

Application of porous medium for efficiency improvement of a concentrated solar air heating system

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Abstract. The objective of this study is to evaluate the thermal efficiency of a concentrated solar collector for a high temperature air heating system. The proposed system consists of a 25-m² focused multi-flat-mirror solar heliostat equipped with a porous medium solar collector/receiver which was installed on the top of a 3-m tower, called 'tower receiver'. To know how the system efficiency could be improved by using porous medium, the proposed system with and without porous medium were tested and the comparative study was performed. The experimental results reveal that, for the proposed system, application of porous medium is promising, the efficiency can be increased about 2 times compared to the conventional one. 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.

1. Introduction

Currently, energy seem to be one of the most essential human needs to survive, all activities need energy. Literature reveals that the energy consumption is growing rapidly in many countries and almost all the energy resources are fossil based energy which will be depleted by the next few ten years. Moreover, all of the energy conversion processes of fossil based energy release poison emission and/or green-house gas (GHG) to the environment. Relevant to the trend of energy consumption and demand, the energy crisis and environmental problems are now become the serious issues for many countries around the world. One of the best ways to simultaneously overcome these serious issues is the utilization of renewable energy together with energy conservation measures [1, 2]. Therefore, as renewable energy becomes a global priority, solar power is an increasingly viable solution to the world's energy demand and environmental issues. From the global trend with projection forecasting, renewables account for a rising share of the world's total electricity supply, the renewable share of world electricity generation grows from 22% in 2012 to 29% in 2040 [3].

Solar energy is the biggest renewable energy resource of the world with the extra-terrestrial irradiance, radiation falls on a unit area normal to the sun in unit time at the top of the earth's atmosphere, with the accepted amount of 1,376 W/m² and it will not run out [4]. The terrestrial solar radiation is different for each locations around the world as the solar insolation map shown in Figure 1. However, due to solar energy can be utilized only during day time, day length is one of the most important parameter for system design and selection. This parameter mainly depends on the latitude and altitude of the site location.



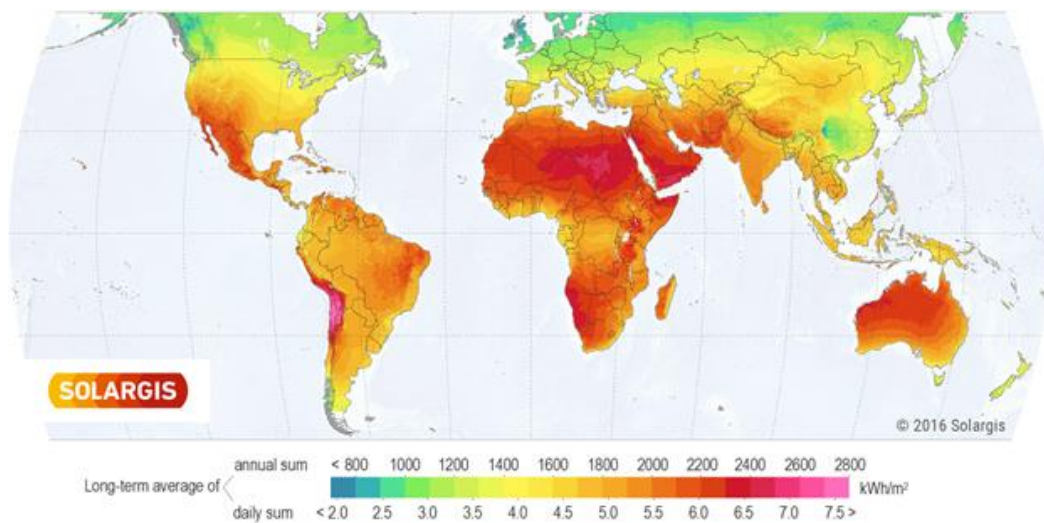


Figure 1. Solar insolation map [6].

Figure 2 shows the amount of solar energy in hours, received each day on an optimally tilted surface during the worst month of the year (based on accumulated worldwide solar insolation data). For every an hour, enough sunlight energy reaches the earth to meet the world's energy demand for a whole year [5]. To reduce the fossil fuel consumption and CO₂ emissions, generating sustainable heat/power from solar, a largest resource and readily available to everyone, can be possibly opted as the best way of above problems mitigation.

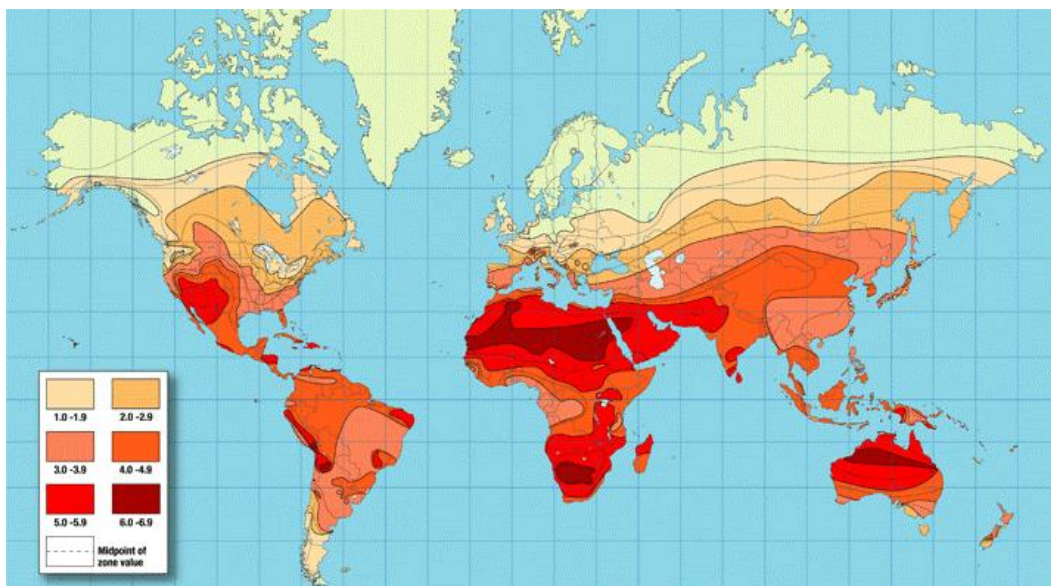


Figure 2. The amount of solar energy in hours [7].

Currently, there are many applications of solar thermal energy, e.g.: domestic and industrial heating and cooling systems, drying, distillation and solar cooking, etc. Solar thermal collector is a device that utilizes the solar radiation to heat a fluid (usually water or air), which can then be used for suitable aforesaid applications. But, when higher output temperatures are required, the concentrated solar collector is taken into consideration. In order to do that, an optical device could be placed between the radiant source and the absorbing surface or receiver. This device that optically reflect and focus incident solar energy onto a smaller receiving area. There are many types of concentrating collector,

e.g.: compound parabolic concentrators (CPC), parabolic trough, parabolic dish and central receiver, etc. Seasonably, the more complex of such systems, the more expensive investment is required.

Like flat plate solar collector, the thermal performance of concentrating collectors depend on the useful energy delivered by 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 literatures review, there are some works regarding the PM solar receiver reported by [8-14]. It can be summarized that they reported the results of theoretical and experiment studies on the PM receiver of the parabolic trough and multi-dish concentrator using liquid as working medium. In addition, the previous work as reported in [15-17] have developed the control system for a solar heliostat positioning by means of the calculation of the real-time sun position to redirect the sun rays for striking it onto the target (called 'tower receiver'). The developed software was implemented with an 11.2-m² solar heliostat. The experimental results demonstrated that the reflection accuracy of the proposed focused multi-flat-mirror solar heliostat was acceptable.

Regarding the aforesaid literature reviews and previous works, there are some research gaps can be contributed from this study: nobody has reported about the performance of the solar collector using PM receiver for air heating system, re-using of metal waste from lathing process (metal swarf) as the porous medium, etc. Moreover, the different of between the receiver of parabolic-trough/multi-dish-concentrator and tower receiver are that the former one was fixed together with the reflector while the later one is on ground supported tower and can carry heavier load. Therefore, the objective of this study was to evaluate the thermal efficiency of a focused multi-flat-mirror solar heliostat equipped with a PM tower receiver for a high temperature air heating system was proposed. To know how the system efficiency could be improved by using porous medium, the proposed system with and without porous medium were tested and the comparative study was performed.

2. Experimental setup

The experimental system, as the schematic diagram shown in Figure 3, was setup at latitude of 14.03N and longitude of 100.72E. This system comprises of two main parts, a PM tower receiver for a high temperature air heating system and a focused multi-flat-mirror solar heliostat as shown in Figure 4 and 5, respectively. The centre of receiver and heliostat are on the same level at 3 m from the ground level. The receiver was located in the south of heliostat with the distance of 20 m.

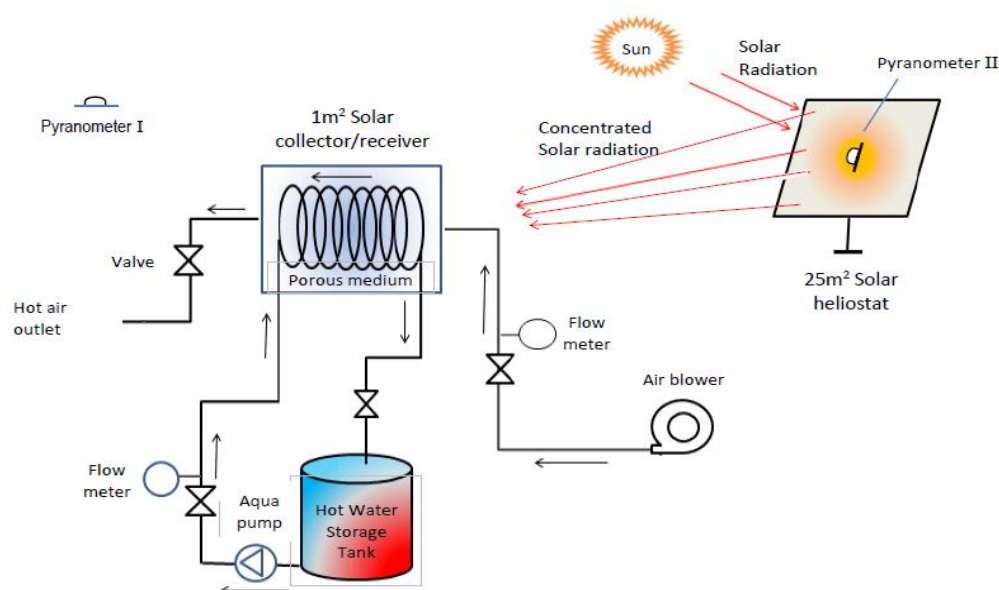


Figure 3. Experimental Setup.

A $0.7 \times 0.7 \times 0.7 \text{ m}^3$ insulated solar tower receiver, as shown in Figure 4 was made of metal sheet. A single glass cover was used to reduce the losses of the solar collector. Air was supplied to the receiver via an adjustable flow rate air blower. The porous medium (as shown in Figure 4 (c)) was fully filled in the receiver box.

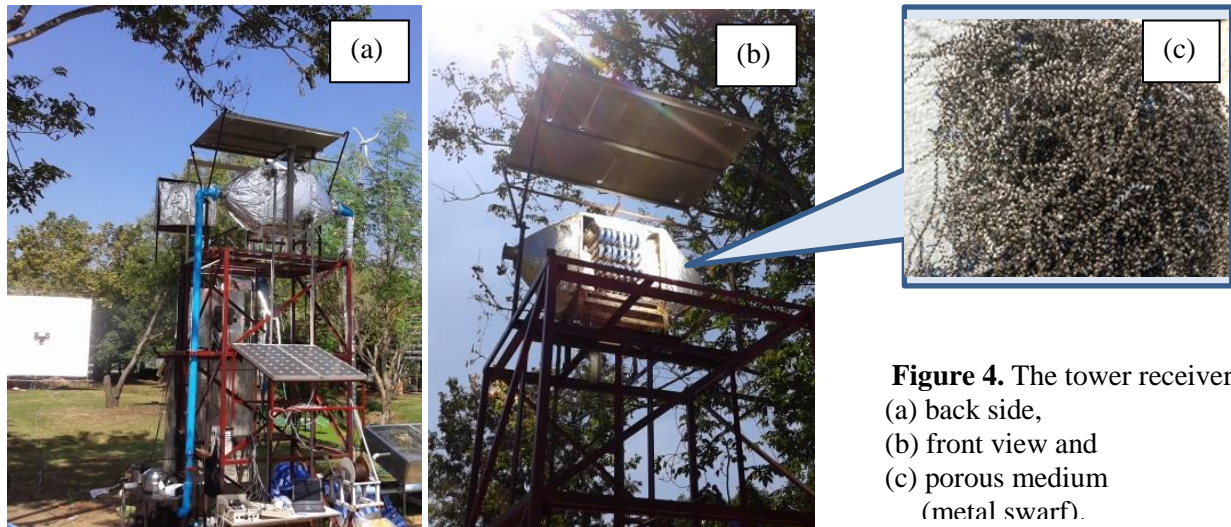


Figure 4. The tower receiver
(a) back side,
(b) front view and
(c) porous medium
(metal swarf).

The $5 \times 5 \text{ m}^2$ focused multi-flat-mirror solar heliostat, as shown in Figure 5, was fabricated by using low cost material available in the market. Its working principle is the same as the system presented by [15–17] but its effective aperture area is bigger. A solar radiation redirection system with a heliostat, 289 flat fixed mirrors, installed on a tower, was proposed. Each $0.3 \times 0.3 \text{ m}^2$ flat mirror are attached on an individual adjustable mounting set, so the desired tilting angle achieves more flexibility. The focus of the heliostat was adjusted under the real solar radiation during 1 to 2 hours before and after solar noon.

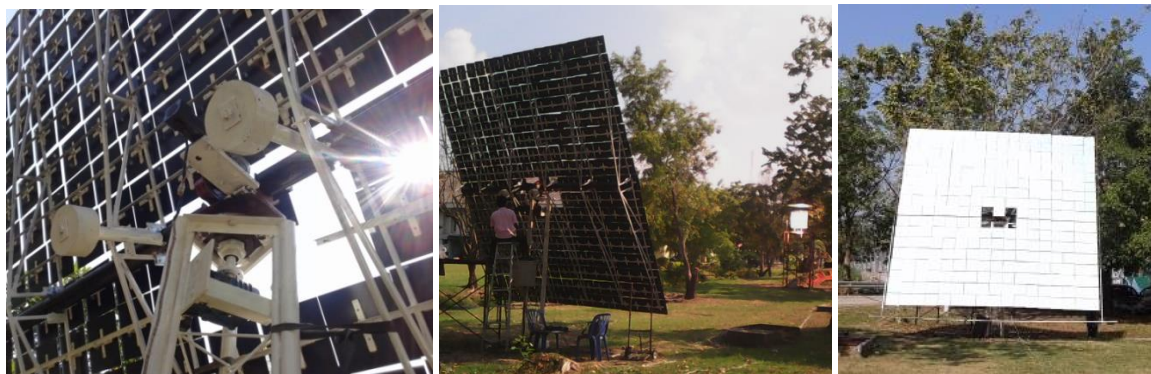


Figure 5. The focused multi-flat-mirror solar heliostat used in this study.

3. Performance evaluation

For evaluating the performance of the proposed system, the experiments were done during 9am to 4pm. The global solar radiation incident on the horizontal and on the heliostat plan were measured using two pyranometers (as shown in Figure 6 (a)). The temperatures of working fluid were measured using K-type thermocouples. The experimental data were collected via a data logger, Graphtec model GL820 (as shown in Figure 6 (b)), with the recording interval of 1 minute.

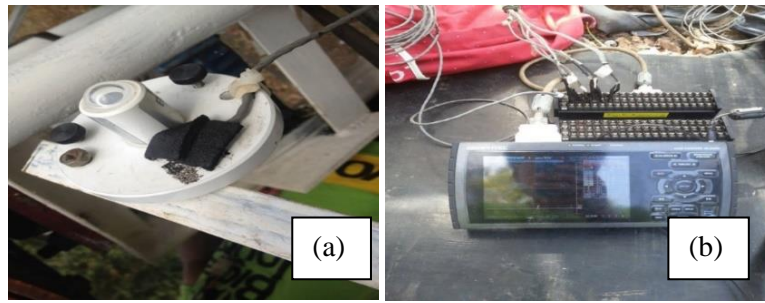


Figure 6. (a) Pyranometer and (b) data logger used in this study.

The ISO 9459-2 [18] was conducted for the performance test of the proposed system. To know the system efficiency, the ratio of useful heat output rate (\dot{Q}_u) to the total input solar energy ($A_c G_T$) was calculated as the following equations [19]:

$$\dot{Q}_u = \rho \dot{V} c_p (T_{c,o} - T_{c,i}) \quad (1)$$

and

$$\eta_c = (\dot{Q}_u / A_c G_T) \times 100\% \quad (2)$$

where,

- \dot{Q}_u = useful heat output rate [W]
- ρ = air density [= 1.127 kg/s]
- \dot{V} = air volume flow rate [m³/s]
- c_p = specific heat of air [= 1.007 kJ /kg.K]
- $T_{c,o}$ = outlet temperature of tower receiver [°C]
- $T_{c,i}$ = inlet temperature of tower receiver r [°C]
- η_c = tower receiver efficiency [-]
- A_c = effective aperture area of solar heliostat [m²]
- G_T = solar irradiance incident on heliostat plane [W/m²]

4. Experimental results and discussions

The experiments were done for more than ten days in January to February 2017, every other day for with- and without-porous medium. The air volume flow rate was fixed at 0.04 m³/s, this value was controlled by manually adjusting the inlet air damper actuator of the blower every half an hour.

4.1. The tower receiver without-porous medium

Figure 7 shows the experimental results when the tower receiver without porous medium was conducted. Figure 7 (a) shows the total solar irradiance and ambient temperature of the clear sky experimental day on January 29, 2017. The data show that the daily average irradiance and ambient temperature were 930 W/m² and 32 °C, respectively. Figure 7 (b) shows the air temperatures at the inlet and outlet and the glass cover of the tower receiver, respectively. The calculated mass flow rate of air was 0.05 kg/s. The average hot air temperature of this day was about 99°C. Figure 7 (c) shows the efficiency of the air heating system without porous medium application, calculated as equation (2). The experimental results demonstrated that the average thermal efficiency of about 12% was obtained.

4.2. The tower receiver with-porous medium

Figure 8 shows the experimental results when the tower receiver without porous medium was conducted. Figure 8 (a) shows the total solar irradiance and ambient temperature of the clear sky experimental day on February 12, 2017. The data show that the daily average irradiance and ambient temperature were 950 W/m² and 32 °C, respectively. Figure 8 (b) shows the air temperatures at the

inlet and outlet and the glass cover of the tower receiver, respectively. With the same air supplied mass flow rate of 0.05 kg/s. The average hot air temperature of this day was about 122°C. Figure 8 (c) shows the efficiency of the air heating system with porous medium application. The experimental results demonstrated that the average thermal efficiency of about 22% was obtained.

From the experimental results, it was found that the performance of the proposed system can be improved significantly by using the porous medium. At the constant air supply mass flow rate of 0.05 kg/s, the thermal efficiency was increased from 99°C to 122°C (increased by 23.23%). The system efficiency can be increased from 12% to 22% (increased by 83.33%). As the information that porous media is a material containing pores typically filled with a fluid (air). Thus, it causes increase in heat transfer in the heat extraction process between solar thermal and air. It exhibit enhanced thermal heat transfer process, such as higher thermal intensity, conductivity, convective heat transfer coefficients and emissivity compared to the conventional single phase process.

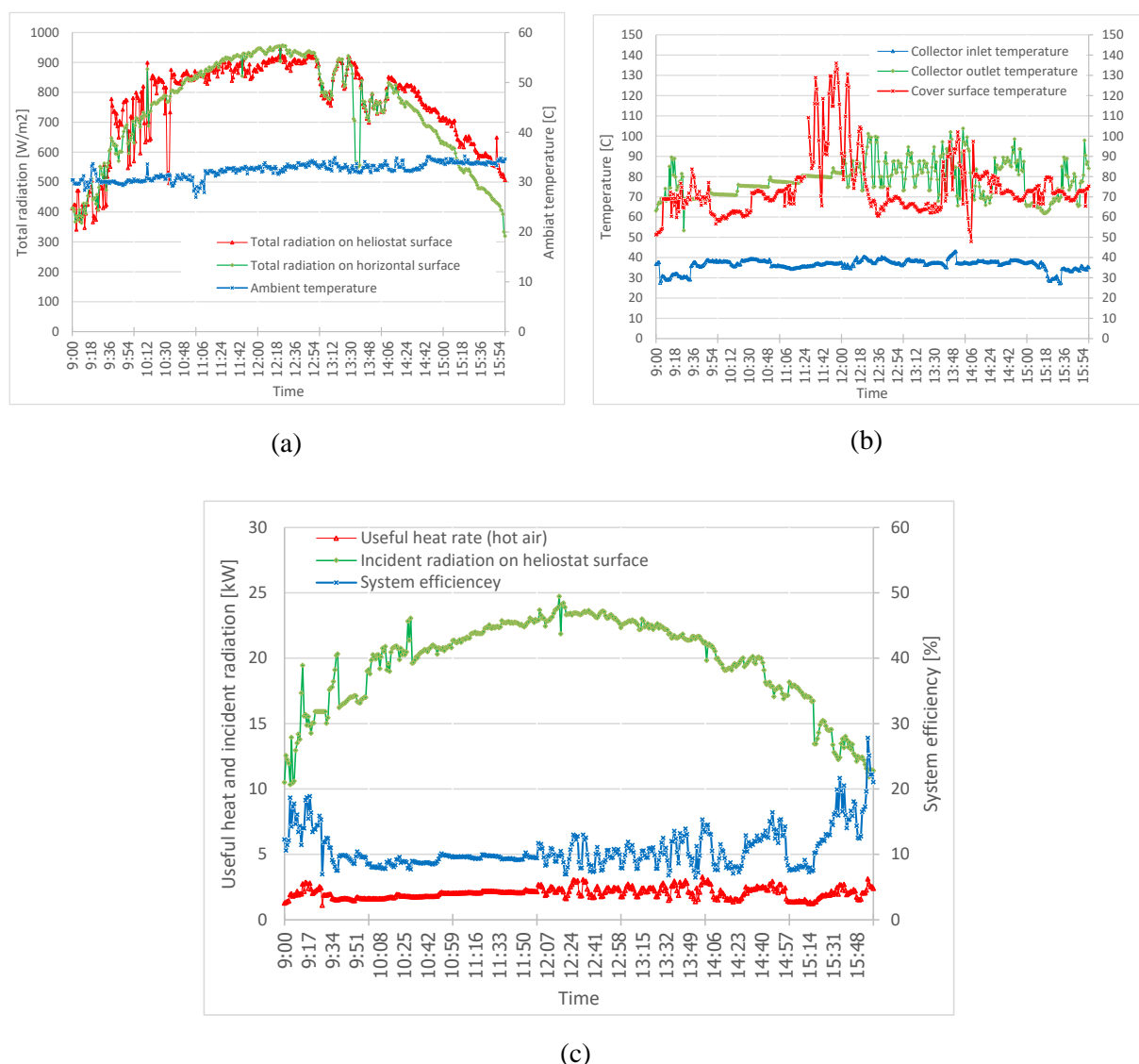


Figure 7. The experimental results when the tower receiver without porous medium was conducted
 (a) total solar irradiance and ambient temperature of the clear sky experimental day
 (b) air temperatures at the inlet and outlet and the glass cover of the tower receiver
 (c) efficiency of the air heating system without porous medium application.

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 air heating system. Hot air temperature and 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 2 times compared to the conventional one. 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.

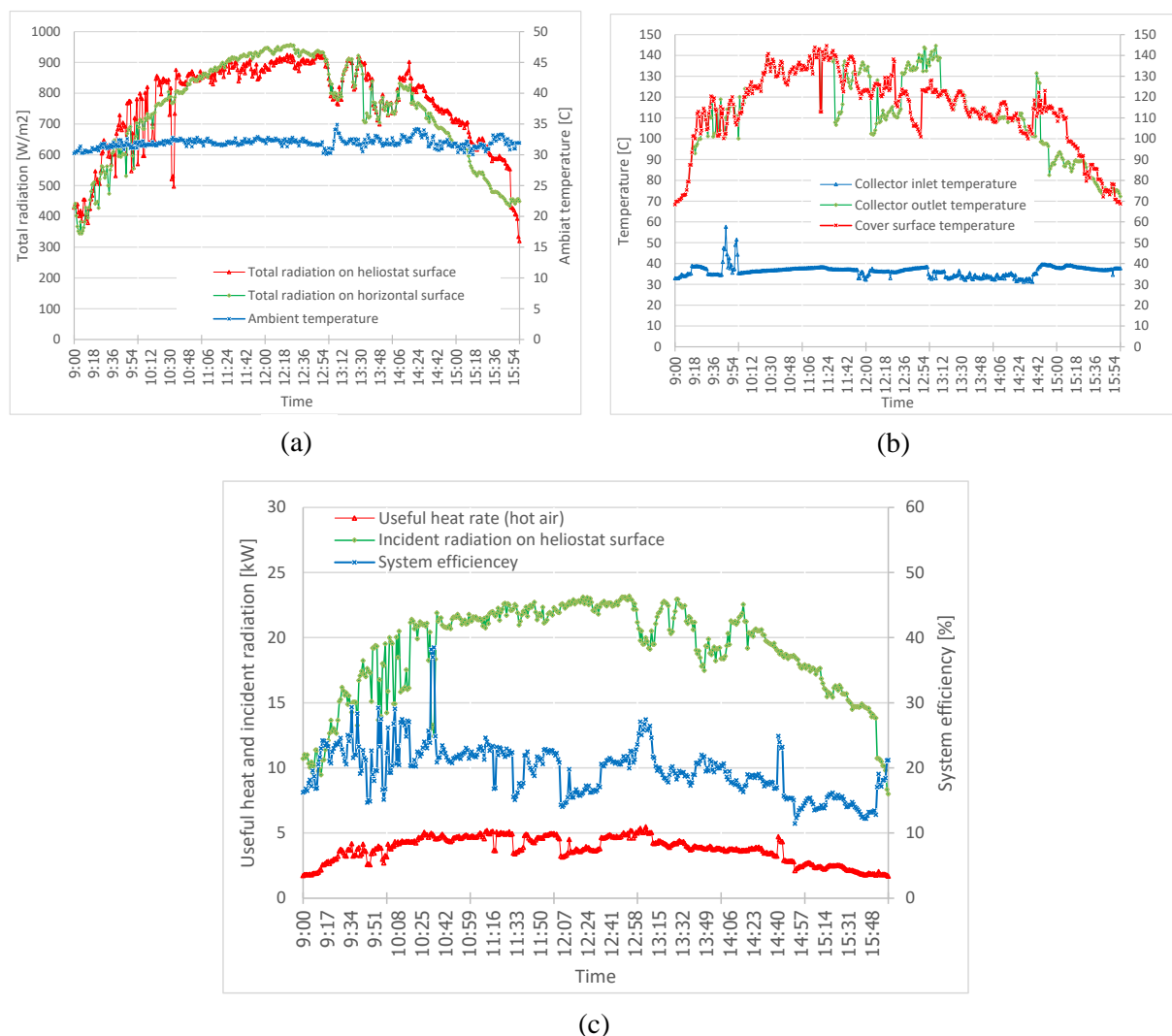


Figure 8. The experimental results when the tower receiver with porous medium was conducted
 (a) total solar irradiance and ambient temperature of the clear sky experimental day
 (b) air temperatures at the inlet and outlet and the glass cover of the tower receiver
 (c) efficiency of the air heating system with porous medium application.

6. References

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