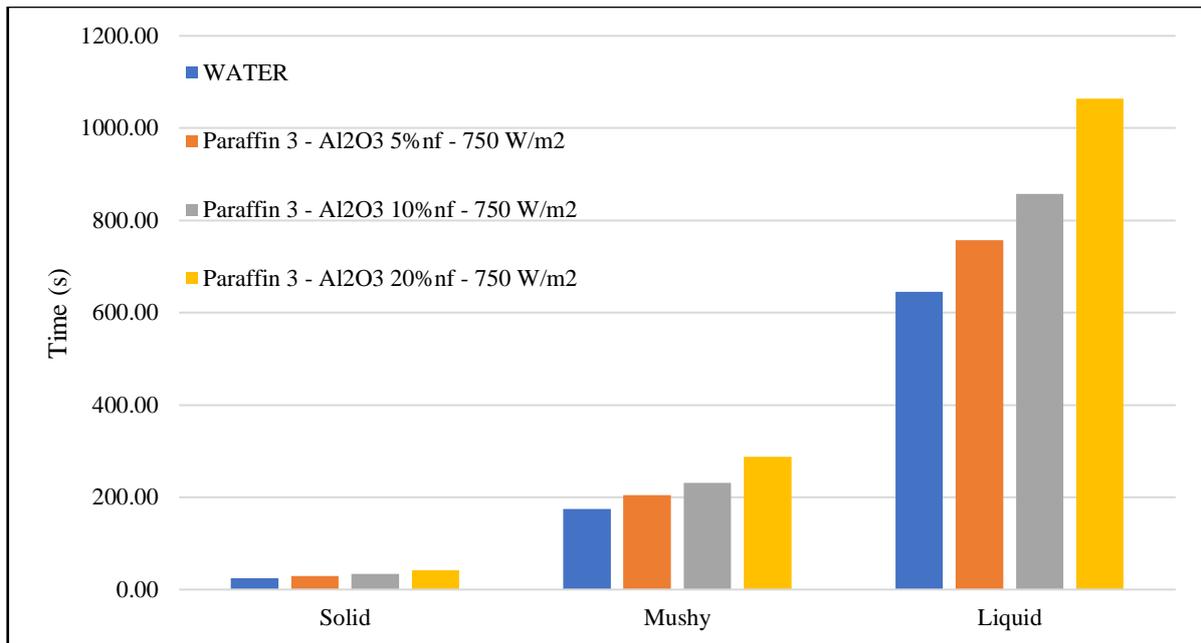


Figure 8. Comparison of time during the phase change material process with Al₂O₃.

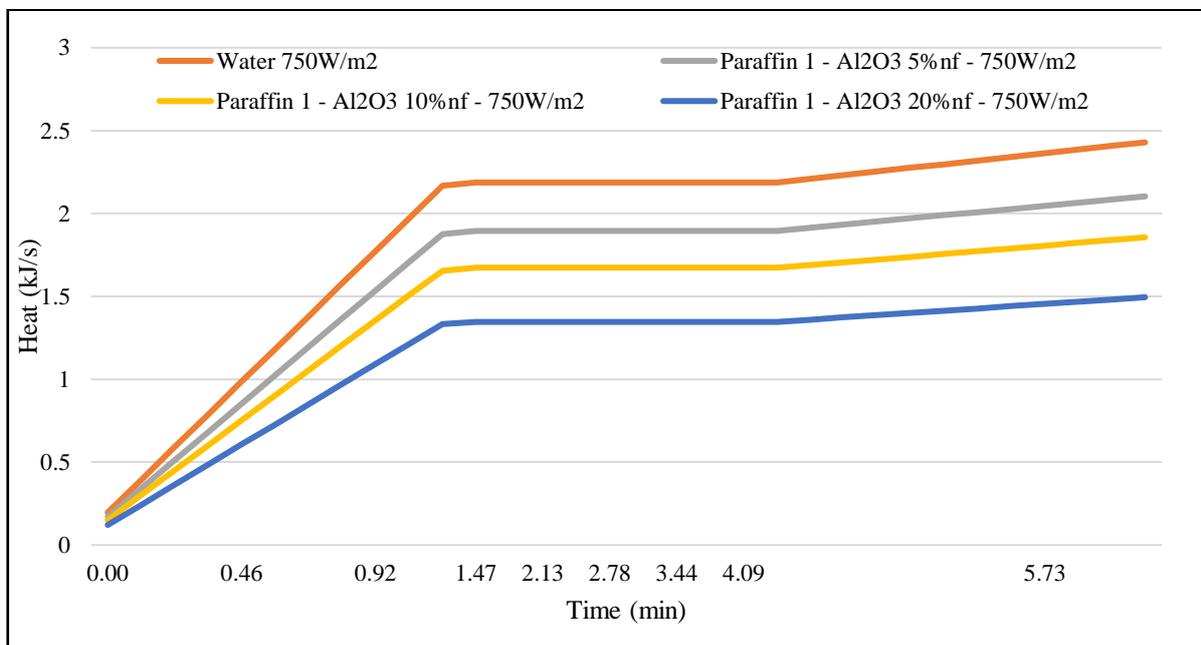


Figure 9. Thermal load during the process of charging PCM 1 with Al₂O₃.

The thermophysical and thermal properties of the nanofluid with various volumetric concentrations of the Al₂O₃ were calculated using equations (13) through (14). The resultant variation in the thermal conductivity and dynamic viscosity in this study agreed well with the results reported in reference [28] and others. Moreover, Figure. 6 through Figure .8 presented the time consumed at solar radiation 750 w/m² by the phase change material process during the solid, mushy and liquid phase change while implementing Al₂O₃ nanofluid as heat transfer fluid at different concentrations. Moreover, it appeared from the data displayed in these figures that the time required for phase change was significantly dependent on the type

of phase change material paraffin. As shown in Table.1 the phase change materials have different fusion temperatures, and their reaction to the nanofluid as heat transfer fluid during the charging process is different. Also, it can be seen that the Paraffin PCM-1 had the highest fusion temperature. It is also evident from the aforementioned figures that augmenting the Al₂O₃ volume concentration increased the melting time of the PCM depending upon the type of phase change material and its thermophysical properties. Thus, the higher the fusion temperature the higher the charging time. Moreover, Figure.9 demonstrated that the higher the fusion temperature the less the charging thermal load required for the phase change process, using nanofluid

Al₂O₃ with higher concentration. This is very beneficial since the thermal storage process can be accomplished with less thermal charging loads using a heating source. Thus, a bigger volume of paraffin can be charged with the same thermal charging load with less thermal energy compared to water as heat transfer fluid. Therefore, it can be concluded that more thermal energy can be stored in the phase change material with less thermal charging load using nanofluid Al₂O₃ compared to water as heat transfer fluid.

Figure. 10 showed the liquid fraction profile at the different melting time for the PCM 1 and nanofluid Al₂O₃ at solar radiation 750 W/m². The results displayed in this figure showed an increased heat transfer rate to the PCM 1 resulted in a higher liquid

fraction accelerating the melting process of the PCM until it reached the threshold level of the liquid region. It is apparent from the data displayed in this figure that the higher the nanofluid concentration the longer the time to reach a liquid fraction of 100% compared to water as heat transfer fluid. Therefore, the less thermal load was needed to reach the threshold of the liquid phase as per Figure.9.

Moreover, Figure. 10 has been constructed to illustrate the impact of the nanofluid Al₂O₃ different volumetric concentration on the development of the phase change and the profile of the liquid fraction during the mushy phase change. This figure clearly illustrated the transformation that took place from solid to liquid phase in the mushy region of paraffin PCM 1.

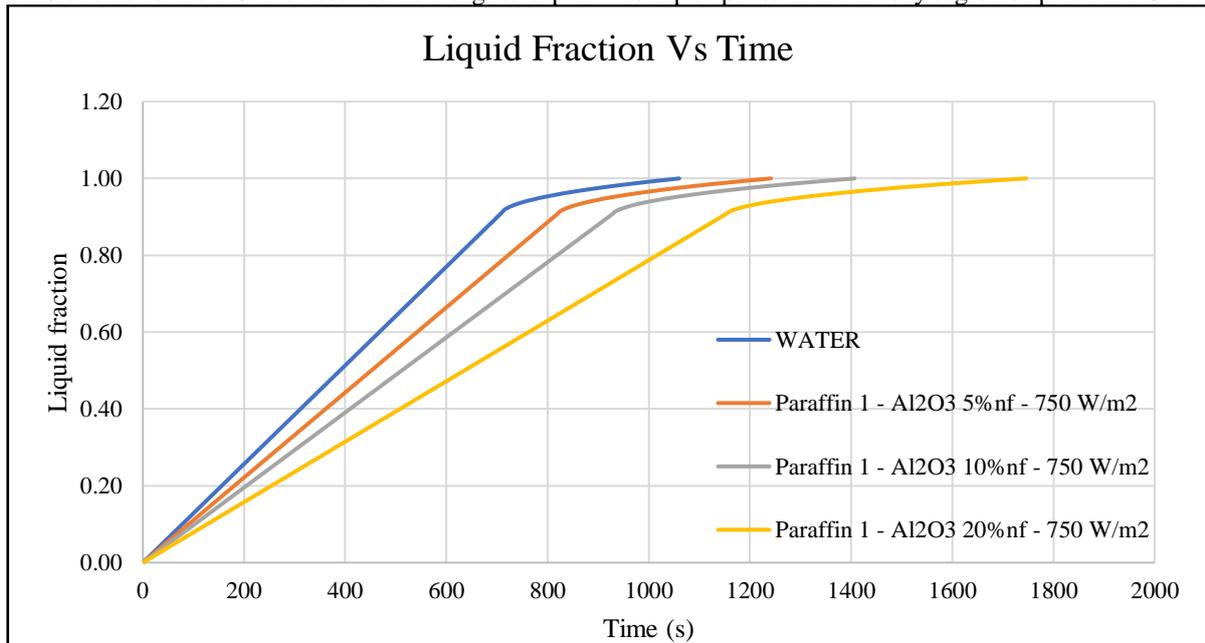


Figure 10. The process of PCM 1 melting with Al₂O₃ at different concentrations.

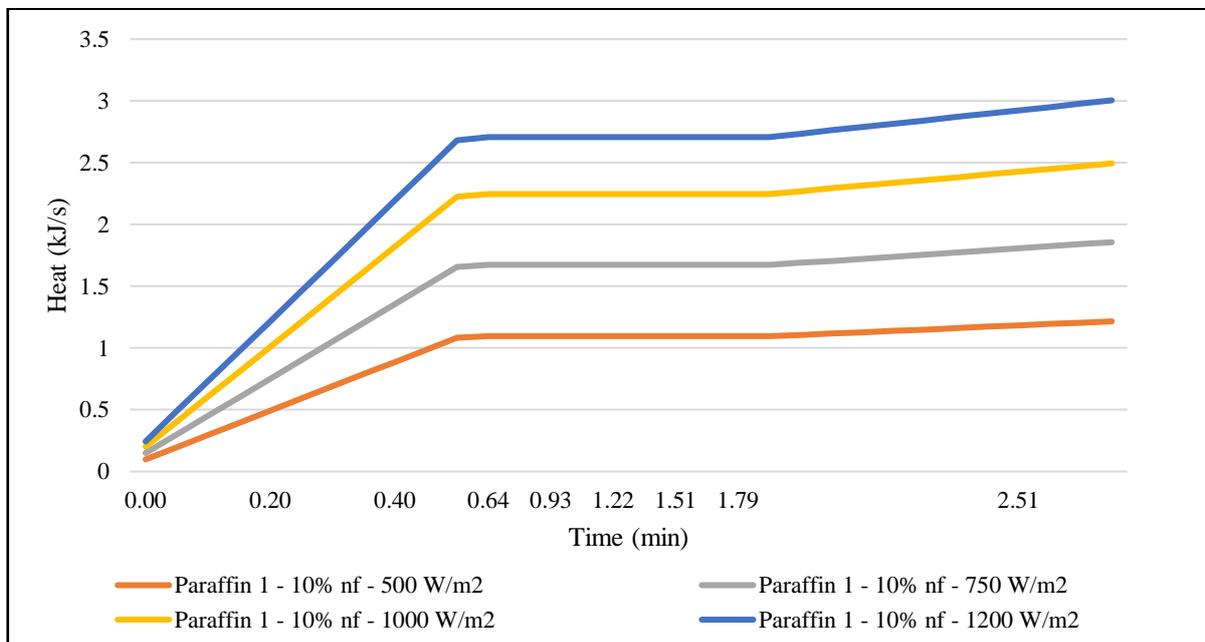


Figure 11. The process of PCM 1 melting with Al₂O₃ at different solar radiations.

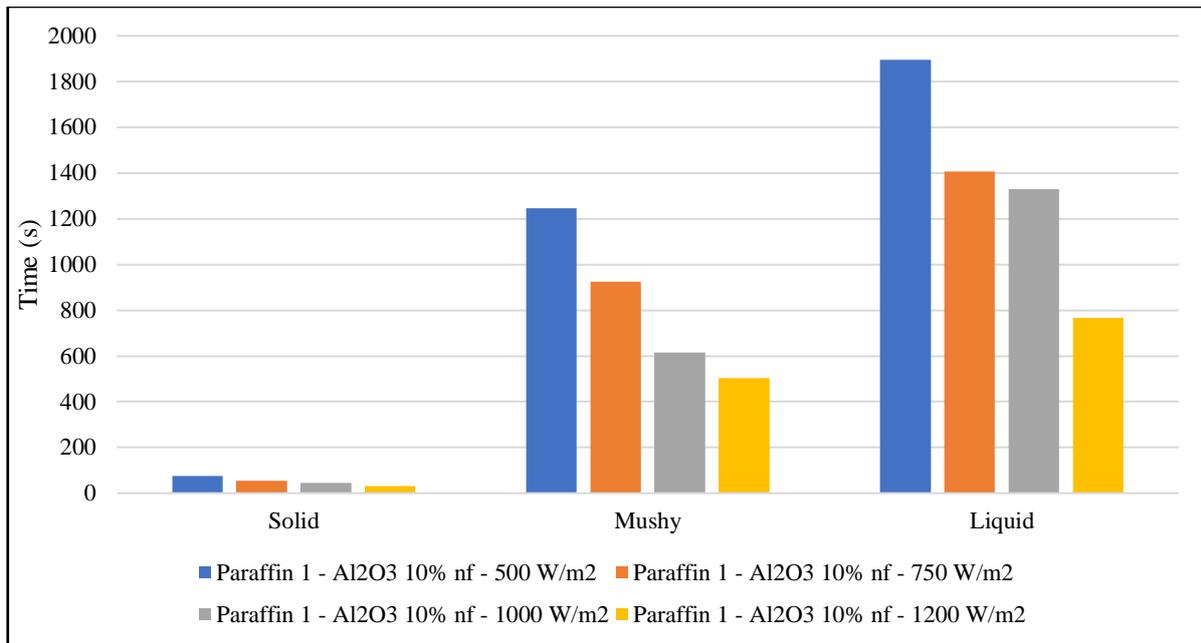


Figure 12. The process of PCM 1 melting with Al₂O₃ at different solar radiations.

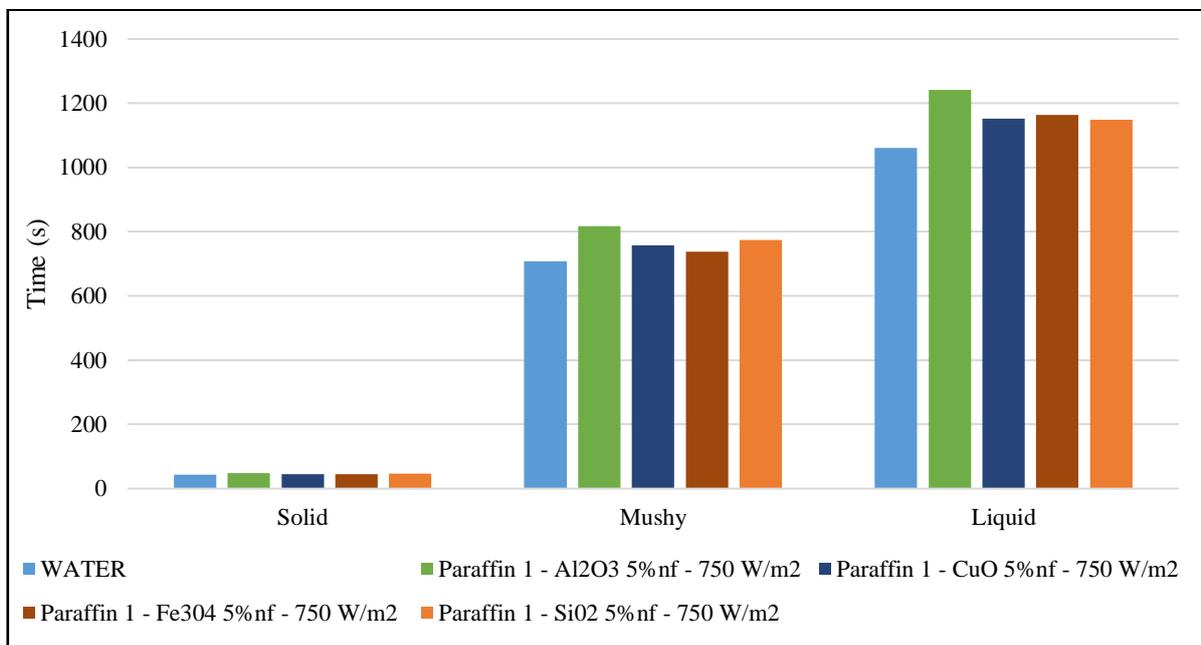


Figure 13. The process of PCM 1 melting with different nanofluids at 5% concentration.

It is quite evident from the results displayed in Figure. 10 that the higher the nanofluid concentration the lower the liquid fraction values. And also, the higher the nanofluid concentration the longer the liquid fraction takes to reach the threshold of 1.00 which represented the full transformation from the mushy phase to the liquid phase. This can be attributed to the fact that the PCM has relatively low thermal

conductivity and the higher the nanofluid concentration the higher the heat transfer from the heat transfer fluid to the PCM and the longer the time it took to absorb the heat necessary for the phase change of the paraffin. Obviously, as per Table.1 other kinds of paraffin will take a longer time to achieve the threshold of liquid phase depending upon their thermal and thermophysical properties.

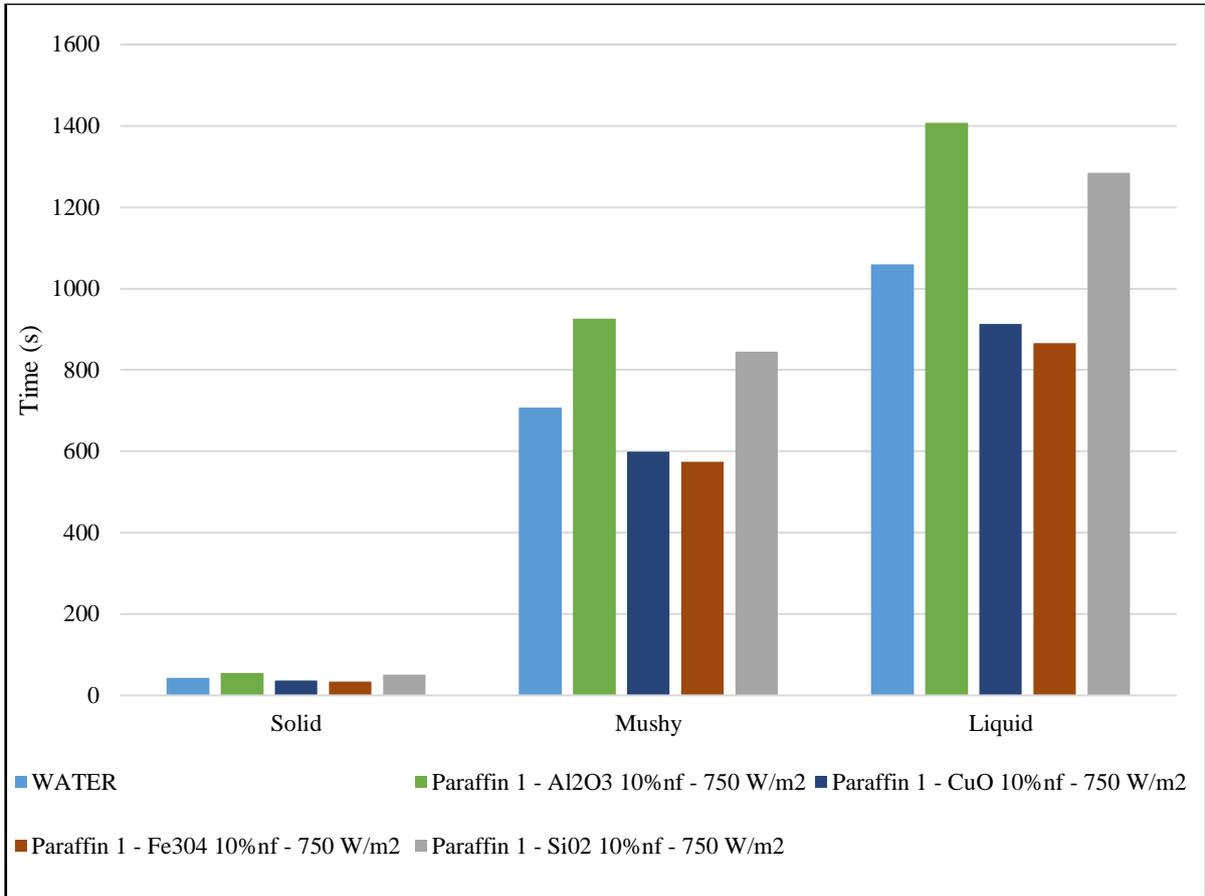


Figure 14. The process of PCM 1 melting with different nanofluids at 10 % concentration.

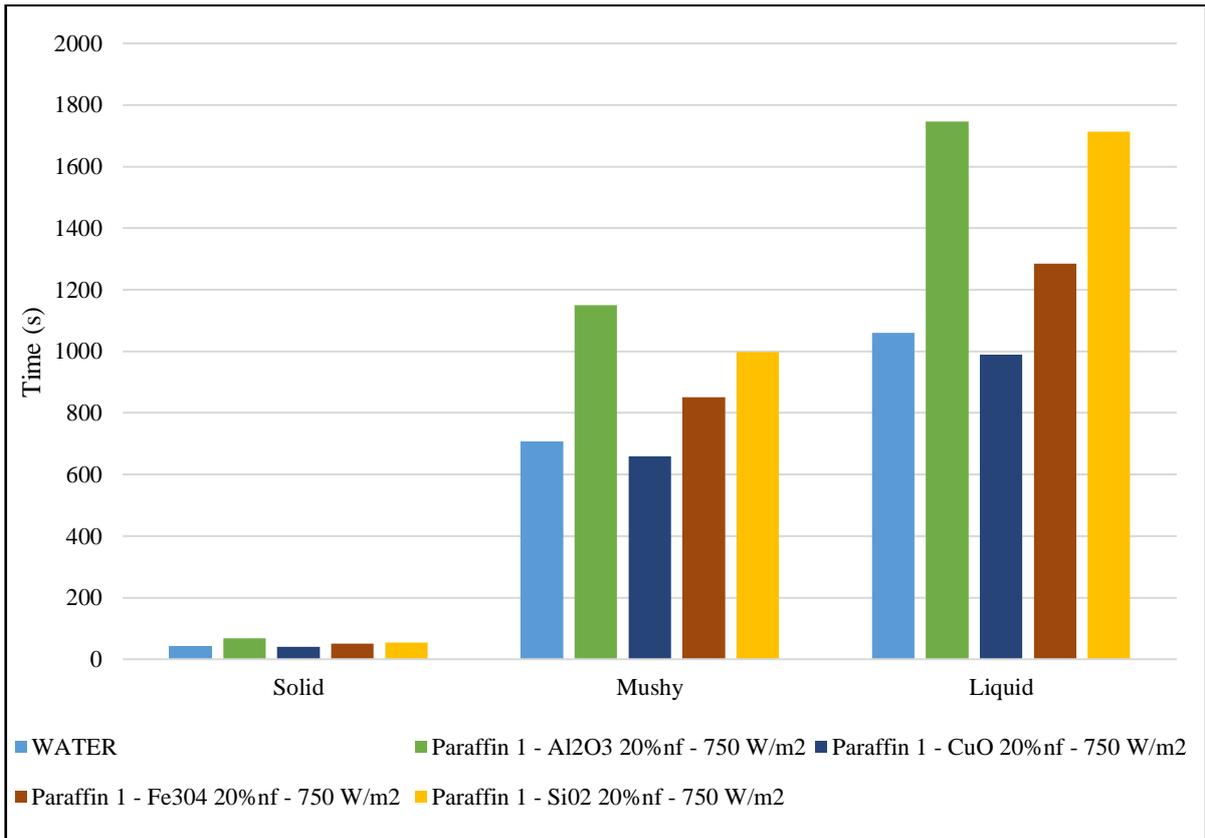


Figure 15. The process of PCM 1 melting with different nanofluids at 20 % concentration.

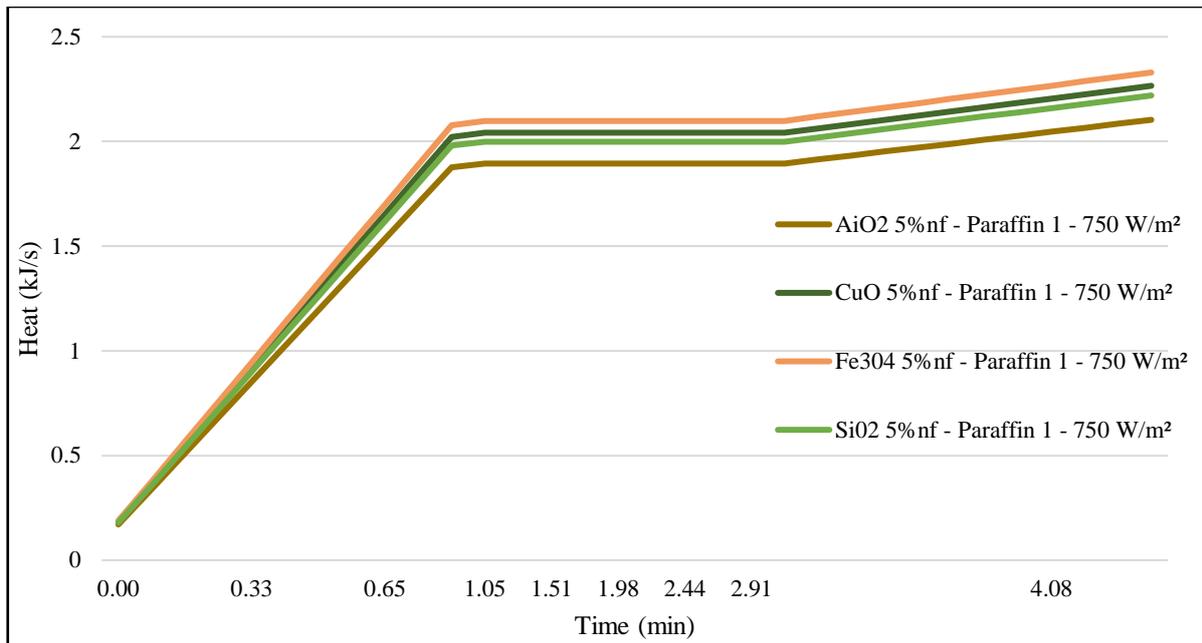


Figure 16. The process of PCM 1 melting with different nanofluids at 5% concentration.

It is well known that the latent heat absorbed by the PCM caused it to melt during the charging process. Desirable characteristics of a solid-liquid PCM include high heat of fusion per volume, congruent melting and freezing characteristics, high thermal conductivity, minimal supercooling, and low thermal expansion. To achieve these desirable properties, higher and continuous heat supplied by the heat transfer fluid is needed. Figure.11 illustrated that a higher heat transfer rate was achieved at higher solar radiation with Paraffin-PCM 1. The same trend was observed for other kinds of paraffin under investigation. Moreover, Figure.12 also showed that the lower the solar radiation the longer the time taken to achieve the change of phase during the three regions; solid, mushy and liquid. Again, we feel the relatively low thermal conductivity of the PCM is the main reason for this observation.

The main objective of this study was to implement the different nanofluids circulating in PV-Thermal solar heat exchangers to improve the heat transfer properties of the heat transfer fluid and enhance the thermal storage process. It is believed that this improvement can be attributed to the enhancement of the thermophysical properties of the nanofluids; thermal conductivity, viscosity and density, which are superior to those of the water. To illustrate the aforementioned argument Figures 13 through Figures 15 have been constructed for solar radiation at 750 w/m² and the different nanofluids under investigation: Al₂O₃, CuO, Fe₃O₄ and SiO₂. It can be observed from the results presented in these figures that during the charging process of the phase change material paraffin PCM 1 that the nanofluid Al₂O₃ used as heat transfer fluid exhibited the longest time compared to other nanofluids and water as base heat transfer fluid for charging the PCM during the three regions solid, mushy

and liquid. Also, these figures indicated that the nanofluid Fe₃O₄ had the shortest time consumed during the charging process. This finding is significant since we believe that using the nanofluid Fe₃O₄ can shorten the charging time required which is very beneficial to the charging process of the PCM. It is also worthwhile mentioning that similar behavior was observed with the other nanofluids PCM 2 and PCM 3 listed in Table .1.

Similarly, Figure. 16 through Figure.18 have been established to show the impact of the use of the different nanofluids under investigation; Al₂O₃, CuO, Fe₃O₄ and SiO₂ on the thermal heat absorbed by the phase change material PCM 1 during the charging process at 750 w/m² solar radiation and the different nanofluids volumetric concentrations; 5%, 10% and 20%. Similarly, to what has been observed in Figure. 13 through Figure.15, the heat absorbed was the highest with nanofluid Fe₃O₄ compared to the other nanofluids understudy and water as base heat transfer fluid. Other PCM2 and PCM 3 experienced the same behavior observed. We believe that this was attributed to the enhanced thermophysical properties of Fe₃O₄ over the other nanofluids studies including water as a base fluid, in the range of temperatures studied. It is worthwhile mentioning that the nanofluids concentration of 20% was only used to demonstrate the impact of higher volumetric concentration on the heat transferred to the phase change material. Similar results were also observed at the other solar radiations; 500, 1000 and 1200 w/m². Therefore, based upon the results presented in Figure.13 through Figure.18, it is recommended to use nanofluid Fe₃O₄ during the charging process of the phase change material over other nanofluids including the water as heat transfer fluid.

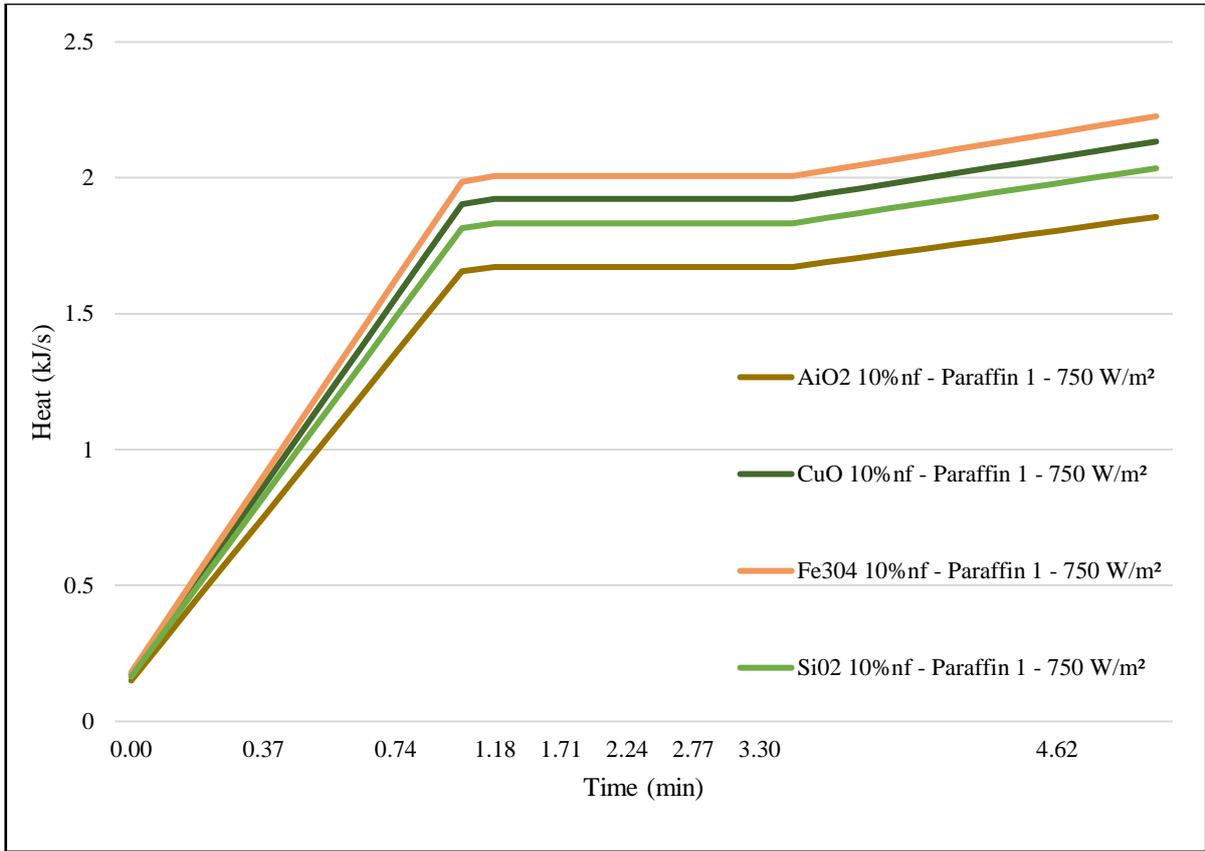


Figure 17. The process of PCM 1 melting with different nanofluids at 10 % concentration.

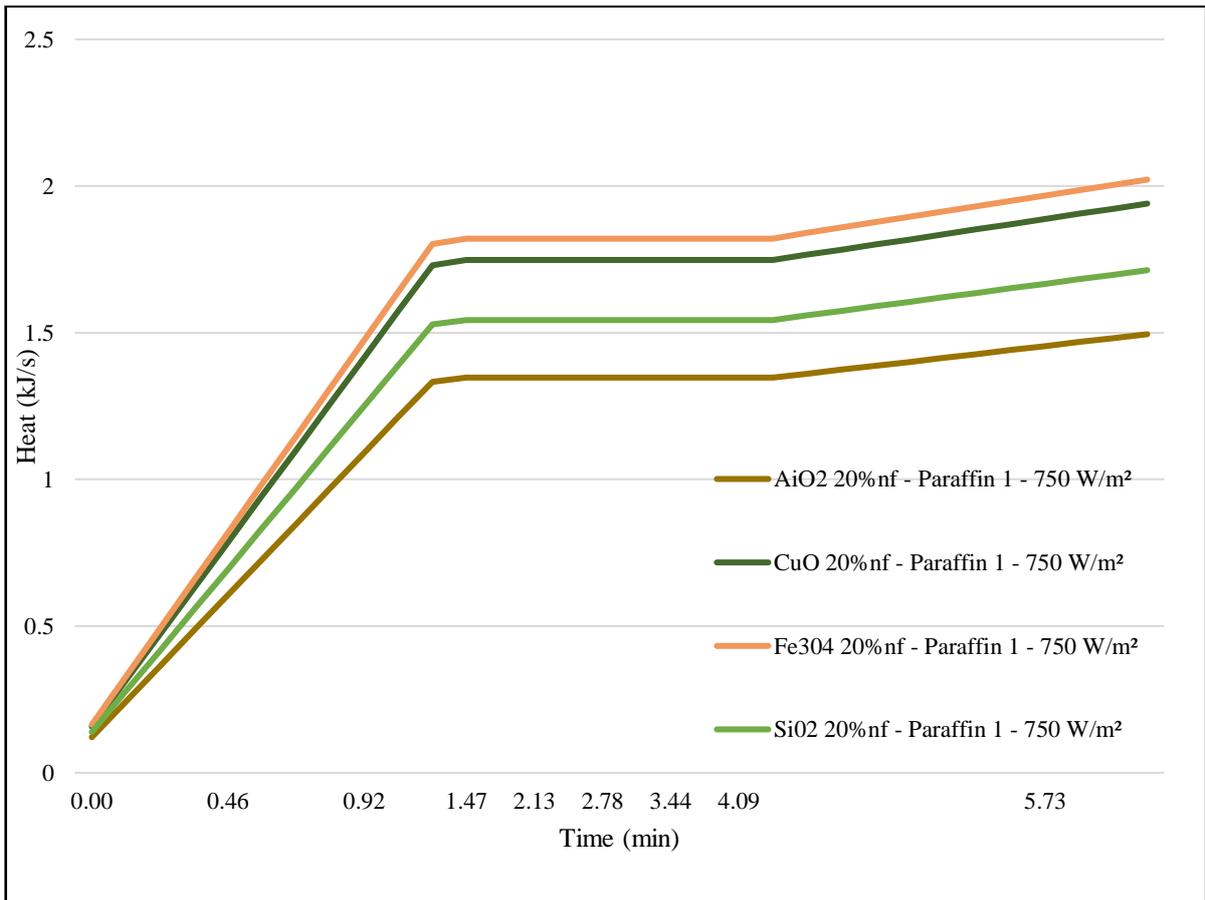


Figure 18. The process of PCM 1 melting with different nanofluids at 20 % concentration.

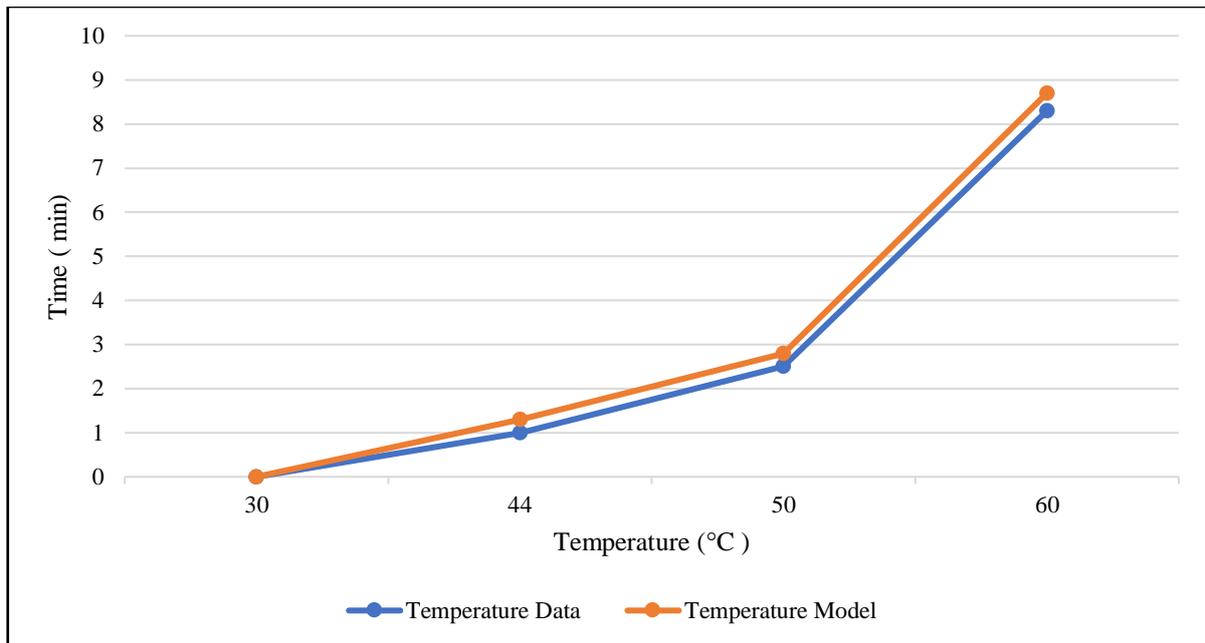


Figure 19. Comparison between model prediction and data reference [29].

VIII. MODEL VALIDATION

Due to the lack of our experimental facility to collect data, and very limited experimental data reported in the literature on nanofluids thermal storage using phase change material, the numerical model presented hereby in equation (1) through (14) was validated against the experimental data reported by Abdulateef et al. [36], during the phase change melting process using Al_2O_3 nanoparticles to enhance the thermal conductivity and other thermophysical properties of the heat transfer fluid and shown in Figure.19. Reference [36] reported that temperatures of the PCM were measured on the top and bottom of the storage tank in the axial direction. Because the melting point of paraffin used in reference [36] was higher than the paraffin used in this study, Figure.19 was used only to show the model prediction and comparison with the data observed in the early stage of the melting process that represented the sensible heating of the PCM. The comparison presented in Figure.19 showed that there were discrepancies between the numerical model's prediction and experimental data [36] that did not exceed 7%. This demonstrated a good agreement between the model's prediction and experimental data of Abdulateef et al. [36]. We believe that the over-prediction of the higher temperatures by our model was attributed to the over-prediction of the heat transfer coefficient and the thermophysical properties of the nanofluid Al_2O_3 that resulted in higher temperatures. Furthermore, it should be noted that Abdulateef et al. [36] did not disclose relevant information on the calculations of the heat transfer coefficient and the thermophysical properties.

IX. CONCLUSIONS

This study presented a mathematical model for predicting the behavior of the thermal storage process

in phase change material (PCM) using nanofluids as the heat transfer fluid in an integrated PV-thermal solar panel loop. The model was established after the energy conservation coupled with the heat transfer equations. This model was intended to study the effect of different operating conditions such as solar radiation, working fluid flow rates, nanofluids, and paraffin temperatures and their impact on the thermal storage process, phase change process and system performance as well as the thermal energy conversion process.

It can be observed from the results presented hereby on the use of these nanofluids as heat transfer fluids during the charging process of the paraffin 1 as well as the other kinds of paraffin under investigation that the nanofluid Al_2O_3 exhibited the longest time compared to other nanofluids and water as the base fluid for charging the PCM during the three regions solid, mushy and liquid. Also, the results indicated that the nanofluid Fe_3O_4 had the shortest time consumed during the charging process. This was significant since using the nanofluid Fe_3O_4 shortened the charging time required which is very beneficial to the charging process of the PCM. It is worthwhile mentioning that similar behavior was observed with the other nanofluids PCM 2 and PCM 3. These results were observed at solar radiations; 500, 750, 1000, and 1200 w/m^2 . It was also recommended to use nanofluid Fe_3O_4 during the charging process.

Finally, a comparison between the model numerical prediction and experimental data reported in the literature showed that discrepancies did not exceed 7% and demonstrated good agreement between the model and the data. However, it's recommended for future studies to perform an experimental study using the different kinds of paraffin wax phase change materials and the nanofluids presented hereby to collect experimental for validation of the proposed model.

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NOMENCLATURES

b_2 & n , Constants equal to 0.3 and 0.6 respectively
 Cp_w , Specific heat of the water $\left(\frac{kJ}{kg K}\right)$
 D_H , Hydraulic diameter (m)
 Cp_s , PCM specific heat at the solid phase $\left(\frac{kJ}{kg K}\right)$
 G , Radiation $\left(\frac{W}{m^2}\right)$
 h , Heat transfer coefficient
 l , Tube length (m)
 m_w , Water mass flow rate $\left(\frac{kg}{s}\right)$
 n , number of finite-difference elements
 R , Tube radius (m)
 $T_{PCM,m}$, The temperature of PCM at m element ($^{\circ}C$)
 V_{PCM} , PCM volume (m^3)

GREEK LETTERS

μ , Water viscosity $\left(\frac{m^2}{s}\right)$
 h_L , PCM latent heat $\left(\frac{kJ}{kg}\right)$
 V_{PCM} , Volume of PCM (m^3)
 ρ_L , Density of PCM at liquid phase $\left(\frac{kg}{m^3}\right)$
 ρ_s , Density of PCM at the solid phase $\left(\frac{kg}{m^3}\right)$
 Q_{tub} , Heat (kJ)

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