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Enhancement of Performance of Thermal Solar Collectors Using Nanofluids

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Abstract: A numerical mathematical model has been developed to predict the thermal behavior of thermal solar collectors using nanofluids. The model is based upon energy conservation equations for nanofluids flow and heat transfer using different nanofluids. The thermal behavior of the solar collectors during charging has been studied numerically, and analyzed using different nanofluid materials. Comparisons were made against literature data for validation purposes of the predictive model. The model fairly predicted nanofluid conditions and compared well with existing data on the subject.

Keywords: Thermal Solar Collectors, Nanofluids, Nano Particles, Thermal Behavior, Numerical Model, Simulation

1. Introduction

Solar thermal offers non-polluting, environmentally friendly and sustainable systems. Solar collectors convert solar irradiation energy to thermal energy that is transferred to working fluids in solar thermal applications. The heat carried by the working fluid can be used to either provide domestic and industrial hot water/heating, or to charge phase change material in a thermal storage tank for heat supply during non-solar periods [1-6].

A Nanofluid is a fluid with suspensions of nano-sized particles. Choi defined the term "nanofluid" and the suspensions of nano-sized particles (1-100 nm) in a conventional fluid base called nanofluid [7]. Computation of thermophysical properties of nanofluids such as thermal conductivity, viscosity, density and specific heat as well as thermal diffusivity are essential to understand their heat transfer behavior [8-12].

Nanofluids exhibit improved thermophysical and heat transfer properties such as thermal conductivity, viscosity and convective heat transfer coefficient. The property improvement of nanofluids depends significantly on the volumetric fraction or concentration of nanofluids particles, shape and size of nanofluid materials. [1-3].

Thermal solar water heating systems are comprised mainly of thermal solar panels, a thermal storage tank and a pump. The heat transfer fluid (HTF) delivers the heat absorbed at the solar panel to the storage thermal tank. It absorbs solar energy and converts it into heat and delivers it to the thermal storage tank for further thermal use.

References [8-12] have investigated the use of nanofluids in solar collectors and their impact on the enhancement of efficiency of flat solar collectors. However, Taylor et al. [13] investigated utilizing the nanofluids receiver in power tower solar collectors theoretically and experimentally in a laboratory large-scale dish receiver. Enhancement of efficiency was observed compared to the base fluid [8-17]. On the other hand, Kullar et al. [14] studied the enhancement of solar irradiance absorption capacity for nanofluid-based concentrating parabolic solar collectors theoretically and comparing the results with experimental data from a conventional concentrating parabolic solar collector. The results of his study demonstrated 5-10 % higher efficiency compared to conventional models.

A mathematical model for describing the heat and mass balances in fluid flow using nanofluids is presented hereby. The model was established after the energy conservation coupled with the heat transfer equation of the heat transfer fluid. In the following sections, simulation results of a thermal solar panel using the different nanofluids will be presented and analyzed. In addition, the simulated results were compared with available data on nanofluids. The mathematical model, in particular, was used to predict the thermal solar panel behavior and the effect of operating conditions such as solar radiation, working fluid flow rates, initial working fluid and nanofluid concentrations on the solar panel heat absorbed and efficiency.

2. Mathematical Model

A schematic of the thermal solar system under study is depicted in Figure.1. The system consists of a thermal solar panel collector, thermal tank, and paraffin wax, piping, pump and as well as control valves. However, in this study, only the thermal tank with water and nanofluids was used in this study. The thermal tank with the single tube heat exchanger was numerically divided into different elements to permit writing the energy and heat transfer equations in finite-difference format for the heat transfer fluid (HTF). The model is based on the following assumptions; the HTF with nanofluids is homogeneous and isotropic, HTF is incompressible and it can be considered as a Newtonian fluid, inlet velocity and inlet temperature of the HTF are constant, thermophysical properties of the HTF and nanofluids the PCM are constant during each element.

The conservation equations and heat transfer equations were written for each element as of the HTF;

Energy conservation and heat transfer equations:

The heat released by the heat transfer fluid HTF can be written as follows, [15],

$$Q = m_w Cp_w \Delta T_w \tag{1}$$

ΔT_w: Heat transfer fluid temperature difference
m_w: Heat Transfer Fluid HTF flow rate
Cp_w: Specific heat of heat transfer fluid

The heat balance for the heat exchanger tube in the tank can be as follows [15];

$$(T_{in} - T_{out}) Cp_w m_w = 2\pi R l h (T_{in} - T_{sfc}) \tag{2}$$

Where the heat transfer coefficient is approximated as [15];

$$h = \frac{K_w}{D_H} b_2 Re^n \tag{3}$$

$$Re = \frac{m_w D_H}{\mu A_f} \tag{4}$$

Where the b_2 and n are numerical constants.

The following relationship was used to relate the thermal conductivity to thermal diffusivity and density of the nanofluids [18];

$$\alpha = \kappa/(\rho . C_p) \tag{5}$$

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

The water (HTF) mass flow rate can be calculated from the heat released by the solar radiation as follows,

Mass flow rate of water:

$$m_w = \frac{G A_{Panel}}{1000 \times Cp_w \Delta T_w} \tag{6}$$

Equation (2) with the finite difference formulation of the time derivative can be used to predict the HTF behavior and nanofluid temperature in the thermal storage tank as follows;

Thermal Tank:

$$T_{tank_{m+1}} = T_{tankt_m} + \frac{m_w Cp_w \Delta T_w}{\rho_S V_{tankt} Cpw_t} \Delta t \tag{7}$$

Where: m_w, Water mass flow rate $\left(\frac{kg}{s}\right)$
Cp_w, Specific heat of water $\left(\frac{kJ}{kg\ K}\right)$
G, Radiation $\left(\frac{W}{m^2}\right)$
R, Tube radius (m)
l, Tube length (m)
h, Heat transfer coefficient
b_2 & n, Constants equal to 0.3 and 0.6 respectively
D_H, Hydraulic diameter (m)
μ, Water viscosity $\left(\frac{m^2}{s}\right)$
K_w, Thermal conductivity of water $\left(\frac{kJ}{ms°C}\right)$
A_{Panel}, Area of solar panel (m^2)
A_f, Flow area (m^2)
Δt: time interval in the finite difference formulation,
Re: Reynolds number
V_{tankt}: Volume of water thermal tank

Once the nano particles are injected into the fluid base (HTF), the thermophysical properties of the HTF with nano particles can be calculated as a function of the concentration of the nano particles flowing in the fluid flow as follows;

$$\alpha_{total} = \alpha_{particles} + \alpha_{base\ fluid} \tag{8}$$

Where α and $\alpha_{base\ fluid}$ represent a particular thermophysical property of the nanofluid under investigation and base fluid.

Taking into consideration, the concentration of the nano particles, Φ, the following can be written to describe the nanofluid thermal and thermophysical properties;

$$\alpha_{total} = \alpha_{base\ fluid} + \alpha_{particles} (\Phi) \tag{9}$$

Where; Φ represents the nano particles concentration.

Finally, the solar panel efficiency with circulating nanofluids can be obtained from the following expression;

$$\eta = Q / G A_{Panel} \tag{10}$$

Where Q is calculated by equations (1), and (2), and G represents the solar radiation $\left(\frac{W}{m^2}\right)$, and A_{panel} is thermal solar panel area.

3. Numerical Procedure

The energy conversion and heat transfer taking place during heat release and absorption in the solar panel tubes and thermal solar tank have been outlined in equations (1) through (10). The aforementioned equations have been solved as per the logical flow diagram shown in Figure 2, where the input independent parameters are defined for the solar panel, nano particles; AiO_2, CuO, Fe_3O_4 and SiO_2 and other dependent parameters were calculated and integrated in the finite-difference formulations. Iterations were performed until a solution is reached with acceptable iteration error. The numerical procedure starts with the use of the solar radiation to calculate the mass flow water circulating in the solar panel. This follows by predicting the base fluid and nanofluids and their thermophysical properties at different concentrations of nano particles, circulating in the solar panel heat exchanger using the finite difference formulation.

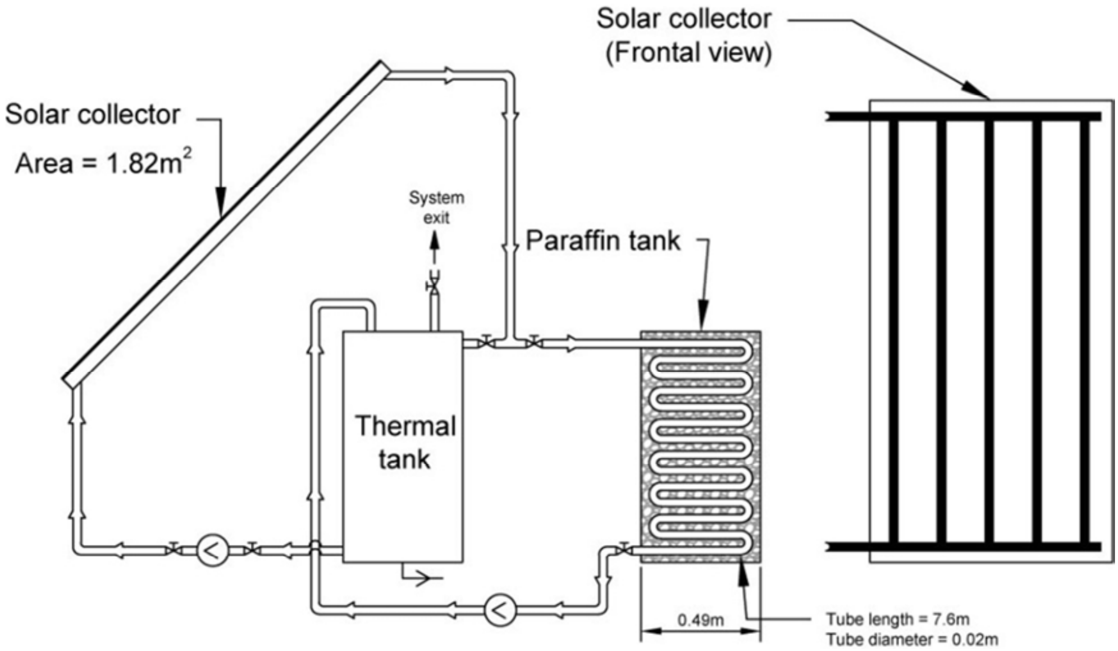

Figure 1. *Schematic diagram of thermal solar panel and Thermal tank with nanofluids system.*

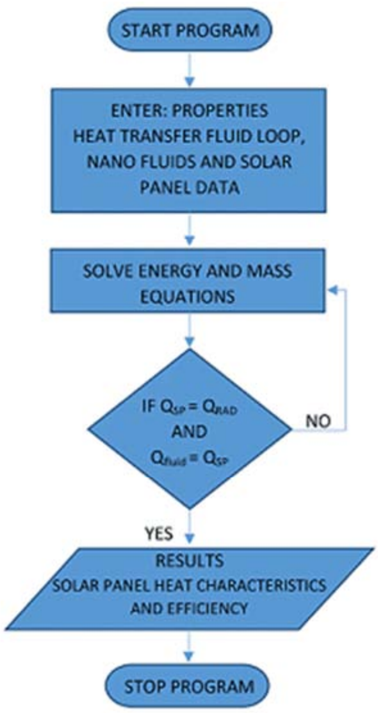

Figure 2. *Logical flow diagram for finite difference scheme.*

4. Discussion and Analysis

The aforementioned system of equations (1) through (10) in finite-difference forms have been integrated and numerically solved and samples of the predicted results of the solar panel efficiency, heat absorbed by solar panel as well as comparison between the various nano particles; AiO_2, CuO, Fe_3O_4 and CiO_2 are plotted in Figures 3 through 18, at different inlet conditions.

The thermal tank employed in this simulation study has a diameter of 0.49 meter and a height of 0.99 meter with a capacity of 100 liters and one path tube heat exchanger of 0.025 meter and 7.5-meter in length. On the other hand, the thermal solar panel has length and width dimensions of 0.90 meter and 12 heat tubes, each of the heat tubes has a diameter of 0.0254 meter. The heat transfer base fluid (HTF); water flows inside the aforementioned tubes of the solar panel, one path tube heat exchanger and the thermal solar loop as shown in Figures 1.

In order to solve equations (1) through (10), the thermal and thermophysical properties of the nano particles AiO_2, CuO, Fe_3O_4 and SiO_2 were obtained from reference [16, 17], and reference [8]. In particular, Allen [8] studied the magnetic field enhanced thermal conductivity analysis of magnetic nanofluids and calculated the thermal conductivity from the measured temperature difference for each nanofluids such as AiO_2, CuO, Fe_3O_4 and SiO_2 at different magnetic fields. His data at zero magnetic fields were considered for this study.

In general, it is quite clear from figures (3) through (21) that the heat absorbed by solar panel and solar panel efficiencies are influenced by the concentrations of the injected nano particles, the nanofluid flow rates and the type of material of the nano particles as well as the thermophysical properties of the particular nanofluids under investigation.

Figure 3 presents the time variation of solar isolation (W/m2) measured at the site and employed in this simulation. It is quite clear that the intensity of radiations depends upon the hour of the day and the month of the year.

In the following, we present the simulations and predicted results as well as an analysis of heat absorbed and solar panel efficiencies under nanofluid flows from 0.001 kg/s to 0.012 kg/s, nano particles concentrations from 0.01 to 0.5 and under solar radiations from 550 W/m2 to 1200 W/m2. It should be noted that the design mass flow rate for the thermal solar panel simulated is 0.0107 kg/s.

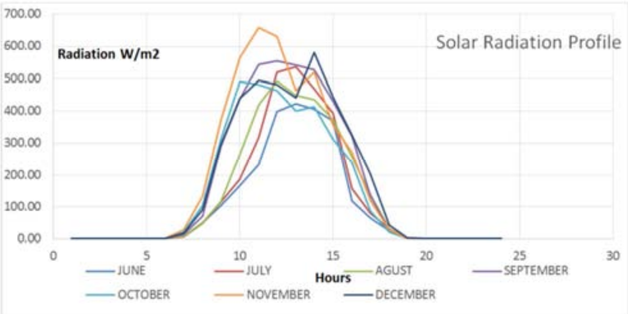

Figure 3. *Time variation of solar intensity W/m2, 2016.*

The heat absorbed by the thermal solar panel calculated by equations (1) and (2) for the heat transfer nanofluid (NFHTF) with suspended particles of the AiO_2, CuO, Fe_3O_4 and SiO_2 with concentration that varies between 0.01 to 0.50, are displayed in Figures 4, 8, 12 and 17. It is quite clear from the numerical values presented in these figure that the heat absorbed by the thermal solar panel and nanofluid increases as the concentration of the nanofluid particles increases. This is attributed to the fact that higher nano particle concentrations increase the thermal, thermophysical properties and heat transfer properties of the HTF and that stimulates the heat transfer from the solar radiation into the fluid circulating in the heat tubes of the solar panel. However, it can also be observed that the higher the flow of nanofluids, the higher the heat absorbed by the thermal solar panel up to the designed mass flow rate for the solar panel. Beyond this point any further increase in the mass flow rate of HTF results in reduction of the heat absorbed by the thermal solar panel due to the heat losses that occurred.

On the other hand, the simulated results of the solar panel efficiency calculated by equation (10) were presented in the figures 5 through 19 for different nanofluid flows, nano particle concentrations and solar radiations as previously discussed and mentioned. It can be observed from the simulated results presented in these figures that increasing the nano particles concentration enhances the solar panel efficiency. Furthermore, the results also showed that higher nanofluid mass flow rate increases the thermal solar panel efficiency. In addition, as discussed previously, increasing the nano particle concentration enhances the heat transfer properties and increases the heat transferred and absorbed by the heat transfer fluid, this in turn enhances the solar panel efficiency. On the other hand as observed in the analysis of the heat absorbed by the thermal solar panel, higher solar radiation reduces the solar panel efficiency.

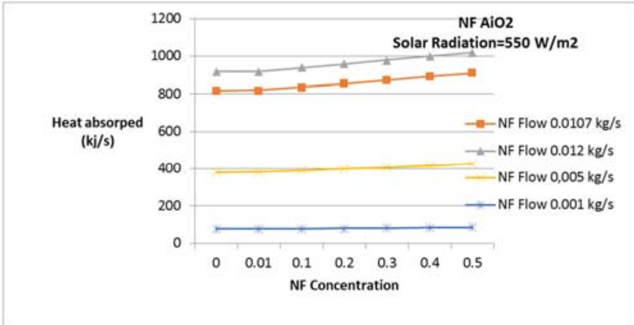

Figure 4. *Predicted heat absorbed by solar panel at different flow conditions for AiO_2.*

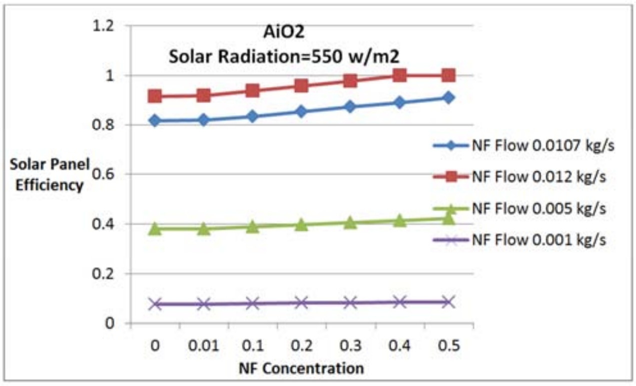

Figure 5. *Solar panel efficiency at different flow conditions for AiO_2.*

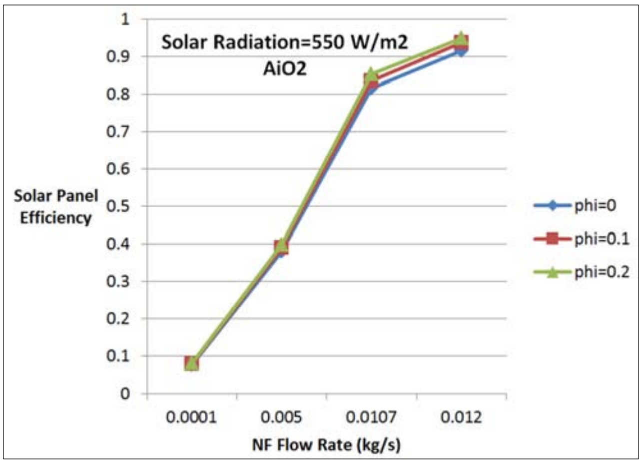

Figure 6. *Solar panel efficiency at different Φ conditions for AiO_2.*

This can be attributed to the fact that the solar panel mass flow rate is designed for optimum solar radiation. and higher values of solar radiation than the optimum design values increases the heat losses and contributes to lower solar panel efficiency. Therefore, it is quite significant and critical to design the solar panel collector flow at the optimum solar radiation in order to avoid heat losses. Furthermore, theoretically, as shown in Figures 5 and 9, the solar panel efficiency could be 100% at higher nano particles concentrations; however, it is highly unlikely to use concentrations higher than 20% due to higher pressure losses, increased pumping power and issues with HTF loop.

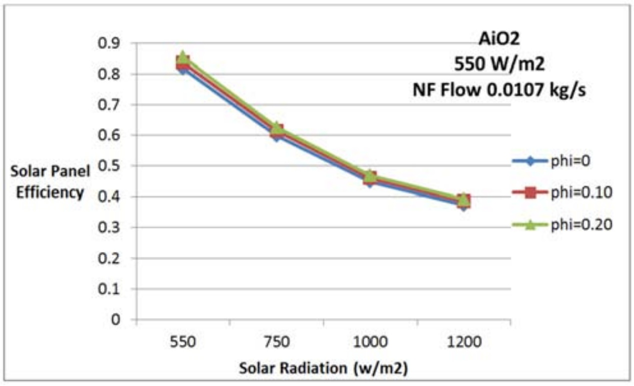

Figure 7. *Predicted solar panel efficiency at different Φ conditions for AiO_2.*

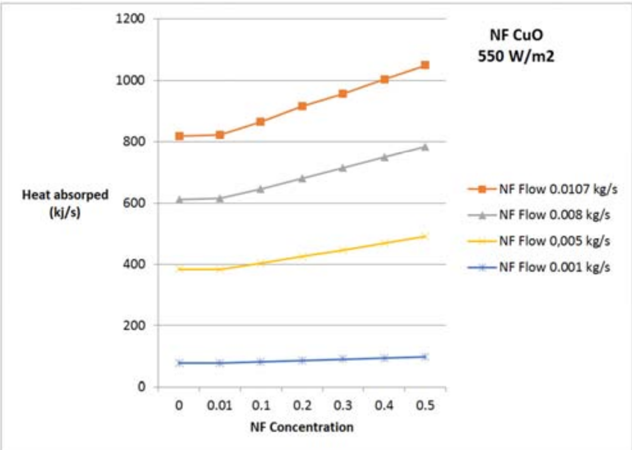

Figure 8. *Predicted heat absorbed by solar panel at different flow conditions for CuO.*

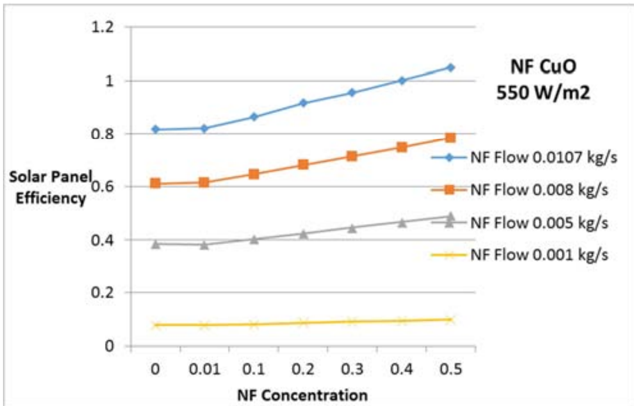

Figure 9. *Solar panel efficiency at different flow conditions for CuO.*

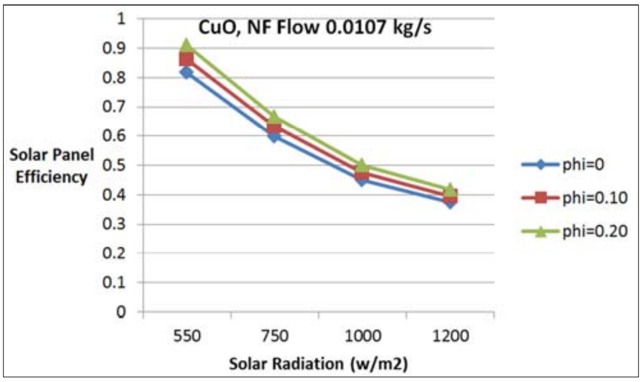

Figure 10. *Solar panel efficiency at different Φ conditions for CuO.*

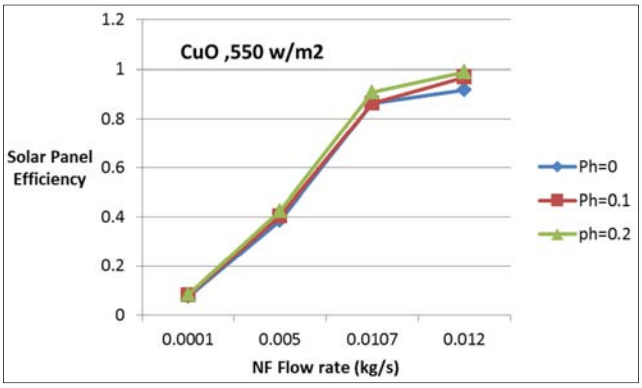

Figure 11. *Solar panel efficiency at different Φ conditions for CuO.*

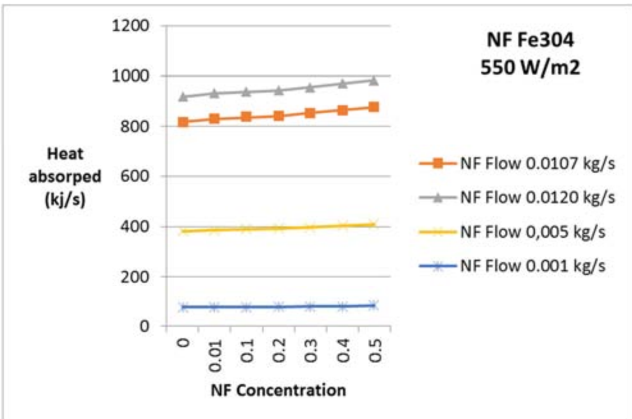

Figure 12. *Solar panel heat absorbed at different flow conditions for Fe_3O_4.*

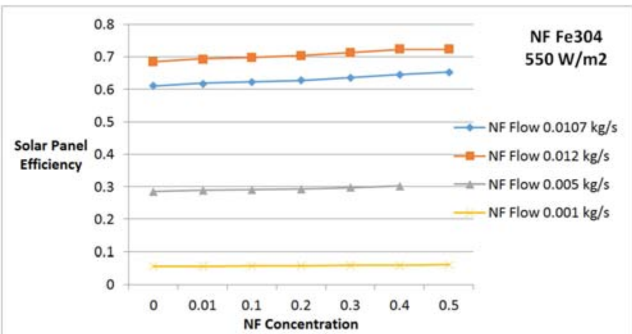

Figure 13. *Solar panel efficiency at different flow conditions for Fe_3O_4.*

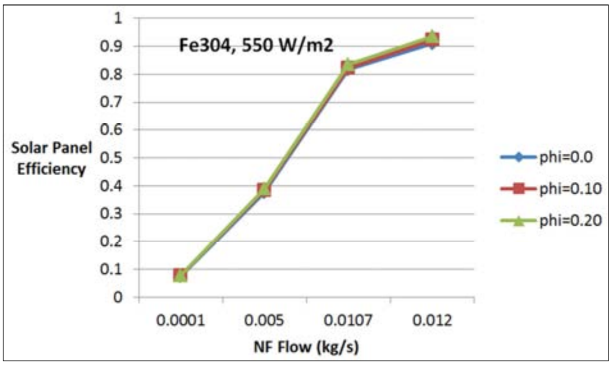

Figure 14. *Solar panel efficiency at different Φ conditions for Fe_3O_4.*

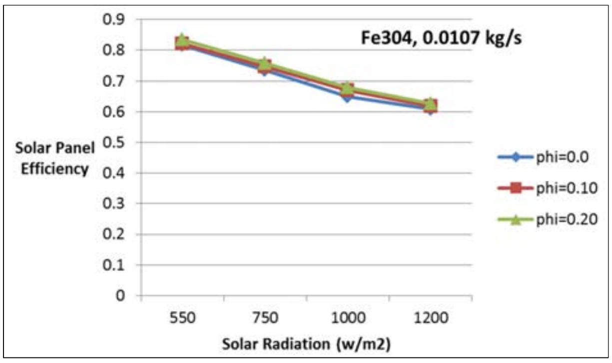

Figure 15. *Solar panel efficiency at different Φ conditions for Fe_3O_4.*

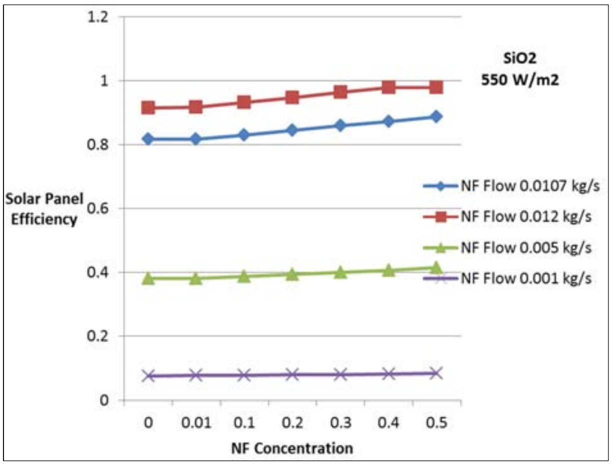

Figure 16. *Solar panel efficiency at different flow conditions for SiO_2.*

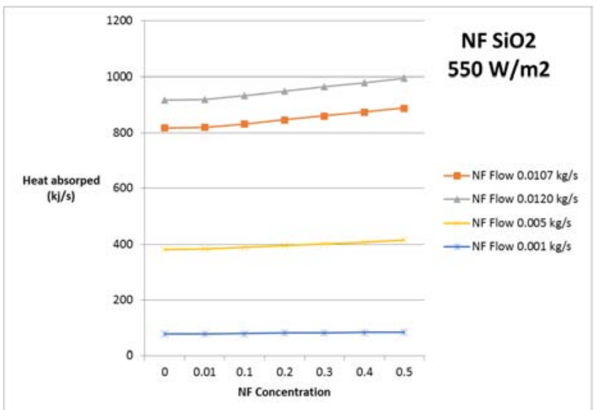

Figure 17. *Solar panel heat absorbed at different flow conditions for SiO_2.*

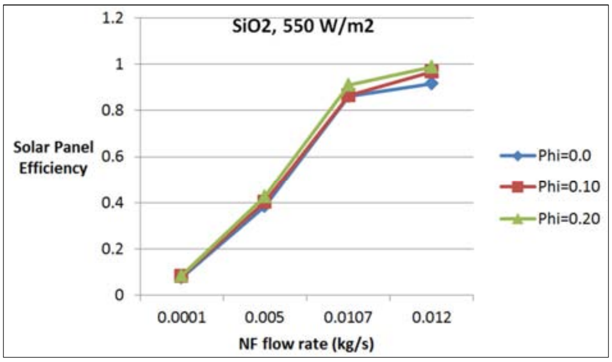

Figure 18. *Solar panel efficiency at different Φ conditions for SiO_2.*

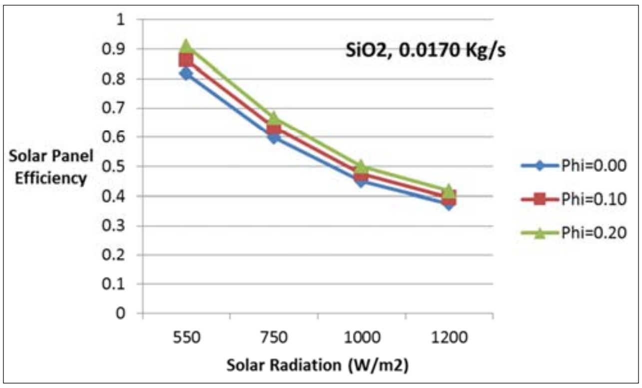

Figure 19. *Solar panel efficiency at different flow conditions for SiO_2.*

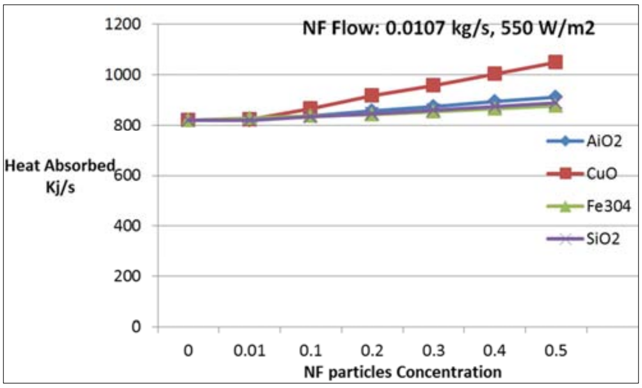

Figure 20. *Solar panel heat absorbed at different nano particles.*

To study the impact of the different nano particles on the heat absorbed from the solar radiation by the heat transfer fluid circulating in the thermal solar panel heat tubes, Figure 20 has been constructed to present the heat absorbed by different nano particles under heat transfer fluid of 0.0107 kg/sec and solar radiation of 550 w/m2. It is quite obvious from the results displayed in that figure that CuO has the highest heat absorption rate while Fe304 has the lowest heat absorption rate by the heat transfer fluid. This is attributed to the fact that CuO has the highest thermal and heat properties among the nano particles under investigation. Furthermore, it can also be pointed out at the low concentration of 1% there is no noticeable difference between the nano particles impact on the heat absorbed by the heat transfer fluid. However, at nano particle concentrations of 10%, it is quite evident that

CuO has the greatest impact on the amount of heat absorbed and this trend continued during this study.

On the other hand, Figure 21 illustrates the impact of the nano particles on the efficiency of thermal solar panels. This figure displays the efficiency of thermal solar panel at constant solar radiation of 550 w/m2 and particles concentration of 10% and different heat transfer fluid flow rates. In general, the numerical results displayed in this figure showed that the different nano particles increase the solar panel efficiency with the increase of the heat transfer fluid (HTF) flow rate. Obviously the maximum enhancement of the solar panel occurred at heat transfer fluid of 0.012 kg/s.

On the other hand, it is quite evident from the numerical results displayed in this figure that nano particles AiO_2 has the highest solar panel efficiency among the nano particles under investigation and CuO has exhibited the lowest efficiency

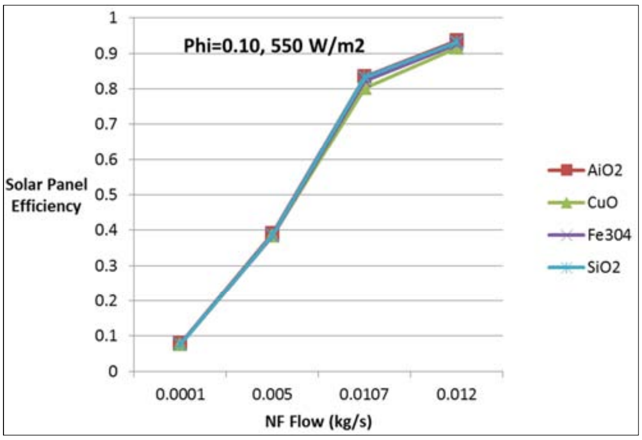

Figure 21. *Solar panel efficiency at different nano particles flow conditions.*

Finally, the dynamic behavior of the heat transfer fluid temperature (HTF) as predicted by equation (7) using the finite difference formulation is presented in Figure 22, where the temperature profile is plotted against the time at solar radiation of 550 W/m2 and at a designed solar panel flow rate of 0.0107 Kg/s and an initial temperature of 29.4°C. The dynamic behavior presented in this figure clearly showed that the temperature of the HTF increases with the increase of heat absorbed from the solar radiation by solar panel heat transfer fluid. Furthermore, it is worthwhile noting that the time needed to absorb the solar radiation is highly dependent upon the solar radiation and the flow rate of the HTF among other parameters as has been presented and shown in Sami [15].

Furthermore, It is also worthwhile noting that the predicted results of the heat absorbed and efficiency of thermal solar panel presented in Figures 3 through 21 on different nano particles concentration appeared to compare fairly with other results on nanofluids published on the enhancement of the solar panel efficiency in the literature namely references [1, 3, 11, 12, and 13].

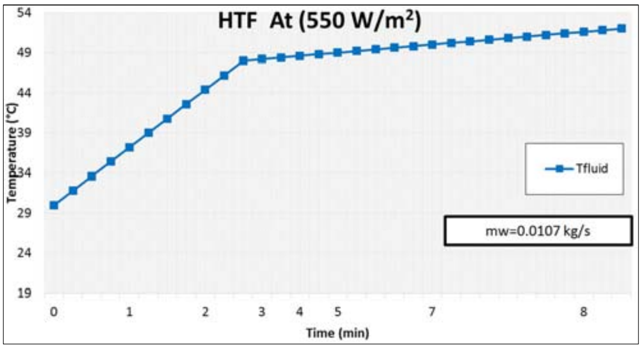

Figure 22. *Temperature profile during heat absorption under solar radiation 550 W/m^2.*

5. Conclusions

During the course of this study, the characteristics of heat transfer fluid with nano particles AiO_2, CuO, Fe_3O_4 and SiO_2 circulating in thermal solar panel and thermal tank have been modeled, presented, analyzed and compared to data published in the literature. The numerical model presented hereby was established after the energy conservation equations coupled with the heat transfer equations of the heat transfer fluid (HTF) using nano particles; AiO_2, CuO, Fe_3O_4 and SiO_2. The numerical resulted presented in this paper showed that the different nano particles increase the solar panel heat absorbed with the increase of the heat transfer fluid (HTF) flow rate. In addition, results also showed that a higher nanofluid mass flow rate increases the thermal solar panel efficiency. Furthermore, it was also shown that increasing the nano particles concentration enhanced the heat transfer properties and consequently increased the heat transferred and absorbed by the heat transfer fluid; this in turn enhances the solar panel efficiency.

In general, the simulated results of our numerical model presented hereby fairly predicted the heat transfer characteristics of the HTF and solar panel efficiencies, and are in agreement and compared well with other data reported in the literature.

Nomenclature

A_{Panel}, Area of solar panel (m^2)
A_f, Flow area (m^2)
C_{pw}, Specific heat of water (kJ/(kg K))
D_H, Hydraulic diameter (m)
G, Radiation (W/m^2)
h, Heat transfer coefficient
K_w, Thermal conductivity of water (kJ/(ms°C))
l, Tube length (m)
m_w, Water mass flow rate (kg/s)
N: number finite different element (N: 1-12)
Q_{tub}, Heat (kJ)
R, Tube radius (m)
$T_{(water\ m)}$, Temperature of HTF at "m" element (°C)
Greek
ρ_w, Density of water flow (kg/m^3)
μ, Water viscosity (mPa.s)

Subscripts
H, Hydraulic
W, HTF
Tub, tube
W, Water

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