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Performance Analysis of Flat Plate Base-Thermal Cell Absorber (FPBTCA): Low Thickness Design

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ABSTRACT

Research to improve flat plate solar collector performance such as design and material used continuously developed. This paper's objective is to analyze the performance of the thermal cell absorber attached to a flat plate absorber collector (FPBTCA) through a low thickness design. It will produce a lightweight and portable collector application with efficient temperature conversion duration and has energy storage ability. Stainless steel and aluminum materials with different thicknesses use as thermal cell absorbers then aluminum materials use as a flat plate absorber base-collector. The experiment performs using a solar simulator with solar radiation of 700 W/m2. Referring to the results in term of heat storage ($Q_{storage}$), the heat transfer rate of the collector ($\dot{Q}$) and efficiency of the collector shows that stainless steel 1.0 mm with an aluminum base absorber (Case E) has a higher value which is 412 kJ, 18.21 kW, and 47.08 %, respectively. The higher total energy gain collected at the bottom plate as dummy load in the drying chamber (T1 and T2) is stainless steel 1.0 mm with an aluminum absorber base-collector (Case E) value of 2.85 kJ. Stainless steel 1.0 mm with an aluminum absorber base-collector (Case E) has the maximum value of energy gain at 300 seconds which is 116.08 J for the bottom plate (T1 and Ta). Flat plate base absorber thermal cell (FPBTCA CASE E) shows better performance in thermal storage than Flat Plate Solar Collector (FPSC).

1. Introduction

Solar energy also known as one renewable energy and involves no pollution effect or green gases emissions [1], also produce less environmental impact compare to fossil fuel power generation [2]. Therefore, the demand for using solar energy is increasing the effect of the population in the world is growing [3]. The Solar dryer is an example of solar thermal application. Generally, there are two types of solar dryer that has been used which is open-air sun drying and convective solar drying [4]. Flat plate solar collector (FPSC) widely used to dry agricultural product [5][6]. The agricultural product

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is drying to increase shelf-life, reduce packaging cost, increase shipping capacity, and enhance appearance [7]. The temperature range of flat plate solar collector (FPSC) is between 30 ℃ and 80 ℃ and it could be passive or active FPSC [8]. The position of FPSC is fixed in its position and oriented directly towards the equator facing south in the northern hemisphere and north in the southern [9].

Flat plate solar collector with the different thickness could affect the energy storage performance and absorber collector temperature. Flat plate solar collector with low thickness design has better performance with short temperature conversion duration but their energy storage performance will be decreased, weather changes such as cloud will rapidly drop collector temperature. There were advantages and disadvantages to using a high thickness absorber collector [10] in designing a flat plate solar collector. The advantages are absorber collector absorbs high heat storage and disadvantages are absorber collector absorbs low temperature. For this case, the temperature output also has a lower temperature. By using phase change material (PCM) inside absorber collector could increase high heat storage but the absorber collector temperature has lower than the absorber collector without phase change material (PCM) [11]. Flat plate solar collector size will affect the absorber collector thickness. When the flat plate solar collector size is small (portable), the absorber collector thickness is low. While the absorber collector thickness is high if the flat plate solar collector is big.

Flat plate solar collector modification could be done by improving of thermal absorber collector to increase the thermal efficiency performance. Absorber thermal collector improvement can be done by attaching fins to the absorber, increase absorber collector surface geometry, corrugated absorber collector, phase change material, porous media and nanofluids as the working fluid. Mohammadi *et al.,* [12] found that when using fins to the flat plate absorber collector could increase the outlet air temperature and efficiency. Another review showed that V-corrugated absorber collector improves the heat transfer coefficient and heat removal factor [13]. A study by Su *et al.,* [14] concludes that by using phase change material with lower melting point give advantages in term of electrical properties to the flat plate solar collector. Arun Venu et. al.[15] concluded that by integrates a porous matrix media with a flat plate absorber collector improves the flat plate solar collector thermal performance. Other results showed that implement using CuO–H2O as working fluid could increase flat plate solar collector efficiency by 16.7 % when compared to water working fluid [16]. The other researcher also study improvement of a flat plate solar collector by using multi-walled carbon nanotubes (MWCNTs) and improved the thermal efficiency [17].

A.C.Mintsa Do Ango *et al.,* [18] apply an experiment by using polymer material as absorber collector in flat plate solar collector. It was found that using polymer material can improve solar collector's economic competitiveness compared to metal absorber collector. Ramalingam Senthil *et al.,* [19] have shown experimentally that using black coating with graphene to the flat plate absorber collector has higher thermal efficiency than standard black coating flat plate absorber collector. The experimental related with the efficiency improvement of the flat plate solar thermal collector with an additional component to absorber [20-24] has been conducted and most of them are studying the performance of flat plate solar collector integrated with fins [25-29]. This experiment was done by using the flat plate solar collector (FPSC) and flat plate base-thermal cell absorber (FPBTCA) integrated with the drying chamber. The flat plate solar collector integrated with the drying chamber has an advantage which is it has the stability of the air temperature when then is no solar radiation [30]. The objective of this research is to find suitable thermal cell absorber material and observe their thickness attach to the absorber base-collector for flat plate base-thermal cell absorber (FPBTCA) to improve the heat storage performance with maintaining temperature output. This will produce a low thickness flat plate solar collector for portable drying application.

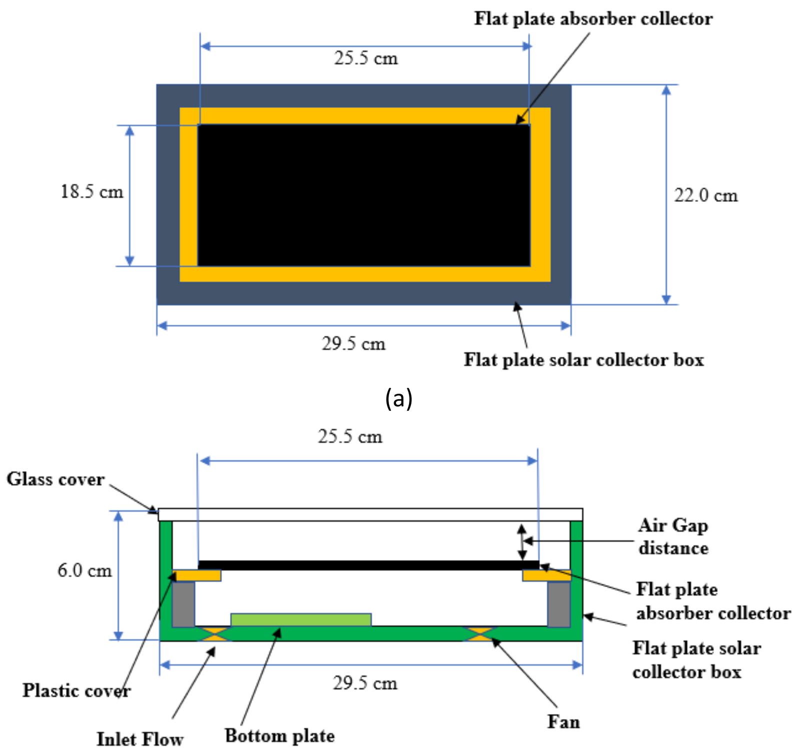
2. Research Methodology

To conduct an experiment, the devices and apparatus used in this work are explained in this section. The temperature of the flat plate absorber collector in this experiment was measured by using APPLENT TECHNOLOGIES, Multi-Channel Temperature Meter (8-CH) (AT4208) and APOGEE INSTRUMENTS, Pyranometer. For calibration purposes, the real-time solar radiation flux was measured using TES ELECTRICAL ELECTRONIC CORPORATION, Datalogging Solar Power Meter (TES-1333R). The Pyranometer and datalogger were calibrated for their validity and reliability before experimenting.

All experimental works have been conducted indoors and under a controlled environment. Details of each experiment conducted are explained in the following sub-sections. A flat plate solar collector was exposed to artificial solar radiation with 700 W/m². The charging process is done for 300 seconds under a simulator. The Discharging process was conducted by removing the solar simulator and the process continue for another 300 seconds. The fan speed used in this experiment is 0.62 m/s and the glass cover thickness are 2.0 mm. All the temperature sensor was analysed and the graph was plotted after the experiment done. Data logger, 8-Channel Temperature Meter was used to recording the data when the experiment is done. The temperature data were collected and recorded every second using a data logger.

3.1 Evaluation of Flat Plate Solar Collector (FPSC)

Figure 1(a) and (b) show the top view and the side view for the aluminum absorber of the flat plate solar collector (FPSC). There are several components inside FPSC which is flat plate absorber collector, glass cover, flat plate solar collector box, bottom plate, outlet fan and insulation at the bottom sides. The air gap distance was used in this experiment is 1.0 cm.



(b)

Fig. 1. (a) Top view (b) Side view of FPSC diagram

Figure 2 represents the temperature location for the FPSC. There are 3 temperature sensors were used in this experiment. T1 is referred as bottom temperature and also known as a dummy load. T2 is referred as drying temperature inside the drying chamber. While T3 is outlet temperature and located at the outlet fan.

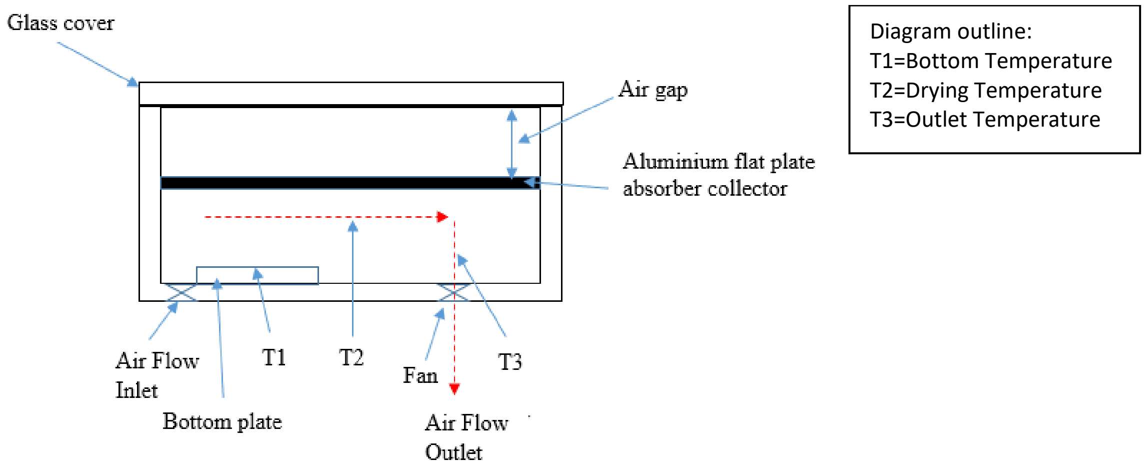
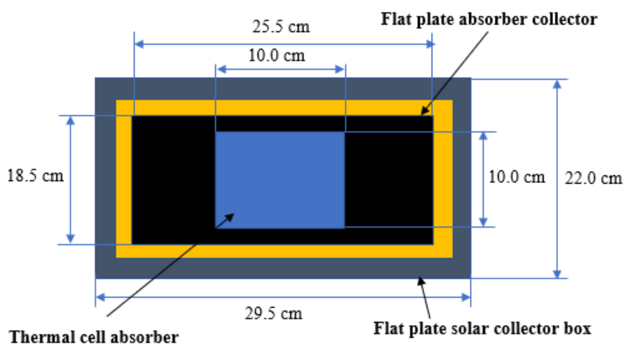


Fig. 2. Temperature sensor location for FPSC

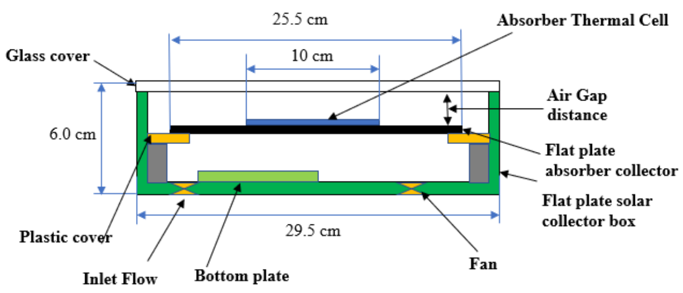
3.2 Evaluation of Aluminum Cell and Stainless Steel Cell with Aluminum (Base Absorber) (FPBTCA)

Figure 3(a) and (b) show the top view and the side view for the aluminum base absorber with thermal cell absorber of the solar thermal collector. There are two types of thermal cell absorber material was used which is aluminum and stainless steel. The FPBTCA component consists of a flat plate absorber collector, absorber thermal cell, glass cover, flat plate solar collector box, bottom plate, outlet fan and insulation at the bottom sides. The air gap distance was used in this experiment is 1.0 cm. Aluminum and stainless steel thermal cell absorber is located at the top of the flat plate absorber collector.

Figure 4 represents the temperature location for the FPBTCA. Based on the schematic diagram, 3 temperature sensors were used in this experiment. T1 is located at the bottom plate and also known as a dummy load. T2 is referred as drying temperature inside the drying chamber. T3 is known as outlet temperature and located at the outlet fan.



(a)



(b)

Fig. 3. (a) Top view (b) Side view of FPBTCA diagram

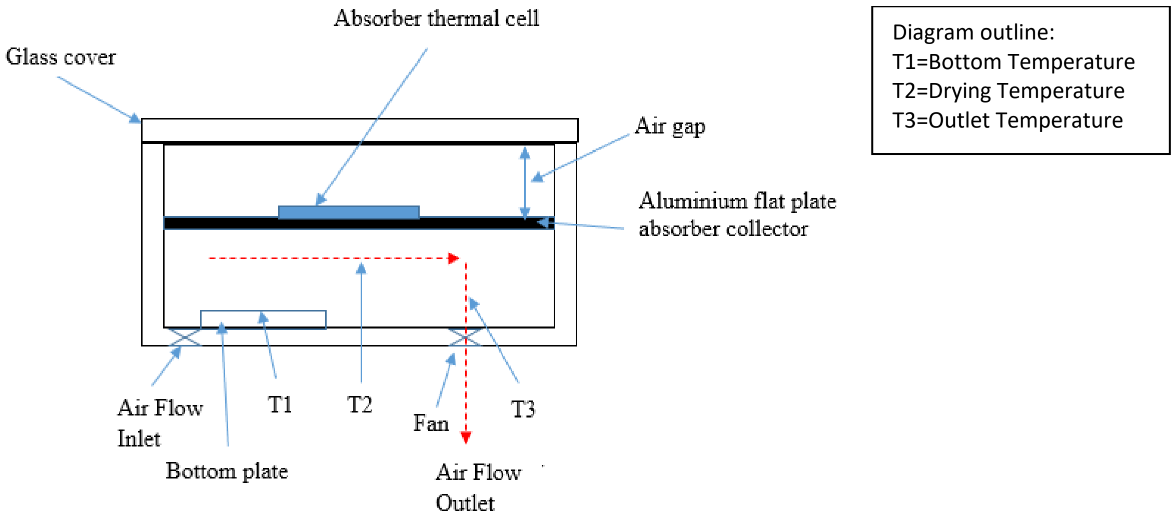


Fig. 4. Temperature sensor location for FPBTCA

3.3 Evaluation of FPSC and FPBTCA Configurations

Table 1 show the experiment table for FPSC and FPBTCA configurations. Aluminum flat plate absorber base-collector, with a thickness of 0.5 mm (Case A) and the weight is 73 g. The absorber collector size is 0.185 m in width and 0.255 m lengths. There are two types of thickness was used for aluminum thermal cell configuration which is 0.5 mm (Case B) and 1.0 mm (Case C). The aluminum cell area is 0.01 m in width and 0.01 m in length. The aluminum cell is attached at the top of the aluminum absorber collector (base absorber). Aluminum cell thickness used is 0.5 mm and the total weight is 95 g respectively. For aluminum cell thickness 1.0 mm the total weight is 102 g. Stainless steel thermal cell thickness was used is 0.5 mm (Case D) and 1.0 mm (Case E). Stainless Steel cell area is 0.01 m width and 0.01 m length. The stainless steel cell is attached at the top of the aluminum absorber (base absorber). The stainless Steel cell thickness used is 0.5 mm and the total weight is 115 g respectively. For Stainless Steel thickness 1.0 mm the total weight is 148 g.

Table 1
Experiment table for FPSC and FPBTCA configurations

No	Type of Case	Types of Absorber (Base)	Thermal cell	Thermal Cell Thickness (mm)	Total Weight (g)	Size (m)
1	CASE A	Aluminum	NA	NA	73	0.185 x 0.255
2	CASE B	Aluminum	Aluminum	0.5	95	0.010 x 0.010
3	CASE C	Aluminum	Aluminum	1.0	102	0.010 x 0.010
4	CASE D	Aluminum	Stainless Steel	0.5	115	0.010 x 0.010
5	CASE E	Aluminum	Stainless Steel	1.0	148	0.010 x 0.010

3.4 Performance Output Analysis of Drying Chamber

The heat transfer rate of the collector is calculated by the Eq. (1)

$$\dot{Q}_{Collector} = \rho A v C_{p(air)}(T_o - T_i) \tag{1}$$

The heat transfer rate of the thermal absorber storage can be obtained by Eq. (2)

$$Q_{Store} = \frac{m_{ab}C_{p(ab)}(T_2 - T_1)}{t_2 - t_1} \tag{2}$$

where the efficiency of the collector and storage is presented as Eq. (3)

$$\eta_{Collector+Storage} = \frac{\dot{Q}_{Collector} + Q_{Store}}{G_t A_c} \times 100\% \tag{3}$$

The solution of Eq. (1) and Eq. (2) to Eq. (3), then the efficiency of the collector and storage is expressed as

$$\eta_{Collector+Storage} = \frac{\rho A v C_{p(air)}(T_o - T_i) + \left(\frac{m_{ab}C_{p(ab)}(T_2 - T_1)}{t_2 - t_1}\right)}{G_t A_c} \times 100\% \tag{4}$$

where,

ρ	=	The density of air (kg/m^3)
A	=	Area of inlet duct (m^2)
v	=	The velocity of air at inlet duct (m/s)
$C_{p(air)}$	=	Specific heat of air (kJ/kgK)
T_o	=	Air outlet temperature (K)
T_i	=	Air inlet temperature (K)
G_t	=	Global solar radiation ($Watt/m^2$)
A_c	=	Area of the collector (m^2)
m_{ab}	=	Mass of thermal absorber (kg)
$C_{p(ab)}$	=	Specific heat of thermal absorber (kJ/kgK)
T_2	=	The temperature of thermal absorber after heat gain (K)
T_1	=	The temperature of thermal absorber before heat gain (K)
t_2	=	Time after heat gain (s)
t_1	=	Time before heat gain (s)

4. Result and Discussion

4.1 Performance of the Absorber Collector Configurations

The flat plate solar collector was exposed to artificial solar radiation for about 300 seconds to stimulate the charging process and a further 300 seconds to stimulate the discharging process when the artificial solar radiation was removed. Table 2 and Figure 5 shows the maximum temperature within 300 s and temperature versus time for various absorber collector configurations. Temperature T1 refer to the temperature that absorbs by aluminum material that attach at the bottom which is referred as a dummy load. The temperature T2 refer to the drying chamber temperature, which is used to drying the product. The temperature T3 refer to the output temperature from the drying chamber to the outside. Therefore T1, T2 and T3 are important when designing the flat plate solar collector.

Table 2
The maximum temperature within 300 seconds of the charging process

Absorber types	T1 (°C)	T2 (°C)	T3 (°C)
Case A	30.9	36.6	38
Case B	30.9	36.6	38
Case C	31.1	36.4	37.8
Case D	31.7	37.1	38.5
Case E	33.4	37.2	38.6

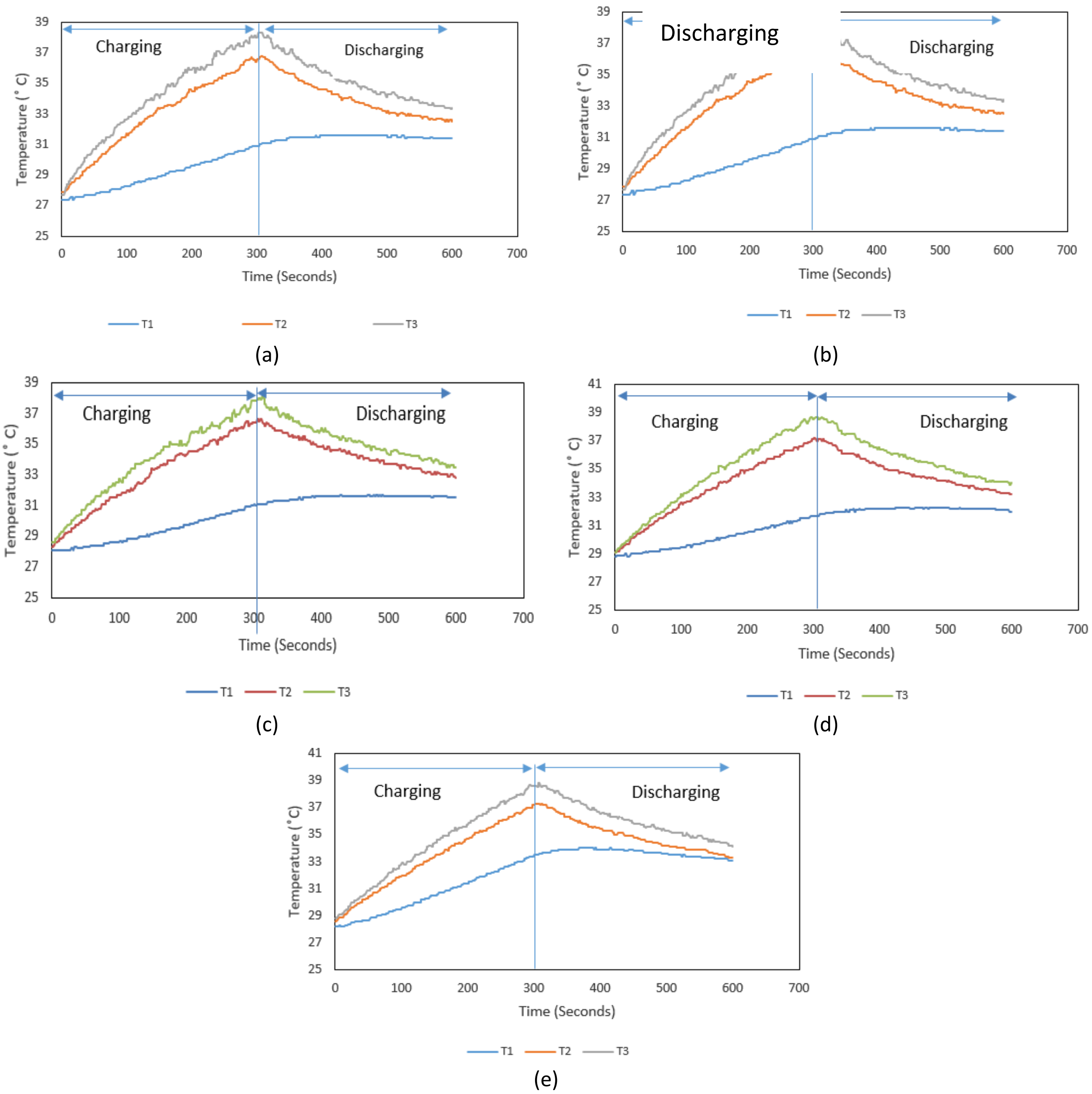


Fig. 5. Temperature versus time for various absorber collector configurations on (a) Case A, (b) Case B, (c) Case C, (d) Case D (e) Case E

Based on the result it shows the maximum temperature of T1 at time 300 seconds is 33.4 °C and the absorber collector is Case E. The temperature T2 when the maximum temperature at time 300 seconds is 37.2 °C and the absorber collector is Case E. Temperature T3 have the maximum temperature at time 300 s is 38.6 °C and the absorber is Case E. Therefore, it can be concluded that the heat absorbs by the absorber collector Case E is transferred fast to the drying chamber and the bottom via conduction and convection heat transfer and thus increased its temperature.

Figure 6 shows the heat transfer diagram for Flat Plate Base-Thermal Cell Absorber (FPBTCA). For the cover glass, the $Q_{radiation}$ and $Q_{convection}$ is applying at the surface of the glass cover. The thermal cell attach to the absorber base-collector has $Q_{radiation}$ and $Q_{conduction}$. Flat plate absorber base-collector has $Q_{radiation}$, $Q_{convection}$ and $Q_{conduction}$. For dummy load in the drying chamber, the heat transfer can be defined as $Q_{radiation}$, $Q_{convection}$ and $Q_{conduction}$.

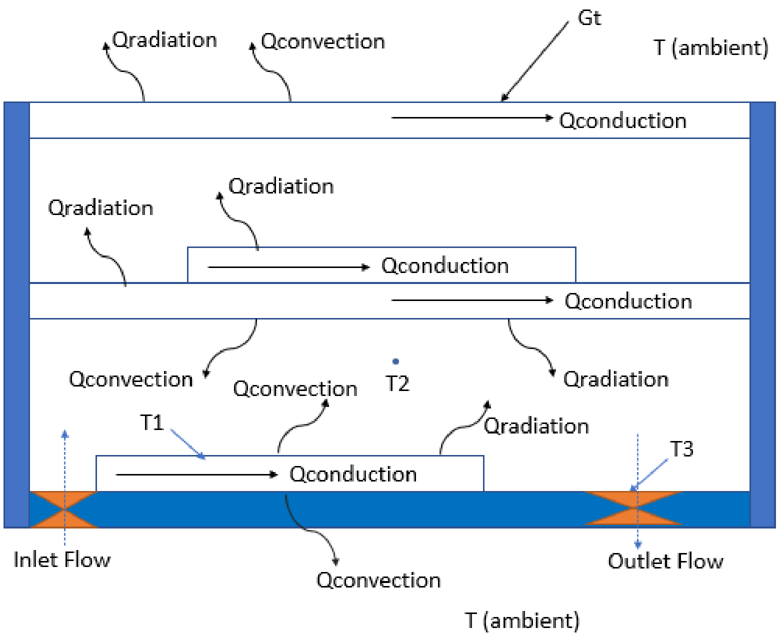


Fig. 6. Heat transfer diagram for a solar thermal collector

Table 3 represent total heat storage (Q storage), heat transfer rate ($\dot{Q}$), efficiency (in %) and energy gain. The Eq. (2) was used to analyse heat storage (Q storage). Based on the result in term of total heat storage (Q storage), it shows that Case E has a higher total of heat storage value which is 412 kJ compare to the other types of thermal absorber collector. Case E has maximum compare to the other types of configurations. Correspondingly, Case E absorbs high radiation then convert it to heat energy and store heat in the system of the drying chamber. For this situation, Case E can to use the heat when the fluctuation of solar radiation.

The Eq. (1) was used to analyse heat transfer rate ($\dot{Q}$). The higher total heat transfer rate ($\dot{Q}$) of the thermal collector collect by the absorber collector is Case E and the value is 47.05 kW. The result in this experiment indicates that the higher increase value of heat transfer rate provides high heat transfer in the drying chamber. For discharging period Case E has a higher heat transfer rate which is 65.25 kW. It shows that Case E has high heat energy during discharging and can be used to supply constant heat to the drying chamber. This led a longer time for the absorber to cool down when the simulator is turning off.

The Eq. (3) was used to analyse efficiency (%). The results show that Case E has a higher value of efficiency in the drying chamber which is 47.08 per cent than another configuration. The most interesting finding was that Case E can give the best performance in term of efficiency. The performance of collector efficiency significantly depends based on the shape factor [33] of the absorber collector. It can be concluded that the system in Case E has higher heat storage and heat transfer rate ($\dot{Q}$). Case E has better operational performance in the system compare to Case A, Case B, Case C and Case D.

The Eq. (1) was applied to calculate energy gain. The energy gain (in KJ) for T1 and T2 at the bottom plate for each case absorber collector and cumulative energy gain by the different type of absorber collector. The bottom plate used as a dummy load to evaluate for heat absorption performance of the drying chamber. The higher total energy gain collect by dummy load is Case E and the value of heat gain is 2.85 KJ. The higher energy gain collect at the dummy load shows that the high temperature difference between T1 and T2. Based on the condition, bottom plate for Case E absorb high energy gain and could be used when drying product.

The results obtained from the analysis of energy gain value from the drying chamber for each case of the experiment. T1 is referred as the temperature at the bottom plate surface and T ambient is temperature inlet. The result shows Case E has a higher energy gain, which is at 300 s and 600 s and the energy gain value is 116.08 J and 102.81 J respectively, compares to the other configuration. Case E provide the higher temperature difference between T1 and T ambient. It can be concluded that the capability of Case E to store high energy at 300 s and 600 s.

The energy gain value from the drying chamber for each type of absorber collector. T3 is the temperature outlet for the drying chamber and T ambient is the temperature inlet. From this data, it can be seen that the drying chamber of Case E has a higher value of energy gain which is 1279.16 J at 300 s. Case E also has higher energy at 600 s which is 609.83 J than another configuration. The energy storage can be used for drying when the simulator is turning off. The performance of the flat plate collector could be optimized when losses are reduced minimally and by increasing the outlet temperature [34] inside the drying chamber.

Table 3
The value for total heat storage (Q storage), heat transfer rate ($\dot{Q}$), efficiency (in %) and energy gain

	Case A	Case B	Case C	Case D	Case E
Q storage					
Total Heat Storage, Q (kJ)	181	236	254	322	412
Heat transfer rate ($\dot{Q}$)					
($\dot{Q}$) Charging (kW)	45.25	45.25	45.25	49.79	47.05
($\dot{Q}$) Discharging (kW)	57.10	57.10	57.10	63.19	65.26
Total ($\dot{Q}$) gain (kW)	11.86	11.86	11.86	13.39	18.21
Efficiency (%)	25.51	30.40	32.00	39.10	47.08
Energy gain (kJ) for T1 and T2					
Total Energy gain (kJ)	2.66	2.66	1.57	1.7	2.85
Energy gain (J) for T1 and Ta					
Energy (J) at 300 s	26.82	29.85	36.48	56.38	116.08
Energy (J) at 600 s	41.72	46.43	49.75	66.33	102.81
Energy gain (J) for T3 and Ta					
Energy (J) at 300 s	586.92	763.80	820.08	982.39	1279.16
Energy (J) at 600 s	249.44	324.62	348.53	462.30	609.83

Figure 7 show an example analysis for heat transfer rate ($\dot{Q}$) on FPBTCA (Case E). Heat transfer rate ($\dot{Q}$) was calculate based on Eq. (1). The table shows the data for 300 seconds charging and 300 seconds time period. The total experiment time was done in 600 seconds. The temperature difference is between T3 and Ta (ambient) was used for the calculation. The value of the area is

0.0441 m^2 and the fan constant speed of 0.62 m/s was used in this experiment. The density of air (ρ_{air}) apply in this experiment is 1.11 kg/m^3. Specific heat for air ($c_{p(air)}$) is 1005 kJ/kg.K was used in the calculation. Case E represent the highest ($\dot{Q}$) charging (with a value of 47.05 kW) and highest ($\dot{Q}$) discharging (with a value of 65.26 kW) as compare to other types of configurations. The total ($\dot{Q}$) gain for Case E is 18.21 kW.

CB	CC	CD	CE	CF	CG	CH	CI	CJ	CK	CL
Heat Transfer Rate ($\dot{Q}$)	Time	T3(°C)	Ta(°C)	T3(K)	Ta(K)	A(m²)	Vair(m/s)	ρair (kg/m3)	Cp(air) kJ/kg K	($\dot{Q}$) (W)
	588	34.4	29	307.4	302	0.0441	0.62	1.11	1005	164.71
	589	34.4	29	307.4	302	0.0441	0.62	1.11	1005	164.71
	590	34.4	29	307.4	302	0.0441	0.62	1.11	1005	164.71
	591	34.4	29	307.4	302	0.0441	0.62	1.11	1005	164.71
	592	34.3	29	307.3	302	0.0441	0.62	1.11	1005	161.66
	593	34.3	29	307.3	302	0.0441	0.62	1.11	1005	161.66
	594	34.2	29	307.2	302	0.0441	0.62	1.11	1005	158.61
	595	34.2	29	307.2	302	0.0441	0.62	1.11	1005	158.61
	596	34.2	29	307.2	302	0.0441	0.62	1.11	1005	158.61
	597	34.2	29	307.2	302	0.0441	0.62	1.11	1005	158.61
	598	34.2	29	307.2	302	0.0441	0.62	1.11	1005	158.61
	599	34.2	29	307.2	302	0.0441	0.62	1.11	1005	158.61
	600	34.1	29	307.1	302	0.0441	0.62	1.11	1005	155.56
								$\dot{Q}$ Charging (kW)		47.05
								$\dot{Q}$ Discharging (kW)		65.26
								Total ($\dot{Q}$) gain (kW)		18.21

Fig. 7. The analysis for heat transfer rate ($\dot{Q}$) on FPBTCA (Case E)

5. Conclusion

Based on the experiment were done under simulation with 300 seconds charging and 300 seconds discharging shows the result of the performance for different types of thermal absorber collector. There are several conclusions as follows

i. Thermal cell absorber gives a significant effect to the performance of FPBTCA than FPSC.
ii. Aluminum absorber base with stainless steel cell 1.0 mm thickness (Case E) is selected as a design parameter for FPBTCA.
iii. Aluminum absorber base with stainless steel cell 1.0 mm thickness (Case E) has good performances in term of outlet temperature which is, it has high outlet temperature, inside drying chamber compared to the other absorber collector configurations.
iv. Aluminum absorber base with stainless steel cell 1.0 mm (Case E) has high performance in term of heat storage ($Q_{storage}$), the heat transfer rate of the collector ($\dot{Q}$) and efficiency of the collector (%).
v. Aluminum absorber with stainless steel cell 1.0 mm (Case E) has higher energy gain at the bottom plate which is known as a dummy load.
vi. The research proved the performance of the thermal cell absorber attach with flat plate absorber collector (FPBTCA) can be used to produce low thickness design and lightweight portable collector application.

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