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A Comparative Study of Magnetized Nanofluids Cuo and AIO203 in an Integrated Solar Photovoltaic-Thermal, Heat Pipe and Heat Pump Hybrid System

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ABSTRACT: A comparative study is presented here and applied to a “hybrid system to enhance the thermal energy efficiency and reduce carbon footprint, which is composed of photovoltaic-thermal solar panels, heat pipe, and heat pump, is presented hereby”. A “two-dimensional heat transfer and fluid flow dynamic model was developed and presented using CUO and AiO203 to describe the behavior of the different components of the hybrid system under different solar irradiance conditions, AiO203 Nanofluid, and different refrigerants”. The model is based on “dynamic mass and energy equations coupled with the heat transfer formulas, and thermodynamic properties of nanofluid, and refrigerants mixtures. Finally, the presented model has been validated, and its prediction is fairly compared with available data.” It confirmed that CUO performs superior to AiO203 and other nanofluids reported in the literature.

KEYWORDS: Numerical modeling**,** simulation, photovoltaic-thermal solar, heat pipe, heat pump, refrigerants, nanofluids, hybrid system performance, model validation.

INTRODUCTION

Nanofluids are engineered colloidal suspensions of nanoparticles within a base fluid. These advanced fluids have gained significant attention due to their “enhanced thermal properties and wide range of applications in heat transfer systems, cooling technologies, and biomedical fields. Among various nanoparticles, copper oxide (CuO) and aluminum oxide (Al2O3) are widely used due to their availability, stability, and impressive thermal properties”. This study aims to provide a “comparative analysis of CuO and Al2O3 nanofluids in terms of their thermal conductivity, viscosity, stability, and overall performance in solar photovoltaic (PV) thermal applications”.

CuO and Al2O3 nanoparticles are typically synthesized through chemical precipitation, sol-gel, or hydrothermal methods. The “nanoparticles are dispersed in base fluids such as water, ethylene glycol, or oil with surfactants and ultrasonication to ensure uniform dispersion. Proper dispersion of nanoparticles is crucial for maintaining the stability and performance of nanofluids in solar PV thermal applications”.

“Thermal conductivity is a key parameter in evaluating the performance of nanofluids. CuO nanofluids generally exhibit higher thermal conductivity compared to Al2O3 nanofluids due to the superior intrinsic thermal conductivity of copper oxide. This property makes CuO nanofluids more suitable for solar PV thermal applications, where efficient heat transfer is essential for enhancing energy conversion efficiency”. Studies have shown that the “enhancement in thermal conductivity increases with higher nanoparticle concentration and smaller particle size. For example, CuO nanofluids can achieve up to 30% enhancement in thermal conductivity compared to base fluids, while Al2O3 nanofluids typically show an enhancement of 15-20%.

“Viscosity affects the pumping power and flow behavior of nanofluids. Al2O3 nanofluids tend to have lower viscosity compared to CuO nanofluids at similar concentrations, making them more suitable for solar PV thermal applications where minimal resistance to flow is required. However, the increase in viscosity with nanoparticle concentration must be carefully managed to avoid excessive energy consumption. The stability of nanofluids is essential for long-term performance in solar PV thermal systems. Both CuO and Al2O3 nanofluids require surfactants or pH adjustments to prevent sedimentation and agglomeration. Al2O3 nanofluids generally exhibit better stability due to their higher surface charge and lower density compared to CuO nanofluids, making them more suitable for long-duration applications”.

Recently, “solar PV thermal systems integrate photovoltaic panels with thermal collectors to simultaneously generate electricity and capture heat [1-4]. CuO nanofluids are preferred in these systems for their superior thermal conductivity, which helps improve heat transfer efficiency and maintain lower operating temperatures of the PV panels. This leads to enhanced electrical efficiency and overall system performance. Al2O3 nanofluids, with their better stability and lower viscosity, are more suitable for long-term applications where consistent performance and minimal pressure drop are required”.

The comparative “study of CuO and Al2O3 nanofluids in solar PV thermal applications reveals that each nanofluid has distinct advantages depending on the application [33-41]. CuO nanofluids offer superior thermal conductivity, ideal for high-performance heat transfer applications. Conversely, Al2O3 nanofluids provide better stability and lower viscosity, making them suitable for applications requiring long-term usage and minimal flow resistance. The selection between CuO and Al2O3 nanofluids should be based on the specific requirements of the solar PV thermal system, balancing thermal performance, viscosity, and stability”.

“Heat pipes are designed to transfer heat with the minimal temperature difference between the heat source and the heat sink Literature has shown that Heat pipes are increasingly popular as passive heat transfer technologies due to their high efficiency when the appropriate refrigerants are used [1-3, 18, 20, 24-28]”. “It has been reported in the literature that New PV technologies [1-29] have been shown to improve the energy utilization efficiency of solar PV, such as multi-junction cells, optical frequency shifting, and concentrated photovoltaic (CPV) systems, among others; however, are expensive”.

“The modeling and simulation of a novel hybrid system of solar photovoltaic-thermal panels, heat pumps, and heat pipes hybrid systems” along with a comparative study of the aforementioned nanofluids are presented hereby, as an innovative approach to improve “PV efficiency, deliver efficient thermal energy, and power, and reduce the carbon footprint”.

A schematic diagram of the hybrid system under study is shown in Figure 1 and Figure 1a. This, consequently, enhances the “energy conversion efficiency of solar photovoltaic and hybrid systems. The conceptual “photovoltaic-thermal panel integrated heat pipes and heat pump was modeled and analyzed using a two-dimensional dynamic model based on the heat transfer and nanofluid fluid flow conversion equations”, and presented in the following analysis.

MATHEMATICAL MODEL

“The hybrid system in question is composed of the PV solar panel and Thermal solar tube collector as well as heat pipe and thermal tank,” as shown in Figure 1 and Figure 1a. This hybrid system consists of a “photovoltaic panel welded on the backside and thin parallel tubes for the circulation of the cooling fluid. The nanofluid flows through the “thermal solar collector copper pipes and carries the recovered excess heat away from the solar PV panel and thermal panel as shown in Figure 1 and Figure.2.

Solar PV MODEL

It is well known that the cell temperature impacts the PV output current and performance, and its time variation can be determined from references [18-22, 41]. 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:”

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

PV THERMAL MODEL

The heat absorbed by the PV solar cell can be calculated by the following [27]:

$$Q_{in} = \alpha_{abs} G S_p \tag{2}$$

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 [27,28,41];

$$mC_{p\_module}\frac{dT_C}{dt} = Q_{in} - Q_{conv} - Q_{elect} \tag{3}$$

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, equation (3)

Q_{conv}: Energy loss due to Convection

Select: Electrical power generated as defined by equation (1).

The thermal heat calculated by equation (3) is fed to the heat exchanger, where the evaporator section of the heat pipe is placed as shown in Figures 1 and 2. This “heat is absorbed by the refrigerant in the evaporator section of the heat pipe and transmitted by the natural circulation of the refrigerant to the condenser section that drives the evaporator of the heat pump.”.

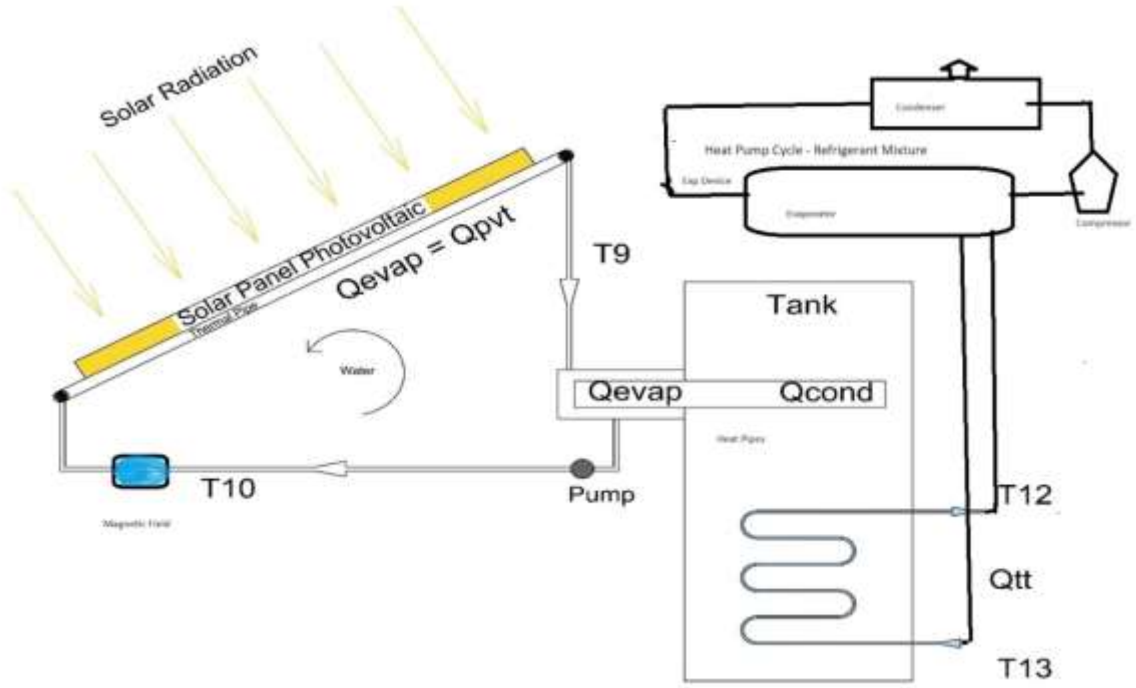

Figure 1: PV/Thermal-Heat Pipe hybrid system

Heat Pipe MODEL

"The pressure drop in heat pipes of the fluid flow has to be compensated by the pumping pressure in the wick and the capillarity as prescribed by Tardy and Sami [20], Endale [9], and Reay and Kew [23]";

$$\Delta Pp = \Delta Pi + \Delta Pv + \Delta Pg \qquad (4)$$

Where ΔPp, ΔPl, ΔPv, and ΔPg are the total pumping pressure, pressure drop for liquid return from the condenser, pressure drop for vapor flow in the evaporator, and gravity head, respectively.

"The thermophysical properties of the working fluid used and the wick properties determine the design of the heat pipe". The main design limitations were extensively discussed by Interested readers in the "capillary, sonic, entrainment limit, and boiling limits of the heat pipes Tardy and Sami (2009), Fargali et al. (2008); Reay and Kew (2006), and Tardy and Sami (2008)".

Readers interested in the details of the energy balance under natural convection heat transfer in the thermal tank (C.F. Figure 1)for a single-control volume of heat pipe submerged in the thermal tank [9] may consult reference Sami (41);

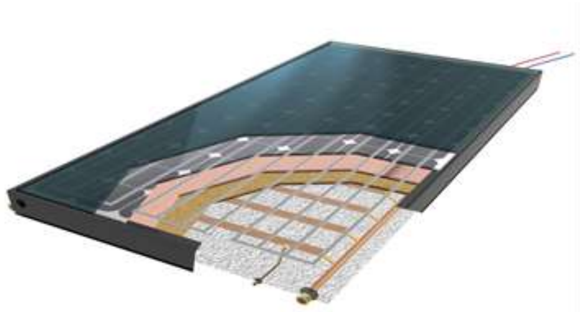

Figure 2 PV Thermal solar collector

Heat Pump MODE

The "steady-state energy balance equations of the water source heat pump" are presented in [23] and [15–22, 41]. The "refrigerant mass flow rate circulating in the heat pump in question can be calculated as follows":

$$mref = mpv * Cpw * (T9 - T10)/(\eta_{hx} * (h1 - h4)) \qquad (5)$$

$T9$ and $T10$ are the inlet and outlet temperatures of the HTF to the evaporator, respectively.

The heat compressor power required to drive the heat pump is:

$$Qcomp = \eta c * mref * (h2 - h1) \qquad (6)$$

Where ηc is the compressor efficiency.

The condenser heat capacity can be calculated as follows:

$$Qcond = \eta hx * mref * (h2 - h3) \qquad (7)$$

and, $h3 = h4$

Where the $h1$, $h2$, $h3$, and $h4$ are the "enthalpies of the refrigerant at the inlet and outlet of the compressor, and the inlet and outlet to the expansion valve, respectively. The enthalpies of the refrigerants were determined using pressure and temperature [32].

Finally, the "coefficient of performance, *COP*, which describes the heat pump efficiency," is

$COP = Qcond/Qcomp$

Qcond and *Qcomp* are the thermal energy at the condenser and compressor, respectively.

The thermal efficiency of the heat pipe.

$$\eta_{hp} = \frac{Q_{cond\ hp}}{Q_{evap\ hp}} \quad (8)$$

Where, $Q_{cond\ hp}$ represents the heat released by the condenser section of the heat pipe and $CapQ_{evap\ hp} = Q_{th} * \eta$ where Q_{th}Calculated by equation (4) is η Is the thermal efficiency of the heat exchanger where the evaporator section of the heat pipe is placed?

Finally, the "hybrid system energy conversion efficiency for harnessing energy from solar PV and solar thermal and solar PV and heat pump, but not supplying the compressor power" is:

$$\eta shwtpv = (Qcond + P(t))/(Qin + Qcomp) \quad (9)$$

Where Qin and Qcomp are defined in equations (2) and (9).

Magnetized Nanofluids*:*

Equations (14) through (16) 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 different magnetic forces Gauss" published in the literature properties ([4] through [6]) as a function of the properties outlined in the Table.1

Table 1: Thermophysical Properties of magnetized nanofluids

	Ai$_2$0$_3$	**CuO**	**Fe304**	**SiO$_2$**
C$_{p\ nf}$	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

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

NUMERICAL PROCEDURE

The numerical model presented hereby is based upon the "energy conversion and heat transfer mechanisms taking place during various processes; solar PV-Thermal, heat pipe, and heat pump" as well as a thermal tank as shown in Figure 1, which are described in Equations (1) through (9). The nanofluid AI2O3 and CUO, heat transfer fluid, circulates separately in thermal tubes welded in the back of the PV panel, driving the heat pipe and the heat pump. This permits the calculation for each nanofluid apart from the "electrical power output of the solar PV panel, thermal energy recovered from the solar PV panel and supplied to the heat pipe to drive the heat pump, in terms of solar radiation and other geometrical parameters and boundary conditions". Dependent parameters were calculated and integrated into the "finite-difference formulations". "Iterations were performed until a converged solution" was reached with an acceptable iteration error".

RESULTS AND DISCUSSION

However, the "numerical simulation presented hereby was conducted with two Nanofluids AIO203 and CUO, under different conditions such as; PV cell temperatures from 10°C through 70°C, ambient temperatures from 10°C through 38°C and solar radiations; 550, 750, 1000, and 1200 w/m^{2}as well as different refrigerants filled in the heat pipe with lower Global Warming Potential (GWP) such as R134a (HFC 134a), R123 (HCFC 123), R125 (HFC 125), R32 (HFC 32), R152a (HFC 152a), R1234ze (HFO 1234ze), R1234fz((HFO 1234zf). Thermodynamic and thermophysical properties were obtained using the methodology outlined and presented in reference [31]. Readers interested in the specifications of parameters used in this study are advised to consult references [41]".

Equations (1) through (3) demonstrate that the "power produced by the PV-thermal solar collector is independent of the type of nanofluids used and depends uniquely on solar radiation. Thus, the higher the solar radiation, the higher the power produced by the PV-thermal solar collector".

It also appears from equations (2) and (3) that the "thermal energy generated by the PV-Thermal solar collector is dependent upon the solar radiation and the concentration of the nanofluids circulation in the thin tubes heat exchanger molded to the PV solar collector as shown in Figure .2, thus increasing the solar ration increases the thermal energy produced and delivered to the heat pipes system. Moreover, the greater the concentrations of the nanofluids, the higher the thermal energy produced. As pointed out elsewhere in this paper, the nanofluids generally exhibit higher thermal conductivity, which increases with higher concentrations, consequently increasing the thermal energy produced. This is well illustrated by the results displayed in Figure .4, where the thermal energy produced by nanofluids is higher than that produced by water as a heat transfer fluid.

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 and cools down gradually depending upon the changes in solar radiation in a dynamic response, and consequently, the power output from the PV panel". This has been reported and discussed in the literature, where similar observations were presented in references [15, 30].

As shown in Figure 2, the "PV-Thermal is composed of a PV solar collector and thin heat exchanger pipes bonded to the back of the PV solar model, without any air gap to ensure complete heat transfer by "conduction, convection, and radiation to the fluid flowing in the thermal pipes". This "heat transfer fluid from the PV thermal heat exchanger drives the evaporator section of the heat pipe and the thermal heat absorbed from the heat transfer fluid evaporates the refrigerant in the evaporator section of the heat pipe. The vapor refrigerant is then circulated by natural convection and carried to the condenser section of the heat pipe, where it dissipates its heat of condensation to the water in the thermal tank, as shown in Figure 1. It is also worth mentioning that the nanofluids AIO203 and CuO are used as heat transfer fluids in the PV-thermal solar collector.

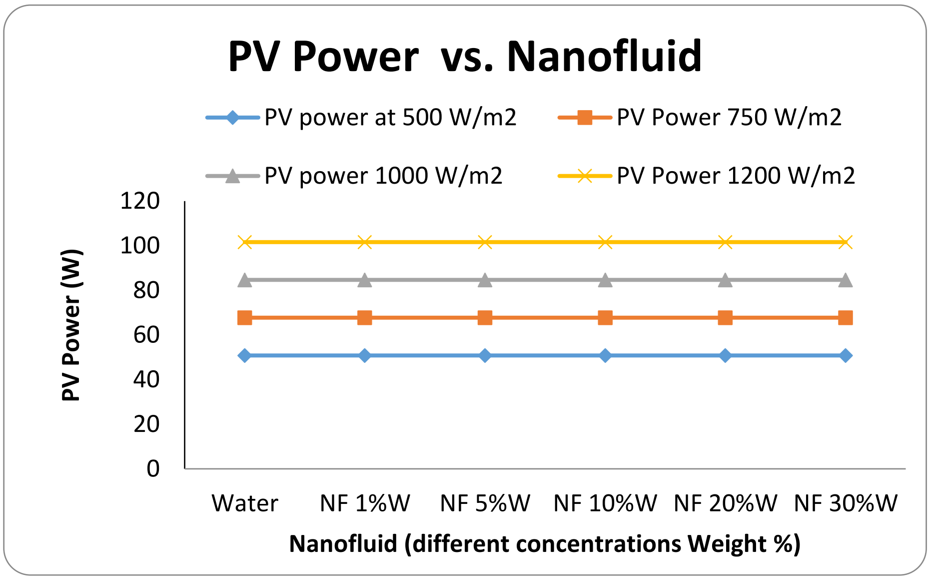

Figure 3 PV solar Power at different nanofluids

Figure 5 shows the "impact of higher solar radiation on the thermal energy generated by the PV Thermal solar collector and consequently the increase of the quaternary refrigerant mixture mass flow rate circulating in the heat pump. Thus, it can be observed further that the higher the nanofluid concentrations, the higher the thermal energy produced and the higher the quaternary refrigerant mass flow rate. This is mainly due to the higher thermal energy supplied to the evaporator of the heat pump enhances the rate of refrigerant evaporation and consequently the refrigerant mass flow rate circulating in the heat pump. The higher the increase in the refrigerant mass flow rate, the higher the energy delivered at the condenser". side. Thus, eventually, this leads to "an increase in the Coefficient of Performance of the heat pump and the integrated efficiency of the hybrid system" in question.

Equation (7) determines the "thermal energy released from the hybrid system under investigation through the heat pump condenser, where the vapor refrigerant mixture is condensed and releases its thermal energy to the environment. The results are shown in Figure 6, illustrating that the higher the solar radiation, the higher the thermal energy emitted from the heat pump condenser. In addition, the use of nanofluids as a heat transfer fluid circulating in the PV-Thermal solar collector enhances the thermal energy emitted from the heat pump condenser. In particular, the higher the nanofluid concentration, the higher the thermal energy released from the heat pump condenser".

The "compressor is designed to increase the pressure and temperature of the refrigerant by compressing it. Higher refrigerant flow results in more frictional losses in pipes and components and higher suction and discharge pressure drops. Thus, increasing volume flow, the compressor has to compress more gas in each cycle, which also boosts the required power. Thus, to increase the mass flow rate of the refrigerant, the compressor power needed to be increased as calculated by equation (6) in terms of the enthalpy difference across the compressor. It has been shown in Figure 7, also that the higher the concentrations of nanofluids, the higher the friction losses and the higher the compressor power consumed. As illustrated in Figure 5, the higher the solar radiation and the higher the nanofluid concentration higher the refrigerant mixture mass flow, which results in the compressor power increasing".

The integrated efficiency of the proposed innovative system is presented in Figures .1 and 2, where it is calculated by equation (9). Figure 8 presents the “Integrated thermal efficiency of the PV thermal-heat Pipes system at different solar radiation and nanofluid concentrations. It is quite evident from the results presented in this figure that the “higher the nanofluid concentrations, the higher the integrated thermal conversion efficiency” and also the “the higher the solar radiation, the higher the integrated thermal efficiency”. This can be attributed to higher solar radiation increases the temperature of the heat transport fluid circulating in the PV-Therm solar collector, and also higher nanofluid concentrations increase the rate of absorption of the solar radiation incident on the PV-Therm solar collector and consequently increase its temperature. Both contribute to increasing the heat transport fluid circulating in the Solar PV-Them collector”.

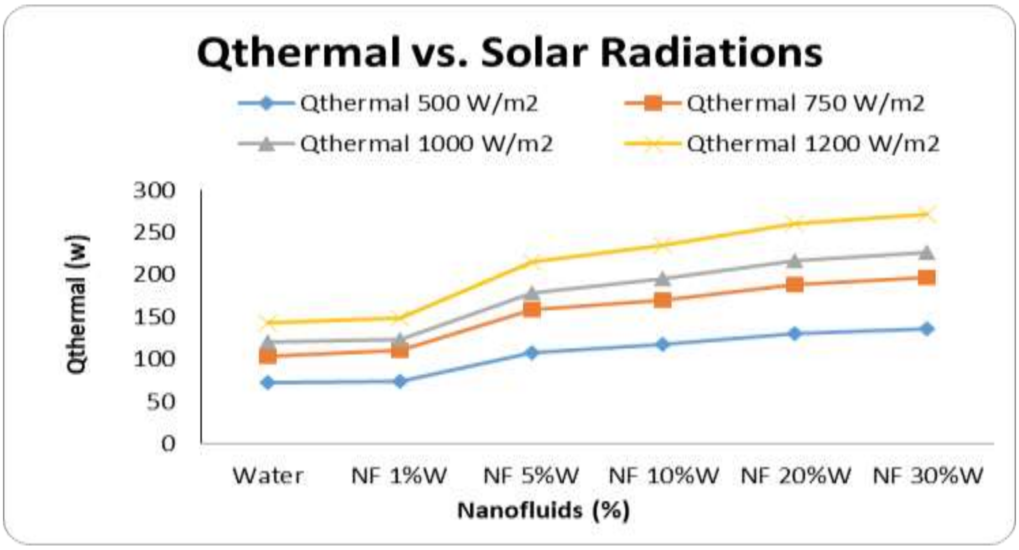

Figure 4: Thermal energy at different solar radiation and concentrations of nanofluids.

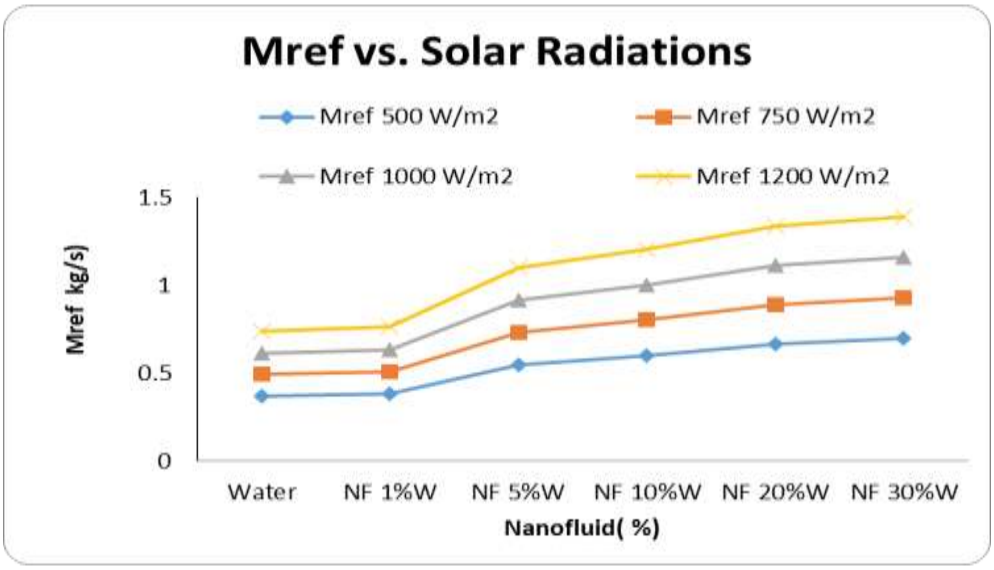

Figure 5: Impact of nanofluid concentrations on refrigerant mass flow rate

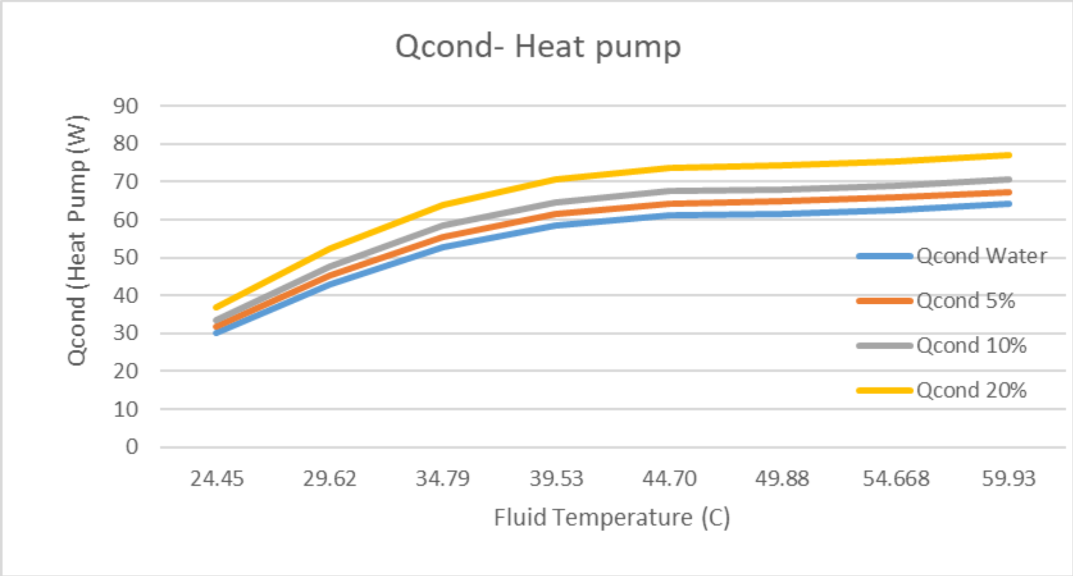

Figure 6: Heat pump condenser at different nanofluid temperatures.

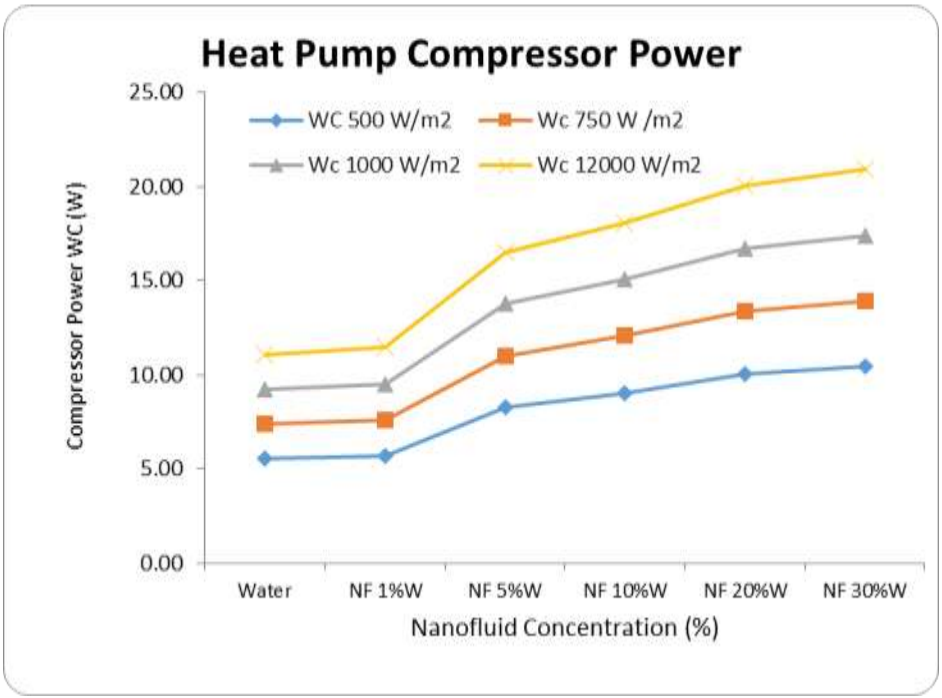

Figure 7: Heat Pump Compressor Power Consumed at Different Nanofluid Concentrations

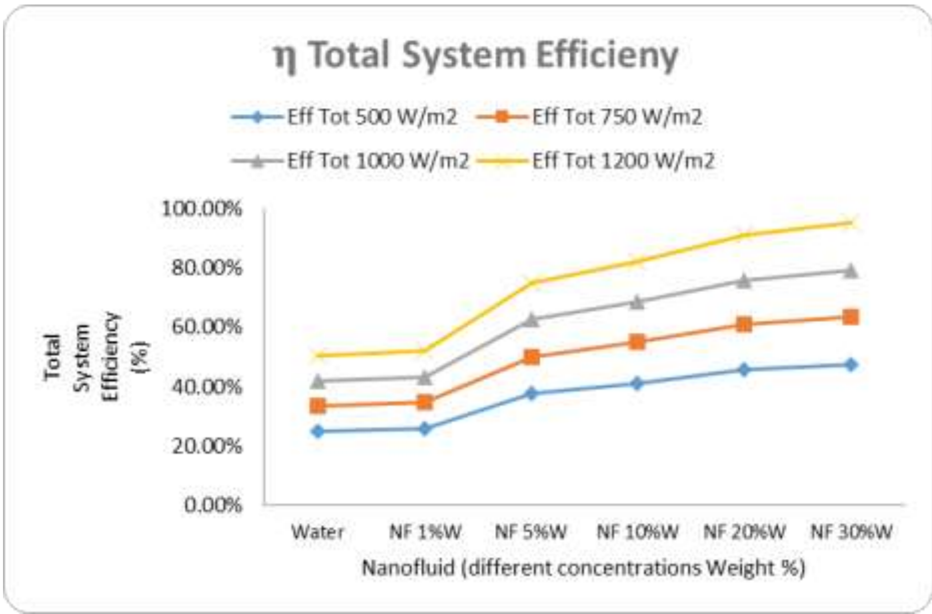

Figure 8 Integrated thermal efficiency at PV thermal-heat Pipes system

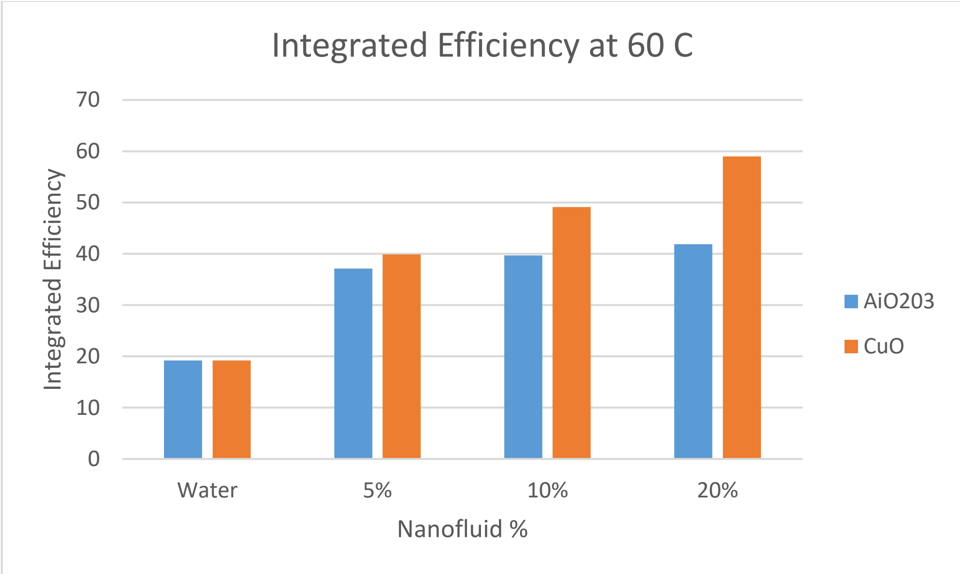

Figure 9 Comparison between nanofluids AiO203 and CuO

The "CuO nanoparticles have higher intrinsic thermal conductivity (~20 W/m·K) compared to Al_2O_3 (~30 W/m·K for alumina); thus, the thermal conductivity of CuO is higher than Al_2O_3 nanofluids at the same particle loading. Due to the higher thermal conductivity, CuO nanofluids often show better convective heat transfer coefficients, which is beneficial in many applications such as Cooling systems, Heat exchangers, and Solar collectors. CuO nanofluids can often achieve similar or better thermal performance at lower volume fractions, reducing viscosity penalties and potential clogging issues".

Notably, Figure 9 demonstrates that "CuO nanofluids are often better than Al_2O_3 nanofluids in terms of heat transfer performance, particularly where maximizing thermal conductivity is the main goal. This is reflected in the higher integrated efficiency of the hybrid system under study. However, Al_2O_3 nanofluids might be more suitable for long-term stable, less corrosive, and cost-sensitive applications".

The designer of the "PV-T integrated heat pipe must ensure that the PV solar panel characteristics and cell temperatures, site solar radiation of the site, the ambient conditions, and the refrigerant characteristics and thermodynamic properties are taken into consideration in the decision-making."

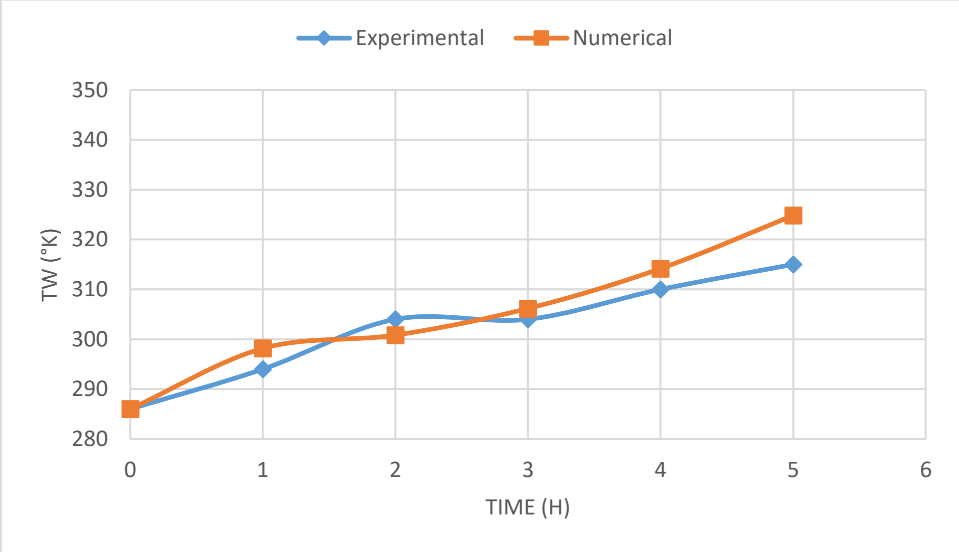

Figure 10 Comparison between model and experimental data [9]

Model validation

The "Model's prediction of the water temperature in the thermal tank where the condenser section of the heat pipe is placed and the experimental data reported" in reference [9], as shown in Figure 10. confirms clearly that our "model predicted fairly the dynamic data of the water temperature in the thermal tank". It can also be noticed that some "discrepancies exist between the model's prediction and the data, which are attributed to the heat losses and the calculation of the heat transfer coefficient in the thermal tank".

The "PV surface is heated up because of the direct exposure to sunlight, however, the rear side of the photovoltaic thermal system was cooled by the nanofluids. The impact of cooling on the temperature reduction of the PV cells throughout the experiment reported by reference [42] was compared to predicted results, and plotted in Figure. 11. The cooling by nanofluids helps increase heat exchange among the absorbing plate with tubes, which represent (less hot than the rear side of the PV module) and the rear of the PV module, which represents the hottest side, enhancing the heat convection between circulated nanofluids in the wall and conduction of the tube with the absorbing plate, decreasing the PV cells temperature and conseqyentlu enhances the PV solar collector efficiency. The thermal properties, such as thermal conductivity and HT, etc., of the nanomaterials dispersed in the nanofluid have increased the heat convection between the tube wall and CuO nanofluid. It led to a lower PV cell temperature depending on the volume fractions of nanofluids. It can also be seen that some "discrepancies exist between the model's prediction and the data, which are due to the heat losses and the calculation of the heat transfer coefficient in the PV thermal heat exchanger.".

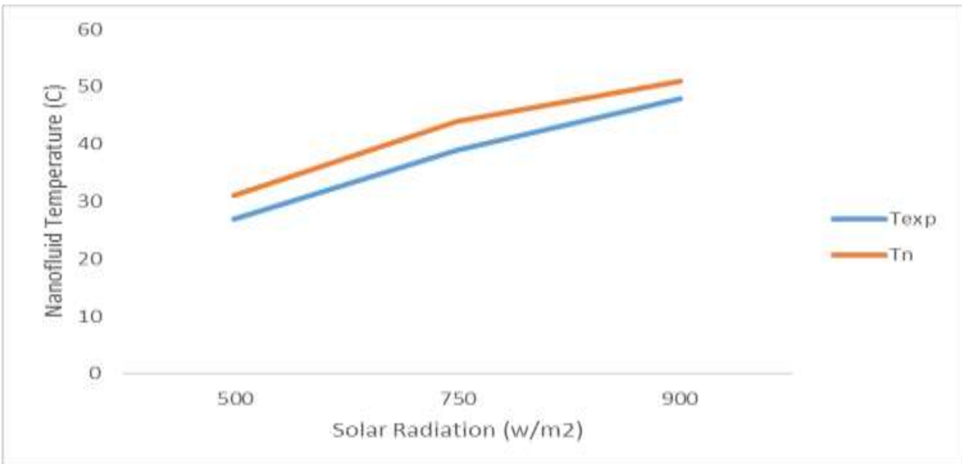

Figure 11 Comparison between model and experimental data [42]

CONCLUSIONS

A comparative study is presented here and applied to a "hybrid system to enhance the thermal energy efficiency and reduce carbon print, which is composed of photovoltaic-thermal solar panels, heat pipe, and heat pump, is presented hereby". A "two-dimensional heat transfer and fluid flow dynamic model was developed and presented using magnetized nanofluids CUO and AiO203 to describe the behavior of the different components. This comparative study is presented under different parameters such as "solar irradiance, material properties, and boundary conditions for the solar PV panel, as well as the heat pipe filled with different refrigerants".

The results presented hereby showed that the "higher the solar radiations the higher the evaporator temperatures and heat pipe temperature and obviously the higher the thermal heat transferred to the heat pipe evaporator section, and consequently the higher the heat released from the heat pipe condenser section in the thermal tank that drives the heat pump." It was also observed that the "higher the nanofluid concentrations, the higher the thermal conversion efficiency, and the higher the solar radiation the higher the thermal heat released, power generated, and the integrated system efficiency".

The "CuO nanoparticles have higher intrinsic thermal conductivity (~20 W/m·K) compared to Al_2O_3 (~30 W/m·K for alumina); thus, the thermal conductivity of CuO is higher than Al_2O_3 nanofluids at the same particle loading, as well as higher integrated hybrid efficiency".

Finally, the present model, when compared well with " the experimental data reported in the literature.

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)
h Refrigerant enthalpy
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 (9250 J/K)
$N_{p:}$ 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)
$Q_{convection}$ 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_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/m^2K)
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)
x Humidity ratio (kg_{water}/kg_{dry_air})
α_{abs} Overall absorption coefficient
η_{Hybrid} System efficiency
ηPvPV module efficiency
$\eta_{Thermal}$ Efficiency of thermal process
ρw Density of water vapor (Kg/m³)
∂Q Convection heat transfer rate
Q Thermal heat (kj/s)
ε Emissivity of PV cell

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