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Impact of Magnetic Field on the Dynamic Performance of Photovoltaic-Thermal Panel with Nanofluids

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Authors' contributions

The sole author designed, analyzed, interpreted and prepared the manuscript.

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ABSTRACT

The performance of a hybrid solar collector photovoltaic-thermal solar panel system under a magnetic field using nanofluids was presented hereby. A two-dimensional dynamic heat transfer and fluid flow model was developed to describe the behavior of the photovoltaic cell-thermal panel at different conditions such as solar irradiance, nanoparticles, different magnetic field gauss forces. different material properties, and boundary conditions. The model has been established after the dynamic mass and energy equations coupled with the heat transfer relationships, and thermodynamic properties as well as material properties under different magnetic gauss forces. Comparisons were made against literature data for validation purposes of the predictive model. The model fairly predicted the key parameters under different nanofluids conditions, magnetic fields, and compared well with existing data on the subject.

Keywords: Dynamic modeling; simulation; photovoltaic-thermal solar hybrid system; nanofluids; magnetic field; model validation.

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NOMENCLATURE

$Area_{cell}$	: PV cell area (m^2)
$Area_{pipe}$	: Pipe area (m^2)
$Area_{HT}$	: Heat transfer area (m^2)
C_{p_water}	: Thermal capacity of water (J/kgK)
D	: Internal Pipe diameter (m)
E_{gO}	: Bandgap energy of semiconductor (1.1 eV)
G	: Total Solar radiation incident on the Pv module (W/m^2)
H	: Convective heat transfer coefficient module (W/m^2K)
h_{water}	: Heat transfer coefficient (W/m^2K)
I	: Output current of the Pv module (A)
I_o	: Diode saturation current per module (A)
I_{ph}	: Light generated current per module or photocurrent (A)
I_{rs}	: Module reverse saturation current (A)
I_{sc}	: Short circuit current (A)
k	:Boltzmann's constant ($1.3806503*10^{-23}$ J/K)
Ki	: Short-circuit of a Pv cell at SRC (mA/°C)
K_{Pv}	: Thermal conductivity of Pv cell (W/mK)
L_{cell}	: Length of a Pv cell (m)
$\dot{m}$	:Water flow (Kg/s)
mC_{p_module}	: Thermal capacity of the Pv module
m_{water}	:mass of water (Kg)
n	:Ideality factor of the diode (q)
N_p	: Total number of cells connected in parallel
N_{pipes}	: Number of pipes
N_s	: Total number of cells connected in series
nTE	:number of Thermal Elements in a pipe
P	: Power generated by Pv module (W)
Pa	: Atmospheric pressure of moist air (Pa)
Pw	: Partial pressure of water vapor in moist air (Pa)
q	: Electronic charge (C)
$Q_{conduction}$	: Energy due to conduction (W in Electrical Process) (W/m^2 in Thermal Process)
$Q_{convection}$	: Energy due to convection (W in Electrical Process) (W/m^2 in Thermal Process)
Q_{elect}	: Electrical power generated (W)
Q_{in}	: Energy received due to Solar irradiation (W/m^2)
Q_{in_cell}	: Energy incident on one Pv cell due to solar radiation (W/m^2)
$Q_{radiation}$	: Energy due to radiation (W/m^2 in Thermal Process)
$Q_{Thermal}$	: Energy from thermal process (W)
R_d	: Fouling factor - or unit thermal resistance of the deposit (m^2K/W)
R_s	: Diode series resistance per module (Ω)
R_{sh}	: Diode shunt resistance per module (Ω)
S_c	: Total surface area of Pv cells in a module (m^2)
S_p	: Total area of the PV module (m^2)
T	: Operating temperature (k)
T	: Time (s)
T_a	: Ambient temperature (°C)
T_C	: Pv Cell Temperature (°C)
T_{db}	: Dry bulb temperature (°C)
T_f	: Fluid temperature (°C)
T_f	: Fluid temperature (°C)
T_{f_in}	: Fluid temperature at the inlet (°C)
T_{fHx}	: Maximum temperature at the Heat Exchanger (°C)
T_{fHx+1}	: Fluid temperature at thermal element 1 (dx) (°C)
T_m	: Module Back-surface temperature (°C)
T_r	: Nominal temperature (298.15 K)
U	: Thermal conductance of clean heat exchanger (W/m2K)
Ud	: Thermal conductance of heat exchanger after fouling (W/m2K)
V	: Output voltage (V)
V_{oc}	: Open circuit voltage (V)
Vt	: Diode thermal voltage (V)
α_{abs}	:Overall absorption coefficient
η_{Hybrid}	:Hybrid system efficiency
ηPv	:PV module efficiency
$\eta_{Thermal}$	:Efficiency of thermal process
ρw	: Density of water vapor (Kg/m^3)
∂Q	: Convection heat transfer rate
ε	: Emissivity PV cell
σ	: Stefan-Boltzmann constant (5.67E-08 W/m^2K^4)

1. INTRODUCTION

The PV cell technology was invented in 1894 by Charles Fritts, where sunlight is converted into electrical energy. This energy can be harnessed and supplied to the electrical microgrid and used in remote areas. Currently, the efficiency of commercial solar PV is up to 15%, and most of the incoming solar radiation energy is either absorbed or reflected and significant excess heat is dissipated and wasted. To improve the solar PV's efficiency a novel concept of combined photovoltaic-thermal solar panel hybrid system concept using nanofluids has been developed [1-11]. It is a simple hybrid system where the PV cells are cooled through water-based nanofluids flows. The solar irradiance is converted into electrical energy in the PV's cell; the excess thermal energy generated due to the intrinsic conversion efficiency limitation of the cell is dissipated into the water-based nanofluids. This in turn reduces the cell temperature and enhances the conversion efficiency of the cell. Therefore, the net result is an enhancement of the combined photovoltaic-thermal efficiency of the hybrid system [12-52].

It was found In the presence of an external magnetic field, the thermal conductivity of magnetite nanofluids increases with the volumetric concentration percentage of magnetic particles with increasing the magnetic field strength [10,11].

Allen [11] studied the magnetic properties of four water-based nanofluids consisting of Al_2O_3, CuO, Fe_3O_4, and SiO_2 in his master thesis and analyzed the effect of the application of an external magnetic field on the thermal conductivity of the nanofluid. He reported that when the magnetic field was applied, the magnetic dipole moments of the particles aligned and the particles come in contact with each other to form chains in the direction of the applied magnetic field. When the magnetic field was applied parallel to the direction of heat flow, it caused the effective thermal conductivity in the direction of the magnetic field to increase. It was also suggested by Allen [11] that a higher thermally conductive fluid can be applied to solve numerous heat transfer problems.

It was reported by Katiyara et al. [12] that a magnetic field induced augmented thermal conductivity of magneto-nano colloid involving magnetic oxide nanoparticles, viz. Fe_2O_3, Fe_3O_4, Nickel oxide (NiO), Cobalt oxide (Co_3O_4), dispersed in different base fluids such as heat transfer oil, kerosene, and ethylene glycol. Experiments reveal the augmented thermal transport under the external applied magnetic field, with kerosene-based MNCs showing relatively low magnetic field (~ 600 G) intensities as compared to the heat transfer oil and EG-based MNCs. Also, it was observed that Co_3O_4 nanoparticles show an insignificant effect on the thermal conductivity enhancement of MNCs due to their minimal magnetic moment. Katayama et al. [12] proposed an analytical approach to understanding the mechanism and physics behind the thermal conductivity enhancement under the external applied magnetic field, in tune with near field magnetostatic interactions as well as Neel relaxivity of the magnetic nanoparticles. Furthermore, the analytical model was able to predict the phenomenon of enhanced thermal conductivity as a function of physical parameters such as chain length, size and types of nanoparticles, fluid characteristics, magnetic field intensity, saturation magnetic moment, nanoparticle concentration and good agreement with the experimental results has been observed.

A review has been presented by M. S. A. Rahim and I. Ismail [13] on the magnetorheological fluids materials with the capability to reversibly change from liquid to near solid state under the presence of external magnetic fields. The review highlighted the recent developments of magnetorheological fluid and nanofluid in the field of thermal behavior. Special emphasis was placed on the understanding of their thermal conductivity property by using several parameters which included particle volume fraction, shape and size of particles, materials of particles and base fluid, and magnetic field. Reference [13] showed that the increase in particle volume fraction and magnetic field strength may increase the thermal conductivity of the magnetorheological fluid. A relationship between these parameters and thermal conductivity has been developed from the theory and experimental and reported by this reference

Sheikholeslami et al. [14] employed Koo-Kleinstreuer-Li correlation for MHD nanofluid flowing over two vertical permeable sheets for Al_2O_3-water under the influence of free convection is investigated. They used the Runge-Kutta method for the numerical solutions and discussed the effects of various physical parameters on nanofluids. The results indicated that the enhancement in heat transfer is an increasing function of the Hartman number.

In a recent paper published by reference [15], the effect of using nanofluids of various kinds on improving heat transfer and increasing the efficiency of solar collectors was reviewed and other studies have been presented regarding the effect of electromagnetic field on improving heat transfer and its effect on solar collectors. In the paper, the electromagnetic effect of thermo-hydrodynamics behavior of nanofluids has been examined and reported. The results of the previous research that was reviewed showed that the use of nanofluids has a clear effect on improving the thermal efficiency of solar collectors and improving heat transfer in high proportions, as well as between studies that adding the effect of electromagnetic overflow on solar collector systems has had a positive effect in improving heat transfer and improving properties Physical fluid.

A study published in reference [16] on the studies available literature on the thermal conductivity and the viscosity of the magnetic nanofluids in the presence of the magnetic field has been collected, reviewed, compared, discussed. Reference [16] observed that there is a contradiction between the results which were presented in the literature. The differences between the available experimental results which may be caused by the application of the external magnetic field have been discussed by categorizing and comparing the studies which investigated the influence of the similar parameters by using the most similar samples. Additionally, magnetic field-dependent thermal conductivity and viscosity models available in the literature have been reviewed.

Lucian Pîslaru-Dănescu et. al.[17] proposed in the book chapter a new type of cooling agent based on magnetic nanofluid to replace the classical cooling fluids in electrical power transformers. A mathematical model and numerical simulation results are very useful for investigating the heat transfer performances of the magnetic nanofluid. Based on this study, it was tested the cooling performance of this magnetic nanofluid for two types of electrical power transformers as compared to classical methods. They also presented a microactuator based on the same magnetic nanofluid. Based on this study, it was tested the cooling performance of this magnetic nanofluid for two types of electrical power transformers as compared to classical methods. Also presented a microactuator based on the same magnetic nanofluid.

A novel combined concept and simulation model of the photovoltaic-thermal solar panel hybrid system operating with nanofluids and under the influence of a magnetic field was presented in this study. This novel concept using magnetic was intended to enhance the energy conversion efficiency of the PV- Thermal solar hybrid system by using utilizing excess thermal energy dissipated by the conversion process to produce domestic hot water (DHW). The conceptual photovoltaic-thermal panel design was modeled and analyzed using a two-dimensional dynamic model based upon the heat transfer and fluid flow conversion equations. The model was developed to describe the steady-state and dynamic behavior of a combined photovoltaic cell-thermal panel hybrid system under different solar irradiances, nanofluids, magnetic field forces, material properties, ambient, heat transport fluid flow conditions, and excess thermal energy recovered by the panel. The predicted results presented herein include the efficiency of energy conversion of the hybrid system, PV cell, and the amount of excess thermal energy recovered by the panel and transferred to the fluid transport flow under different conditions.

2. MATHEMATICAL MODEL

The PV solar panel-and-tube, nanofluid water base cooled PVT solar collector as shown in Fig. .1 was analyzed and numerically modeled in this research work under the influence of magnetic field force. It consists of a photovoltaic solar panel and welded thin parallel tubes on its backside for the circulation of the cooling heat transport fluid with nanofluids. The parallels thin tubes were soldered to the PV solar panel and connected to a thermal tank from which water-based nanofluids flow through the solar collector copper pipes and carry the excess heat away from the PV-thermal panel as shown in Fig. 1. Various water-based nanofluid flow rates were analyzed at different conditions of magnetic field forces to assess their impact on the performance of the PV-Thermal hybrid system. This hybrid system was intended for power generation by the PV solar panels and using the thermal excess heat transferred to produce hot water for domestic and/ or industrial use. Also, the model in question examined the enhancement in the hybrid system efficiency of the solar PV panel at various operating temperatures. The model is presented in the following sections.

2.1 PV Thermal Model

In the following thermal analysis, it is assumed that all PV cells behave the same; therefore, it is applied to the PV solar panel and adopted from Sami[52];

The heat absorbed by the PV solar cell can be calculated by the following [18-22, 52];

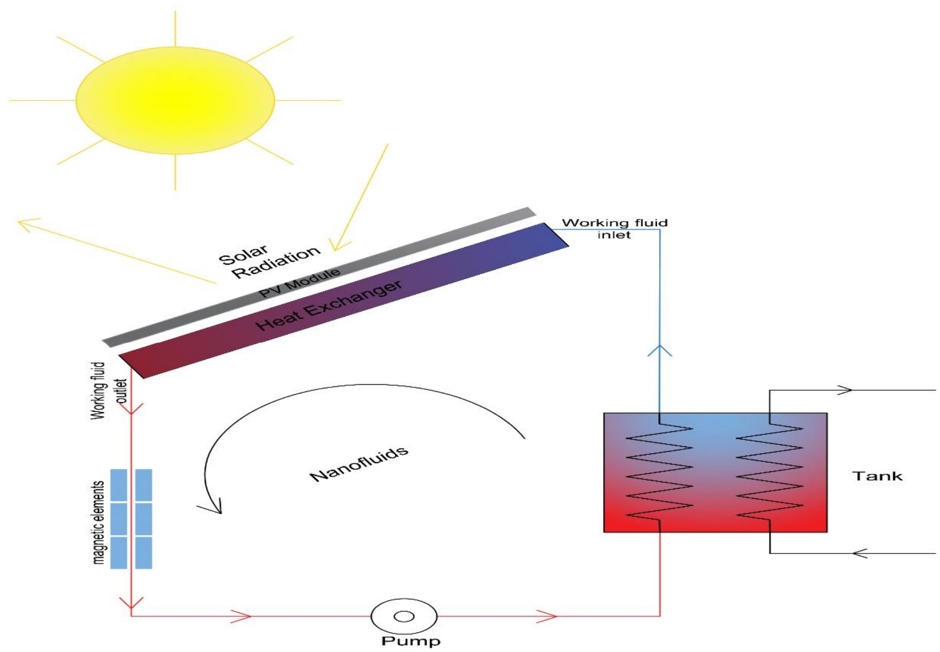

Fig. 1. PV/Thermal hybrid system with the magnetic field using nanofluids

$$Q_{in} = \alpha_{abs} G S_p \quad (1)$$

Where;

α_{abs}: Overall absorption coefficient
G: Total Solar radiation incident on the PV module
S_p: Total area of the PV module

Meanwhile, the PV cell Temperature is computed from the following heat balance [18-22];

$$mC_{p\_module} \frac{dT_C}{dt} = Q_{in} - Q_{conv} - Q_{elect} \quad (2)$$

Where;

T_C: Pv Cell Temperature
mC_{p_module}: Thermal capacity of the PV module
t: time
Q_{in}: Energy received due to solar irradiation
Q_{conv}: Energy loss due to Convection
Q_{elect}: Electrical power generated

And the Solar energy absorbed by the PV cell, Qin, is given by equation (1).

2.1.1 Thermal energy incident in a PV cell

The energy loss due to heat convection can be obtained from;

$$Q_{conv} = S_p H (T_C - T_a) \quad (3)$$

H: Convective heat transfer coefficient
T_a: Ambient temperature

The electrical power generated is given by;

$$Q_{elect} = \eta G S_c \quad (4)$$

η: Module efficiency
S_c: Total surface area of PV cells in a module

The thermal energy transferred from the PV cells to the Heat Transfer Fluid (HTF) is determined from the heat balance across the PV cell and HTF in terms of the heat transfer mechanisms; conduction, convection, and radiation as follows [1,17 through 22,52];

$Q_{conduction} = Q_{convection} - Q_{radiation}$ (5)

$$Q_{conduction} = \frac{K_{Pv} \times \Delta T(T_c - T_m)}{L_{cell}} \quad (6)$$

T_m: Module Back-surface temperature
K_{Pv}: Thermal conductivity of PV cell
L_{cell}: Length of a PV cell

The heat transfer by convection is determined from;

$$Q_{convection} = h_{water} \times \Delta T(T_m - T_f) \quad (7)$$

$Q_{convection}$: Energy due to convection
h_{water}: heat transfer coefficient
T_f: Fluid temperature

And the heat transfer by radiation is;

$$Q_{radiation} = \varepsilon \times \sigma(T_m^{\ 4} - T_f^{\ 4}) \quad (8)$$

$Q_{convection}$: Energy due to radiation
ε : Emissivity PV cell
σ: Stefan-Boltzmann constant

The finite-difference formulation was used to determine the heat transfer fluid temperature as follows at each element. The heat transfer fluid tube is divided into, *nTE*, elements;

$$T_f = T_{f\_in} + \frac{\partial Q}{m_{water} C_p} \times t \quad (9)$$

t: time
T_{f_in}: Fluid temperature at the inlet and *t* represents the time step iteration

The thermal energy transferred from the PV cell to the heat transfer fluid is obtained by;

$$Q_{Thermal} = \dot{m} \times C_{p\_water} \times \Delta T(T_{fHx+1} - T_{f\_In}) \quad (10)$$

$Q_{Thermal}$: Energy from the thermal process
T_{fHx+1}: Fluid temperature at thermal element 1

The energy transferred to heat transfer fluid is calculated by the integration of the aforementioned equations along the length of each tube. In this analysis, the mainstream temperature of the heat transfer fluid flow is considered as the average temperature of the inlet and outlet of each finite-difference element;

$$Q_{in} = \dot{m}_w C_{p\_water} (T_{f+1} - T_f) \quad (11)$$

$\dot{m}_w$: Water flow.
T_{f+1}: Water temperature at the next element.
C_p: Specific heat of HTF.

2.2 PV Model

The solar photovoltaic panel is constructed of various modules and each module has consisted of arrays and cells. The dynamic current output can be obtained as follows [13-16,52];

$$I_P = I_L - I_o\left[\exp\left(\frac{q(V + I_P R_S)}{AkT_C} - \frac{V + I_P R_S}{R_{sh}}\right)\right] \quad (12)$$

I_p: Output current of the Pv module
I_L: Light generated current per module
I_o: Reverse saturation current per module
V: Terminal voltage per module
R_s: Diode series resistance per module
R_{sh}: Diode shunt resistance per module
q: Electric charge
k: The Boltzmann constant
A: Diode ideality factor for the module

Where;

$$I_o = BT^3 c\left[\exp\left(-\frac{E_{go}}{KT_C}\right)\right] \quad (13)$$

And;

$$I_L = P_1 G[1 - P_2(G - G_r) + P_3(T_C - T_r)] \quad (14)$$

Where;

The PV cell temperature, Tc, and is influenced by various factors such as solar radiation, ambient conditions, and wind speed. It is well known that the cell temperature impacts the PV output current, performance, and its time-variation can be determined from references [8-16];

The AC power of the inverter output P(t) is calculated using the inverter efficiency η_{inv} , output voltage between phases, neutral V_{fn}, and for single-phase current I_o and $cos\varphi$ as follows;

$$P(t) = \sqrt{3}\,\eta_{inv} V_{fn} I_o \, cos\varphi \quad (15)$$

Finally, the hybrid system PV-thermal energy conversion efficiency for harnessing energy from solar radiation is given by;

$$\eta_{SH} = \frac{P(t) + Qthermal}{Qin} \quad (16)$$

Where Q_{th} and Q_{in} are the solar thermal heat transferred to the HTF and solar irradiance. The respective values are given by equations (1) and (16), respectively. Besides, $P(t)$ is the PV solar electrical output and defined by equation (15).

2.2.1 Nan fluid heat transfer fluid

The basic heat transfer fluid in the PV-Thermal loop as shown in Fig.1 is water-based nanofluids. Nanofluids have been added to the water-based flow to enhance their thermal properties. References [17-21,52] presented equations to calculate the thermophysical and thermodynamic properties of nanofluids such as specific heat, thermal conductivity, viscosity, and density employing the law of mixtures, as a function of the volumetric concentration of nanoparticles;

$$\alpha_{total} = \alpha_{particles} + \alpha_{base\ fluid} \quad (17)$$

Where α represents a particular thermophysical property of the nanofluid under investigation.

The nanofluid thermal and thermophysical properties, α_{total}, can be calcualted as follows;

$$\alpha_{total} = \alpha_{base\ fluid} + \alpha_{particles.}(\Phi) \quad (18)$$

Where; Φ represents the nano particles volumetric concentration.

The thermal conductivity is related to thermal diffusivity and density of the nanofluids as follows;

$$\lambda = \alpha\, \delta\, C_p \quad (19)$$

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

The specific heat is calculated for nanofluids as follows [17-21];

$$c_{pnf} = \frac{(1-\emptyset)(\rho Cp)_{bf} + \emptyset(\rho Cp)_p}{(1-\emptyset)\rho_{bf} + \emptyset\rho_p} \quad (20)$$

Where "*nf*" and "*bf*" refer to nanofluid and basic fluid, respectively. Ø is the nanofluid particle concentration. ρ represents the density.

The density of nanofluids can be written as follows [17-21,52];

$$\rho_{nf} = \emptyset_p \rho_p + (1-\emptyset)\rho_{bf} \quad (21)$$

ρ_p represents the density of the nanoparticle.

2.2.2 Thermophysical properties with magnetic field

Magnetorheological nanofluid heat transfer fluids are smart materials made of magnetic particles that can enhance flow characteristics in the presence of a magnetic field. However, the field-dependent thermal conductivity of magnetorheological fluids plays an important role in heat transfer and dissipation in potential new applications. Magnetic nanofluids with a low concentration of nanoparticles can significantly enhance their thermal. This research considers that magnetic metallic solids under different magnetic forces Gauss improve thermal and thermophysical properties compared to those of fluids, and nanofluids and exhibit significantly higher thermal properties compared to conventional heat transfer fluids. In the following, we present the formulas developed based upon the magnetic data published in the literature properties [10 through 23]; was used to taking into account the impact of the magnetic field as outlined in Table.1.

Where "b" represents the nanofluid specific property and "a" is the magnetic field force in Gauss. $Cp_{nf,}$ Knf, and h are the specific heat, thermal conductivity, and heat transfer coefficients of nanofluids.

Equation (19) can be used to determine other thermophysical properties such as; α is the thermal diffusivity, ʎ and ρ represent the thermal conductivity and density as a function of the properties outlined in the Table.1.

2.3 Numerical Procedure

The model describing the energy conversion and heat transfer mechanisms of nanofluids under the magnetic field force taking place during various processes PV-Thermal shown in Fig.1 are outlined in Equations (1) through (21). The model presented hereby is based on mass and energy balances of the individual components of the PV/T hybrid system; PV cell and the heat transfer fluid flowing under magnetic treatment in thermal tubes welded in the back of the PV panel. This permitted the prediction of the electrical power output of the PV panel and the characteristics of the water-based nanofluids in terms of solar radiation, different nanofluids, magnetic force Guass, and other geometry parameters.

These equations have been solved as per the logical flow diagram presented in Figure 2, where, the input parameters of the solar PV conditions such as solar radiation, ambient temperature, and humidity as well as other independent parameters such as nanofluids are defined. Dependent parameters were calculated and integrated into the system of finite-difference formulations for conservation equations under nanofluids and magnetic fields. Iterations were performed until a converged solution was reached with an acceptable iteration error.

The numerical procedure starts with using the solar radiation, ambient conditions to calculate the solar PV cell temperature, and PV cell back temperature as well as heat transfer fluid mass flow rate circulating in the thermal closed-loop using nanofluids and under magnetic field at specified conditions. The thermodynamic and thermophysical properties of Heat Transfer Fluid were employed to calculate the water-based nanofluids flow rate. This follows by using the finite-difference formulations to predict the time variation of the PV cell temperature, the PV back temperature, and thermal heat transferred to the Heat Transfer Fluid, Heat transfer fluid outlet temperature at the heat exchanger, as well as other hybrid system power outputs and efficiencies. Finally, hybrid system efficiency is calculated at each input condition.

3. RESULTS AND DISCUSSION

Equations (1) through (21) representing the present numerical model have been solved taking into account the heat and mass transfer mechanisms during the solar PV-Thermal energy conversion process under magnetic field forces. The above-mentioned equations were coded with finite-difference formulations and solved as per the logical flow chart depicted in Fig .2. Besides, for validation, the predicted simulated results for PV-Thermal solar panels were compared to the data published in the literature under various conditions.

In the following sections, we present analysis and discussions of the numerical results predicted as well as validations of the proposed simulation model. The simulations were performed for temperature differences across the thermal tubes of the heat exchanger welded under the PV solar panels of 5, 10, 15, 20, and 25 °C. However, only results will be presented and analyzed for the temperature difference of 15 °C across the thermal tube. It is worthwhile noting that the numerical simulation presented hereby was conducted under different conditions such as; PV cell temperatures from 10°C through 38°C, ambient temperatures from 10°C through 38°C, solar radiations; 500, 750, 1000, and 1200 w/m^2, different nanofluids; Al2O3, Fe304, SiO2, CuO at various concentrations; 5,10 and 20%, however, this study was only concerned with nanofluid concentrations of 5% and other concentrations were presented for demonstration purposes. Also, the study was done under a magnetic force that varied from 127 Gauss to 3000 Gauss.

The PV panel characteristics under consideration in this study were obtained from Fargali et al. [22]. The parameters adopted in this study were; Total surface area of the PV module (SP) is 0.617 m^2, Total surface area of cells in module (Sc) is 0.5625 m^2, module efficiency 12% at reference temperature (298 K), the overall absorption coefficient is 0.73, and Temperature coefficient is 0.0045 K-1. Interested readers in the full range values of the other parameters are advised to consult Fargali et al. [22]. This model assumed the solar PV panel was covered in PV cells, with no packing material and no gaps between the cells on a panel. Also, the PV solar panels were cooled using a thermal tube heat exchanger bonded to the back of the PV solar panel without any air gap to ensure complete heat dissipated from the PV cells by conduction, convection, and radiation were fully absorbed by the fluid transport fluid flowing in the thermal pipes.

It has been reported in the literature [21, 22, and others] that an increase in the PV cell temperature due to solar radiation resulted in an increase in the back cell temperature and consequently the heat transport fluid temperature due to the heat transfer from solar energy by conduction and convection as well as radiation, respectively. Furthermore, Figs 3 through 5 demonstrated the dynamic behavior of the PV cell temperature, back cell temperature, as well as heat transport fluid temperature. It can be seen that the higher the cell temperature the higher the back cell and fluid temperatures and the higher the solar radiations the higher the energy absorbed by the PV cell, and consequently the higher the temperature of the cell until reaches the design temperature.

The effects of the PV panel operating temperature on the output efficiency have been well documented in the literature [19 through 21, 22], where the increasing temperature of the PV cell decreased the amount of power available. However, it is important to note that the changes in the PV cell temperature caused by solar radiation have a dynamic nature. The PV panel heats up and cools down gradually depending upon the changes in solar radiation in dynamic response and consequently the power output from the PV panel.

Table 1. Thermophysical properties as a function of magnetic field forces in Gauss [26-28, 35-42]

	Ai203	CuO	Fe304	SiO2
Cp nf	b = 0.1042a + 6226.5	b = 0.2011a + 5730.8	b = 0.8318a + 4269.8	b = 0.6187a + 4293.2
K nf	b = 2E-05a + 1.4888	b = 5E-05a + 1.3703	b = 0.0002a + 1.0209	b = 0.0001a + 1.0265
h	b = 0.0031a + 73.092	b = 0.0031a + 73.073	b = 0.003a + 73.225	b = 0.003a + 73.231

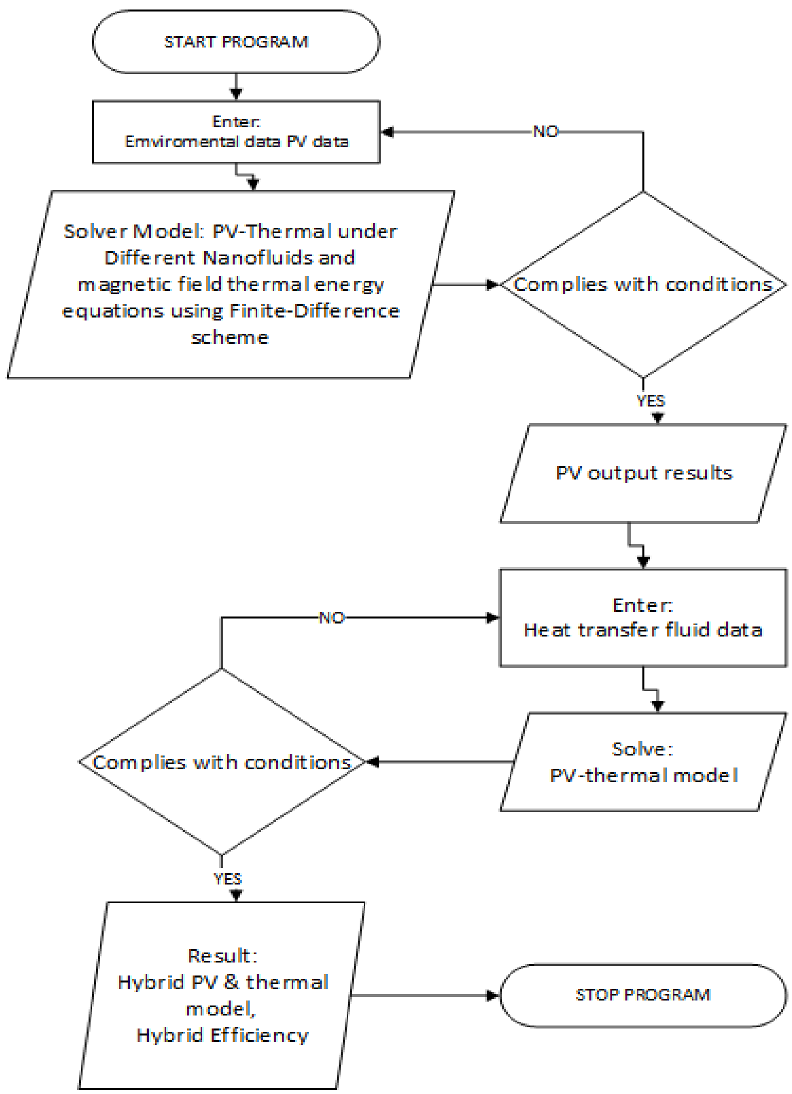

Fig. 2. Logical flow diagram

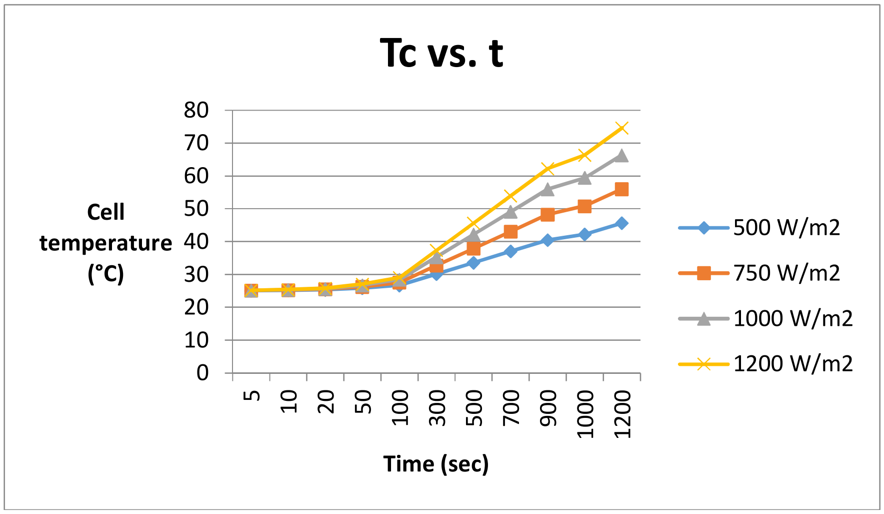

Fig. 3. Cell temperatures at different solar radiations

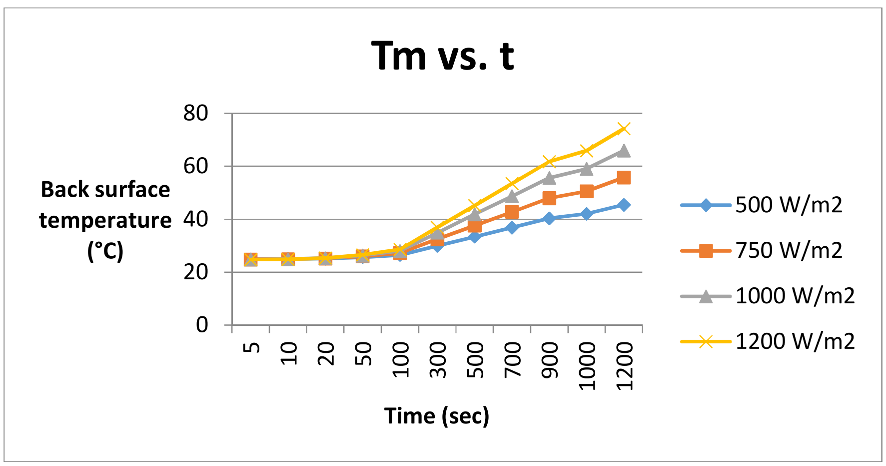

Fig. 4. Back cell temperatures at different solar radiations

The dynamic behavior of the PV cell temperature, back cell temperature, as well as heat transport fluid temperature, has been plotted at different solar radiations figs 3 through 5, at constant ambient temperature as well as heat exchanger temperature difference of 15 °C. It was quite evident from the results presented in these figures that the cell temperatures, as well as the other ones, increase with the increase of solar radiation. This can be interpreted as per equations (1) and (2) where the dynamic cell temperatures are expressed in terms of the heat balance across the PV cells.

The data presented in the aforementioned figures showed that the higher the solar radiation the higher the interfacial temperatures. It appears from the temperature gradient presented in these figures that the heat flow from the solar energy converted to the thermal heat energy that was absorbed by the heat transfer fluid, and clearly illustrated the impact on the different temperatures of the PV cell, the PV back temperature, and the fluid temperature.

Fig.6 showed that the higher the solar radiation the higher the thermal energy absorbed and also shows that once the cell temperature stabilizes the thermal energy absorbed reaches the steady-state level. As expected the heat transport fluid mass flow rate increased at higher solar radiation. This is because the higher solar radiation results in higher thermal energy transferred to the fluid flow and consequently this increased the fluid flow mass flow rate.

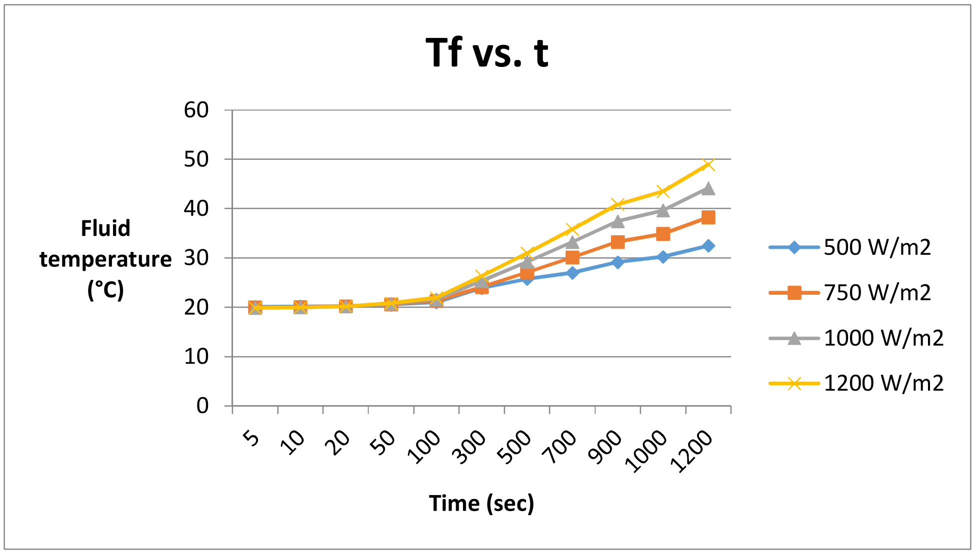

Fig. 5. Heat transport fluid temperature at different solar radiations

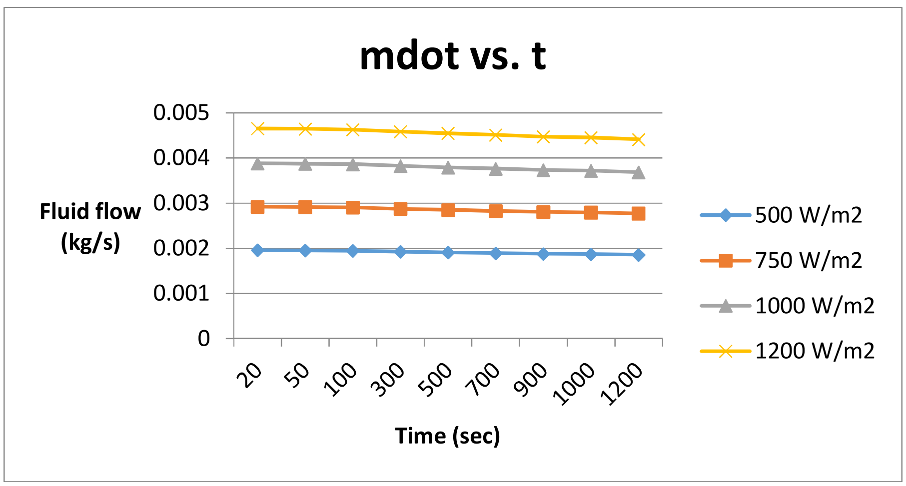

Fig. 6. Water mass flow rate at different solar radiations and heat exchanger temperature difference 15°C

The solar thermal radiation convective thermal energy converted and transferred to the heat transport fluid flow circulating beneath the PV solar panel has been depicted in Figs 7 through 9, under different nanofluid Ai2O3 concentrations and at the maximum magnetic field force of 3000 Gauss. Nanofluid Ai2O3 was used in this study as a reference base nanofluid because it has been reported the most in the literature for comparison purposes. The hybrid system thermal efficiency as defined in equation (16) was determined as thermal energy and electrical power generated divided by the solar radiation absorbed by the PV solar panel. It is quite evident from the results presented in Fig.9 that the higher the nanofluid concentration the higher the hybrid thermal conversion efficiency. Similar observations were noted regarding the other main parameters of the hybrid system in questions in Figs.7 and .8 that the higher the nanofluid Ai2O3 concentrations the higher the thermal energy generated.

Figs .10 through 13 were constructed to analyze the thermal energy converted and transferred to the nanofluid heat transport fluid at different temperatures and concentrations %10, circulating beneath the PV-Th solar panel under solar radiation of 750 w/m2 and different magnetic field forces. The depicted results in these figures demonstrated that the higher the magnetic field force the higher the thermal energy produced and in turn resulted in higher the thermal efficiency of the PV-Thermal solar panel and higher the hybrid system efficiency. This is significant since as per Fig 8 the thermal energy transferred to the heat transport fluid was the highest at magnetic field force of 3000 Gauss compared to other magnetic field forces under this investigation. The enhancement in thermal conductivity of the magnetic nanofluids can be explained based on the interaction among the dispersed nanoparticles and how the behavior changes in presence of a magnetic field. The phenomenon of enhancement of thermal conductivity can be explained based on chain formation due to particle-particle interactions and alignment along the magnetic field [12], which results in the formation, conducting, and diffusing of heat. A higher magnetic field charge can cause heat transport fluid nanofluid water-based molecules to be attracted to each other and formed clusters When passed through a magnetic field, some of the physical properties like surface tension, viscosity, the dielectric constant, and electrical and thermal conductivity were changed under the influence of the magnetic field, reported by Cai et al [35], compared to the none magnetic fields. Pang et al. [36] found also that the magnetic fields reduced the specific heat, increased the soaking degree and hydrophobicity of water to materials, and depressed its surface tension force, and increased refractive index and electrical conductivity. If the particles are loosely packed within the fibrils, such as occurring at low magnetic fields or low concentrations, the effective volume of the fluid in between two consecutive particles within the chains is higher and thereby the chain's ability to conduct heat is low. As the magnetic field intensity increases, the force of attraction among the nanoparticles is also increased and reaches maxima at CMF. It is believed that the aforementioned changes caused by the magnetization of the heat transport fluid and its thermophysical properties enhanced the thermal energy transferred to the heat transport fluid and in turn, increased the PV-Th thermal efficiency as well as the hybrid system efficiency.

To study the impact of the different Ai2O3 concentrations on the thermal energy generated at the PV-Th solar panels and the hybrid system efficiency Figs 14 and 15 were constructed at solar radiation of 750 w/m2 and different magnetic field forces up to 3 Tesla and compared with water-based heat transport fluid. The results showed that the higher the nanofluid concentration the higher the thermal energy absorbed and the higher the hybrid system efficiency. It is believed that this was due to higher concentrations of nanofluid enhanced the thermophysical properties of the heat transport fluid, heat transfer coefficient, and the thermal energy transferred. The impact of the increase of the magnetic field forces on the heat transport fluid thermal capacity has been addressed elsewhere in this paper.

Figs 16 and 17, demonstrated that the increase in radiative forcing resulted in higher surface temperatures and an increase in the

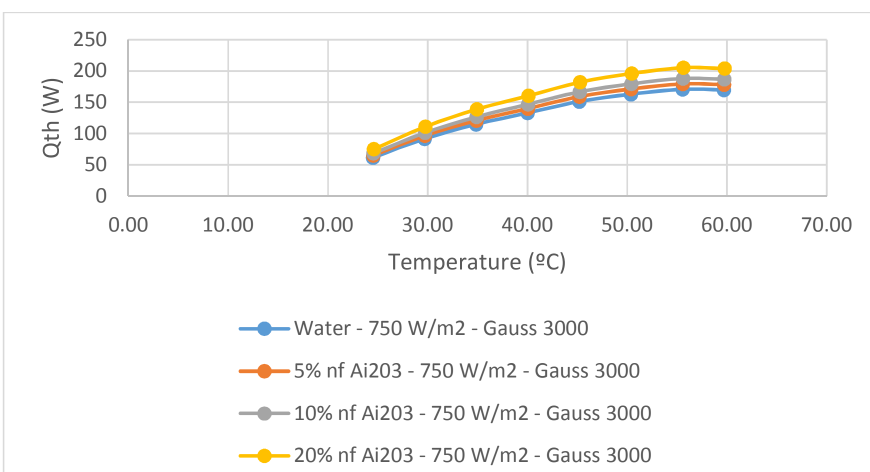

Fig. 7. Thermal energy generated at PV-Th solar panels

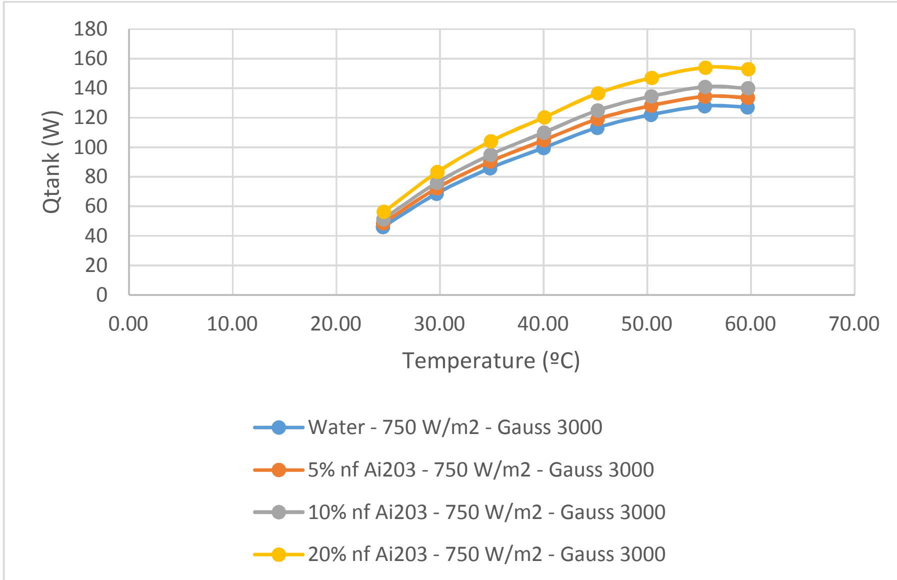

Fig. 8. Thermal energy generated at thermal tank by PV-Th solar panels

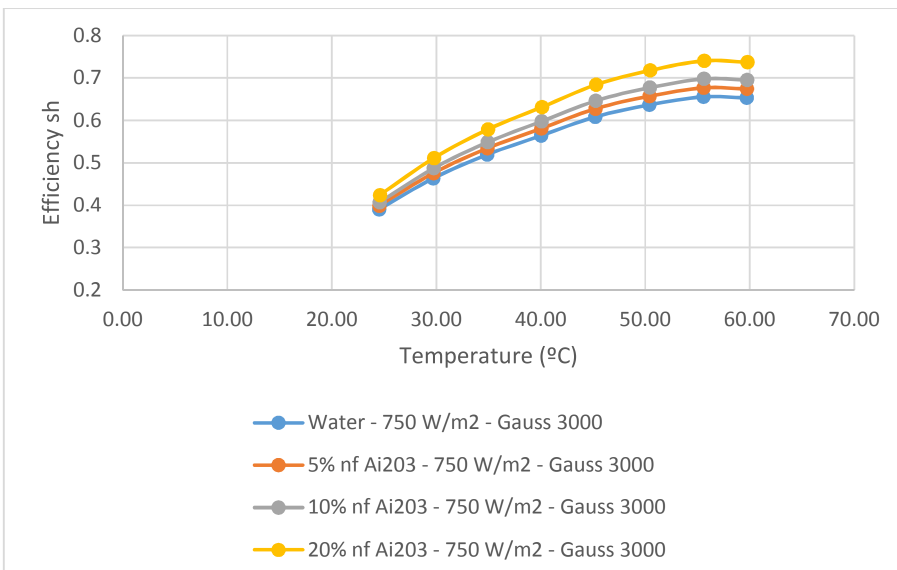

Fig. 9. Hybrid system efficiency at PV-Th solar panels

water-holding thermal capacity that in turn increased the thermal energy transferred to the nanofluid heat transport fluid and the hybrid system efficiency. It can be interpreted as temperature increases, both the number of free electrons and lattice vibrations increase. Thus the thermal conductivity of the metal was expected to increase. Also, the fluid molecules' spatial velocity increased at higher temperatures, heat will be transferred through the material at a higher rate. This means in particular the thermal conductivity increased drastically as the temperature increases. Therefore, the higher the solar radiation the higher the fluid temperature, the higher the thermal energy transfer, and the higher the hybrid system efficiency.

In general, the thermal conductivity of suspended nano-sized particles is higher than the base heat transport fluids. Oxides, metals, nitrides, and nonmetals are used as nanomaterials in nanofluids. The thermal conductivity of a specific material is considered the most dominant characteristic affecting heat transport and is highly dependent on several factors. These include the temperature gradient, the properties of the material, and the heat flow path. However, results obtained from various laboratories and studies reported [24] are not consistent and there are also controversies on the heat transfer mechanisms of nanofluids. Thus, this study investigated the impact of different nanofluids, Ai2O3, Cu, Fe304, and SiO2, obtained results were plotted at different magnetic forces up to 3000 Gauss, at solar radiation 750 w/m2 for comparison purposes, and Figs 18 and 19 were chosen to illustrate the impact of the different nanofluids on the thermal energy transferred to the heat transport fluid and hybrid system efficiency.

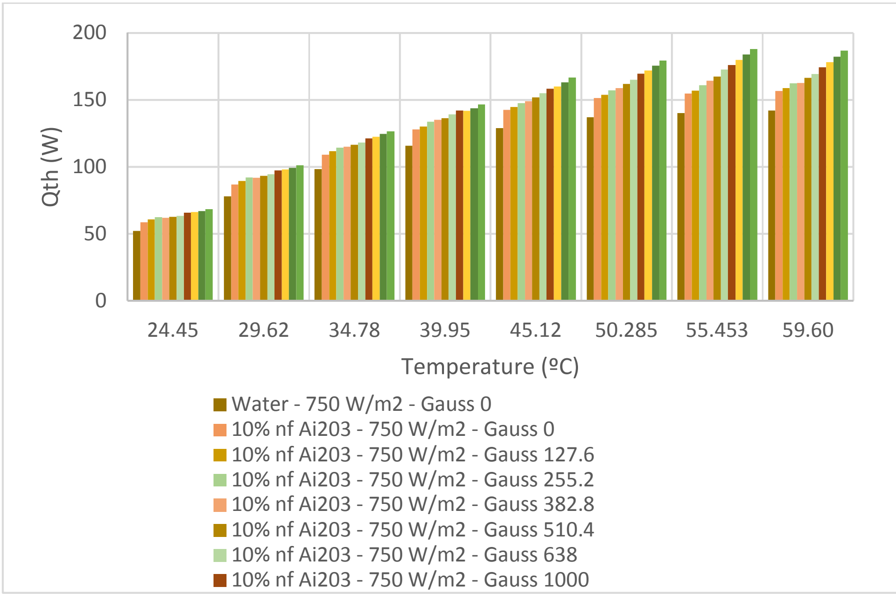

Fig. 10. Thermal energy generated at PV-Th solar panels at different magnetic field Guass forces

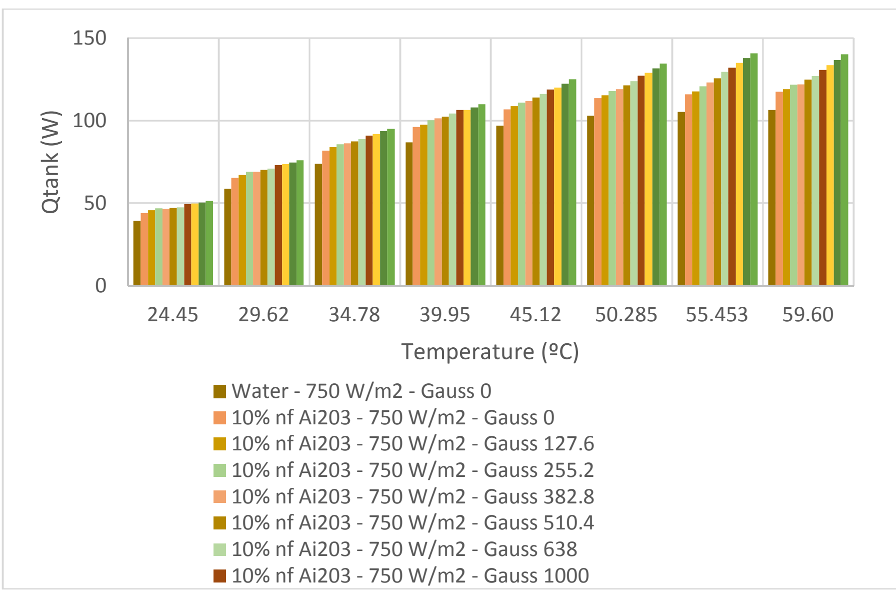

Fig. 11. Thermal energy generated at the thermal tank at different magnetic field Gauss forces

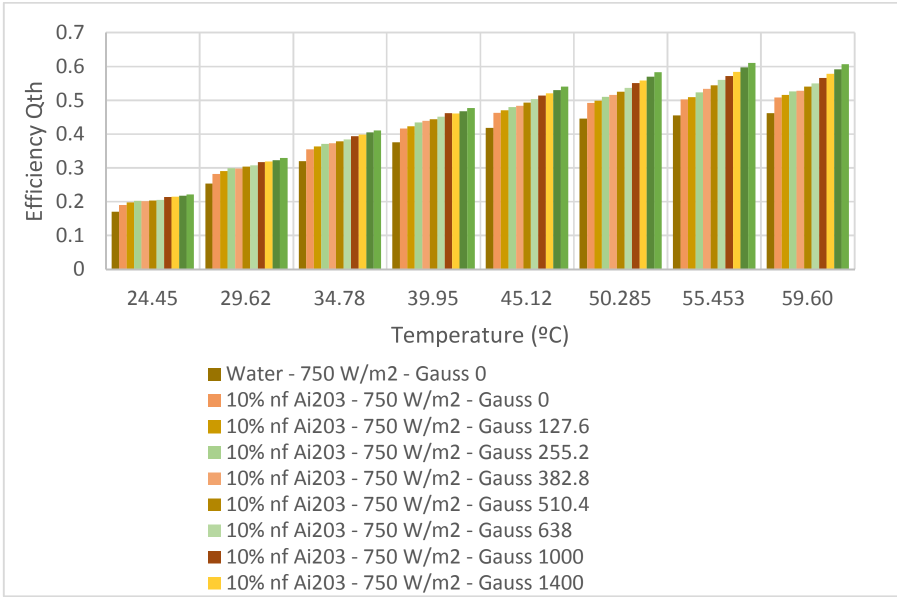

Fig. 12. Efficiency to generate thermal energy at the thermal tank at different Gauss forces

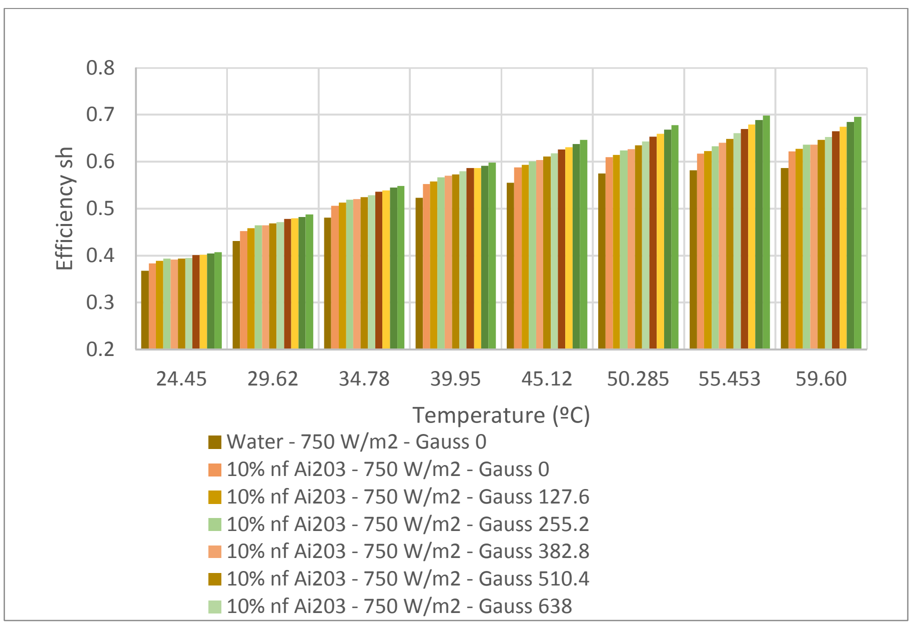

Fig. 13. Hybrid system efficiency to generate thermal energy and power at different Gauss forces

Furthermore, to the results displayed in Figs. 18 and 19, it is quite evident that the CuO exhibits superior characteristics over the other nanofluids presented in these figures Ai2O3, Fe304, and SiO2, and the higher the magnetic field Gauss forces the higher the hybrid efficiency and the thermal energy transferred to the heat transport fluid. This is because CuO nanofluids not only have high thermal conductivity but also make good compatibility with basic liquid, thus the nanofluid CuO has higher thermodynamic and thermophysical properties higher than the other nanofluids under investigation including the water as heat transport fluid. It has been shown also by other references [21 through 28}.] that the heat transfer coefficient of nanofluid becomes higher than that of pure fluid at the same Reynolds number and increased with the increasing of the mass fraction of CuO nanoparticles. Results also indicated that at very low volume concentrations nanofluid has no major impact on heat transfer parameters and the pressure of nanofluids increased by the mass fraction increase.

It was reported in the literature [26-28] that the thermal conductivity of magnetorheological fluid increases with increasing magnetic field in the temperature intervals from 0 to 50 °C and from 50 to 100 °C and the direction of the magnetic field influenced the thermal conductivity. As reported by reference [27,28], the increase in thermal conductivity under an external magnetic field is attributed to the effective conduction of heat through the chainlike structures formed under the magnetic field when the dipolar interaction energy becomes greater than the thermal energy [26-27].

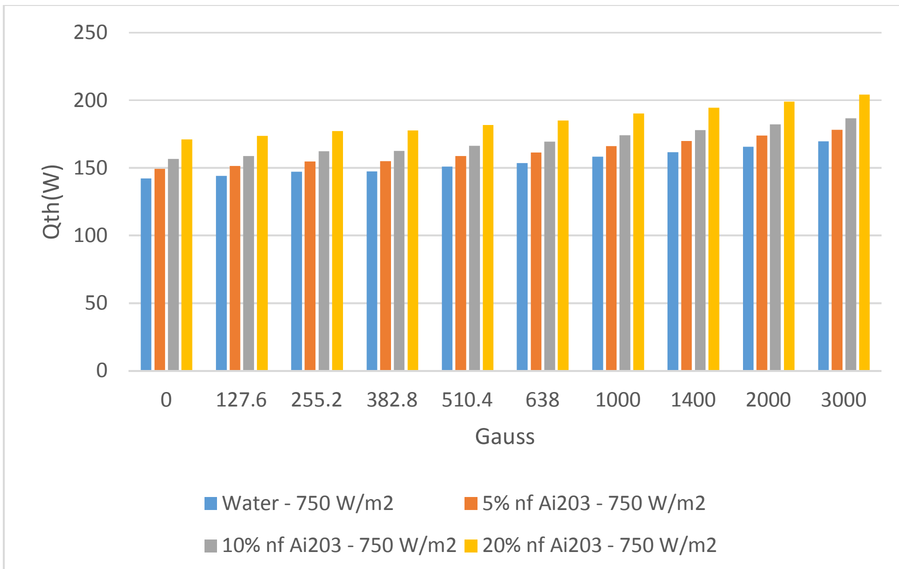

Fig. 14. Thermal energy at different Gauss forces and different concentrations

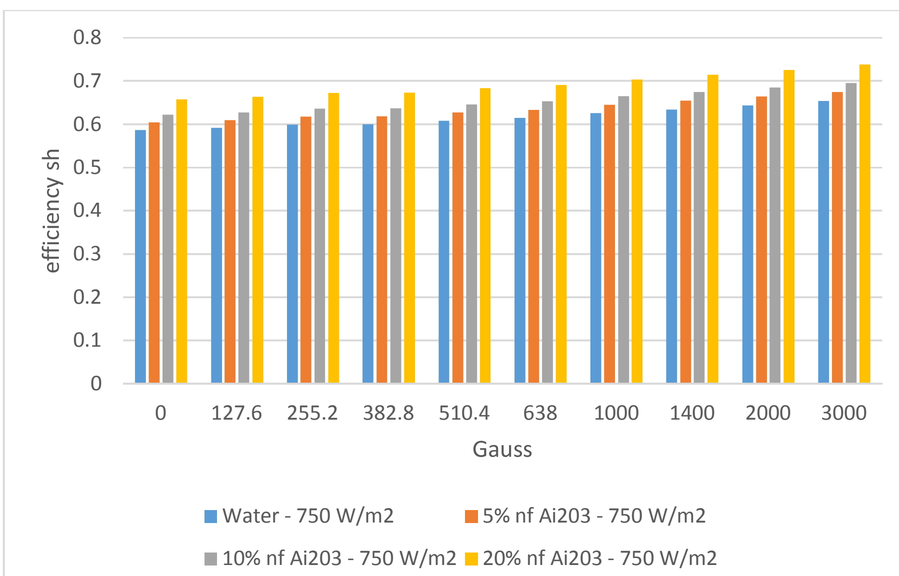

Fig. 15. Hybrid system efficiency at different Guass forces and different concentrations

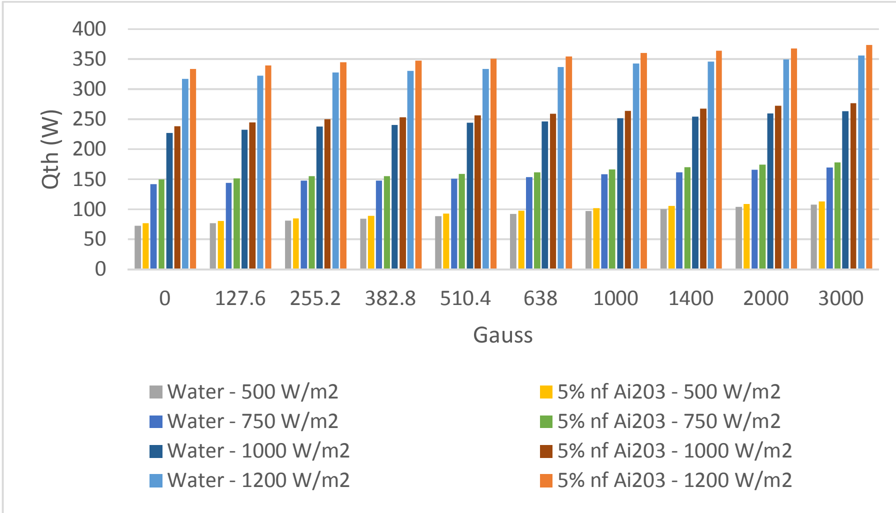

Fig. 16. Thermal energy produced at different magnetic forces and solar radiations

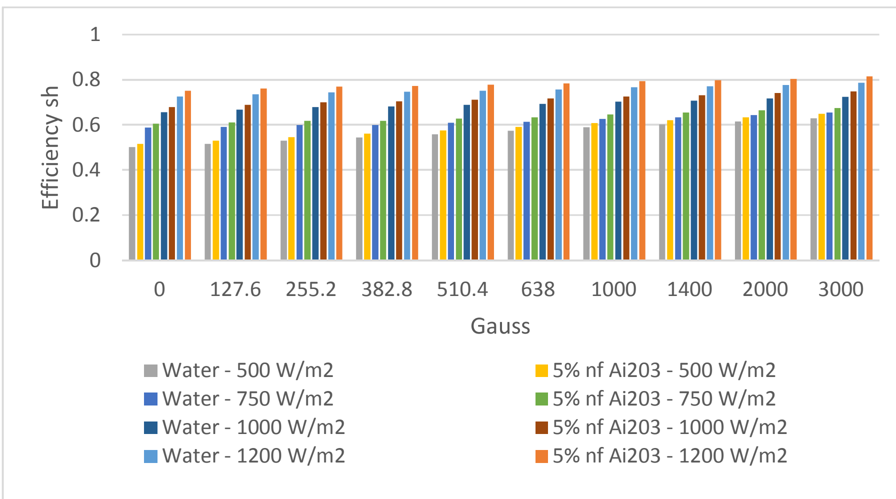

Fig. 17. Hybrid efficiency to produce thermal energy at different magnetic forces and solar radiations

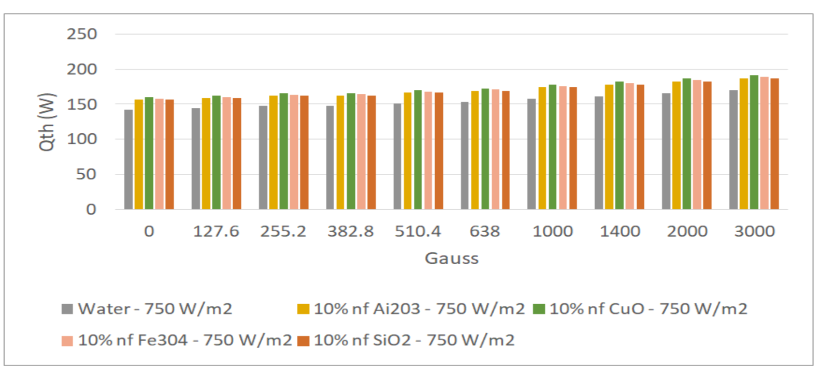

Fig. 18. Thermal energy produced at different magnetic forces at different nanofluids

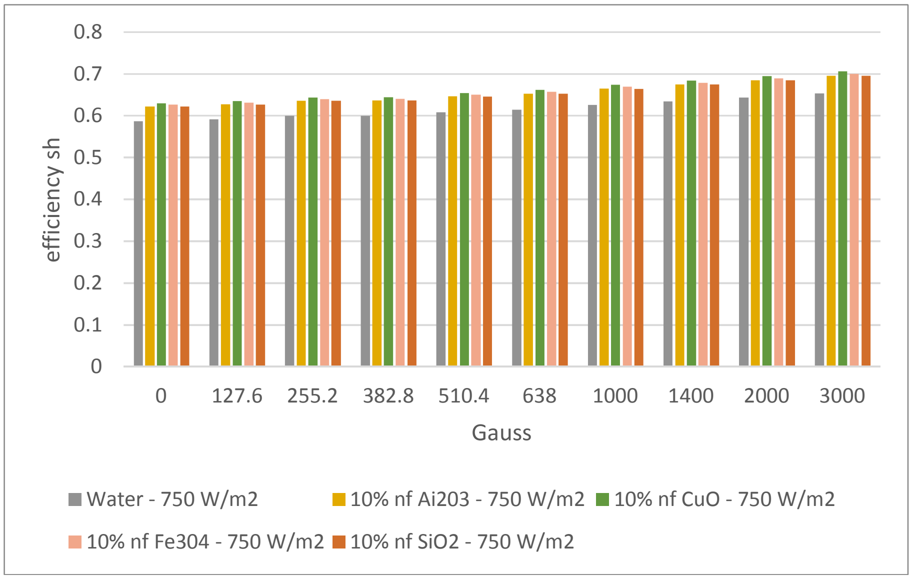

Fig. 19. Hybrid efficiency to produce thermal energy at different magnetic forces at different nanofluid

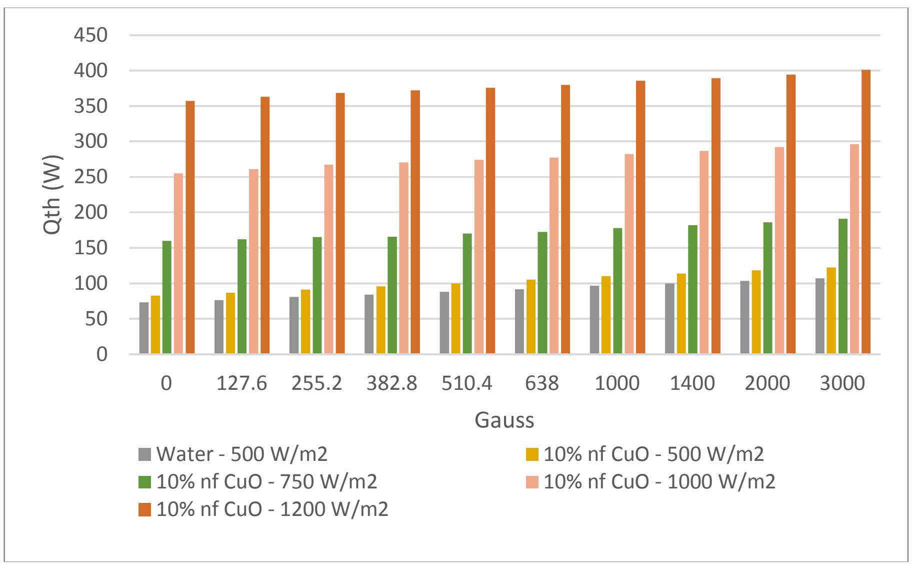

Fig. 20. Thermal energy produced at different magnetic forces at different solar radiations

The thermal potential driver for heat flow from the PV cell to the fluid is the thermal energy transferred and the hybrid system efficiency is plotted at different solar radiations and different magnetic field forces in Figs 20 and 21 with nanofluid CuO. The results presented in these figures clearly show that the higher the solar radiation the higher the thermal energy transferred to the heat transport fluid and the the higher hybrid system efficiency. This is attributed to the fact that higher solar radiation increased heat flow from the solar energy to the fluid that causes that effect and in turn, it enhanced the hybrid system efficiency. Furthermore, this increase is limited by the maximum temperature allowed by the PV semiconductor material and design. This observation has been in agreement with others in the literature as long as the increase in the PV cell temperature was within the limitation imposed by the manufacturer. Similar observations have been noticed with the other nanofluids.

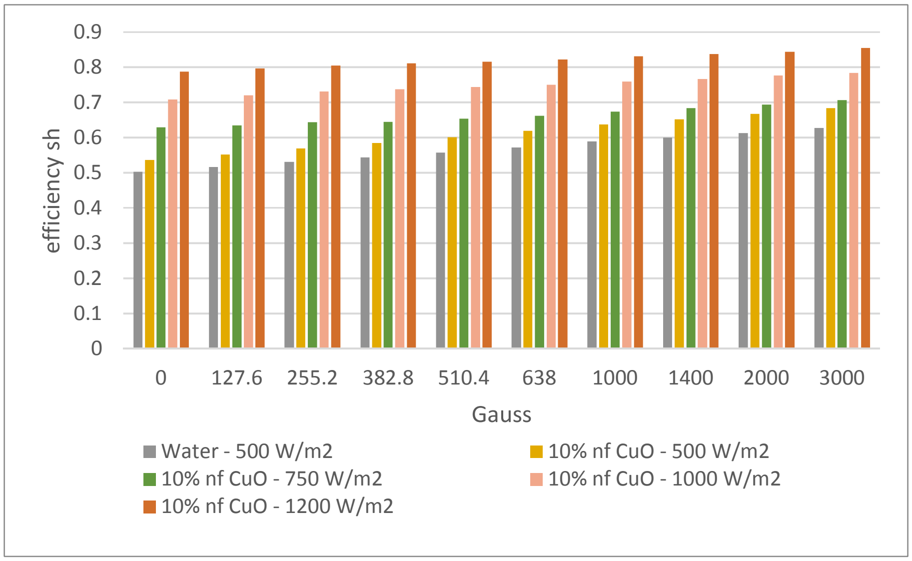

Fig. 21. Hybrid efficiency to produce thermal energy at different magnetic forces at different solar radiations

On the other hand, it can be seen from the results presented in these figures that as the magnetic field forces across the heat transfer tubes increased and the thermal energy transferred to the heat transport fluid increased and in turn, the hybrid system efficiency exhibited higher values. It is believed that this increase was due to the increase of the heat transfer coefficient. This was support by very recently reported work by reference [39] that ferrofluid additives caused a tremendous improvement in the heat transfer of the fluid. The use of the alternating magnetic field also led to an increase in the heat transfer rate along with the spiral coil. Based on the results obtained in the constant volume fraction, if pure water is considered as the base fluid, then the ferrofluid with a constant magnetic field, the ferrofluid without a magnetic field, the ferrofluid with an alternating magnetic field of 5 Hz, and the ferrofluid with an alternating magnetic field of 50 Hz increased the heat transfer by 19%, 26%, 33%, and 43%, respectively.

3.1 Model Validation

The numerical model prediction is described in equations (1) through (21), to validate it, we have constructed Figs 22 through 24 to compare the numerical results predicted by the model with data presented in the literature for solar PV namely references [21,22]. In particular, it is quite apparent from the comparison presented in Fig 22 that the model prediction fairly compares with the data of the dynamic PV cell temperature presented by Fargali et al. data [21]. The comparison presented in this figure also showed that the model and data have the same trend, however, some discrepancies exist. It is believed that the discrepancies are because the Fargali et al. [16] did not provide full disclosure of the various parameters used in equations (12) through (15) and Reference Rajapakse et al. [51, 21, 22] had to be consulted on the various missing parameters in Fargali et al. [21]. However, as pointed out in references [21, 22] taking into account the complexity of the PV cell temperature phenomena and its thermal behavior, we feel that our model fairly predicted the PV cell dynamic profile. Furthermore Fig. 23 displayed a comparison between model prediction and data reported at references [21, 22} on the power produced by PV solar panels. It quite evident that our model predicted fairly the power data at different amperages.

The thermal energy was calculated using equations (10) through (15) under magnetic field up to and nanofluids as heat transport fluids. Experimental data on magnetic filed and nanofluids were scared and hardly reported in the literature. The data reported by reference [49] on nanofluid Fe304 were considered and compared at the different magnetic fields up to 7000 Gauss and at a temperature difference of 15 C. Joubert [49] reported that the stability of the results under magnetic field was found to be poorer for nanofluids of a lower volume

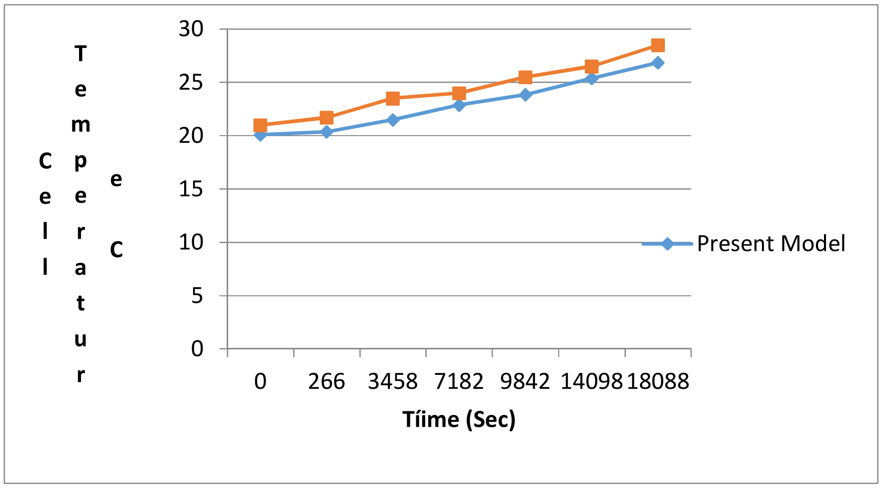

Fig. 22. Comparison between present model prediction for cell temperature and Fargali et al. data [21]

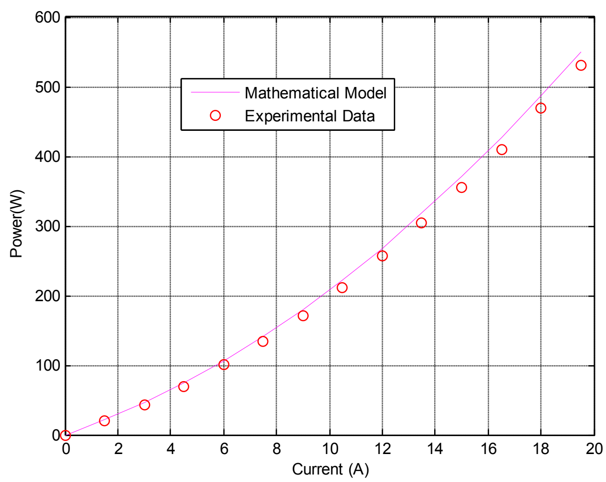

Fig. 23. Comparison between present model predictions of PV characteristics [21, 22]

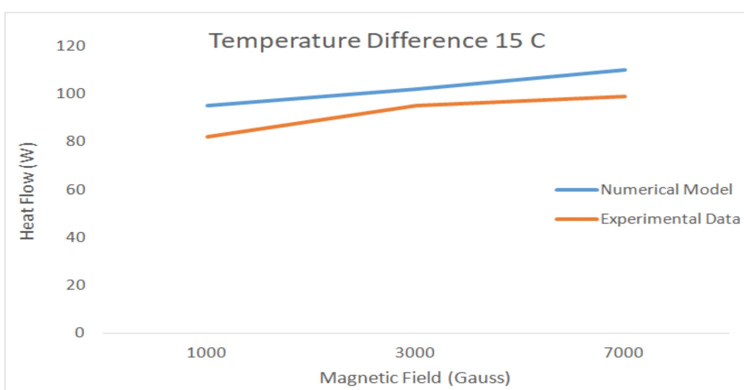

Fig. 24. Comparison between present model and data for Nanofluid Fe 304 data at different magnetic fields [49]

concentration, coupled with the possibility of higher settlement rates due to the additional magnetic force on the nanoparticles. The nanofluid Fe304, the choice for his study was found to be the nanofluid with a 0.1% volume concentration. The results of our model prediction were compared to the data of reference [49] at similar conditions and plotted in Fig. 24. The comparison showed discrepancy exited and varied between 8% to 14% with the model over predicting the experimental data of reference [49] at higher magnetic fields. Its believed that these discrepancies stem from the fact the heat transfer coefficient under the magnetic field was not similar and the thermophysical properties of Fe304, as well as the PV-Thermal heat transfer efficiency, were not fully disclosed at each nanofluid concentration by reference [49].

4. CONCLUSIONS

The mass and energy balances of a novel combined concept of a photovoltaic-thermal solar panel hybrid system have been developed, integrated, and solved to predict the dynamic total power generated, efficiencies, and the key important parameters of a hybrid system under different solar irradiance, material properties, magnetic field, and different boundary conditions. The model is based on dynamic mass and energy equations coupled with the heat transfer coefficients, thermophysical properties of nanofluids, thermodynamic constants, and as well as other material properties.

It is evident from the results presented that the higher the solar radiations the higher the thermal and hybrid efficiencies. It is also observed that the hybrid efficiency exhibits lower values than the thermal efficiency since the PV solar panel efficiency is significantly lower than the thermal efficiency.

Furthermore, the PV simulation study results showed that the higher the solar radiation the accelerated increase in the PV cell temperature. Consequently, it also shows the higher the solar radiation the higher the PV power and PV amperage. As far as the simulation of PV-Th, it was demonstrated that the higher the concentration the higher the hybrid system characteristics. Besides the higher, the magnetic field the higher the thermal energy and the hybrid system efficiency. The hybrid system characteristics were impacted by the type of nanofluids and the nanofluid CuO had the highest hybrid system characteristics compared to the other nanofluids under consideration. The designer of the PV panel and its cell temperature must take into consideration the solar radiation, type of nanofluid as well as ambient conditions. Finally, the model prediction was compared fairly with the PV-Thermal data available in the literature at different conditions of solar radiations, nanofluid concentrations, and magnetic field forces.

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COMPETING INTERESTS

Author has declared that no competing interests exist.

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