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Performance of force circulation cross-matrix absorber solar heater integrated with latent heat energy storage material

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Abstract. The utilization of thermal energy storage in the thermal absorber applications has been increasingly important especially in the application where there is a mismatch between energy demand and energy supply. This technology implies that the heat is stored during charging or discharging process through melting and freezing of the thermal energy storage material so that it can be used in the future. This paper presents the outcome of the experimental investigation on the performance of cross-matrix absorber (CMA) utilizing paraffin as the thermal energy storage material. Experiments were carried out by exposing the CMA under different artificial solar radiation (300 W/m^2, 500 W/m^2, 700 W/m^2 and 900 W/m^2) for 30 minutes followed by 30 minutes of discharging process. Based on the observation, it was found that smaller mass flow rate value of 0.005 kg/s gave the highest temperature output regardless of the intensity of solar radiation as compared to the other after 30 minutes of charging process. In terms of heat gain by the thermal absorber, it was concluded that the highest mass flow rate of 0.01 kg/s passing through the absorber lead to the higher heat gain by the CMA, hence prolonged the cooling down / discharging period as shows by the result, where case with maximum mass flow rate (0.01 kg/s) consistently contributed to the higher heat gain by the absorber. This feature is very useful in the solar thermal collector related applications such as crop drying and domestic building heating. The heat gain by the absorber is also contributed by the intensity of the solar radiation.

1. Introduction

Solar energy system is always associated with the renewable, clean and abundant of its quantity. Annually, there are about 3,400,000 EJ of solar radiation reaching the earth surface and this value exceeding the total of all non-renewable energy combined [1]. Despite all the blessed, the progress in the solar energy system applications especially for solar air collector are always struck with the problem of the durability of the solar technology equipment in delivering the energy towards the end user. Due to nature of solar radiation is a periodic energy resource [2], [3], there is a time when energy demand does not synchronize with the energy supply[4]–[6] make it less efficient to the overall performance of the solar air collector. Fortunately, this problem can be addressed with the utilization of thermal energy storage material integrated with solar air collector. Latent heat energy storage material was viewed as the most promising candidate as compared with other types of heat storage material such as sensible heat and chemical heat storage material because it offer several advantages over the two such as high energy density over the volume ratio [7], [8], narrow temperature range [9]–[12] and easily found in the market [13].

In the last decade, plentiful of experimental research related with the integrating of the flat plate thermal absorber with latent heat energy storage materials [14]–[23] have been conducted and fair number of them are studying the performance of flat plate absorber integrated with latent heat storage material numerically [23]–[25] with the most of the outcome were the improvement of an overall collector performance. Most recent innovation by [26] with the implementation of an array of flat micro-heat pipe whereby the heat was transmitted to the liquid refrigerant before transferred to the storage section containing latent heat storage material due to capillary force. Despite improvement of efficiency (59.5% and 91.7% during charging and discharging process, respectively), the device still cannot meet the space heating requirement and require additional 323 W of power form auxiliary heating equipment.

From the literature, a few research focused on the implementation of matrix-type absorber integrated with latent heat storage material. A. Sohif *et al* [27] conducted an experimental study to predict an output temperature of solar air heater integrated with phase change material (PCM). The material was paraffin with embedded aluminum powder was placed inside the steel cylindrical. S. Bouadila *et al.*[28], [29] designed and tested the solar air heater integrated with latent heat storage material by placing the material inside steel spherical capsules acting as absorber. Based on exergy and energy analysis, it was concluded that the heater was performed better than conventional flat plate heater. A.A. Razak *et al* [30] using cross-matrix absorber with the implementation of bi-metal (Aluminum and stainless steel) to investigate the effect of sensible heat energy storage capability of the absorber. However, due to the opposite value of thermal diffusivity of both materials, output temperature stability was difficult to achieved [31]. In this paper, the outcome of the investigation on the effect of integrating the latent heat storage material with the CMA is presented.

2. Materials and methods

2.1. Material description

In this experiment, aluminum (6063-T5) having 1mm thickness has been divided into type-A and type-B tube and were arranged in the arrangement as shown in the Figure 1 and the detail of the tubes are presented in the Table 1. In this work, only type-B tubes was considered to be filled with paraffin in order to measure the absorber performance. The incorporation of paraffin in other tubes will be considered in the future work. Meanwhile, latent heat energy storage material was made by paraffin in which has 58 °C – 60 °C melting temperature range. The paraffin was prepared by grinding process to make it into a small granular form in order to ease its insertion to the aluminum tubes. In order to ensure the consistency and the accuracy of the experimental result, the weight of paraffin granule were carefully measured. In this case, the paraffin weight of 48 g has been chosen as a proper suitable value for the aluminum tube dimension. This amount represent third-quarter of the total tube volume in which is essential to avoid for liquid paraffin leakage and inefficient melting if more paraffin wax is used. In addition, if the amount is too small, will results less heat storage which is insignificant to the purpose of this study.

2.2. Test rig description

The solar radiation test rig was designed in order to perform the investigation in this work. The test rig consists of solar simulator, mixing chamber, thermal absorber and discharge chamber as depicted in Figure 2. The solar simulator was designed and fabricated to emulate artificial solar radiation to the fabricated cross-matrix absorber. It consisted of nine units of 150 W halogen lamp which are capable to radiate 1350 W/m^2 solar radiation at maximum setting. In order to regulate solar radiation, dimmer switch was installed at the simulator circuit to obtain required artificial solar radiation. Mixing chamber is the part of the test rig where the incoming air will be heated before entering the thermal absorber unit. It comprises of two units of incandescent lamp that acted as a heater in order to control the input air temperature at the required values.

Table 1. Detail description of Aluminum tube used in the experiment

Detail description	Type A	Type B
Dimension (L x W x H), cm	32.6 x 1.91 x 1.91	42.7 x 1.91 x 1.91
Weight without end cap, g	45	64
Weight with end cap, g	62	80
Thickness, mm	1	1
Density, kg/m^3	2700	2700
Thermal conductivity, W/m.K	200	200
Specific heat capacity, J/kg.K	900	900
Paraffin content	No	Yes

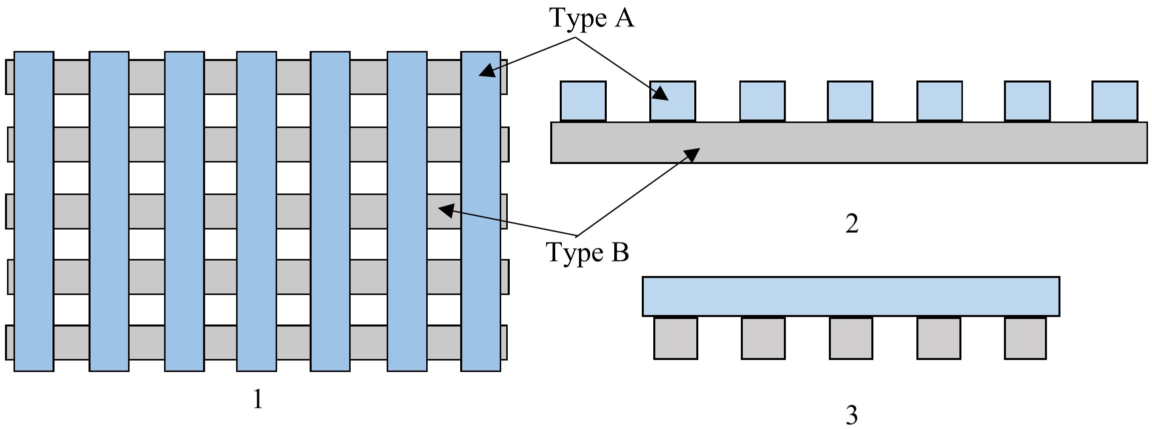

Figure 1. Tube arrangement of 1-set cross-matrix absorber for single layer; 1- top view, 2- front view, 3- side view

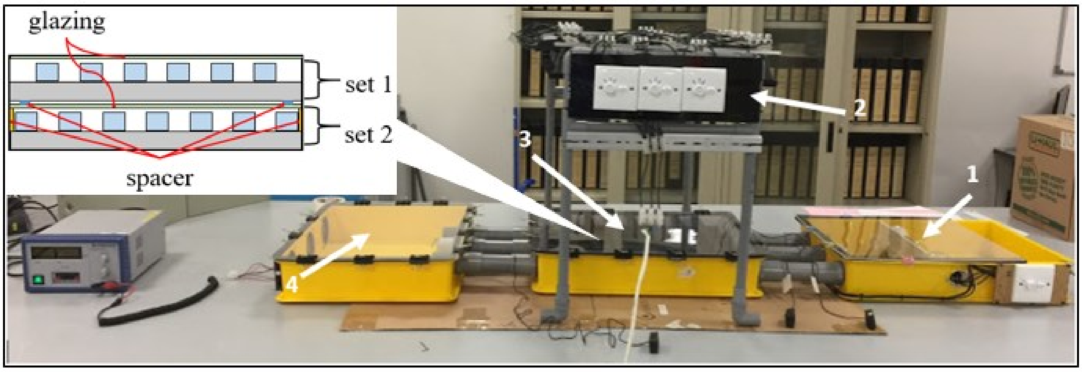

Figure 2. The solar radiation test rig; 1- Mixing chamber, 2- solar simulator, 3- thermal absorber unit, 4- discharge chamber, 5- detail of thermal absorber unit

Thermal absorber was built from the containment with dimension of (53 x 40 x 9) cm consisted of 2-set of cross-matrix absorber in which each 1 set was built from 7 pieces of Aluminum tube type-A and 5 pieces of Aluminum tube type-B. Two units of 4 mm thick polycarbonate glazing were placed at the top of set 1 absorber and in between of set 1 and set 2 thermal absorber, respectively. Thermal insulation was placed in the four-side and bottom of the thermal absorber casing to reduce heat losses. Discharge chamber is the section where the temperature output was measured. It contained three units of suction fan (24 V DC) with each unit's speed can be regulated using the regulated BK Precision® power supply.

2.3. Methodology

The experiment was conducted with the cross-matrix absorber being exposed to four different values of artificial solar radiation of 300 W/m^2, 500 W/m^2, 700 W/m^2 and 900 W/m2, while the input air temperature was maintained at 30 °C. The structure of the experiment was designed so that all radiation values were to be assigned with different setup parameters. The temperature data was measured and recorded using five units of digital temperature sensors where the location of the sensors were shown in Figure 3. The experiment was started with charging process for about 30 minutes and followed by discharging process for another 30 minutes. The temperature data was recorded for every 1 minute time span under the control environment. This procedure was also repeated for the other setup parameters. The performance of the absorber was then determined based on the calculation.

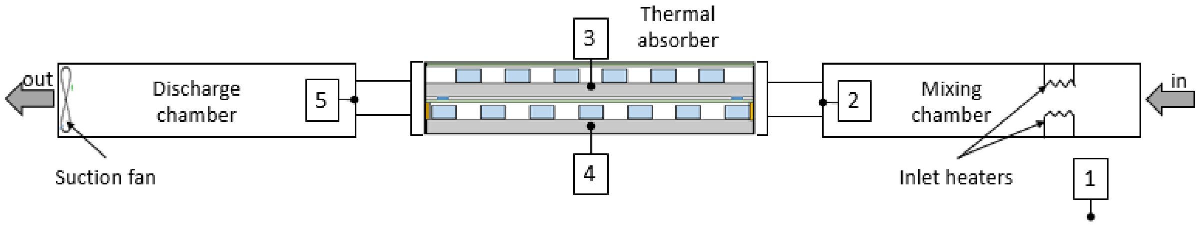

Figure 3. Location of temperature sensors; 1- ambient, 2- inlet duct opening, 3-type-B Aluminum tube of set 1 absorber, 4-type-B Aluminum tube of set 2 absorber, 5-outlet duct opening

In this particular work, the setup parameter for air velocity was measured using anemometer supplied by LT Lutron, Taiwan. The measured air velocities were 1.8 m/s, 2.3 m/s and 3 m/s and the corresponding mass flow rate was then calculated using the following expression

$$\dot{m} = \rho_a v_a A_a \tag{1}$$

where ρ_a is the air density considering it as a perfect gas at constant pressure and A_a is the cross sectional area of the duct at the opening of the thermal absorber containment. Wind speed at the vicinity of the test rig however was assumed to give no significant impacts on the result and hence was not measured. The useful heat gain rate across the cross-matrix absorber was then calculated based on the following expression

$$\dot{Q}_u = \dot{m}_a c_a (T_{out} - T_{in}) \tag{2}$$

For thermal absorber with the heat storage material, sometimes it is more useful to describe the cumulative parameter to measure the performance [2]. Hence, the cumulative heat gain is given by the following expression

$$\dot{Q}_u = \int_0^t \dot{m}_a c_a (T_{out} - T_{in}) \tag{3}$$

with T_{out} is the temperature at the discharge chamber, measured at the opening outlet duct. $\dot{m}_a$ and c_a were mass flow rate and specific heat for air, respectively.

3. Results and discussion

The results presented in figure 4 shows the behavior of output temperature of the absorber with respect to their different solar radiation. The highest point on each graph indicate the end of charging process and the beginning of the discharging process. Based on the result, the minimum mass flow rate of 0.005 kg/s is observed to consistently provide higher temperature output as compared to the other two mass flow rate values. The maximum temperature achieved within 30 minutes of charging process are 57.5 °C, 54.2 °C, 47.1 °C and 42.4 °C for solar radiation of 900 W/m^2, 700 W/m^2, 500 W/m^2 and 300 W/m^2, respectively. Meanwhile, highest mass flow of 0.01 kg/s provides minimum charging temperature for all solar radiation. Therefore, it can be concluded that the lower the mass flow rate gives an ample time to the aluminum tube to transfer the heat to the moving air via convection heat transfer and thus increased its temperature. However, the result showed otherwise for the heat gain by the absorber.

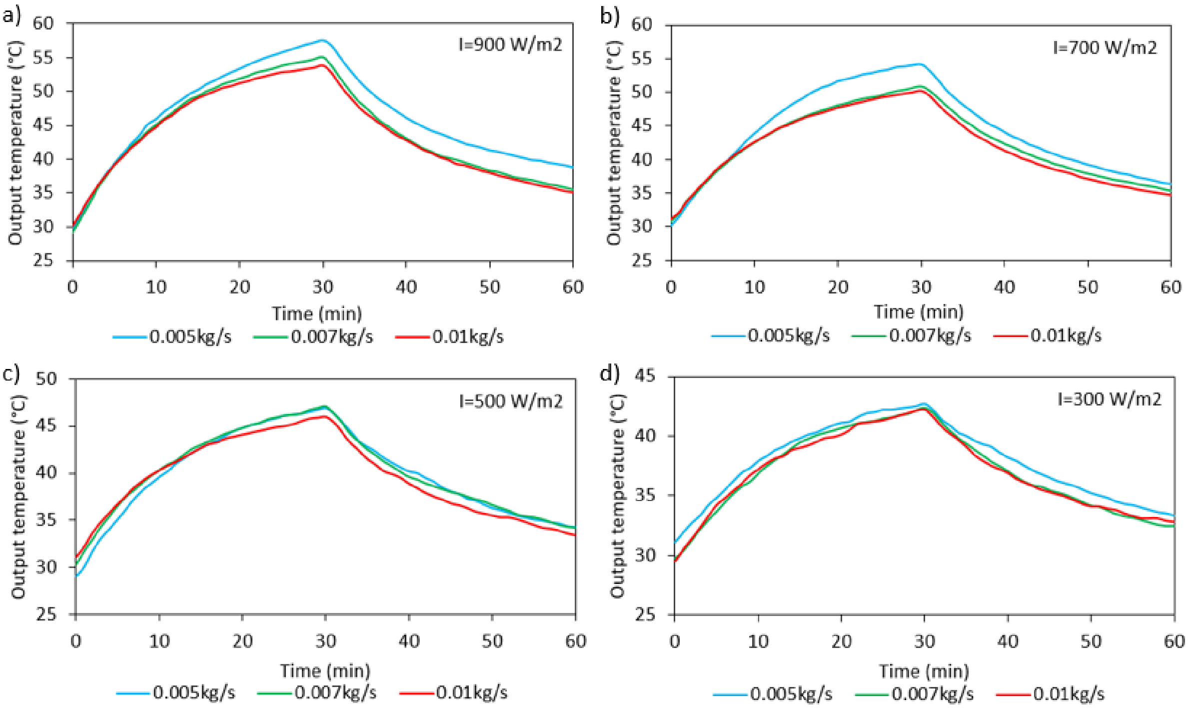

Figure 4. Temperature output of the absorber based on different solar radiation; a) 900 W/m^2, b) 700 W/m^2, c) 500 W/m^2, d) 300 W/m^2

Heat gain measured the capability of the absorber to absorb and store the heat from the radiation source[32] by increasing the outlet air temperature compared with inlet air temperature. The higher the heat gain means the absorber is better in terms of storing the heat, hence provide the longer time for the temperature to cool down during the off sunshine or when the solar simulator is turning off. This behavior is presented in the figure 5, where the heat gain of the absorber is plotted against experiment duration for each case of respective mass flow. It is observed that the mass flow rate of 0.01 kg/s consistently provided higher heat gain for all solar radiation value. In addition to the large amount of latent heat energy stored by the paraffin, the small amount of heat received by the higher mass flow rate from the absorber lead to the temperature of the absorber increase drastically as compared to when lower mass flow rate of air moving through it. Hence, this lead to the longer time for the absorber to cool down when the simulator is turning off. This feature will especially useful for the drying and domestic building heating applications. Besides, the works from A. A. Razak *et al.* [33] concluded that an empty aluminum tube without thermal storage energy easily disperses heat, causing rapid temperature decreasing when in the discharge mode.

As for case of 900 W/m^2 radiation, heat gain by the absorber for mass flow rate of 0.01 kg/s was 49.25 W as compared with 37.29 W when mass flow rate was 0.005 kg/s. Table 2 and figure 6 present the details of heat gain by the absorber for each case and cumulative heat gain by the absorber with respect to mass flow rate and solar radiation, respectively. Hence, it can be concluded that the intensity of solar radiation and higher air mass flow rate contributed to the heat gain of the absorber.

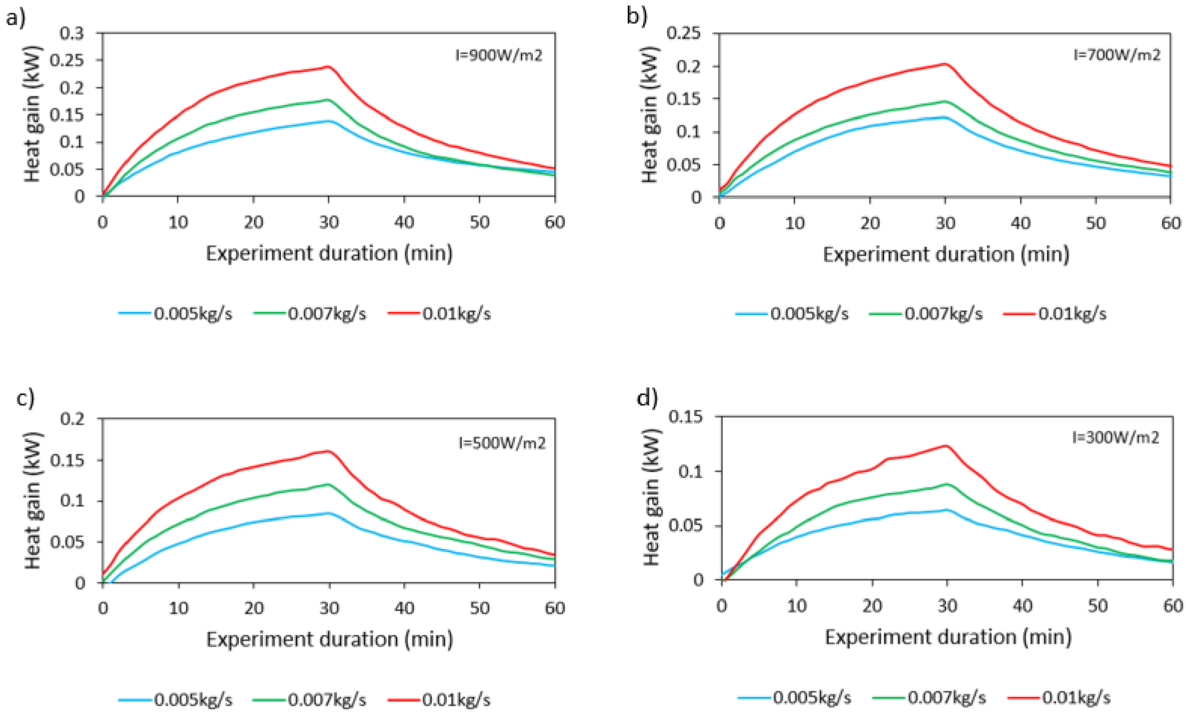

Figure 5. Heat gain variation of the absorber with respect to the mass flow rate and solar radiation values

Table 2. Heat gain value (in W) of absorber for each case of the experiment after the completion of discharging process

Solar radiation (W/m^2)	**900**			**700**			**500**			**300**		
Mass flow rate (kg/s)	0.005	0.007	0.01	0.005	0.007	0.01	0.005	0.007	0.01	0.005	0.007	0.01
Heat gain (W)	37.29	47.24	51.25	37.29	47.23	49.27	22.11	34.17	36.18	17.57	17.58	29.15

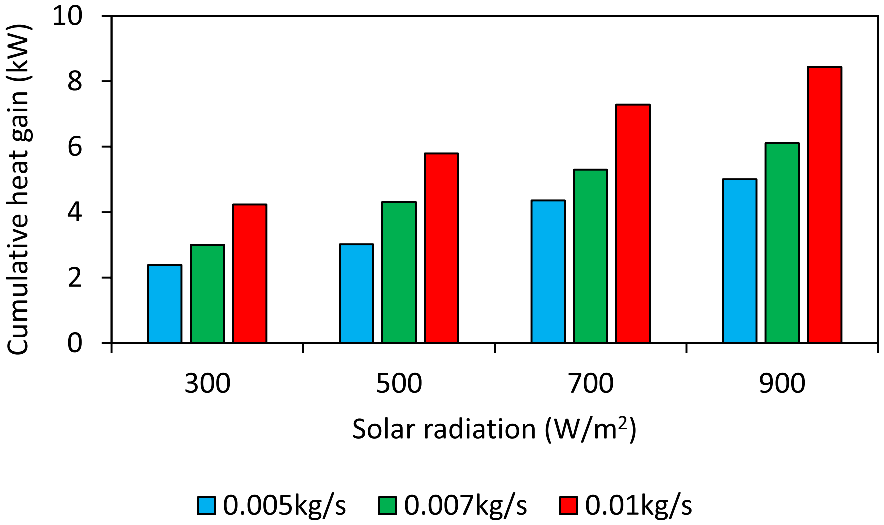

Figure 6. Cumulative heat gain by the CMA with respective mass flow rate and solar radiation values

4. Conclusion

Investigation on the effect of mass flow rate to the output temperature of the absorber was performed using solar simulator to produce four different radiations of 300 W/m^2, 500 W/m2, 700 W/m^2 and 900 W/m^2. It is observed that smaller mass flow rate of 0.005 kg/s provided an ample time for the moving air to receive the heat from absorber material lead to the increasing of output temperature of 57.5 °C, 54.2 °C, 47.1 °C and 42.4 °C for solar radiation of 900 W/m^2, 700 W/m^2, 500 W/m^2 and 300 W/m^2, respectively. The performance of thermal absorber during cooling down / discharging period was also determined through the calculation of heat gain. It can be concluded that higher mass flow rate prolonged the cooling down / discharging period. The highest mass flow rate in this work, 0.01 kg/s consistently obtaining the highest heat gain for all cases of solar radiation. This feature was useful for the thermal absorber to be utilized in the various applications such as crop drying and domestic building heating. Intensity of the solar radiation also provides a major contribution to the total heat gain by the thermal absorber. Further investigations to improve of the overall performance of the CMA are required to extend the current work.

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