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Efficiency improvement of a concentrated solar receiver for water heating system using porous medium

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Abstract. This experimental study aims at investigating on the performance of a high temperature solar water heating system. To approach the high temperature, a porous-medium concentrated solar collector equipped with a focused solar heliostat were proposed. The proposed system comprised of two parts: a 0.7x0.7-m^2 porous medium receiver, was installed on a 3-m tower, and a focused multi-flat-mirror solar heliostat with 25-m^2 aperture area. The porous medium used in this study was the metal swarf or metal waste from lathing process. To know how the system efficiency could be improved by using such porous medium, the proposed system with- and without-porous medium were tested and the comparative study was performed. The experimental results show that, using porous medium for enhancing the heat transfer mechanism, the system thermal efficiency was increased about 25%. It can be concluded that the efficiency of the proposed system can be substantially improved by using the porous medium.

1. Introduction

Nowadays, solar energy plays a tremendous role as the most powerful renewable energy source for a sustainable developments. It is the biggest energy resources and can be said that every hour, solar energy reaches the earth is enough for the world's energy demand for a whole year. Among the applications of solar thermal energy, solar water heating and solar air heating systems (SWHS and SAHS) are impressive in their beneficial manner [1]. Owing to it is a renewable energy based system and can be possibly developed for a high efficiency environmental friendly system, such system is vital and should be encouraged for overcoming the energy and environmental issues [2, 3].

The literatures reported that the total energy consumption for heating water in many countries around the world is ranging from 18 to 23% [1]. There are many applications of SWHS, e.g.: air conditioning (heating and cooling), washing, drying, and distillation, etc. Almost all of the SWHSs are comprised of a solar thermal collector. In terms of the solar collector of SWHS, it is designed to fulfill the required temperature as per the local climatic conditions. Actually, when the high temperature is required, the concentrated solar collector is taken into consideration. There are many types of concentrating collector, e.g.: flat plate collector equipped with tilted plate reflectors, parabolic trough, parabolic dish and central receiver, etc.

The thermal performance of the solar collectors mainly depend on the useful energy produced from the collector, this mainly depends on the collector's heat removal factor (F_R) and overall heat loss coefficient (U_L). To improve the efficiency of solar collector, by enhancing the heat removal factor and reducing heat loss, the application of porous medium (PM) was proposed for this current study.

From the literature and previous works, it can be summarized that no one performed in which porous medium (PM) is used for improving the performance of the SWHS [1, 4]. Moreover, the literatures also reveal that there is no one proposed in which the solar heliostat and tower receiver are used as a SWHS. Therefore, it was proposed in this study with the aim to investigate on the performance of a PM concentrated solar collector (PMCSC) of a small scale high temperature water heating system.

2. Experimental setup

Figure 1 shows the schematic diagram of the forced circulation PMCSC. It was setup at latitude of 14.03N and longitude of 100.72E. This system consists of two main components, a PM tower receiver and a focused solar-heliostat as shown in figure 2 and 3, respectively. The tower receiver was located in the south of heliostat with the distance of 20 m. The center of tower receiver and heliostat are on the same horizontal level at 3 m from the ground level.

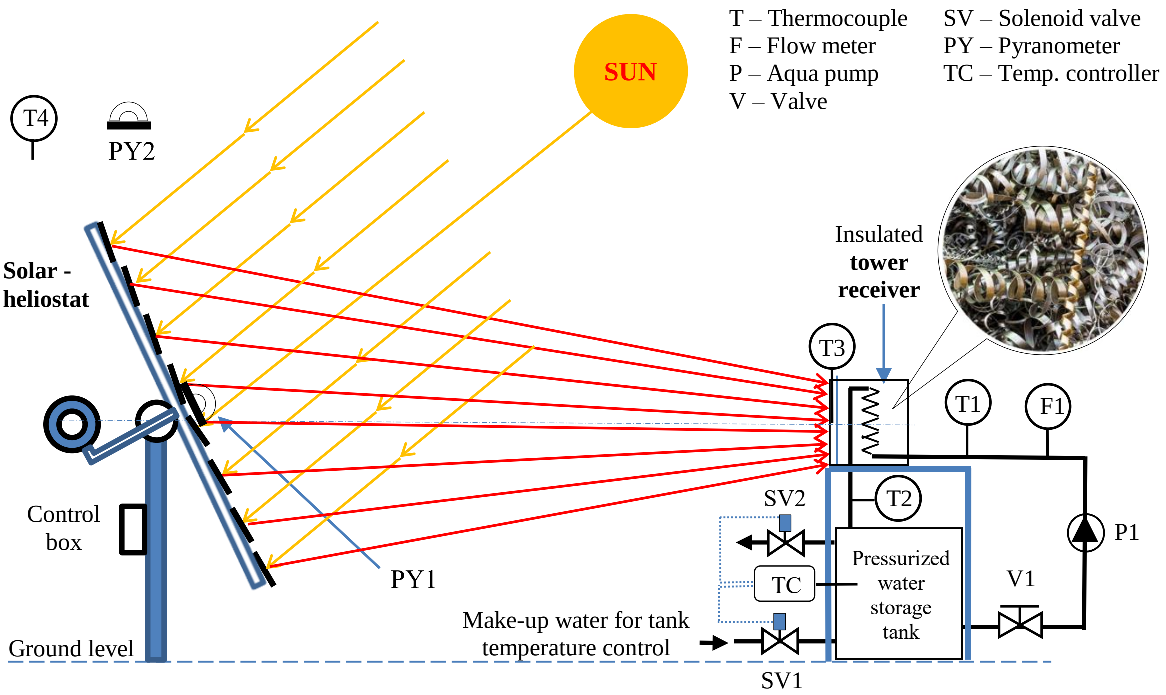

Figure 1. Schematic diagram of the forced circulation PMCSC system used in this study.

Figure 2 shows a 5x5-m^2 focused solar heliostat used in this study. It was fabricated by using the local low-cost materials. Regarding this low investment cost, it may be attractive or suitable for some small enterprises of heat process applications, such as: cooking, cooling (via absorption or adsorption refrigeration cycles), heating, drying, etc. The working principle and control system of this heliostat were described as in [5-7]. The aperture area of this current heliostat was bigger than two times of the previous one. The solar radiation strike on this heliostat would be redirected to the tower receiver via 289-plate of flat fixed mirrors. Each plate has 0.3x0.3-m^2 and was individually attached on an adjustable mounting set, so the desired tilting angle can be achieved with more flexibility. With this configuration, this tracking solar thermal system cloud be fabricated by using lighter and simpler structure, compared with the parabolic dish system. The focus of the heliostat was adjusted under the real solar radiation during 1 to 2 hours before and after solar noon.

Figure 3 shows a 0.7x0.7x0.7-m^3 insulated solar tower receiver. It has multi U-tube bundle with common inlet and outlet headers. A single glass cover was used to reduce the losses of the solar collector. Water was supplied to the receiver via an aqua pump (P1). The porous medium (as shown in figure 1) was fully filled in the receiver box.

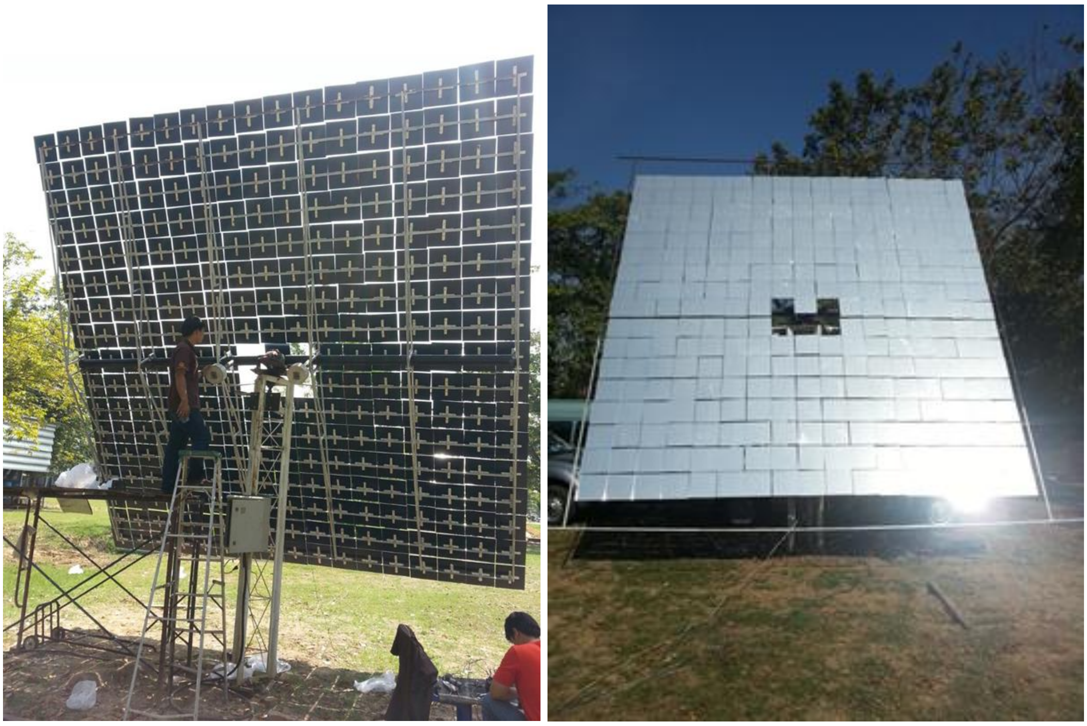

Figure 2. The focused multi-flat-mirror solar heliostat used in this study.

Figure 3. Photos of insulated solar tower receiver used in this study.

The temperatures of water and air at different locations (as shown in figure 1) were measured with K-type thermocouples. The flow rate was recorded on hourly basis. Radiation data included global horizontal radiation (PY2) and global horizontal radiation on tilted surface (on heliostat, PY1) were also measured and recorded. All temperature and solar radiation measurements were recorded using a data logger (Datataker model DT605) at 1-minute intervals.

The flow rate of water was manually controlled by a flow control valve (V1). During the test, the hot water was drawn off at the bottom of the pressurized water storage tank. A pump circulated water through the U-tube bundle of the tower receiver. To avoid the water evaporation under atmospheric pressure, the water temperature at the middle level of the tank was controlled at about 60 °C by means of draining hot water at the top and filling the make-up water at the bottom of the tank.

The comparative study was conducted to compare two different cases of study, with- and without-PM in order to find the most efficient one. The PM used in this study was the waste metal scrap or swarf from the lathing process. The experiments were conducted at the time from 9am to 4pm. During the test, the water mass flow rate was fixed at 0.04 kg/s. Thus, to maintain this value, the water flow rate was measured and manually adjusted every half an hour.

3. Evaluation of system performance

The steady conditions of the ASHRAE 93-1986 solar flat plate collector test standard [9] was conducted for this current study with steady state conditions, at steady radiation conditions, steady fluid flow, constant inlet temperature, and constant ambient conditions, are chosen for the analysis. The collector outlet water temperature is also constant. The useful energy gain ($\dot{Q}_u$) from the solar collector and collector efficiency (η_c) during the steady state condition were then estimated as [8]:

$$\dot{Q}_u = \dot{m}c_p\left(T_{c,o} - T_{c,i}\right) \tag{1}$$

and

$$\eta_c = \dot{Q}_u / A_c G_T \tag{2}$$

The tests were conducted on clear sky days when high quantity of the solar beam radiation and the collector surface is closely normal to the direct ray. The expression for determine the useful energy could be written as [8],

$$\dot{Q}_u = A_c F_R\left[G_T(\tau\alpha) - U_L\left(T_{c,i} - T_a\right)\right] \tag{3}$$

Substituting equation (3) into equation (2), gives,

$$\eta_c = F_R(\tau\alpha) - \left[F_R U_L\left(T_{c,i} - T_a\right)\right] / G_T \tag{4}$$

where, F_R is the collector heat removal factor
$(\tau\alpha)$ is the collector transmittance-absorptance product
U_L is the overall heat loss coefficient
C_p is the specific heat of water.

4. Experimental results and discussions

The experimental system of forced circulation PMCSC system was operated during winter season (18 February to 11 March 2017). The water volume flow rate was fixed at 0.04 l/s, this value was controled by manually adjusting the inlet air damper actuator of the blower every half an hour. The weather data of testing days and experimental data are shown in figure 4. The daily incident solar radiation during these days varied in the range of 18 to 21 MJ/m^2-day.

It should be noted that only data that consistent to the test standard was choosen for the performance anlaysis in the next sections. The steady state conditions during 5 minutes interval must be [9]:

- Solar radiation : >790 W/m²; ±32 W/m²
- Inlet water temperature : ±1 °C
- Water flow rate : ±1.1 lite/hr
- Ambient temperature : ±1.5 °C

4.1 The tower receiver without-porous medium

Figure 4 shows the average ambient temperature and total instantaneous solar radiation when the tower receiver without porous medium was conducted.

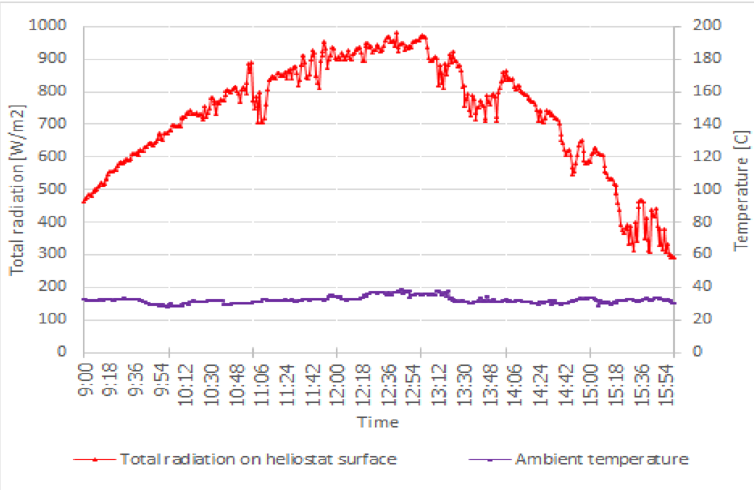

Figure 4. Ambient temperature and total solar radiation (case: without PM).

Figure 5 shows the hot water temperature as a function of solar irradiance during the steady state condition, when the tower receiver without porous medium was tested. The graph shows that the temperature of the hot water produced from the tower collector during the steady state condition varied in the range about 80 to 130°C with the average of about 114°C. This temperature can be reached this level when the total solar irradiance incident on the heliostat should be in the range of 800 to 950 W/m^2 with pressurized circulation system.

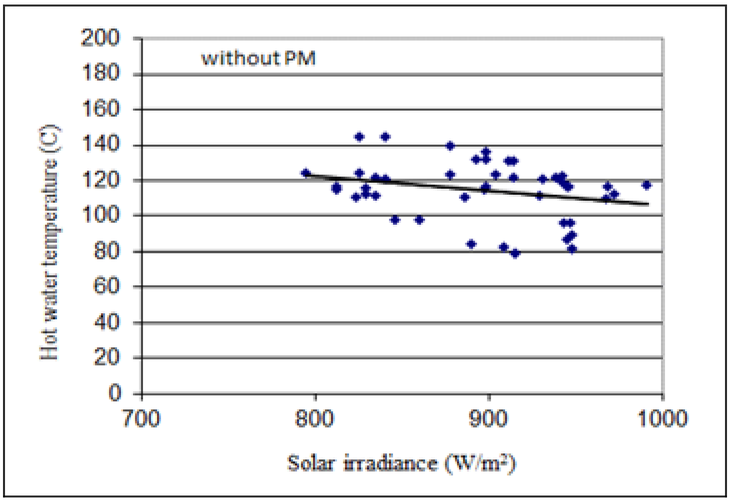

Figure 5. Hot water temperature as a function of solar irradiance (case: without PM).

Figure 6 shows the influence of solar irradiance on the useful heat output (calculated as equation (1)) during the steady state condition. The experimental results show that with the 25m^2 heliostat, the proposed system without porous medium can produce the hot water with heat output rate about 9 kW when the solar irradiance is about 800 to 950 W/m^2.

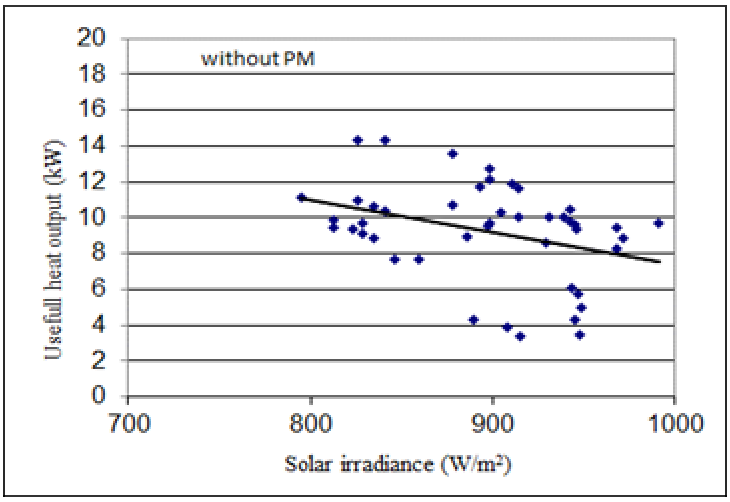

Figure 6. Useful heat output as a function of solar irradiance (case: without PM).

The most important performance index is overall system efficiency. Figure 7 shows the efficiency data of the proposed system without the porous medium. The vertical axis shows efficiencies during steady state condition, determined from equation (2). It can be seen that the average efficiency of about 42% can be obtained.

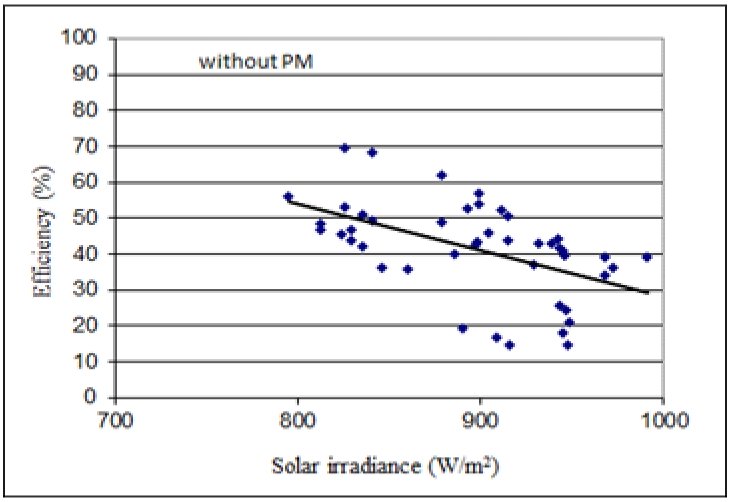

Figure 7. Overall efficiency as a function of solar irradiance (case: without PM).

4.2 The tower receiver with-porous medium

Figure 8 shows the average ambient temperature and total instantaneous solar radiation when the porous medium was used for performance improvement of the proposed PMCSC.

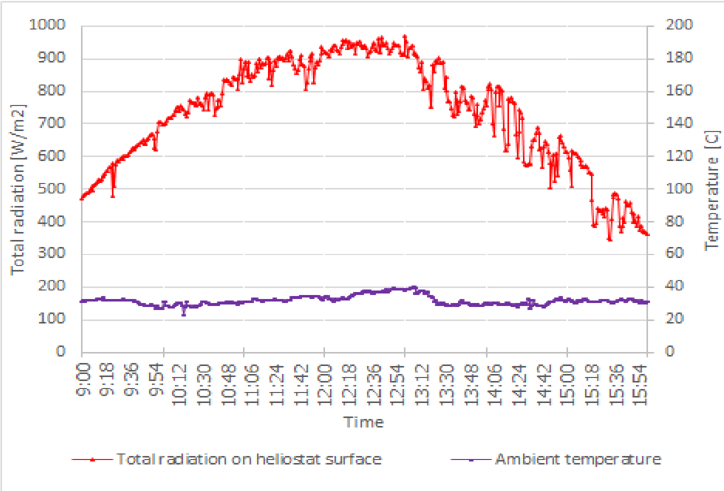

Figure 8. Ambient temperature and total solar radiation (case: with PM).

Figure 9 shows the hot water temperature as a function of solar irradiance during the steady state condition, when the PM was used for enhancing the heat transfer effectiveness of the tower receiver. The graph shows that the temperatures of the hot water produced from the tower collector during the steady state condition were higher than the case of without-PM and they varied in the range about 100 to 140 °C. This temperature can be reached this range when the total solar irradiance incident on the heliostat should be in the range of 800 to 950 W/m^2 with pressurized circulation system.

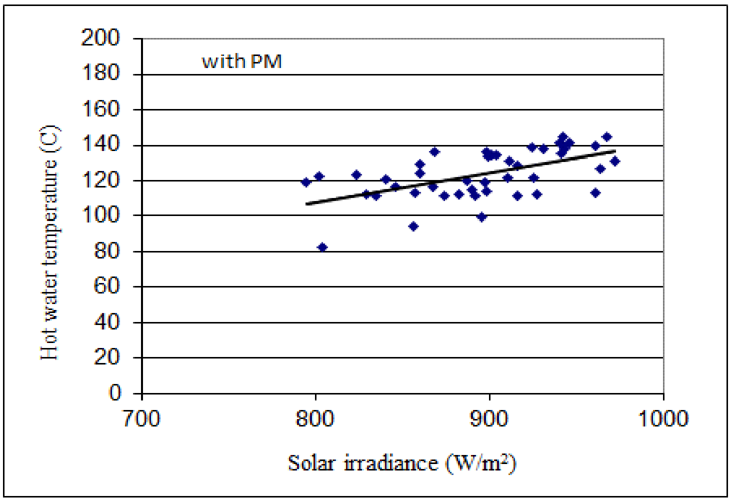

Figure 9. Hot water temperature as a function of solar irradiance (case: with PM).

Figure 10 shows the influence of solar irradiance on the useful heat output of PMCSC (calculated as equation (1)) during the steady state condition. The experimental results show that with the 25m^2 heliostat, the proposed system with porous medium can produce the hot water with heat output rate about 11 kW when the solar irradiance is about 800 to 950 W/m^2.

Figure 11 shows the efficiency data of the proposed PMCSC system. The vertical axis shows efficiencies during steady state condition, determined from equation (2). It can be seen that the average efficiency of about 52% can be obtained.

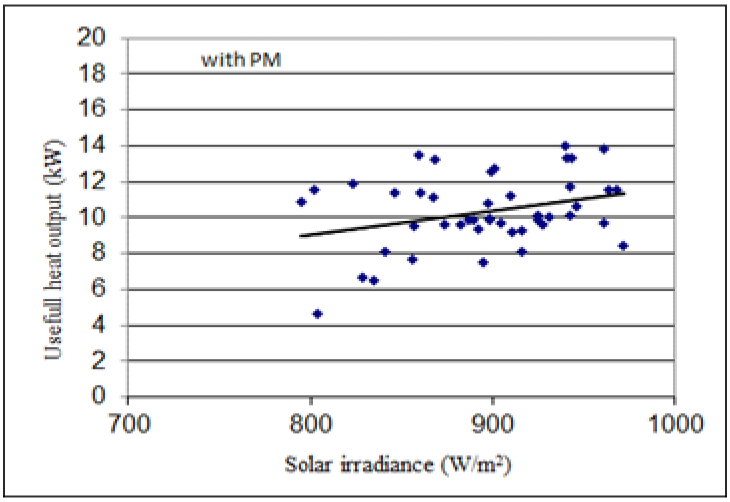

Figure 10. Useful heat output as a function of solar irradiance (case: with PM).

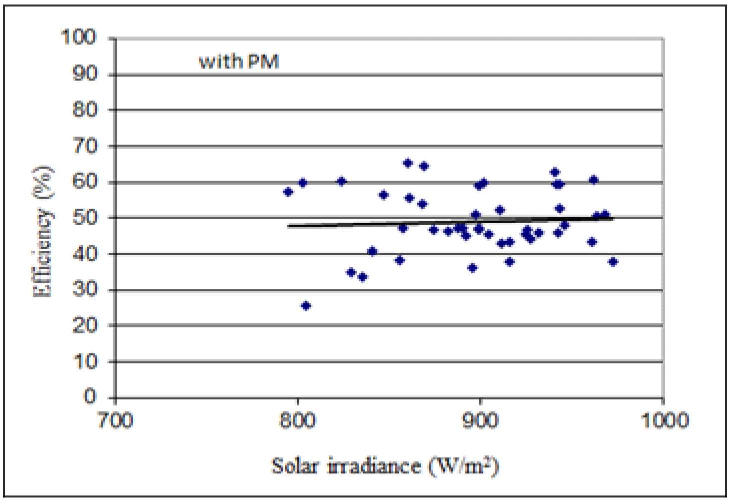

Figure 11. Overall efficiency as a function of solar irradiance (case: with PM).

4.3 Comparison between the receiver with- and without-porous medium

From the experimental results analysis of chosen steady state data, it was found that the performance of the proposed system can be improved significantly by using the porous medium. The different of two cases of study: with- and without-porous medium was summarized as shown in table 1. At the constant water flow rate, the temperature of hot water produced from the proposed system was increased from 114 to 126°C (increased by about 10%).The overall system efficiency can be increased from 42% to 52% (increased by about 25%).

In addition, as aforesaid about two important parameters, $F_R(\tau\alpha)$ and $F_R U_L$ (as in equation (4)) which are used to describe how the flat plate solar collector efficiently works, are also taken into account for this study. Due to the $F_R(\tau\alpha)$ is an indication of how energy is absorbed and $F_R(\tau\alpha)$ is an indication of how energy is loss. From the experimental result and analysis, in can be summarized that the values of $F_R(\tau\alpha)$ and $F_R U_L$ cannot be used for describing the behaviour of this proposed system, owing to the plot between $[(T_{c,i} - T_a)]/G_T$ and the efficiency (η_c) resulted in negative slope.

Table 1. The differences of average values between two cases of study.

Average data (Figure 4 – 11)	$T_{f,i}$ [°C]	$T_{f,o}$ [°C]	G_T [W/m²]	Ta [°C]	$T_{f,o}$ - $T_{f,i}$ [°C]	Flow rate [kg/s]	Qu [kW]	($T_{f,o}$ - T_a)/G [°C m²/W]	Eff. [%]
Case: w/o PM	59.21	114.43	895.64	33.93	55.23	0.04	9.26	0.09	41.74
Case: w/ PM	63.26	126.37	894.64	33.74	63.11	0.04	11.08	0.1	52.36
Different	**4.05**	**11.94**	**-1.00**	**-0.19**	**7.88**	**0.00**	**1.82**	**0.01**	**10.62**
[%]	**6.84**	**10.43**	**-0.11**	**-0.56**	**14.27**	**0.00**	**19.65**	**11.11**	**25.44**

5. Conclusions

Experimental study was conducted to prove the hypothesis that porous medium can improve the performance of a concentrated solar collector for a high temperature water heating system. Hot water temperature and overall system thermal efficiency were compared between with- and without-porous medium tower receivers at constant controlled variables. The experimental results reveal that, for the proposed system, application of porous medium is promising, the efficiency can be increased about 25%. In addition, due to the porous medium used in this study was the waste material with very low cost. It can be summarized that the substantial efficiency improvement with very low investment cost of the proposed system seem to be a vital measures for addressing the energy issues.

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