SSRG International Journal of Thermal Engineering
ISSN: 2395-0250/ https://doi.org/10.14445/23950250/IJTE-V11I1P101

Volume 11 Issue 1, 1-11, Jan-Apr 2025

Original Article

A Novel Concept of Solar Photovoltaic-Thermal, Heat Pipe and Heat Pump Hybrid System using AiO203 Nanofluid

S. Sami

TransPacific Energy, Inc, Las Vegas, NV, USA.

Corresponding Author : dr.ssami@transpacenergy.com

Received: 01 January 2025 Revised: 03 February 2025 Accepted: 21 February 2025 Published: 05 March 2025

Abstract - *A numerical prediction of a novel hybrid system concept to enhance thermal energy efficiency and reduce carbon print composed of photovoltaic-thermal solar panels, heat pipe, and heat pump is presented hereby. This model is intended to assess the performance and energy conversion process of the hybrid system as well as the individual efficiencies and integral system efficiency of this process to produce useful thermal energy for a variety of applications and electricity. A two-dimensional heat transfer and fluid flow dynamic model was developed and presented 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, as well as refrigerant mixtures. Finally, the presented model has been validated, and its prediction is fairly compared with available data.*

Keywords - *Numerical modeling, Simulation, Photovoltaic-thermal solar, Heat pipe, Heat pump, Refrigerants, Nanofluids, Hybrid system performance, Model validation.*

1. Introduction

Heat pipes play a crucial role in thermal energy recovery due to their efficiency in transferring heat. They can be used in a variety of settings, from recovering waste heat in industrial processes to improving the efficiency of heat exchangers in HVAC systems. Their versatility makes them suitable for both high and low-temperature applications. Heat pipes are designed to transfer heat with a minimal temperature difference between the heat source and the heat sink. They use a combination of thermal conductivity and phase change to move heat efficiently from one point to another.

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, 24-34]. It has been reported in the literature that New PV technologies 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, they are expensive. To improve solar PV's efficiency, a novel concept of combined photovoltaic-thermal solar panel hybrid system concept has been developed and implemented [3-12], where the PV cells of the solar PV panels are cooled by heat transport fluid flows and excess thermal energy is generated that can be used for various domestic or industrial applications". Despite significant advancements, several research gaps persist that present opportunities for further investigation and development: advanced working fluids, wick structure optimization, dynamic modeling, and control. Addressing these research gaps will contribute to the advancement of heat pipe technology, enabling more efficient and reliable thermal management solutions.

Hybrid energy systems combine multiple types of energy sources to optimize performance, reliability, and sustainability. By integrating different "energy sources (e.g., solar, wind, diesel generators, and batteries), hybrid systems reduce dependency on any single source. This diversity can improve reliability and ensure a more stable energy supply, especially in remote or off-grid locations. Hybrid systems can leverage the strengths of various energy sources to operate more efficiently. Combining renewable energy sources with storage systems can reduce the need for expensive grid power or fuel, lowering operational costs, reducing greenhouse gas emissions and reliance on fossil fuels, support environmental sustainability, and helping meet regulatory or corporate sustainability goals. Hybrid systems can incorporate energy storage solutions like batteries or pumped hydro to store excess energy when generation exceeds demand and improve overall energy use efficiency.

Pei et al. designed and constructed a novel heat-pipe photovoltaic/thermal system [18] to simultaneously supply electrical and thermal energy. Another transient mathematical model for the integrated HP-PV/T-PCM system with thermal storage presented by Sweidan et al. [25] was used to predict its performance under solar conditions and PCM melting point, using the model introduced by Naghavi [28] for heat pipe solar water heater system (HPSWH) with phase change material (PCM). On the other hand, Liang et al. [12] presented a dynamic model of a novel solar heating system based on hybrid photovoltaic/thermal and heat pipes technology and using the TRNSYS simulation platform. Also, Endalew [9], in his master's thesis, studied experimentally and validated the performance of heat pipe solar collectors for water heating. Furthermore, a hybrid photovoltaic solar-assisted loop heat pipe/heat pump (PV-SALHP/HP) water heater system has been developed and numerically studied by Dai et al. [3], saving 40.6% power consumption over HP mode. The novelty of this study is to present and analyze the modeling and simulation of a novel hybrid system of solar photovoltaic-thermal panels, heat pumps, and heat pipes hybrid systems, as an innovative approach to improve PV efficiency, deliver efficient thermal energy and power, and reduce the carbon footprint. To our knowledge, such a topic has not been reported in the literature, and a broader range of applications, including electronics cooling, aerospace, and energy systems, have come across it. A schematic diagram of the hybrid system under study is shown in Figures .1 and 1. a. This consequently enhances the energy conversion efficiency of the solar photovoltaic and the hybrid system. The conceptual photovoltaic-thermal panel integrated heat pipes and heat pump were modeled and analyzed using a two-dimensional dynamic model based on the heat transfer and nanofluid fluid flow conversion equations.

2. Mathematical Model

The study presented herein is based partly on the concept reported by Yang et al. [1] and an extension of the modeling reported by Sami and Campoverde [26], where a flat plate solar collector is attached to a PV panel. 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. This hybrid system consists of a photovoltaic panel welded on the backside and thin parallel tubes for the circulation of the cooling fluid. The various flow tubes in contact with the PV solar panel are connected to a heat exchanger where the evaporator section of the heat pipe is placed. The water 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. The heat pipe condenser section is placed in a thermal tank that supplies hot water demand". A typical PV panel output is in DC and connected to a load controller and batteries, as well as an inverter for converting the DC output into AC for potential use in applications where AC is required. In the following sections, the energy conversion process and the enhancement of the hybrid system efficiency and the characteristics of solar PV/Thermal panels as well as heat pipe are presented at various operating temperatures, different solar radiations, and different refrigerants filled in the heat pipe.

2.1. Solar PV Model

The solar photovoltaic panel is constructed of various modules, and each module consists of arrays and cells [13-15], [17], and [27,28]. The PV cell temperature 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 and performance, and its time variation can be determined from references [18-22]. 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;"

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

2.2. PV Thermal Model

The following thermal analysis is performed for a single PV cell; however, it is assumed that all PV cells behave the same; therefore, it can be applied to the whole PV solar panel. 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] and Figure. 1-a

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

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
Q_{elect}: Electrical power generated as defined by equation (1).

The thermal energy transferred from the PV cell 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 [27,28]. This 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 Figure 1. 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 of the heat pipe placed in the thermal tank.

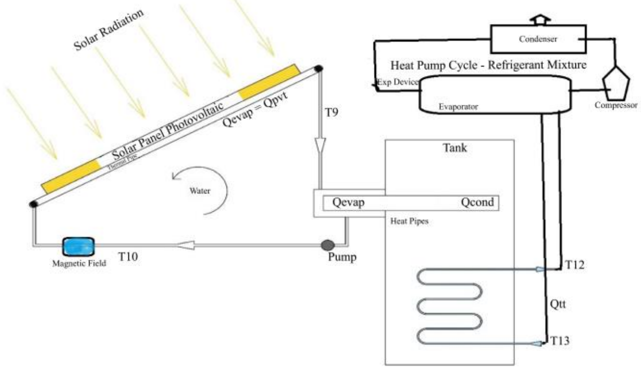

Fig. 1 PV/Thermal-Heat Pipe hybrid system

2.3. 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, and pressure drop for vapor flow in the evaporator and gravity head, respectively.

The thermophysical properties of the working fluid used, as well as the wick properties, determine the design of the heat pipe. The main design limitations were extensively discussed in Tardy and Sami (2009), Fargali et al. (2008), Reay and Kew (2006), and Tardy and Sami (2008).

Interested readers in the capillary, sonic, entrainment limit, and boiling limits of the heat pipes are advised to consult the aforementioned references.

Natural convective heat transfer heat pipes using two-phase thermosyphon principles have been reported in the literature and studied by Endalew [2011] in water heating applications. On the other hand, Reference [9] also discussed the Forced convective condensers under either crossflow or parallel-flow patterns. In the present study, as shown in Figure .1, the condenser section of the "heat pipe is directly inserted into the storage thermal tank where the natural convective heat transfer takes place, and natural convection heat transfer mechanisms in the thermal tank are considered in this study. It was assumed that the condensing water flow was stagnant, and there was no temperature gradient along the axis of the heat pipe. The following gives the energy balance under natural convection heat transfer in the thermal tank for a single-control volume of heat pipe submerged in the thermal tank [9].

$$V_w\, P_w C_w \frac{dTw}{dt} = \pi\, do\, I_{cond} h_{eff}\left(T_{hp} - T_w\right) - U_{tan} A_{tan}\left(T_{hp} - T_a\right) \qquad (5)$$

Where V_w represents the water volume in the thermal tank, and $U_{tan}A_{tan}$ is the overall heat transfer coefficient in the thermal tank and the equivalent area in the tank, respectively. In addition, T_{hp} ,T_w T_a Are the temperatures of the heat pipe, water, and ambient air, respectively.

The following considers the energy and mass balance equations for the condenser section of the heat pipes.

$$Q_{cond\ hp} = h_{eff} * \left(T_{hp} - T_w\right) * d_o * Io * \pi \qquad (6)$$

Where Io is the length of the condenser section of the heat pipe

$$Q_{evap\ hp} = Q_{th} * \eta$$

On the other hand, the thermal energy drawn from the thermal tank could be delivered for domestic or industrial use. However, in this study, driving the heat pipes, as shown in Figure 1 is.

$$Q_{tt} = \eta_{hx} * m_{wQtt} * Cp_w * (T_{12} - T_{13}) \qquad (7)$$

Where the m_{wQtt} represents the water mass flow rate circulating between the thermal tank and the user application in question.

T_{12} and T_{13} are the supply and return temperatures from the user application, respectively. η_{hx} is the thermal tank efficiency.

2.4. Heat Pump MODE

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

$$mref = mpv * Cpw * (T9 - T10)/(\eta_{hx} * (h1 - h4)) \qquad (8)$$

Where $T9$ 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:

$$Qcomp = \eta c * mref * (h2 - h1) \quad (9)$$

Where ηc is the compressor efficiency.

The condenser heat capacity can be calculated as follows:

$$Qcond = \eta hx * mref * (h2 - h3) \quad (10)$$

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 [31].

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.

On the other hand, the thermal energy drawn from the thermal tank and delivered to the heat pump's evaporator is:

$$Qtt = \eta hx * mwQtt * Cpw * (T7 - T8) \quad (11)$$

Where the *mwQtt* represents the water mass flow rate circulating between the thermal tank and the evaporator. *T*7 and T8 are the supply and return temperature from the user application, respectively.

The water mass flow rate for supplying hot water to the user's application is as follows:

$$m_{w_{Qtt}} = \frac{Q_{tt}}{\eta_{hx} * Cp_w * (T_{12} - T_{13})} \quad (12)$$

Furthermore, the evaporator heat capacity is:

$$Qe = \eta hx * mref * (h1 - h4) \quad (13)$$

The water mass flow rate in the condenser-thermal tank loop" can be calculated by the following equation:

$$mwqc = Qcond\ \eta hx / (Cpw * (T5 - T6))$$

The water mass flow rate for supplying hot water to the heat pump evaporator is:

$$mwQtt = Qtt\eta h/(Cpw * (T7 - T8)) \quad (14)$$

The efficiency of the solar PV panels can be expressed as follows.

$$\eta_{pv} = \frac{Q_{elec}}{Q_{colector}}$$

Where Q_{elec} It is calculated by equation (4), and the PV thermal solar efficiency is:

$$\eta hs = P(t) + Qth/Qin$$

Where *Qth* and *Qin* are the solar thermal heat transferred to the HTF and solar irradiance, respectively, and PV represents the power supplied by the PV solar panels.

The thermal efficiency of the heat pipe can be obtained by using the following equation:

$$\eta_{hp} = \frac{Q_{cond\ hp}}{Q_{evap\ hp}} \quad (15)$$

Where, $Q_{cond\ hp}$ represents the heat released by the condenser section of the heat pipe and $Q_{evap\ hp} = Q_{th} * \eta$ Where Q_{th}calculated by equation (3) is and 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:

$$\eta shwtpv = (Q\text{cond} + P(t))/(\text{Qin} + Qcomp) \quad (16)$$

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

2.5. 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, are described in Equations (1) through (16). The nanofluid Ai2O3 heat transfer fluid circulates in thermal tubes welded in the back of the PV panel and drives the heat pipe and, consequently, the heat pump. This permits the calculation of 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.

The numerical procedure starts with solar radiation and ambient conditions to calculate the characteristics of different discrete volumes such as solar PV cell temperature, PV cell back, heat pipe, and heat pump at specified conditions. The thermophysical and thermodynamic properties of the refrigerant mixture circulating in the heat pipe and the heat pump are determined using the NIST REFPROP database reference [30].

3. Results and Discussion

The following sections present an analysis and discussion of the predicted numerical results and validations of the proposed numerical model in equations (10) through (16). Only results are presented and analyzed for the temperature difference of 15 °C across the thermal tube heat exchanger.

However, the numerical simulation presented hereby was conducted 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 [30]".

Among the parameters used in this study is the total surface area of the PV module (SP) is 0.617 m^2, the Total surface area of cells in module (Sc) is 0.5625 m^2, module efficiency of 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 Faragali et al. [17].

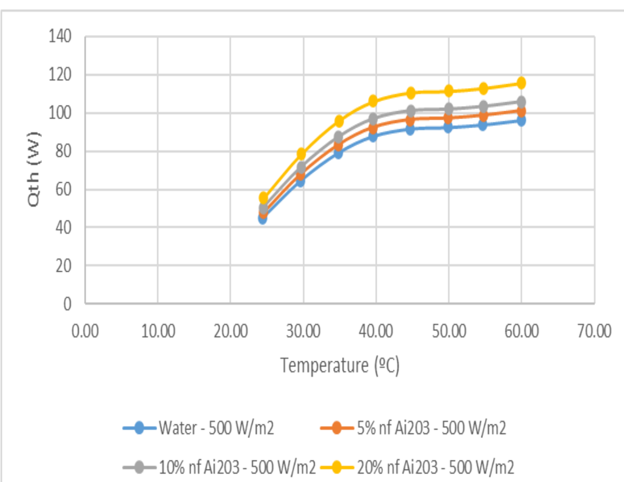

Fig. 2 Thermal Energy PV-Thermal collector at different Heat transport fluid temperatures

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. (C.F.1). 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 condensation heat to the water in the thermal tank," as shown in Figure 1.

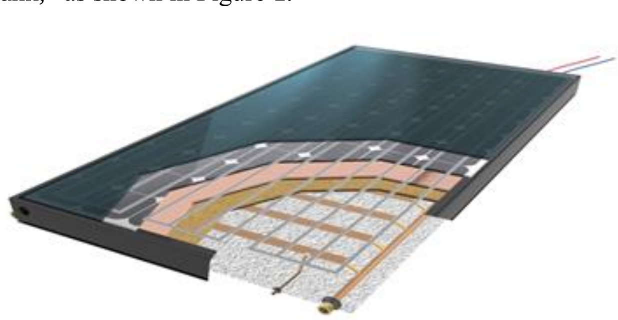

Fig. 1(a) PV -Thermal solar collector [18].

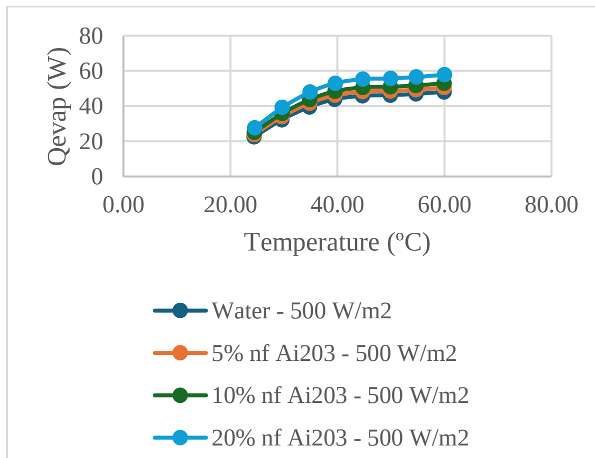

Fig. 3 Heat pipe Evaporator thermal energy

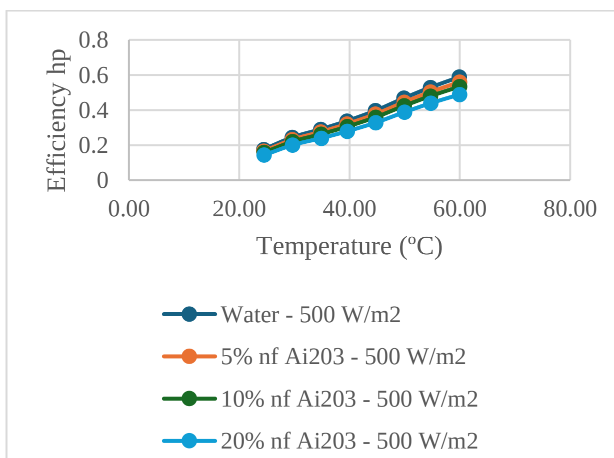

Fig. 4 Heat Pipe thermal efficiency

The increase in the "thermal energy building up in the thermal tank drives the evaporator of the heat pump where the compressor delivers the vapor refrigerant to the condenser as illustrated in Figure 3, where the heat of condensation is dissipated to the cooling medium that can be used for domestic or industrial use".

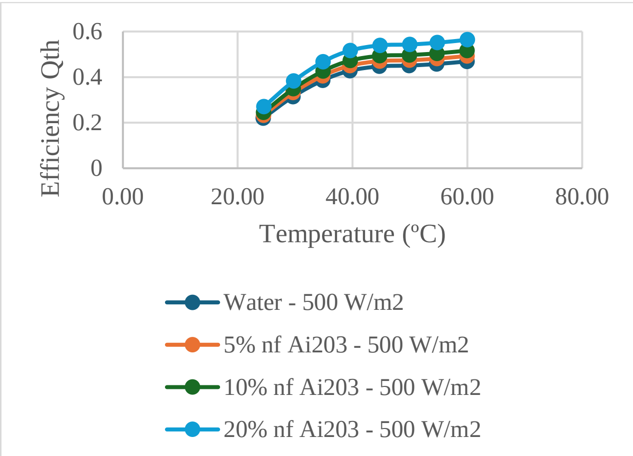

Fig. 5 Integrated thermal efficiency at PV thermal-heat Pipes system

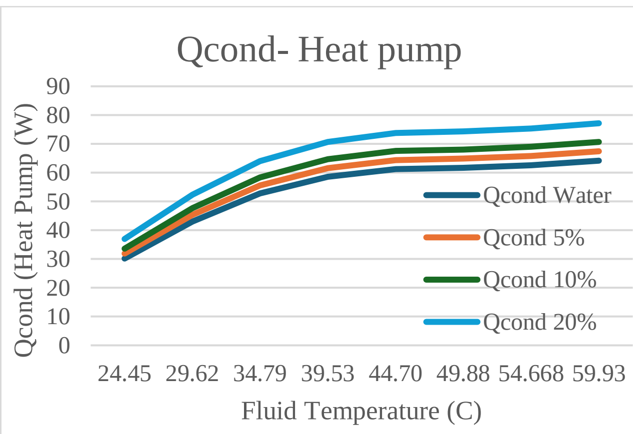

Fig. 6 Heat Pump Condenser thermal energy at different concentrations

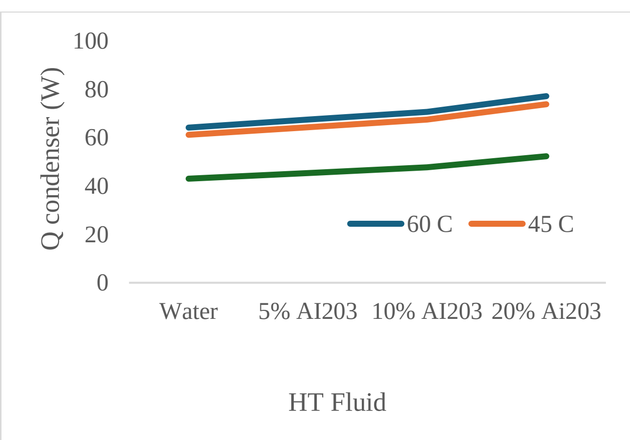

Fig. 7 Heat Pump Condenser thermal energy at different temperatures

Furthermore, Figures 2 through 5 show the dynamic behavior of the integrated behavior of the PV-Thermal and the heat pipes and different heat transfer fluid temperatures at solar radiation of 500 W/m^2. These figures support the statement that the higher the cell temperature, the higher the back cell and higher fluid temperatures, as well as the thermal energy delivered to the evaporator section of the heat pipe.

However, it is important to note that the changes in the PV cell temperature caused by solar radiation have a dynamic nature," as demonstrated in Figure 5. The "PV panel heats up 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 have been presented in references [15].

Equations (8) through (14) were used to determine the "heat released by the condenser section of the heat pipe. To analyze the results of this heat released by the condenser section of the heat pipe", Figures.6 and 7 have been constructed to show the heat released by the "condenser section of the heat pipe filled with the refrigerant mixture as working fluid" and plotted at different nanofluid concentrations and heat pipe temperatures. It is quite clear from the results presented in this figure that the "higher the solar radiation, the higher the heat released from the PV-solar collector to the evaporator and the higher the thermal energy released by the condenser section of the heat pipe.

The data in these figures also demonstrated that higher concentrations of the nanofluid increase the heat transport fluid by activating the heat pipe evaporator and thermal energy at the heat pipe condenser side. Furthermore, the data also showed that the thermal energy produced by the PV-solar collector is higher when the nanofluid is used as heat transport fluid compared to the water.

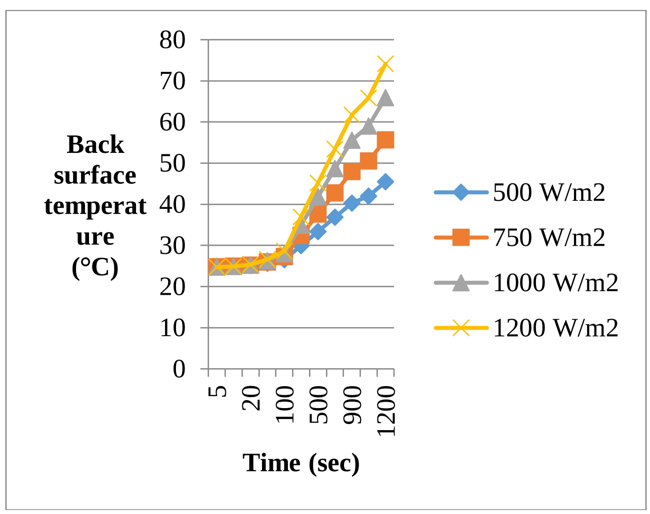

Fig. 8 Back PV Cell temperature at different solar radiation

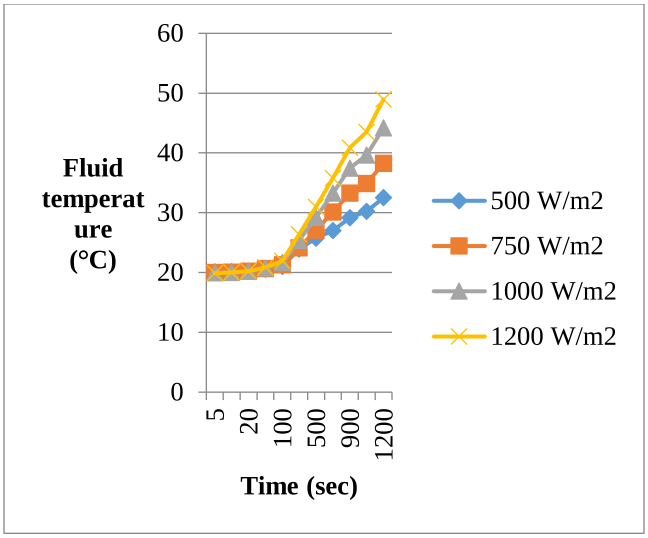

Fig. 9 Fluid temperature exiting the thermal pipes at the PV-Thermal Solar Collector.

The results shown in Figures 8 and 9 indicated that ‘’the systems stabilized after 1200 seconds, and the desired heat transport fluid flow and its temperature were reached after this time elapsed as shown. As expected, the heat transfer fluid mass flow rate and its temperature increased at higher solar radiation. This is because the higher solar radiation results in higher cell temperature and thermal energy that is transferred to the heat transport fluid. Consequently, this increases the fluid flow mass flow rate and its temperature and has the desired effect of cooling down the cell temperature for better PV efficiency. Furthermore, the results presented in these figures also suggest that the ‘fluid flow mass flow rate is quasi-constant during the thermal conversion process.

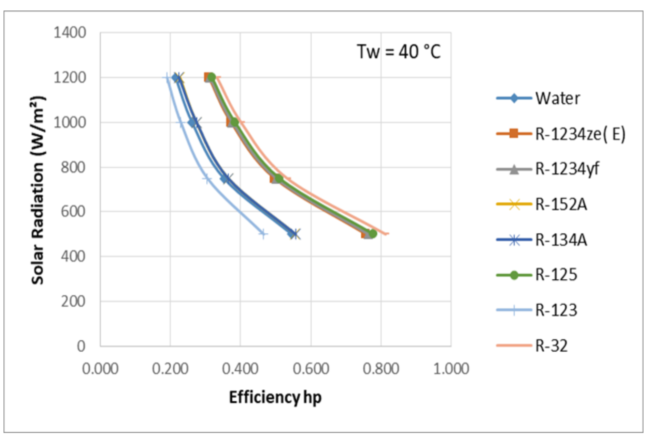

Fig. 10 Hear pipe efficiency at different working fluids.

Other important characteristics of the solar PV-thermal system integrated heat pipe are presented in Figure 10, where the heat pipe efficiency is shown at different solar radiation. The data presented show that the higher the solar radiation, the higher the efficiency of the heat pipe. However, the results displayed in these figures also show that the higher efficiencies of the heat pipe and, consequently, the hybrid system were observed with “refrigerants R-32 and R-125 used as working fluids in the heat pipe. This is significant, and thereafter, it is recommended that R-125 and R-32 be used in the heat pipe as working fluids for this application. For the maximum efficiency of the hybrid system among the other refrigerants under investigation. This is attributed to the fact that the characteristics and thermodynamic properties of the R-125 and R-32 R 407C are the main drivers behind the high efficiency of the hybrid system.

The integrated efficiency of the proposed innovative system is presented in Figure .11, which is calculated by equation (10) at different nanofluid concentrations and heat transfer fluid temperatures. Integrated thermal energy efficiency is defined as the heat transfer divided by the solar radiation absorbed by the PV panel. It is quite evident from the results presented in this figure that the “higher the nanofluid concentrations, the higher the thermal conversion efficiency. It is quite evident from the results presented in this figure that the higher the solar radiation, the higher the thermal heat and efficiency are released.

The thermal capacity represents the characteristic of the working fluid; the wick and the container of the heat pipe determine the condenser section thermal capacity of the heat pipe as per equations (10) through (14) and Tardy and Sami [20], Endale [9] and Reay and Kew [23]. It is believed that the limitations imposed by the condenser section of the heat pipe determine the amount of heat released. This could result in higher heat losses during the energy transfer process inside the heat pipe at higher solar radiation. Therefore, it is believed that higher solar radiation does not necessarily result in higher heat pipe efficiency. The heat pipe design must be based on the site's solar radiation, and the appropriate geometry of the heat pipe must be selected to maximize the energy conversion efficiency of the heat pipe at this particular solar radiation.

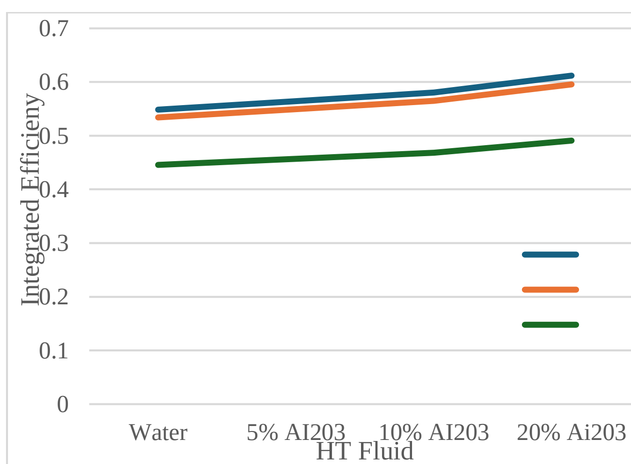

Fig. 11 Integrated efficiencies at Solar 750 irradiances (w/m^2)

During this study, the "thermal heat was released from solar PV panels at different solar radiations and heat pipe temperatures for two heat pipes. The heat pipe temperature is the temperature where the heat pipe's evaporation and condensation of the working fluid take place. The working fluids filled in the heat pipe were water and refrigerants. The heat balance performed at the hybrid system suggested that two heat pipes result in an optimized performance of the system in question.

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 considered in the decision-making".

3.1. Model Validation

The numerical model describing the novel hybrid system under investigation is presented in Equations (1) through (16) and validated only data available in the literature. In the following sections. The model is based upon the determination of the PV solar panel characteristics, cell temperatures and heat dissipated from the solar PV panel. Figures 12 and 13 have been constructed to "validate the proposed model prediction of the PV solar panel and the PV against available experimental data in the literature [17, 22].

It is quite evident from the comparison presented in Figure .12 that the model prediction fairly compares with the dynamic PV cell temperature data presented by Faragali et al. data" [17]. The comparison showed that the model and data have the same trend as the data; however, some discrepancies exist because Faragali et al. [17] did not provide full disclosure of the various parameters used in equations (6) through (9). Reference Rajapakse et al. [29] However, as pointed out in references [8, 12, and 17], 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.

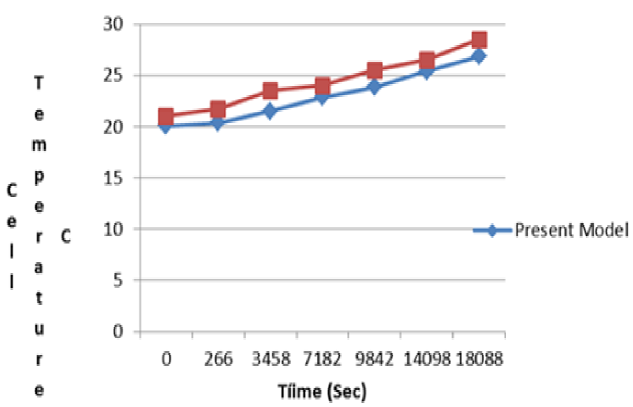

Fig. 12 Model's validations for cell temperature [17]

A comparison between the model's prediction and experimental data [17] is presented in Figure 13. The solar PV model shows the characteristics of the solar PV panel; power at a different amperage that varies with solar radiation is displayed. The present model predicted solar PV characteristics very well.

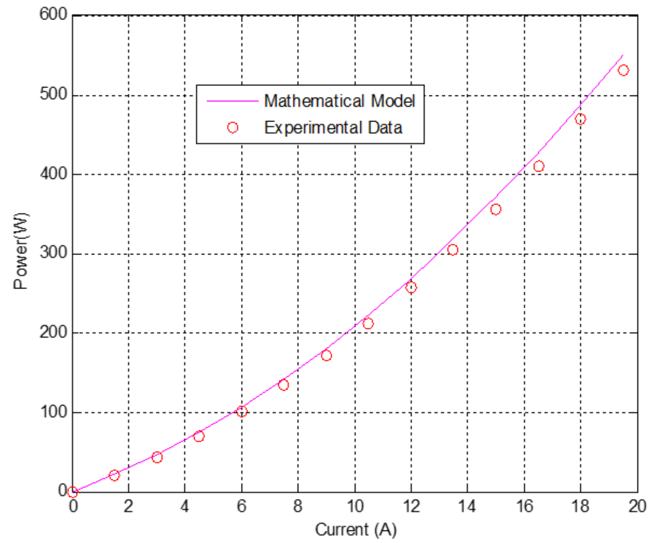

Fig. 13 Comparison between model and experimental data [17, 30]

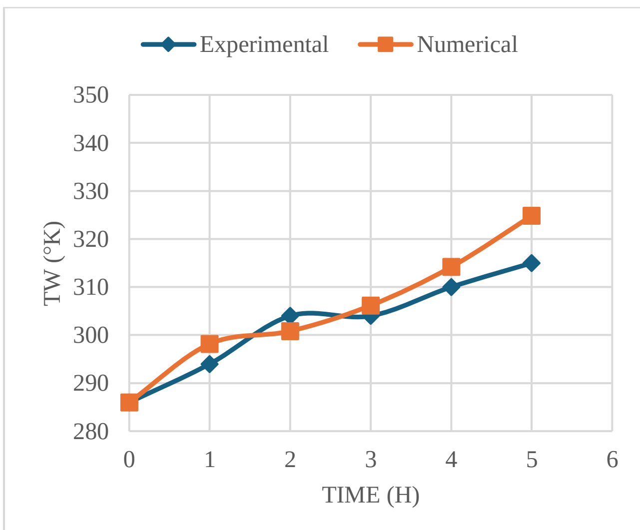

Fig. 14 Comparison between model and experimental data [9]

Finally, the comparison displayed in Figure 13 between 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] 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.

4. Conclusion

A novel integrated approach has been developed, compromising solar PV-thermal collector, heat pipe, and heat pump to produce thermal energy and power" as well as enhancing "the PV solar conversion efficiency using magnetized AiO203 Nanofluid as heat transfer fluid. Numerical modeling is based upon the "energy conversion equations describing the mass and energy balances that have been integrated and solved to predict the "dynamic performance and efficiencies. This current 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 such as water, R-134a, R-152a, R-32, R-125, R1234fz, and R-1234fy and R-123.

It is quite clear from the results presented during this investigation that the higher the solar radiation, the higher the evaporator temperatures and heat pipe temperature and the higher the thermal heat transferred to the heat pipe evaporator section, consequently the higher the heat released from the heat pipe condenser section in the thermal tank that drives the heat pump, which could also be supplied to domestic or industrial demand.

In addition, the data presented also demonstrated that the "refrigerants R-32 and R-125 filled in the heat pipe yield the maximum efficiency of the hybrid system among the other refrigerants under investigation.

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 considered in decision-making.

It was also observed that the "higher the nanofluid concentrations, the higher the thermal conversion efficiency and the higher the solar radiations, the higher the thermal heat released, power generated, and the integrated system efficiency".

Finally, when compared with "experimental data reported in the literature, the present model predicted the solar PV characteristics, the thermal behavior of the heat pipes, and the water temperature dynamic profile well.

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)
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_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)
x Humidity ratio (kg_{water}/kg_{dry_air})
α_{abs} Overall absorption coefficient
η_{Hybrid} Hybrid system efficiency
ηPvPV Module efficiency
$\eta_{Thermal}$ Efficiency of thermal process
ρw Density of water vapor (Kg/m^3)
∂Q Convection heat transfer rate
Q Thermal heat (kj/s)
ε Emissivity PV cell

Acknowledgement

The research work presented in this paper was made possible through the support of TransPacific Energy Inc. The author also would like to thank the research team members at TransPacific Energy Inc. for their great help in performing the different computations.

References

[1] D.J. Yang et al., "Simulation and Experimental Validation of Heat Transfer in a Novel Hybrid Solar Panel," *International Journal of Heat and Mass Transfer*, vol. 55, no. 4, pp. 1076-1082, 2012. [CrossRef] [Google Scholar] [Publisher Link]

[2] Pei Gang et al., "A Numerical and Experimental Study on a Heat Pipe PV/T System," *Solar Energy*, vol. 85, no. 5, pp. 911-921, 2011. [CrossRef] [Google Scholar] [Publisher Link]

[3] Nannan Dai et al., "Simulation of Hybrid Photovoltaic Solar Assisted Loop Heat Pipe/Heat Pump System," *Applied Science*, vol. 7, no. 2, pp. 1-15, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[4] Y. Tripanagnostopoulos et al, "Hybrid Photovoltaic/Thermal Solar Systems," *Solar Energy*, vol. 72, no. 3, pp. 217–234, 2002. [CrossRef] [Google Scholar] [Publisher Link]

[5] Trond Bergene, and Ole Martin Lovvik, "Model Calculations on a Flat-plate Solar Heat-Collector with Integrated Solar Cells," *Solar Energy*, vol. 55, no. 6, pp. 453–462, 1995. [CrossRef] [Google Scholar] [Publisher Link]

[6] H.G. Teo, P.S. Lee, and M.N.A. Hawlader, "An Active Cooling System for Photovoltaic Modules," *Applied Energy*, vol. 90, no. 1, pp. 309-315, 2012. [CrossRef] [Google Scholar] [Publisher Link]

[7] H. Hashim, J.J. Bomphrey, and G. Min, "Model for Geometry Optimization of Thermoelectric Devices in a Hybrid PV/TE System," *Renewable Energy*, vol. 87, no. 1, pp. 458-463, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[8] H.P. Garge, and R.K. Agarwal, "Some Aspects of a PV/T Collector/Force Circulation Flat-Plate Solar Water Heater with Solar Cells," *Energy Conversion and Management*, vol. 36, no. 2, pp. 87–99, 1995. [CrossRef] [Google Scholar] [Publisher Link]

[9] Abede Endalew, "*Numerical Modeling and Experimental Validation of Heat Pipes Solar Collector for Water Heating*," Master Thesis, KTH Industrial Engineering and Management, Sweden, pp. 1-69, 2011. [Google Scholar] [Publisher Link]

[10] Bjornar Sandnes, and John Rekstad, "A Photovoltaic/Thermal (PV/T) Collector with a Polymer Absorber Plate, Experimental Study, and Analytical Model," *Solar Energy*, vol. 72, no. 1, pp. 63-73, 2002. [CrossRef] [Google Scholar] [Publisher Link]

[11] Xudong Zhao, "*Investigation of a Novel Heat Pipe Collector/CHP System*," PhD Thesis, University of Nottingham, pp. 1-245, 2003. [Google Scholar] [Publisher Link]

[12] Ruobing Liang, Jili Zhang, and Chao Zhou, "Dynamic Simulation of Novel Solar Heating System Based on Hybrid Photovoltaic /Thermal Collectors (PVT)," *Procedia Engineering*, vol. 121, pp. 675-682, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[13] S. Sami, and E. Marin, "Simulation of Solar Photovoltaic, Biomass Gas Turbine and District Heating Hybrid System," *International Journal of Sustainable Energy and Environmental Research*, vol. 6, no. 1, pp. 9-26, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[14] Samuel Sami, and Jorge Rivera, "A Predictive Numerical Model for Analyzing Performance of Solar Photovoltaic, Geothermal Hybrid System for Electricity Generation and District Heating," *Science Journal Energy Engineering*, vol. 5, no. 1, pp. 13-30, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[15] S. Sami, and E. Marin, "A Numerical Model for Predicting Performance of Solar Photovoltaic, Biomass and CHP Hybrid system for Electricity Generation," *International Journal of Engineering Sciences & Research Technology*, vol. 6, no. 1, pp. 1-22, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[16] Clara Good et al., "Hybrid Photovoltaic-Thermal System in Buildings-A Review," *Energy Procedia*, vol. 70, pp. 683-690, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[17] Hanaa Faragali, Faten H. Fahmy, and Mohamed A. Hassan, "A Simulation Model for Predicting the Performance of PV/Wind-Powered Geothermal Space Heating System in Egypt," *The Online Journal on Electronics and Electrical Engineering (OJEEE)*, vol. 2, no. 4, pp. 321-330, 2008. [Google Scholar] [Publisher Link]

[18] Pei Gang et al., "A Numerical and Experimental Study on a Heat Pipe PV/T System," *Solar Energy*, vol. 85, no. 5, pp. 911-921, 2011. [CrossRef] [Google Scholar] [Publisher Link]

[19] S. Sami, and E. Marin, "Dynamic Modeling and Simulation of Hybrid Solar Photovoltaic and PEMFC Fuel Power System," *RA Journal of Applied Research*, vol. 4, no. 5, pp. 1666-1683, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[20] F. Tardy, and Samuel M. Sami, "Thermal Analysis of Heat Pipes During Thermal Storage," *Applied Thermal Engineering*, vol. 29, no. 2-3, pp. 329-333, 2009. [CrossRef] [Google Scholar] [Publisher Link]

[21] John A. Duffie, and William A. Beckman, *Solar Engineering of Thermal Process*, Wiley, pp. 1-944, 1974. [Google Scholar] [Publisher Link]

[22] J.M. Coulson et al., *Chemical Engineering: Fluid Flow, Heat Transfer and Mass Transfer*, 6th ed., Elsevier Science, vol. 1, pp. 1-895, 1999. [Google Scholar] [Publisher Link]

[23] David Reay, Ryan McGlen, and Peter Kew, *Heat Pipes: Theory, Design and Applications*, Technology & Engineering, pp. 1-384, 2006. [Google Scholar] [Publisher Link]

[24] F. Tardy, and S. Sami, "An Experimental Study Determining Behaviour of Heat Pipes in Thermal Storage," *International Journal of Ambient Energy*, vol. 29, no. 3, pp. 162-168, 2008. [CrossRef] [Google Scholar] [Publisher Link]

[25] A. Sweidan, N. Ghaddara, and K. Chali, "Optimized Design and Operation of a Heat-pipe Photovoltaic Thermal System with Phase Change Material for Thermal Storage," *Journal of Renewable and Sustainable Energy*, vol. 8, no. 2, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[26] S. Sami, and C. Campoverde, "Dynamic Simulation and Modeling of a Novel Combined Photovoltaic –Thermal Panel Hybrid System," *International Journal of Sustainable Energy and Environmental Research*, vol. 7, no. 1, pp. 1-23, 2018. [Google Scholar] [Publisher Link]

[27] Zhao Xuxin et al., "Comparative Study on Performances of a Heat-pipe PV/T System and A Heat-Pipe Solar Water Heating System," *International Journal of Green Energy*, vol. 3, no. 3, pp. 229240, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[28] Mohammad Sajad Naghavi et al., "Analytical Thermal Modeling of a Heat Pipe Solar Water Heater System Integrated with Phase Change Material," *Computer Applications in Environmental Sciences and Renewable Energy*, pp. 197-208, 2015. [Google Scholar]

[29] Athula Rajapakse, and Supachart Chungpaibulpantana, "Dynamic Simulation of a Photovoltaic Refrigeration System," *International Energy Journal*, vol. 16, no. 2, pp. 67-101, 1994. [Google Scholar] [Publisher Link]

[30] Jens Glembin et al., "Thermal Storage Tanks in High-Efficiency Heat Pump Systems – Optimized Installation and Operation Parameters," *Energy Procedia*, vol. 73, pp. 331-340, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[31] X. Yang, Y.Y. Yan, and D. Mullen, "Recent Developments of Lightweight, High-performance Heat Pipes," *Applied Thermal Engineering*, vol. 33–34, pp. 1-14, 2012. [CrossRef] [Google Scholar] [Publisher Link]

[32] Jobin Jose, and Tapano Kumar Hotta, "Thermal Performance Analysis and Optimization of a Heat Pipe-based Electronic Thermal Management System Using Experimental Data-driven Neuro-genetic Technique," *Thermal Science and Engineering Progress*, vol. 54, 2024. [CrossRef] [Google Scholar] [Publisher Link]