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Numerical investigation for performance study of photovoltaic thermal nanofluids system

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Abstract

In this paper, a numerical and mathematical model was performed to evaluate performance of photovoltaic thermal nanofluids system. The energy balance equations for every layer of the photovoltaic thermal system are solved using numerical simulations. The objective of this work is to study theoretically a new configuration of the photovoltaic thermal system which includes stainless steel rectangular tube and nanofluids as a working fluid for extracts heat from photovoltaic panel. Three different volume concentrations of Titanium Oxide, TiO_2 from 0.5 to 1.5%v with effects of mass flow rate and solar irradiance were studied. Results indicated that the electrical and thermal efficiencies is proportional to mass flow rate and the best results achieved with lower volume concentration. Nanofluids provide a higher performance due to higher specific heat, Nusselt number and heat transfer coefficient. It is also found that, volume concentration of 0.5%v under average solar irradiance of 650W/m^2 with equal to average climate in Malaysia has shown the higher efficiencies in electrical and thermal respectively.

Keywords: Photovoltaic thermal collector, TiO_2 Nanofluid, Electrical efficiency, Thermal efficiency

INTRODUCTION

With an average solar radiation of 1643 kWh/m^2 per year, is favorable for the development of solar energy for electricity generation in Malaysia [1]. Market demand for solar PV has grown over the last decade and is expected to continue to accelerate in the coming years. The primary energy consumption is expected to rise 1.6% annually and Malaysia power demand is expected to reach 18,947 MW in 2020 [2]. The capacity of electricity generation through Renewable Energy is at 50 MW and is expected to increase by 2000 MW in 2020 [1]. One of the problems faced by the solar system (Photovoltaic) is the increase in high temperatures, especially on the weather in Malaysia, this high temperature will result in a decreasing of electric efficiency of photovoltaic system. To overcome this problem, a hybrid photovoltaic thermal collector (PVT) was introduced. A PVT system provides a better recovery of the solar energy per unit area of the collector [3].

Many theoretical studies have been reported for hybrid PVT liquid water heating system, T.T.Chow [4] performed analysis of photovoltaic thermal collector by explicit dynamic model for single glazed flat plate water heating PVT collector, which includes seven node model for predicting multi-dimensional thermal conduction on photovoltaic panel and absorber plates. K.Touafek et al.[5] presented theoretical and experimental study of sheet and tubes hybrid PVT collector at Ghardaia in south of Algeria. Their study focused on distribution of temperatures in the different layers of PVT collector. The results shown external and internal parameters influenced on the operating characteristics and effectiveness of the PV collector.

Parametric analysis has been carried out by Arvind Tiwari and Sodha [6], of various configurations of hybrid PV/thermal air collector for both experimental and theoretical model. They concluded that, an overall efficiency increase linearly with mass flow rate of air through the duct. However, overall solar cell efficiency decreased with increase of temperatures.

Recently, new concept of hybrid PVT was introduced by M.Y.Othman et al [7], this system includes PVT combination with water and air heating. Results from experiment had shown electrical efficiency was achieved at 17% and thermal efficiency was recorded at 76%. Many researchers studied and investigated PVT systems configuration for the last decade in the literature [8-14].

In this paper, a mathematical model of hybrid collector which using Titanium Oxide, TiO_2 nanofluid as a working fluid was performed by evaluating the temperature for every layers and influence of thermal and electrical performance was studied.

MODELLING OF PHOTOVOLTAIC THERMAL SYSTEM

The photovoltaic thermal nanofluid system in this work is consists of a photovoltaic panel, a stainless steel rectangular duct for nanofluids channel and insulation layer as shown in figure 1.

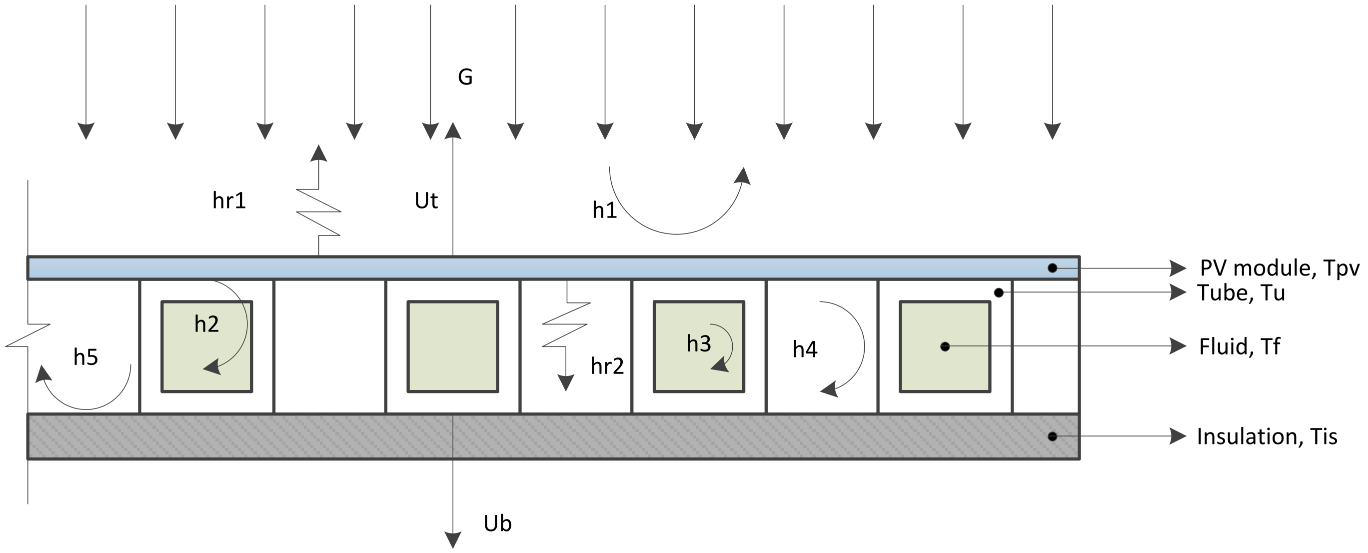

Figure 1: Cross sectional view of photovoltaic thermal nanofluids collector

Thermal and electrical performances to be evaluated for PVT nanofluids collector are based on heat transfer characteristic which developed from steady state condition for energy balance equations with nanofluids. Three different volume concentrations of Titanium Oxide, TiO_2 with 0.5%v, 1.0%v and 1.5%v were selected for this study. In order to simplify analysis and calculation, a few assumptions are made in the numerical simulation

- Nanofluids flow is uniform in velocity and temperature.
- Thermo-physical properties of nanofluids are constant.
- The system under steady state condition.

Energy balance of the system can be written as follows.

Photovoltaic panel

$$G\alpha_c\tau_c = hr_{pv-sky}\left(T_{pv} - T_{sky}\right) + hc_{pv-a}\left(T_{pv} - T_a\right)$$
$$+ F'hc_{pv-f}\left(T_{pv} - T_f\right) + hr_{pv-b}\left(T_{pv} - T_b\right)$$
$$+G\beta_c\left[\eta_{ref}\left(1 + \gamma\left(T_{pv} - T_{stc}\right)\right)\right] \qquad (1)$$

Where α_c, τ_c are absorption and transmittance of photovoltaic panel, β_c is the ratio of the cell area to the collector area which known as the packing factor, G is solar irradiance in W/m^2 , η_{ref} photovoltaic panel rated efficiency , γ photovoltaic panel temperature coefficient for mono-crystalline ($\gamma = 0.0045$) and T_{stc} is standard test condition temperature (25°C ≈ 298K) respectively.

Fluid in tube

$$F'hc_{pv-f}\left(T_{pv} - T_f\right) + hc_{b-f}\left(T_b - T_f\right)$$
$$= \frac{2\dot{m}C_p}{WL}\left(T_f - T_{fi}\right) \qquad (2)$$

$\dot{m}$, C_p and L are the mass flow rate, nanofluid specific heat and total length of tube, respectively. F' is collector efficiency actor, which can be calculated using :

$$F' = \frac{\frac{1}{U_L}}{W\left[\frac{1}{U_L\left[D_i + (W - D_i)F\right]}\right] + \frac{1}{D_i hc_{f-b}}} \qquad (3)$$

W is spacing between tube , D_i , U_L , F are hydraulic diameter, overall losses, fin efficiency and hc_{f-b} is the convective heat transfer coefficient between fluid and tube. Fin efficiency factor can be define as :

$$F = \frac{tanh\left(M\frac{W - D_i}{2}\right)}{\sqrt{M\frac{W - D_i}{2}}} \qquad (4)$$

Where hydraulic diameter for rectangular tube,

$$D_i = \frac{2ab}{a + b} \qquad (5)$$

Considering for both thermal efficiency and photovoltaic cell, coefficient M which calculated by [15].

$$M = \sqrt{\frac{U_L}{K_b\delta_b K_{pv}\delta_{pv}}} \qquad (6)$$

K_b , δ_b are tube thermal conductivity , tube thickness and K_{pv} , δ_{pv} are photovoltaic cell thermal conductivity and cell thickness, respectively.

Bottom tube

$$hr_{pv-b}\left(T_{pv} - T_b\right) = hc_{b-f}\left(T_b - T_f\right) + \frac{K_{ins}}{\delta_{ins}}(T_b - T_{ins}) \quad (7)$$

K_{ins}, δ_{ins} are referred to thermal conductivity and thickness of insulation layer, respectively.

Insulation

$$\frac{K_{ins}}{\delta_{ins}}(T_b - T_{ins}) = h_w(T_{ins} - T_a) \quad (8)$$

HEAT TRANSFER COEFFICIENT

The heat transfer coefficient that are applied in energy balance equations for each layer are defined as follows:

The radiation heat transfer coefficient, h_{r1} is from surface of photovoltaic which related to ambient and sky temperature.

$$hr_1 = hr_{pv-sky} = \sigma\varepsilon_{pv}\left(T_{pv}^2 + T_{sky}^2\right)\left(T_{pv} + T_{sky}\right) \quad (9)$$

Where $T_{sky} = 0.0552T_a^{1.5}$ (10)

T_a , σ are ambient temperature and Stefan Boltzmann constant, respectively. The radiation heat transfer coefficient between rectangular tube and photovoltaic panel is defined as:

$$hr_2 = hr_{pv-b} = \frac{\sigma\left(T_{pv}^2 + T_b^2\right)\left(T_{pv} + T_b\right)}{\left(\frac{1}{\varepsilon_{pv}} + \frac{1}{\varepsilon_b} - 1\right)} \quad (11)$$

h_1 is the convection heat transfer coefficient between photovoltaic panel , ambient temperature and wind velocity.

$$h_1 = hc_{pv-a} = 2.8 + 3.3V_{wind} \quad (12)$$

Where V_{wind} is wind velocity in m/s , which taken as 2 m/s.

h_2 is the convection heat transfer coefficient between photovoltaic panel and fluid in tube.

$$h_2 = hc_{pv-f} = \frac{N_u h_{nf}}{D_i} \quad (13)$$

Where N_u and h_{nf} are Nusselt number correlation and heat transfer coefficient for nanofluids, respectively. For turbulent flows , Nusselt number can be calculated by the following equation [16].

$$Nu_{nf} = 0.074Re_{nf}^{0.707}Pr_{nf}^{0.385}\phi^{0.074} \quad (14)$$

The Reynolds number of the nanofluids is defined as :

$$Re_{nf} = \frac{\rho_{nf}D_iV_{nf}}{\mu_{nf}} \quad (15)$$

The Prandtl number can be calculated from following equation:

$$Pr_{nf} = \frac{\mu_{nf}C_{nf}}{K_{nf}} \quad (16)$$

Where ϕ is percentage of nanofluid volume concentration in %Vol and ρ_{nf}, V_{nf}, μ_{nf}, C_{nf} are nanofluid properties which density, fluid velocity, viscosity and specific heat respectively.

THERMO PHYSICAL PROPERTIES OF NANOFLUIDS

In this study TiO_2-H_2O is selected and its thermo physical of particles is summarized in table 1. Timofera et al. [17] suggested an equation for calculating thermal conductivity of nanofluids, which is defined as follows:

$$k_{nf} = (1 + 3\phi)k_w \quad (17)$$

Table 1: Physical properties on TiO2 and H_2O particles

	K (W/mK)	ρ (kg/m^3)	C(J/kg.k)	μ(kg/ms)
TiO_2	8.4	4175	692	
H_2O	0.609	997	4180	0.001002

For calculating nanofluids viscosity, Drew and Passman [18] suggested equation which is defined as follows:

$$\mu_{nf} = (1 + 2.5\phi)\mu_w \quad (18)$$

The density and specific heat for nanofluids are estimated based on mixture relation with water which given as:

$$\rho_{nf} = \phi\rho_p + (1 - \phi)\rho_w \quad (19)$$

$$C_{nf} = \frac{(1 - \phi)(\rho_w C_w) + \phi\left(\rho_p C_p\right)}{(1 - \phi)\rho_w + \phi\rho_p} \quad (20)$$

NUMERICAL SOLUTION PROCEDURE

In this works, the mean ambient, photovoltaic surface, tube, fluid and input fluid temperature were initially guessed. The equations (1,2,7 and 8) can be presented in a form of 4 x 4 matrix,

$$[A][T] = [C] \quad (21)$$

$$\begin{bmatrix} A_1 & A_2 & A_3 & 0 \\ A_4 & A_5 & A_6 & 0 \\ A_7 & A_8 & A_9 & A_{10} \\ 0 & A_{11} & 0 & A_{12} \end{bmatrix}\begin{bmatrix} T_{pv} \\ T_b \\ T_f \\ T_{ins} \end{bmatrix} = \begin{bmatrix} C_1 \\ C_2 \\ 0 \\ C_3 \end{bmatrix} \quad (22)$$

Where,

$$\begin{aligned} A_1 &= hr_{pv-sky} + hc_{pv-a} + F'hc_{pv-f} + hr_{pv-b} \\ &\quad + G\gamma\beta_c\eta_{ref} \end{aligned} \tag{23}$$

$$A_2 = -hr_{pv-b} \tag{24}$$

$$A_3 = -F'hc_{pv-f} \tag{25}$$

$$A_4 = F'hc_{pv-f} \tag{26}$$

$$A_5 = hc_{b-f} \tag{27}$$

$$A_6 = -F'hc_{pv-f} - hc_{b-f} - \frac{2\dot{m}C_p}{WL} \tag{28}$$

$$A_7 = hr_{pv-b} \tag{29}$$

$$A_8 = -hr_{pv-b} - hc_{b-f} - \frac{k_{ins}}{\delta_{ins}} \tag{30}$$

$$A_9 = hc_{b-f} \tag{31}$$

$$A_{10} = \frac{k_{ins}}{\delta_{ins}} \tag{32}$$

$$A_{11} = \frac{k_{ins}}{\delta_{ins}} \tag{33}$$

$$A_{12} = -\frac{k_{ins}}{\delta_{ins}} - h_w \tag{34}$$

$$\begin{aligned} C_1 &= G\alpha_c\tau_c + hr_{pv-sky}T_{sky} + hc_{pv-a}T_a \\ &\quad - G\beta_c\eta_{ref}(1 - \gamma T_{stc}) \end{aligned} \tag{35}$$

$$C_2 = \frac{-2\dot{m}C_p}{WL}T_{fi} \tag{36}$$

$$C_3 = -T_a h_w \tag{37}$$

The thermal efficiency of PVT collector is expressed as [19].

$$\eta_{th} = F_R\tau\alpha_{pv} - F_R U_L\left(\frac{T_{if}-T_a}{G}\right) \tag{38}$$

Electrical efficiency of photovoltaic panel in function of temperature is given as [20].

$$\eta_{pv} = \eta_{ref}\left[1 - \gamma\left(T_{pv} - T_{stc}\right)\right] \tag{39}$$

RESULTS AND DISCUSSIONS

In this study, TiO_2-H_2O nanofluids with nanoparticles concentration (ϕ: 0.5,1.0 and 1.5V%), different mass flow rates (0.125,0.134,0.142,0.151,0.164 and 0.174 kg/s) were tested under three different solar irradiances (1000, 850 and 650 W/m^2) are used for investigating the performance of electrical and thermal efficiencies. From figure 2a, it can be noticed that lowest nanofluids concentration results in reduction of photovoltaic surface temperature and enhance heat transfer rates. In addition to the low concentration, high mass flow rates also helped the process of heat transfer from the surface of photovoltaic panel to the fluid. The lowest temperature was 35.6°C at solar irradiance of 650 W/m^2.

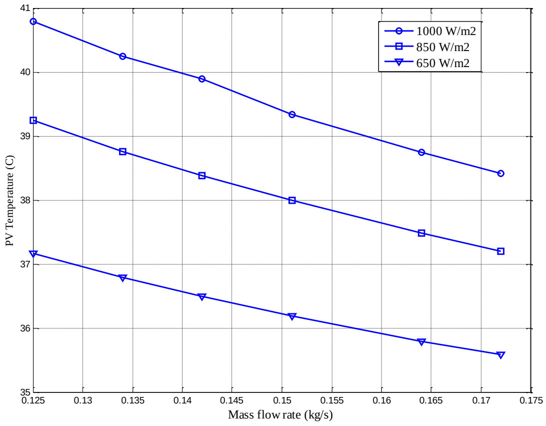

Figure 2a: Photovoltaic surface temperature with concentration of 0.5%v

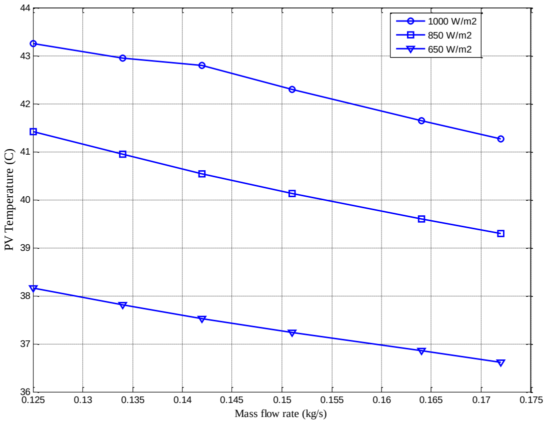

Figure 2b : Photovoltaic surface temperature with concentration of 1.0%v

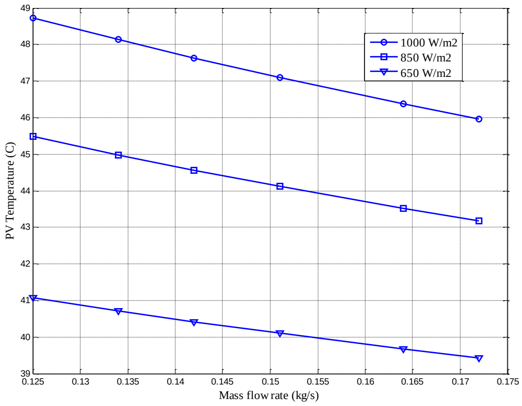

Figure 2c: Photovoltaic surface temperature with concentration of 1.5%v

From figure 3a, it is noticed that due to lowest surface temperature, electrical efficiency reduced in small quantity which reduction of 14.38% for 0.5%v , 14.31% (1.0%v) and 14.12% (1.5%v) respectively. For volume concentration of 0.5%v, the highest efficiency was recorded which 0.72% difference compared to rated efficiency of 15.1%.

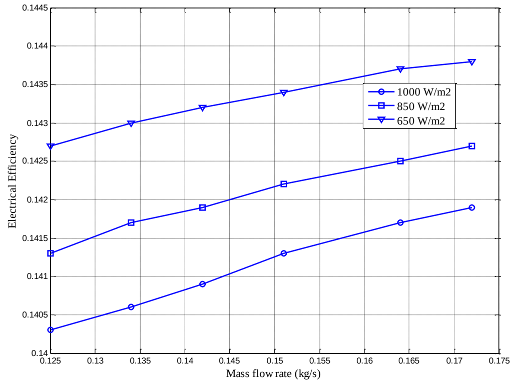

Figure 3a: Electrical efficiency with different concentration of 0.5%v

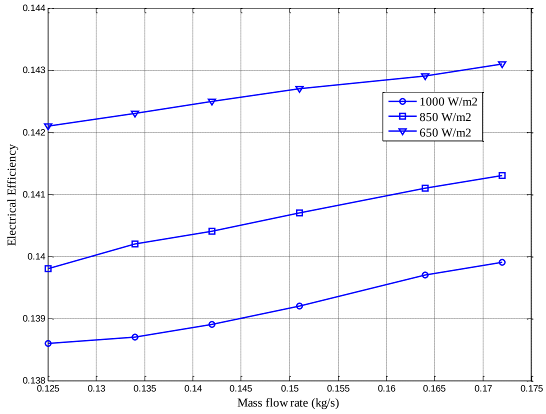

Figure 3b: Electrical efficiency with concentration of 1.0%v

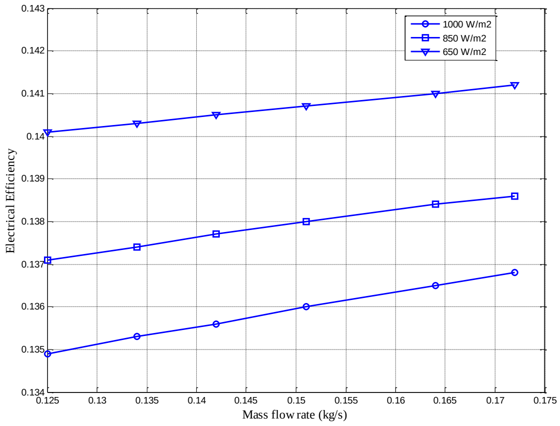

Figure 3c: Electrical efficiency with concentration of 1.5%v

For thermal efficiency in figures 4a,4b and 4c, it can be noticed that increasing volume concentration from 0.5%v to 1.5%v results in decreasing the thermal efficiency. This happen because of pressure build up inside tube due to nanofluids density increased by 38.05% from 0.5%v to 1.0%v and 55.4% from 0.5%v to 1.5%v respectively. Apart from that, increase of volume concentration of nanofluids leads to degradation of the nanofluids specific heat as shown in table 2, due to lower specific heat of TiO_2 nanoparticles compared to bse fluid, H_2O. From figure 4a, the highest thermal efficiency was noticed at 71.7% with 0.5%v, 0.174 kg/s mass flow rates and 650 W/m^2 of solar irradiance.

Table 2: Thermo physical properties of TiO2-H2O nanofluids

	K_{nf} (W/mK)	ρ_{nf} (kg/m^3)	C_{nf}(J/kg.k)
0.5%v	1.5225	2586	1364
1.0%v	2.436	4175	692
1.5%v	3.3495	5764	390

The impact of TiO_2-H_2O nanofluids with difference volume concentrations (0.5%v, 1.0%v,1.5%v) on the electrical and thermal efficiency are studied. Higher specific heat and lower fluid density with lower volume concentration of 0.5%v gave better electrical and thermal efficiency compared to 1.0%v and 1.5%v volume concentrations.

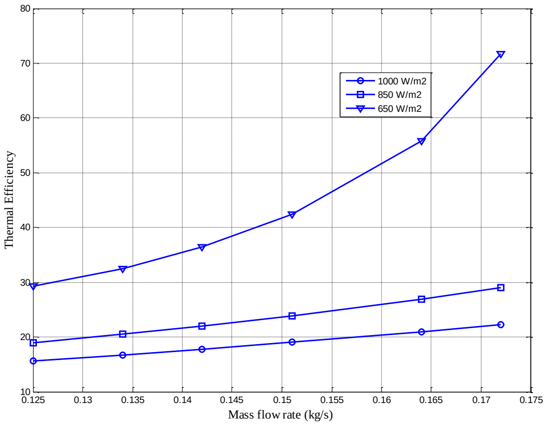

Figure 4a: Thermal efficiency with concentration of 0.5%v

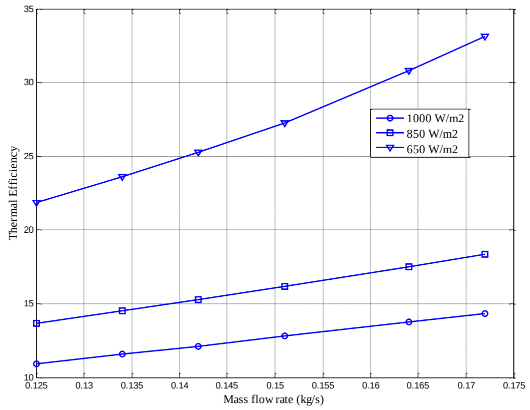

Figure 4b: Thermal efficiency with concentration of 1.0%v

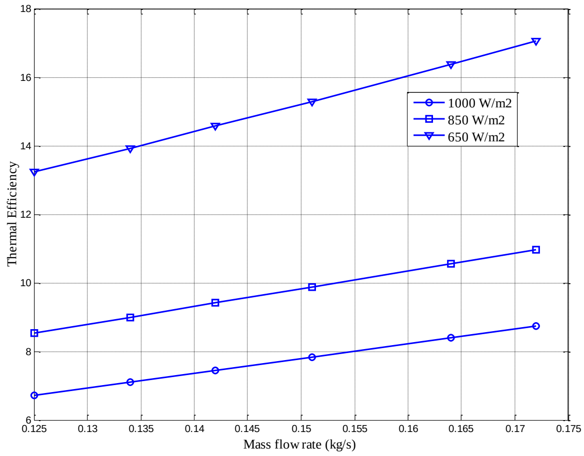

Figure 4c: Thermal efficiency with concentration of 1.5%v

CONCLUSIONS

In this study, a numerical simulation using nanofluids as a working fluid and a mathematical model for predicting performances of a photovoltaic thermal collector system was presented. The electrical and thermal efficiencies of PVT/ nanofluids is strongly dependent on the mass flow rate but inversely proportional to solar irradiance, which was observed approximately 14.38% and 71,71% at the mass flow rate of 0.174 kg/s and 650W/m^2 solar irradiance. In addition, by adding small amount of nanoparticles into pure water leads to enhancement on thermal physical properties. Other than that, lower volume concentration demonstrated the best performances, which contributes higher Nusselt number and specific heat. Pressure drop inside tube was observed reduces due to lower fluid density and this will increase fluid heat transfer coefficient between working fluid and photovoltaic panel.

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