Effect of mass flow rate on thermal performance of flat-plate solar collector integrated with phase change material riser

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Abstract

The solar energy is clean, environmentally renewable energy and can be used in both electricity and heat function. In part of heat production, it commonly used a solar collector that can integrate with many techniques for offering the highest thermal performance which one method is to use the phase change material (PCM). The goal of this research is to study the thermal performance of solar collector with and without phase change material (PCM) riser. The various water mass flow rate per collector area were observed at 0.01, 0.02 and 0.03 kg/s·m^2, respectively. The two novel solar collectors were built in a single copper tube as absorber plate tube with 28.7 mm of outside diameter, 1 mm of thickness and 1,000 mm of length inserted with copper tube riser with diameter of 10 mm and 16 mm which were filled with RT42 phase change material (a melting point between 38 ℃ to 42 ℃). The novel solar collectors were installed for thermal performance testing following ASHRAE standard 93-2003 comparing with the solar collector without PCM riser.

The experiment results show that both of the novel solar collectors were given the thermal performance greater than the solar collector without PCM riser. The novel solar collector that integrated with phase change material riser of 16 mm diameter (PCM1) at 0.03 kg/s□m^2 demonstrated the best of $F_R(\tau\alpha)_e$ and F_RU_L of 0.811 and 9.753 (W/m^2□K)following by the mass flow rate of 0.02 kg/s□m^2 and 0.01 kg/s□m^2, respectively. For the novel solar collector integrated with phase change materials riser of 10 mm diameter (PCM2) gave the $F_R(\tau\alpha)_e$ and F_RU_L of 0.815 and 11.140 (W/m^2□K) at 0.02 kg/s□m^2 following by the results of mass flow rate 0.03 kg/s□m^2 and 0.01 kg/s□m^2, respectively.

Keywords: *Thermal performance, Solar flat plate collector, Phase change material, PCM RT42.*

1. Introduction

The Presently, the energy demand is increased rapidly around the world (UN(unitednation), 2018) along the global economic growth, while energy resource has limited and has decreased amount of fossil fuel such as coal, natural gas and crude oil. Burning of fossil fuel increases the amount of greenhouse gas in the atmosphere that causes of the global warming (WHO, 2018). Solar energy is a potential renewable energy. It's free and environmentally save more than fossil fuel energy. The useful of solar energy can be used in both functional electricity and heat. Heating system by using solar flat plate collector is used in the low range temperature which less than 100 ℃ especially using for water heating production (Gautam, Chamoli, Kumar, & Singh, 2017; Kalogirou, 2014). Although, the solar collector is widely used but many researchers try to enhance its thermal performance by many methods (Cabeza, Castell, Barreneche, de Gracia, & Fernández, 2011). Using phase change materials (PCM) integrated with solar collector is an alternative method. PCM is a chemical composite that can store a large amount of thermal energy during melting or freezing in the storage tank. The thermal accumulation of PCM has been given a large quantity when integrates in the collector, and it can reduce heat loss. The suitable outlet temperature could provide in cloudy day when operated comparing without PCM (Bellan et al., 2015; Cabeza et al., 2011; Gupta, Gaur, Crook, & Dixon-Hardy, 2017; Khalifa, Suffer, & Mahmoud, 2013; Koca, Oztop, Koyun, & Varol, 2008; Koyuncu & Lüle, 2015; Lin, Al-Kayiem, & Aris, 2012; Loem, Deethayat, Asanakham, & Kiatsiriroat, 2019; Wu et al., 2018). The research study between PCM and flat plate solar collector had been published by various techniques, for example: (Koyuncu & Lüle, 2015) studied the domestic chromium solar water collector with PCM filling which the system arranged an absorber pipe for water circulating at 0.02 kg/s□m^2, (Lin et al., 2012) studied the flat-plate solar collector integrated with phase change materials below the absorber plate as thermal energy storage. The absorber plate was modified by the surface extending into the PCM reservoir for heat transfer increasing. The results showed that the comparison of solar flat plate collector in different inclination angles from 10^o-20^o in the case of with and without phase change materials can operate the promising 38 ℃ of hot water temperature for daytime demand and give 52 % of system efficiency, and (Mettawee & Assassa, 2006) studied the compact solar collector that contained the PCM and a copper pipe embedded inside for carrying the heat transfer of system. The result showed that the PCM would be melted by solar radiation with temperature increases gradually by its low-temperature gradient due to the low thermal conductivity and the natural convection grew strongly to solid-liquid interface by re-circulated flow.

In this experiment, it investigates the novel Flat-Plate solar collector which water exchanges accumulation heat directly with absorber plate, the PCM is filled in the copper tube riser that inserts in the copper absorber tube of collector. During operation testing, the solar collector will absorb heat from solar radiation and transfer to the working fluid and PCMs. The thermal performance of this novel system is tested as following to ASHRAE standard 93-2003.

2. Objectives

1. To study the solar Flat-Plate collector integrated with phase change material riser tube.
2. To find thermal efficiency of novel solar collector (PCM 1 and PCM 2) to conventional solar collector using the Ashrae standard 93-2003.
3. To find the effect of mass flow rate on thermal performance Flat-Plate collector integrated performance.

3. Materials and Methods

3.1 *The novel solar collector*

The novel solar collectors in this experiment had two prototype flat-plate solar collectors. Each set consisted of a single copper tube as absorber plate tube with an outside diameter of 28.7 mm, thickness of 1 mm and length of 1000 mm, inside a copper tube was inserted a copper riser. The first prototype was filled with RT42 Phase Change Material (PCM) in riser tube with a diameter of 16 mm and the second one was filled with the same PCM in a diameter of 10 mm. PCM melting point is between 38-42 ℃ (ICNQT, 2018) were inserted into the absorber plate of flat-plate collector. The copper tube plate was welded with a copper absorber plate for increasing aperture surface and painted a black color on the absorber plate. On the above, a single clear glass of 3 mm thickness was installed as a cover greenhouse effect. Around the aluminum frame of novel solar collector was enfolded by the Aroflex foam rubber (density of 40-70 kg/m^3) with thickness 25 mm for heat loss reduction. The perspective dimension of the novel solar collectors was 1090 mm of length, 220 mm of width, and 100 mm of height that shows in Figure 1 and Figure 2.

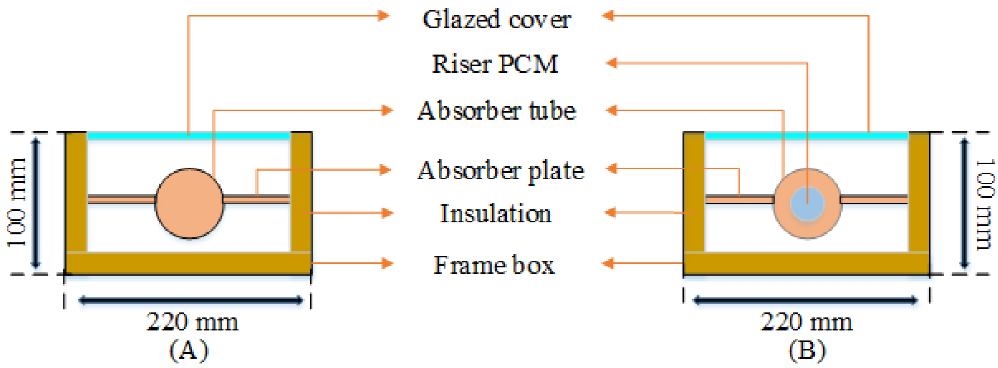

Figure 1 Schematic of (A) The normal collector and (B) The novel solar collector integrated PCM

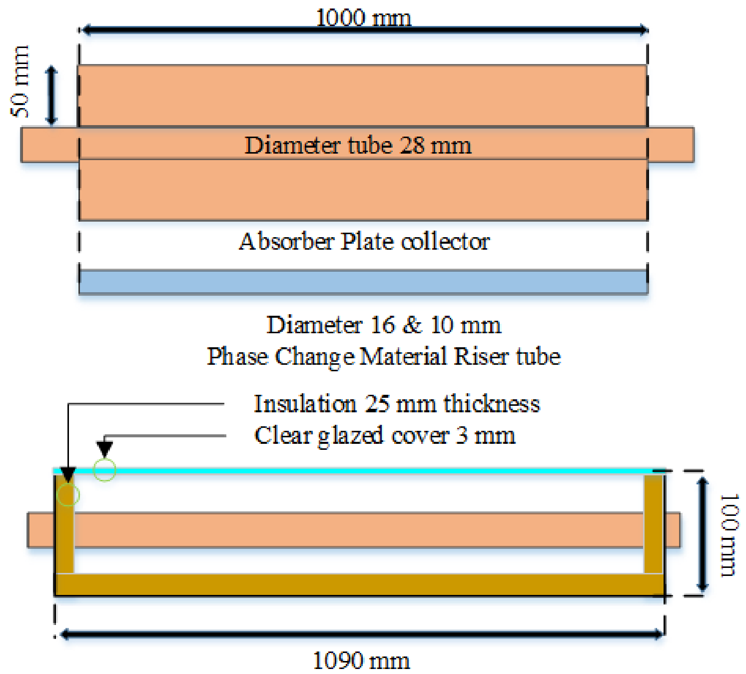

Figure 2 Absorber plate and PCM riser with measure points both novel and conventional solar collector

3.2 Experimental procedure

The experiment divided in three case studies for example, testing with 16 mm of riser diameter (called PCM 1), 10 mm of diameter (called PCM 2) and without PCM riser and was undertaken at the School of Renewable Energy, Maejo University, Chiang Mai, Thailand. All of collectors were installed at 18^{o} of tilt angle facing to the south as shown in

Figure **3**. The water flow rate was circulated through the system by the electrical pump. Each solar collector had own 11 kg of water storage tank with a resistance heater and stored water circulating that collected heat gain from the collector. The mass flow rate was measured by the manual flow meter (Platon), installed the gauge valve to regulate the mass flow rate of water in solar collector system and the bypass valve was used to reduce overload from overpressure in system.

The experiment method was conducted following ASHRAE standard 93-2003 (Polvongsri, 2013) to find out the thermal performance of solar collector. All of parameters, for example, the solar radiation, the ambient temperature, the inlet water temperature, and the outlet water temperature, were set following ASHRAE standard and the mass flow rate of working fluid is adjusted under steady state condition. The resistance heater used to modify the range inlet temperature from 35 ℃ to 65 ℃ during testing. Before doing experiment, the set temperature was pumped with a small pump into the storage tank runs in 5 minutes to make sure the water was stable. While testing, the hot water from solar collector is going through to the storage tank which was collected thermal energy. It made hot water remained on the top of the tank while the bottom still remains the set-inlet temperature even though the temperature water in the storage tank changed as a small value which could be accepted as following to the standard (± Max of (0.1 ℃, 2%)). The type K thermocouple was used to measure the temperature parameters and recorded in the multi channels data logger (Model Lutron, TD-1947 SD). The total solar radiation at a tilt angle of the solar collector was measured by pyranometer (Model Apogee, SP-110) and recorded in data logger (Model Adam 5000 PBC). The error of each instruments was calibrated independently after the experimental data collection.

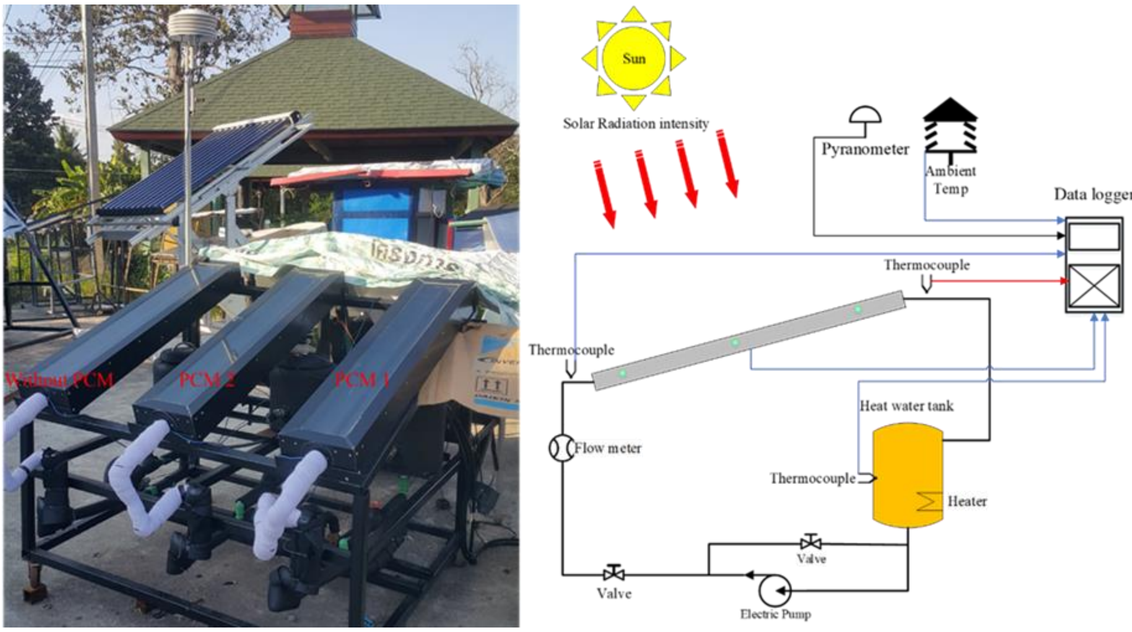

Figure 3 The novel solar collectors integrated with PCM and Conventional collector installation

3.3 Analysis

The data measurement of ambient temperature, inlet water temperature, outlet water temperature, water temperature of storage tank, solar radiation, and mass flow rate would be used to calculate thermal efficiency of solar collector as following Eq.(1) to Eq.(3). The collected heat gained for the solar is calculated by Eq.(1) (Duffie & Beckman, 2013).

$$\dot{Q} = \dot{m}C_p\left(T_o - T_i\right) \tag{1}$$

The Eq.(1) is definition of the collected ability of all kind solar collector which gave the energy output of the collected heat gain $\dot{Q}$, with the mass flow rate through the collector $\dot{m}$, following the temperature of the water before flow through the inside and after leave the collector to the storage tank T_i and T_o. The specific heat of the water as working fluid C_p.

The thermal efficiency of solar collector can be determined as following Eq.(2) and Eq.(3) (Duffie & Beckman, 2013; Polvongsri, 2013).

$$\eta = \frac{\dot{m}c_p\left(T_o - T_i\right)}{I_T A_C} \tag{2}$$

$$\eta = F_R\left(\tau\alpha\right)_e - F_R U_L \frac{\left(T_i - T_a\right)}{I_T} \tag{3}$$

The thermal efficient of the solar collector in Eq.(2) could calculate the collector energy gain as energy output or collected energy of collector and the solar radiation I_T with the collector area A_c as the energy input. In Eq.(3), the thermal efficiency is presented at linear equation relation. The linear equation will result when the efficiencies are obtained from averaged data plated against $(T_i\text{-}T_a)/I_T$ according to Eq.(3). The intersection of the Y-axis is equal to $F_R(\tau\alpha)_e$, and on this axis, the temperature of working fluid entering the collector is nearly the means ambient temperature that the collector efficiency is nearly a maximum value. Therefore, the slope of the linear equation is equal to F_RU_L. This slope indicates that heat loss has been removed from the solar collector that nominated as removed energy parameter. At the intersection of X-axis, the collector efficiency is equal to zero and this point normally called stagnation which usually occurs when there is no fluid flows in the collector.

4. Results and Discussion

4.1 Thermal efficiency of collector

The experimental conditions were set as followed ASHRAE standard 93-2003 (Polvongsri, 2013) which are, the solar radiation intensity is equal or more than 790 W/m^2 and the air velocity set from 2.2-4.4 m/s. The two novel collectors with PCM riser and conventional collector without PCM were tested with various mass flow rate 0.01, 0.02 and 0.03 kg/s·m^2 and the inlet water temperatures were varied at 35, 40, 45, 50, 55, 60, 65 ℃, respectively.

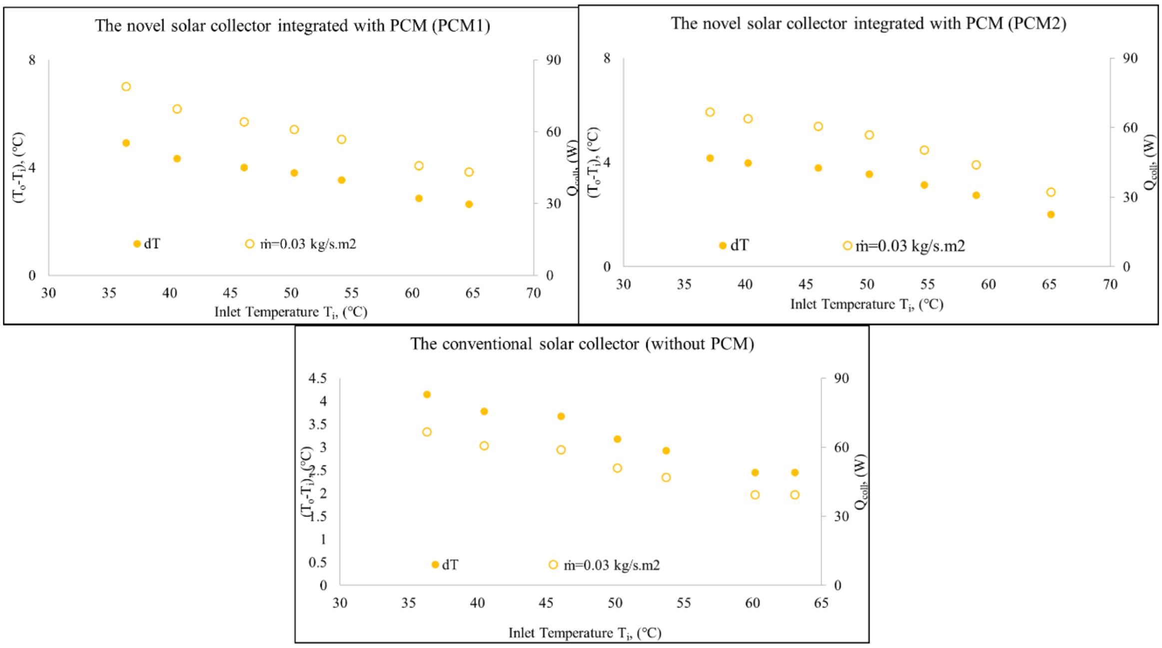

Figure 4 The temperature difference of (T_o-T_i) and collected heat gain from novel solar collector with PCM 1, PCM 2, and the conventional collector without PCM

The temperature difference of (T_o-T_i) and collected heat gain Q_{coll} of novel collector PCM1, PCM2 and without PCM is shown in Figure 4. The results found that in the case of PCM1, PCM2 and without PCM showed the temperature difference between the outlet water temperature and inlet water temperature would give the maximum value to the minimum value at the mass flow rate of 0.01, 0.02 and 0.03 kg/s·m^2, respectively, because the high mass flow rate could gather heat gain of collector more than low mass flow rate. Therefore, the temperature difference (T_o-T_i) was different less than the operation at the higher mass flow rate. Moreover, the temperature difference (T_o-T_i) was changed following to the temperature setting from 35-65 ℃ with the low inlet water temperature through to the solar collector that could collected high thermal energy with less thermal loss. When the inlet water temperature (T_i) increased, the efficiency of the solar collector was decreased because of the large amount of heat that was loosening to the low ambient temperature. At the mass flow rate at 0.01 kg/s·m^2, the temperature differences of (T_o-T_i) PCM 1, PCM 2, and without PCM were 10.1-4.2 ℃, 9.2-4.1℃ and 8.5-3.2 ℃, respectively. At the mass flow rate of 0.02 kg/s·m^2 was 6.1-2.5 ℃, 6.2-2.8 ℃ and 5.5-2 ℃ and the mass flow rate of 0.03 kg/s.m^2 obtained 4.9-4.6 ℃, 4.2-2.1℃ and 4.2-2.4℃, respectively.

The amount of collected heat gain (Q_{coll}) was decreased following the arrangement of inlet water temperature while the high mass flow rate was given a high amount of thermal energy. Otherwise, the collected heat gain (Q_{coll}) was showed that the PCM 1 and without PCM case study were given the highest thermal energy at the mass flow rate of 0.03 kg/s·m^2 while the PCM 2 demonstrated that the mass flow rate of 0.02 kg/s□m^2 gave the highest thermal energy. The various flow rates (0.01, 0.02 and 0.03 kg/s·m^2) given by the Q_{coll} were 78.6-42.5 W, 67.5-26.8 W and 70.6-29.5 W of the PCM 1. In the case of PCM 2 gave 65.7-32.1 W, 69.3-32.4 W and 64.3-28.6 W and finally in the case of without PCM gave 67.4-38.5 W, 60-21.8 W, and 58-22.4 W, respectively.

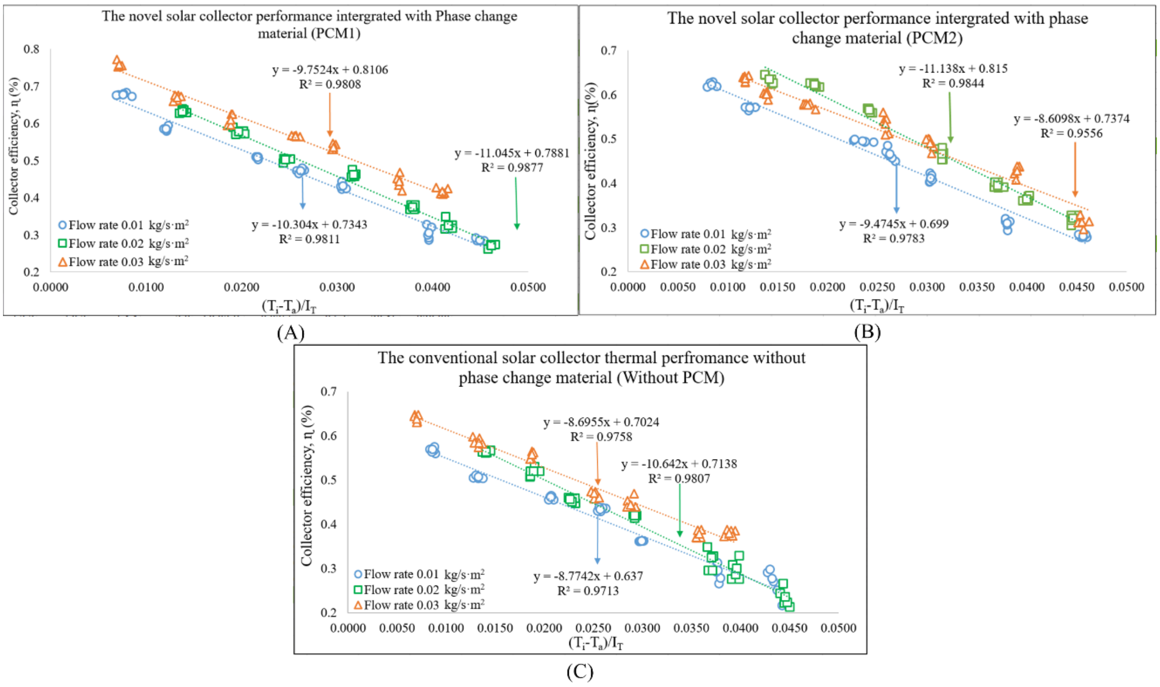

Figure 5 The thermal efficiency of novel solar collector with (A), PCM 1,(B) PCM 2, and (C) conventional collector without PCM

Table 1 The thermal performance analysis data of each collectors

PCM 1 (The novel solar collector integrated with riser phase change materials 16 mm of diameter)			
Category	$F_R(\tau\alpha)_e$	F_RU_L	R^2
Flow rate 0.01 kg/s·m^2	0.734	10.30	0.981
Flow rate 0.02 kg/s·m^2	0.788	11.05	0.987
Flow rate 0.03 kg/s·m^2	0.811	9.752	0.981
PCM 2 (The novel solar collector integrated with riser phase change materials 10 mm of diameter)			
Category	$F_R(\tau\alpha)_e$	F_RU_L	R^2
Flow rate 0.01 kg/s□m^2	0.699	9.474	0.978
Flow rate 0.02 kg/s□m^2	0.815	11.14	0.984
Flow rate 0.03 kg/s□m^2	0.737	8.609	0.956
Without PCM (The conventional flat-plated solar collector)			
Category	$F_R(\tau\alpha)_e$	F_RU_L	
Flow rate 0.01 kg/s□m^2	0.637	8.774	0.97
Flow rate 0.02 kg/s□m^2	0.714	10.642	0.98
Flow rate 0.03 kg/s□m^2	0.702	8.695	0.97

Figure 5 showed that the thermal efficiency of various mass flow rate 0.01, 0.02, 0.03 kg/s□m^2 of novel solar collector integrated with phase change material and conventional collector. The results are represented by the linear regression function between $(T_i-T_a)/I_T$ and thermal efficiency (η). The mass flow rate of the $F_R(\tau\alpha)_e$ in each case were performed on the intersection of Y-axis representing the maximum efficiency and the slope of the equation as the heat loss to environment by following the Eq.(3). The novel solar collector integrated with PCM of riser tube 16 mm outside diameter (PCM1) was given the value $F_R(\tau\alpha)_e$ of 0.734, 0.788 and 0.811, and heat loss F_RU_L of 10.30, 11.05 and 9.75 W/m^2·K by testing various flow rates was showed in Table 1 (PCM1). The novel collector PCM1 tested with mass flow rate at 0.03 kg/s□m^2 is given a highest thermal performance with $F_R(\tau\alpha)_e$ of 0.811 and F_RU_L of 9.75 W/m^2·K.

The novel solar collector integrated with PCM of riser tube 10 mm outside diameter (PCM2) was given the value $F_R(\tau\alpha)_e$ of 0.699, 0.815 and 0.737 and heat loss F_RU_L of 9.474, 11.14 and 8.609 W/m^2·K, respectively, by testing various flow rates was showed in Table 1 (PCM2). The novel collector PCM1 tested with mass flow rate at 0.02 kg/s□m^2 is given a highest thermal performance with $F_R(\tau\alpha)_e$ of 0.815 and F_RU_L of 11.14 W/m^2·K, respectively.

The conventional solar collector without PCM (without PCM) was given the value $F_R(\tau\alpha)_e$ of 0.637, 0.714 and 0.702 and heat loss F_RU_L of 8.774, 10.642 and 8.695 W/m^2·K, respectively, by testing various flow rates was showed in Table 1 (without PCM). The conventional collector tested with mass flow rate at 0.02 kg/s□m^2 is given a highest thermal performance with $F_R(\tau\alpha)_e$ of 0.714 and F_RU_L of 10.642 W/m^2·K, respectively.

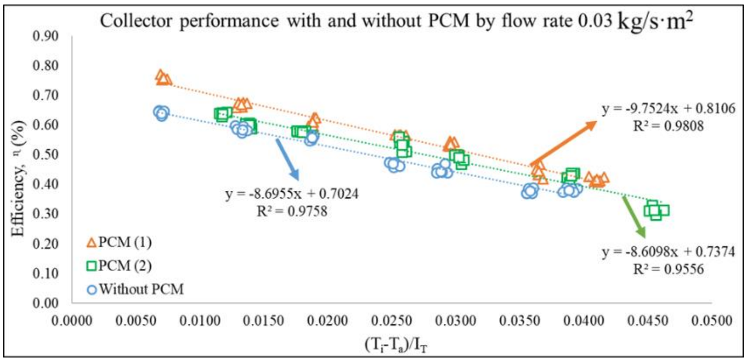

Figure 6 The thermal efficiency of all case studies at the mass flow rate of 0.03 kg/s□m^2

Figure 6 shows the collector efficiency at 0.03 kg/s□m^2 of novel and conventional solar collectors. The result of the experiment confirmed that the both prototype novel solar collectors were given the greater thermal efficiency than the conventional collector. The best mass flow arte was selected at 0.03 kg/s□m^2 which the novel collector PCM 1 was given the highest thermal efficiency than other cases in the Table 1.

4.2 Daily system operation

The novel solar collectors and the conventional collector were experimented for analysis system operation since 8:30 a.m. to 03:00 p.m. under clear sky day condition. The system operated at the best mass flow rate of 0.03 kg/s□m^2 and circulated the water from the 10-liter storage tank to the collector. The results in Figure 7 and Figure 8 showed that the storage tank with initial temperature (T_s) was about 25 ℃ and when the solar radiation (I_T) increased, the storage tank temperature was raised continuously following the variation of solar radiation. The maximum solar radiation was around 830 W/m^2 at 12:30 PM, the temperature T_s of storage tank were increased to 45, 46, and 44 ℃, respectively. The PCM 1 was collected more thermal energy than other collectors until the end of the operating at 3:00 p.m. which the storage tank temperature was 55 ℃ while PCM 2 and without PCM was 53 ℃ and 51℃, respectively.

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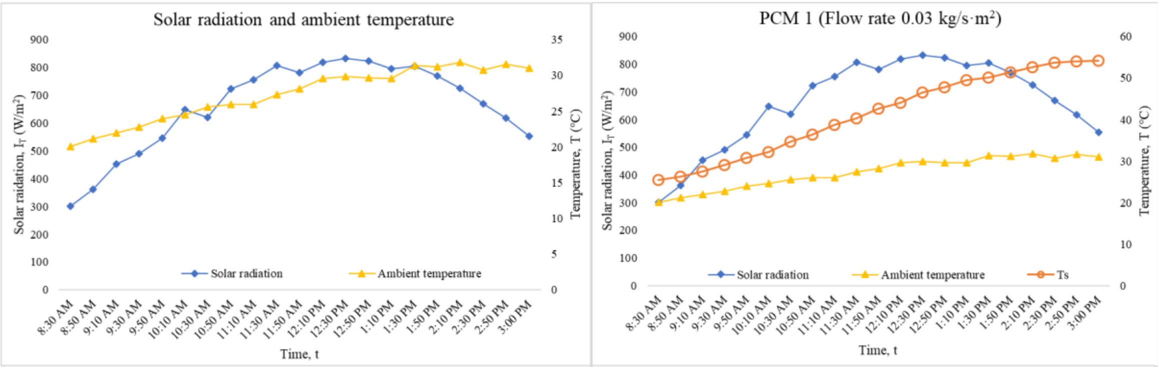

Figure 7 Solar radiation, ambient temperature and the result of daily system operation of novel solar collectors (PCM 1) of the mass flow rate of 0.03 kg/s□m^2

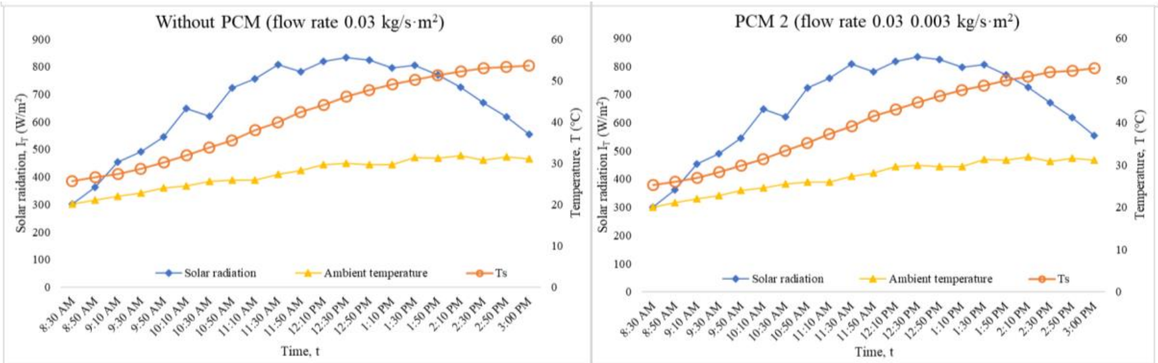

Figure 8 The result of daily system operation of novel solar collectors (PCM 2) of the mass flow rate of 0.03 kg/s□m^2

5. Conclusion

The novel solar collectors that integrated with the phase change materials riser of 16 mm diameter (PCM 1) and 10 mm diameter (PCM2) were experimented comparing the conventional solar collector without PCM riser. The thermal performance testing was conducted following by ASHRAE standard 93-2003. The discovered results showed that both of the novel solar collectors were given the thermal performance greater than the collector without PCM riser. The novel solar collector with 16 mm diameter of riser (PCM 1) represented the suitable $F_R(\tau\alpha)_e$ and F_RU_L which were 0.811 and 9.753 (W/m^2□K) at 0.03 kg/s□m^2, and then was followed as 0.01 kg/s□m^2 and 0.02 kg/s□m^2, respectively. The novel solar collector integrated with phase change material RT42 (melting point between 38 to 43 ℃) is $14.76 per kilogram (Australia Dollar) which was used in the experimental study.

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