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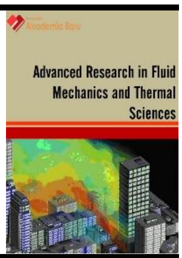

Investigation on The Thermal Performance of Evacuated Glass-Thermal Absorber Tube Collector (EGATC) for Air Heating Application

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ABSTRACT

Existing design of Heat-Pipe Evacuated Tube Collector (HP ETC) for water heating require storage tank while additional heat exchanger require for air heating application which leads to the extra spacing and costing. HP ETC also need to be tilt at the correct angle to optimize the system performance. Furthermore, the installation also needs to be positioned either to south or north facing to ensure the maximum absorption of energy. These could lead to the design limitation. The aim of this research is to investigate on the thermal performance of Evacuated Glass-Thermal Absorber Tube Collector (EGATC) for air heating application. EGATC was developed from conventional Evacuated Tube Collector (ETC) and the comparative result between HP ETC performance were evaluated. The three days outdoor experimental results show EGATC (Day 1: 50.9 °C, Day 2: 53.9 °C, Day 3: 49.2 °C) performed better with slightly higher temperature at outlet temperature compare with HP ETC (Day 1: 46.7 °C, Day 2: 50.3 °C, Day 3: 46.9 °C). It is concluded that EGATC have better performance in term of temperature different and outlet temperature as compared to HP ETC. EGATC (Day 1: 53.6%, Day 2: 50.6%, Day 3: 49.8%) also have greater efficiency in term of heat storage capability as compared to HP ETC (Day 1: 42.7%, Day 2: 41.6%, Day 3: 41.1%). Regarding energy buffer storage, EGATC have better energy storage compared to HP ETC at sudden weather change such as clouds. The outlet temperature of EGATC (42.3 °C) was remained slightly higher compared to HP ETC (39.9 °C) at the beginning. The outlet temperature gradually drops slower during discharging period until the end of the experiment for 15 minutes towards outlet temperature 41.1 °C and 37.2 °C for both EGATC and HP ETC with temperature difference 1.2 °C and 2.7 °C respectively.

Keywords:
Evacuated Glass-Thermal Absorber Tube Collector (EGATC); Heat Pipe Evacuated Tube Collector (HP ETC); Direct-flow Evacuated Tube Collector (Direct-flow ETC); solar air heating application

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1. Introduction

Solar heating system (water and air) operations are more efficient by using solar thermal collector compared to photo-voltaic (PV) system [1]. Numerous types of solar thermal collector namely flat plate collector (FPC) and heat-pipe evacuated tube collector (HP ETC) have been developed in various countries and has become increasingly important for integrated solar heating system in the past years [2]. However, conventional FPC have low thermal efficiency and its exergy efficiency decreased during off-sunshine hour [3]. Several researchers had agreed that ETC have much better efficiency than FPC [4,5]. Solar thermal collector efficiencies were found to be 46.1% and 60.7% for FPC and HP ETC, respectively whilst the system efficiencies were found to be 37.9% and 50.3% [6]. This experiment between FPC and HP ETC was conducted simultaneously with similar environmental conditions. Regarding the performance, HP ETC have better performance to produce high outlet temperature than FPC, especially in cold climates condition [7]. The performance levels of solar thermal collectors can be enhanced through several techniques, such as the usage of extended surface i.e. fins, corrugated absorber, packed bed materials and artificial roughness [8]. A large range of temperature can be obtained by different solar thermal collector configuration, for example 20 °C – 80 °C is the operating temperature of FPC and 50 °C – 200 °C is for HP ETC [9-11]. Although FPC produce low and moderate temperatures of hot air but it is found to be appropriate for drying of agricultural products [3]. To be in line with technological advancements, the technical directions in the development of solar-assisted drying systems for agricultural product should be compact collector design, high efficiency, integrated storage, and long-life drying system [12].

For both FPC or HP ETC, needs to be positioned either to south facing for Northern Hemisphere or north facing for Southern Hemisphere [13]. The use of sun tracker may increase the preliminary setup and maintenance cost for both residential users and solar plants [14]. Furthermore, both needs to be tilted at the correct angle during installation to maximize the performance of the system which can limit its orientation [15,16]. For areas located in the equatorial, the solar collector needs to be flat in order to obtain maximum energy from solar radiation throughout the year [17]. Regarding the panel orientation, the maximum output of the solar PV cell also requires a perpendicular light on its surface where radiation can be captured [18].

The existing design of solar drying for space or air heating system utilize the working liquid as the medium of heat storage which requires large space and needs of special compartment to store the latent heat which led to the additional space and load increment [19-21]. Fudholi *et al.,* [22] had developed greenhouse solar drying system with heat exchanger. This forced convection design consists of the HP ETC, electric heater, blower, water pumps, storage tank and drying chamber required extra space on the design, resulting in load increment. This design is not suitable if the devices are required to be located at the delicate space such as the roof top. For FPC and HP ETC which integrates the energy storage in its system, the energy storage compartment is generally constructed separately from the collector unit [23].

The thermal absorber can be integrated with heat storage material to increase the efficiency. Besides, the integrated design between thermal absorber and evacuated glass eliminates both conduction and convection losses between the absorbing surface and outside ambient temperature [24]. The thickness of the thermal absorber wall and the use of extended surface using fins [8] are act as thermal energy storage material during diffuse radiation condition. In addition, the proper design of inner absorber through the dryer chamber creates the pre-heating and double pass flow, resulting in high cumulative outlet temperature. In order to reduce the thermal losses by convection and conduction all the components involve are designed as a built-in system.

The first evacuated tubular collectors were built and tested by Speyer [25]. Speyer was constructed a U- tube joining the two conduits attached with spiral spring (conduits support) as a thermal absorber which are mounted inside the evacuated glass tube. Kalogirou [26] was among the earlier researchers who introduced efficient HP ETC for water heater and air heating (use water as heat storage material) purposes in 2004.

Based on the authors' knowledge, there have been no study on integration of thermal absorber with evacuated glass for air heating application reported. The aim of the research is to develop the new design of thermal absorber. The enhancement of the thermal absorber design which capable to increase the performance and efficiency of the conventional HP ETC technology will be introduce. This new design is known as Evacuated Glass-Thermal Absorber Tube Collector (EGATC). The integrated evacuated glass tube collector with thermal absorber consists of inner and outer stainless-steel pipe with fins for air heating applications. Several outdoor experiments have been conducted and comparison have been made between EGATC and HP ETC in term of outlet temperature, thermal buffering and efficiency.

2. Research Methodology

The solar thermal collector used in this study was named as Evacuated Glass–Thermal Absorber Tube Collector (EGATC) is shown in Figure 1. The thermal absorber was divided into two (2) parts i.e. inner absorber and outer absorber. Inner absorber consists of small diameter pipe attached with the fins while outer absorber consists of large diameter pipe closed by one side end cap. Both thermal absorbers were integrated together inside the evacuated glass. The novel thermal absorber design creates double pass flow for the system and pre-heating flow at the inner absorber resulting in high cumulative temperature at the outlet temperature. The vacuum pocket of evacuated glass eliminated the heat loss through convection and conduction between the thermal absorber and ambient, so the collectors can operate at higher temperatures [27].

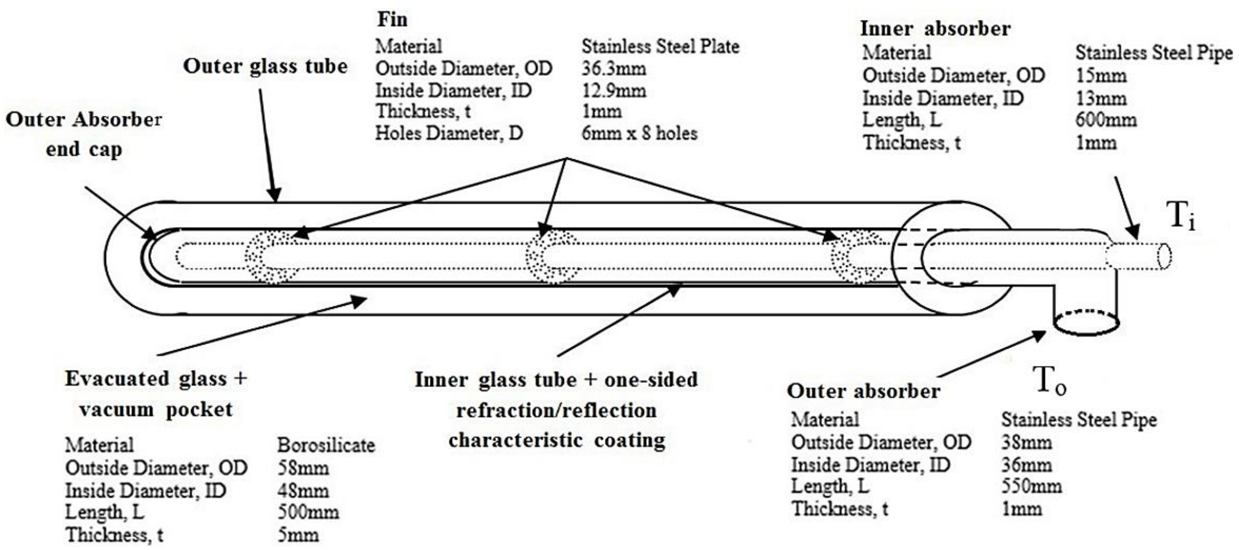


Fig. 1. Evacuated glass – thermal absorber tube collector (EGATC)

The outer glass tube was transparent purposely to transmit solar radiation through vacuum pocket to inner glass tube directly. The inner glass tube is coated by one-sided refraction/reflection characteristic coating which allow the heat transfer via radiation and convection to the gap between inner glass tube and solar thermal absorber. The inner glass tube transmits the short-wavelength solar radiation but block the reflection of the longer-wavelength irradiation to the vacuum pocket. These greenhouse effect phenomena accumulate the heat energy inside the gap simultaneously increased the temperature at outer absorber. Then the heat will be transferred via conduction through fins and convection to inner absorber. Indirectly, the fins and the wall thickness of the thermal absorber will act as the heat storage materials. These heat transfer process will develop the cumulative heat gain inside the solar thermal absorber design. Basically, Evacuated tube collector (ETC) have demonstrated that the combination of a selective surface and an effective convection suppressor can result in good performance at high temperatures [28]. Figure 2 show the heat transfer occur inside the EGATC.

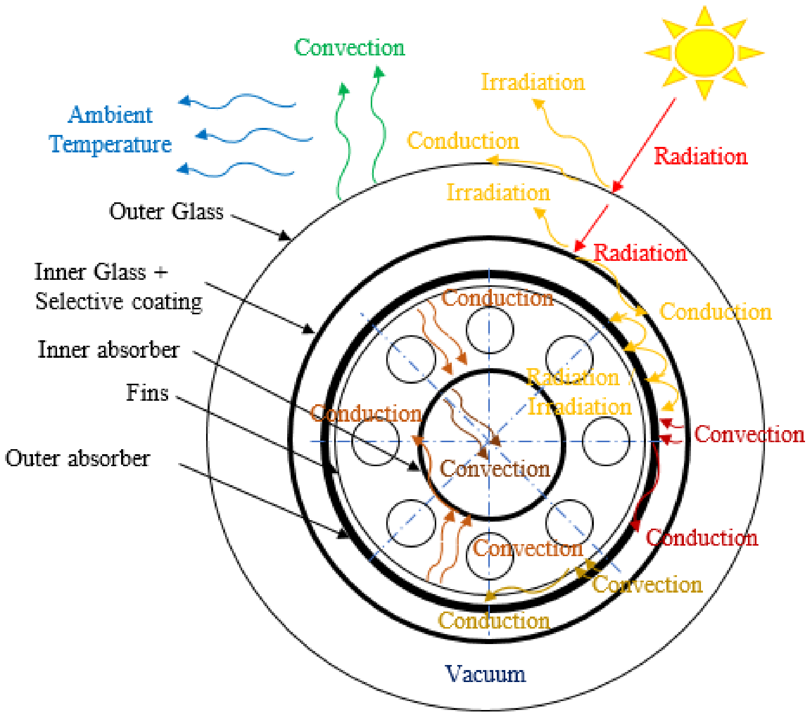
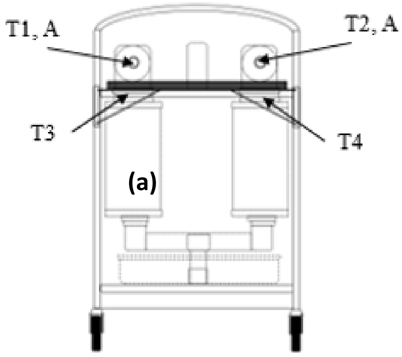


Fig. 2. The heat transfer mechanism involved at the thermal absorber of EGATC

The determination of solar thermal collector performance and efficiency was conducted and the experimental setup including sensor location as shown in Figure 3. Two (2) units of data Logger, 8-Channel Temperature Meter was used to record the data along the experiment. Out of 16-channel, five (5) channels were unused, one (1) channel was allocated for global solar radiation, G_t and others ten (10) channel were allocated for temperature data. Ten (10) unit of K-type thermocouple were used to record the temperature data namely, T1 until T10. T1, T2, T3 and T4 were used to sense the air inlet temperature and air outlet temperature (inside dryer chamber) for both HP ETC and EGATC, while T5 until T9 were used to sense the temperature of the thermal absorber and heat pipe at five (5) different location respectively. Meanwhile T10 was used to record the ambient temperature. The experiment was run under the real solar radiation condition. The temperature and solar radiation data were recorded by data logger every one (1) minute interval. At Day 1, during the initial setup, the fan speed controller was adjusted to 5.0V with the wind speed data are 0.74 m/s. As the data are constantly changing along the experiment, the wind speed data was recorded every four (4) hour intervals to find its average value 0.67 m/s. The same procedure was followed for the next 2 days where the voltage of fan speed controller and average wind speed value were remained for both day

2 and day 3. All the recorded data was analyzed and the graph was plotted after the experiment done.



Label	Description	Label	Description
T1	HP ETC inlet temperature	T8	Center thermal absorber temperature
T2	EGATC inlet temperature	T9	Bottom thermal absorber temperature
T3	HP ETC outlet temperature	T10	Ambient temperature
T4	EGATC outlet temperature	G_t	Global Solar radiation (Pyranometer)
T5	Heat pipe condenser temperature	PV Panel	Photo Voltaic Panel
T6	Heat pipe evaporator temperature	EGATC	Evacuated Glass-Thermal Absorber Tube Collector
T7	Top thermal absorber temperature	HP ETC	Heat Pipe Evacuated Tube Collector
		A	Area of inlet duct, (m^2) ($A = 5.47 \times 10^{-4}$ m^2)

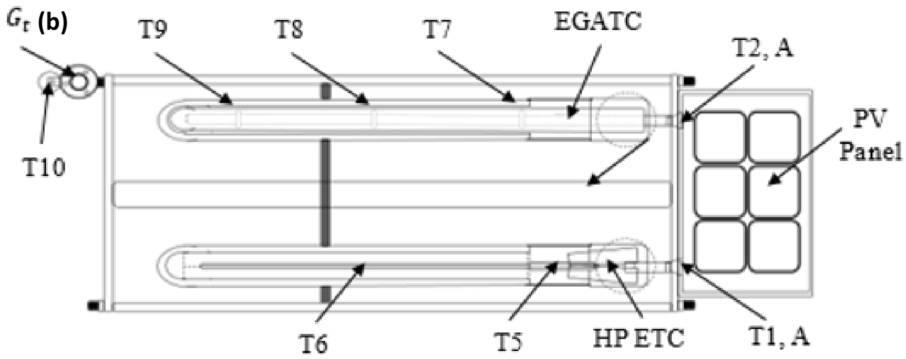


Fig. 3. Experimental setup for determining the solar thermal collector performance and efficiency. (a) Side view and (b) plan view of the test rig

2.1 Device and Apparatus

The experimental devices and apparatus used in this work are explained in this section. The experiment was done to compare the thermal efficiency and performance between EGATC and HP ETC as a control reference. The apparatus was exposed to the real solar radiation within the range 0.1 W/m² to 969.3 W/m² for three (3) days. In order to measure the temperature at the thermal absorber wall and the solar radiation flux, APPLENT TECHNOLOGIES, Multi-Channel Temperature Meter (8-CH) (AT4208) and APOGEE INSTRUMENTS, Silicon-Cell: Self Powered Pyranometer (SP-110-SS) were utilized. While for calibration purposes, the real time solar radiation flux was measured using TES ELECRICAL ELECTRONIC CORPORATION, Datalogging Solar Power Meter (TES-1333R). The reading taken by both Pyranometer and datalogger were calibrated for its validity and reliability before conducting an experiment. The wind speed was measured by TESTO, Digital Display Hot-Wire Anemometer (405-V1).

The thermal absorber acts as heat storage material comprising inner absorber and outer absorber. Inner absorber was made up by stainless steel pipe (with dimensions of 15mm outside diameter x 1.0mm thickness x 600mm length) attached with three (3) stainless steel fins (with dimensions of 36.3mm outside diameter x 12.9mm inside diameter x 1.0mm thickness, 6mm diameter x 8 holes), while outer absorber was made up by stainless steel pipe (with dimensions of 38mm outside diameter x 1.0mm thickness x 550mm length). Both inner and outer absorber were assembled together inside MISOLIE TECHNOLOGY, high borosilicate glass evacuated tube (with dimensions of 58mm outside diameter x 48mm inside diameter x 500mm length) by one-sided refraction/reflection characteristic coating to eliminate heat loss through convection and radiation between the solar thermal absorber and ambient.

As per HP ETC, MISOLIE TECHNOLOGY heat pipe (with dimension of 400mm length (including header) x 14mm header diameter x 8mm pipe diameter) attached with an aluminium fin was assembled together inside the same specification of an evacuated tube with EGATC arrangement. The heat energy collected by both solar collectors was stored inside the separated ventilated drying chamber (with dimensions of 110mm outside diameter x 320mm length). In order to avoid heat losses through the bottom and sides of the chamber, the insulation layer with the thickness of 4 mm was applied. An experimental work has been conducted as the outdoor experiment for three (3) days and were exposed to ambient condition i.e. clouds and rain. The details of an experiment conducted are explained in the following sub-sections.

3. Performance and Efficiency Evaluation of the System

For assumption, the system in this study was considered as a closed system and did not involve any velocity and elevation change. Hence, the heat transfer rate of the collector is expressed as [22,27]:

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

Eq. (1) is used to convert energy from solar radiation into heat in order to increase the outlet temperature of the collector by referring to inlet temperature. While, Eq. (2) is used to calculate energy from solar radiation that converted into energy storage in the thermal absorber by referring to instantaneous energy accumulation for each second. The heat transfer rate of the thermal absorber storage is expressed as [22,27]

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

Hence, the efficiency of the collector and storage is expressed as

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

By resolve the Eq. (1) and Eq. (2) into Eq. (3), 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 = Density of air (kg/m^3)
A = Area of inlet duct (m^2)
v = 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 collector (m^2)
m_{ab} = Mass of thermal absorber (kg)
$C_{p(ab)}$ = Specific heat of thermal absorber (kJ/kgK)
T_2 = Temperature of thermal absorber after heat gain (K)
T_1 = Temperature of thermal absorber before heat gain (K)
t_2 = Time after heat gain (s)
t_1 = Time before heat gain (s)

The outdoor experiment was done for 3 days (12 - 14 November 2019) from 9.30 am until 5.30 pm (refer Figure 4). The experiment was done to monitor the outlet temperature between EGATC air heater and HP ETC air heater. Before, the preliminary experiment has been done at 8° slope angle. According Li *et al.,* [29], typical HP ETC system require slope angle during installation for heat pipe to operate efficiently. Since the result shown non-significant effect due the slope with regard of outlet temperature, the slope angle was considered insignificant in this study.

Fig. 4. The outdoor experiment between EGATC air heater and HP ETC air heater

The results show the inlet and outlet temperature profile for both HP ETC and EGATC air heater during the whole duration of the experiment on Day 1 (Tuesday, 12 November 2019). From the Figure 5, the inconsistent solar radiation profile during the day of experimental work was cloudy with the radiation value fluctuate between 35.6 – 798.9 W/m^2. However, the performance was quite notable where the difference between the outlet temperature for both collectors and ambient during initial stage of an experiment were 8.2 °C and 10.7 °C for HP ETC and EGATC, respectively. The maximum outlet temperature of the day was attained at 10.22 a.m. with solar radiation 673.2 W/m^2. The outlet temperature arises at 46.7 °C for HP ETC and 50.9 °C for EGATC. As the experiment going further, the solar radiation heavy fluctuation does affect the performance of both collectors. However, direct heat conversion characteristic via EGATC influent the outlet temperature profile more consistence as compared to the one with HP ETC due to the thermal buffer effect. This can be shown by the discharge rate of each air heater outlet temperature profile as labelled by “A” and “B”. As per “A”, the temperature discharge rate of HP ETC and EGATC were -0.0012 °C/s and -0.0011 °C/s, respectively with solar radiation drop from 798.9 W/m^2 to 393.2 W/m^2. Meanwhile, as for "B", at 227.7 W/m^2 radiation drop producing temperature discharge rate of -0.0005 °C/s and -0.0003 °C/s for HP ETC and EGATC, respectively.

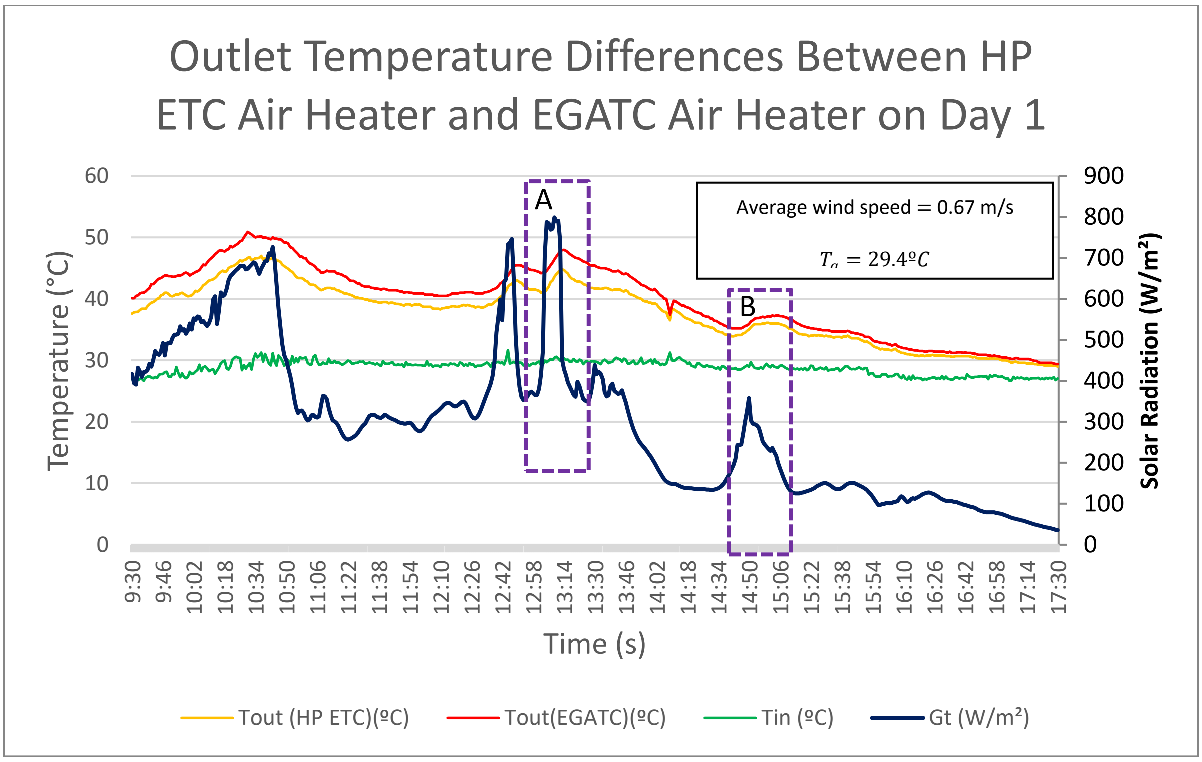


Fig. 5. Outlet temperature differences between HP ETC air heater and EGATC air heater on Day 1

The results of the inlet and outlet temperature profile for both HP ETC and EGATC on Day 2 (Wednesday, 13 November 2019) show on Figure 6. The inconsistent solar radiation profile during the day of experimental work was raining and cloudy with the radiation value fluctuate between 74.4 – 824.9 W/m^2. However, the performance of both collectors was quite notable where the difference between the outlet temperature and ambient during initial stage of an experiment were -1.1 °C and -0.8 °C for HP ETC and EGATC, respectively. The maximum outlet temperature of the day was attained at 13.28 p.m. with solar radiation 469.3 W/m^2. The outlet temperatures were maximum at 50.3 °C for HP ETC and 53.8 °C for EGATC. As the experiment going further, the solar radiation heavy fluctuation does affect the performance of both collectors. However, direct heat conversion characteristic via EGATC influent the outlet temperature profile more consistence as compared to the one with HP ETC due to the thermal buffer effect. This can be shown by the temperature discharge rate of each air dryers outlet temperature profile as labelled by "C" and "D". As per "C", the discharge rate of HP ETC and EGATC were -0.0037 °C/s and -0.0010 °C/s, respectively with solar radiation drop 505.8 W/m^2, from 825.0 W/m^2 to 319.2 W/m^2. Meanwhile, as for "D", at 78.5 W/m^2 radiation drop with solar radiation from 293.0 W/m^2 to 214.5 W/m^2 producing temperature discharge rate of -0.0002 °C/s and -0.0001 °C/s for HP ETC and EGATC, respectively.

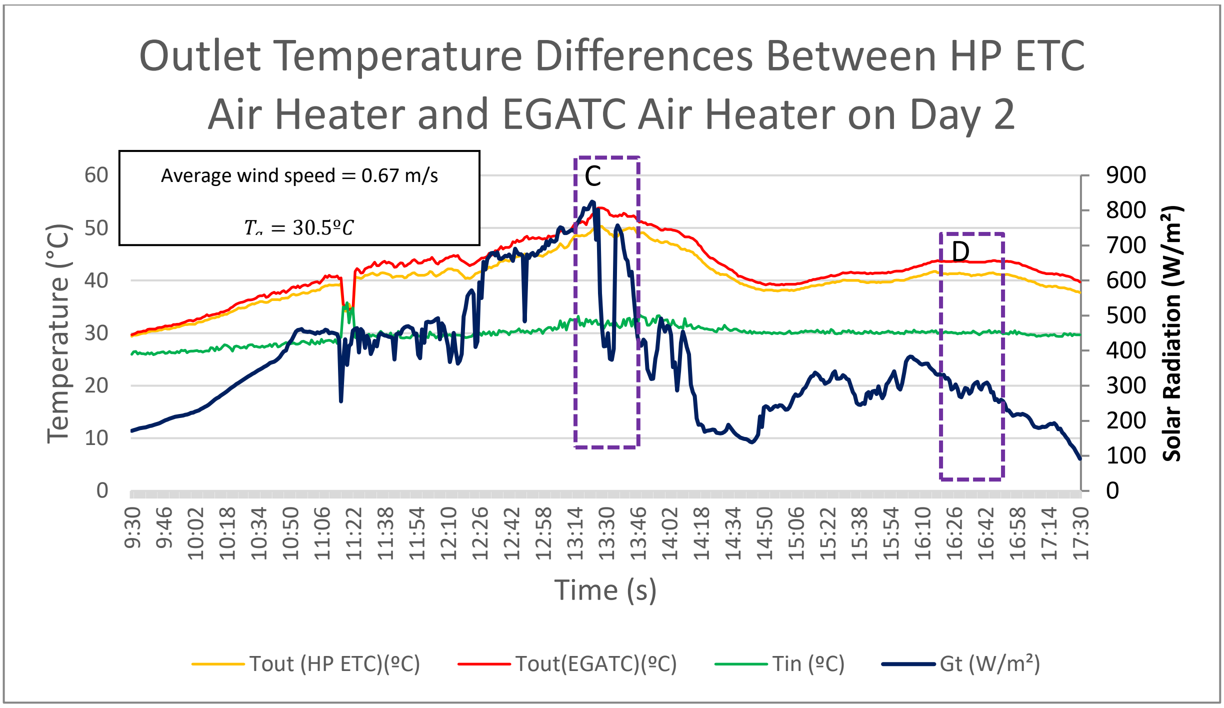


Fig. 6. Outlet temperature differences between HP ETC air heater and EGATC air heater on Day 2

Figure 7 shows the results of inlet and outlet temperature profile for both HP ETC and EGATC on Day 3 (Thursday, 14 November 2019). The radiation value was inconsistent and fluctuate between 0 – 969.3 W/m^2 due to the rainy day. The difference between the outlet temperature for both collectors and ambient during initial stage of an experiment were 3.2 °C and 3.9 °C for HP ETC and EGATC, respectively. The maximum outlet temperature for the day was attained at 11.29 a.m. with solar radiation 420.6 W/m^2. The maximum outlet temperatures were 46.9 °C for HP ETC and 49.2 °C for EGATC. After a while, the solar radiation diffuse for a long duration does affect the performance of both collectors. However, EGATC influent the outlet temperature profile more consistence through its direct heat conversion characteristic as compared with HP ETC. The thermal buffer effect can be shown by the discharge rate of each air dryers outlet temperature profile as labelled by “E” and “F”. As per “E”, the temperature discharge rates of HP ETC and EGATC were -0.0146 °C/s and -0.0084 °C/s, respectively with solar radiation drop 561.9 W/m^2. Meanwhile, as for “F”, with solar radiation drop from 147.1 W/m^2 to 14.9 W/m^2 producing temperature discharge rates of -0.0006 °C/s and -0.0005 °C/s for HP ETC and EGATC, respectively.

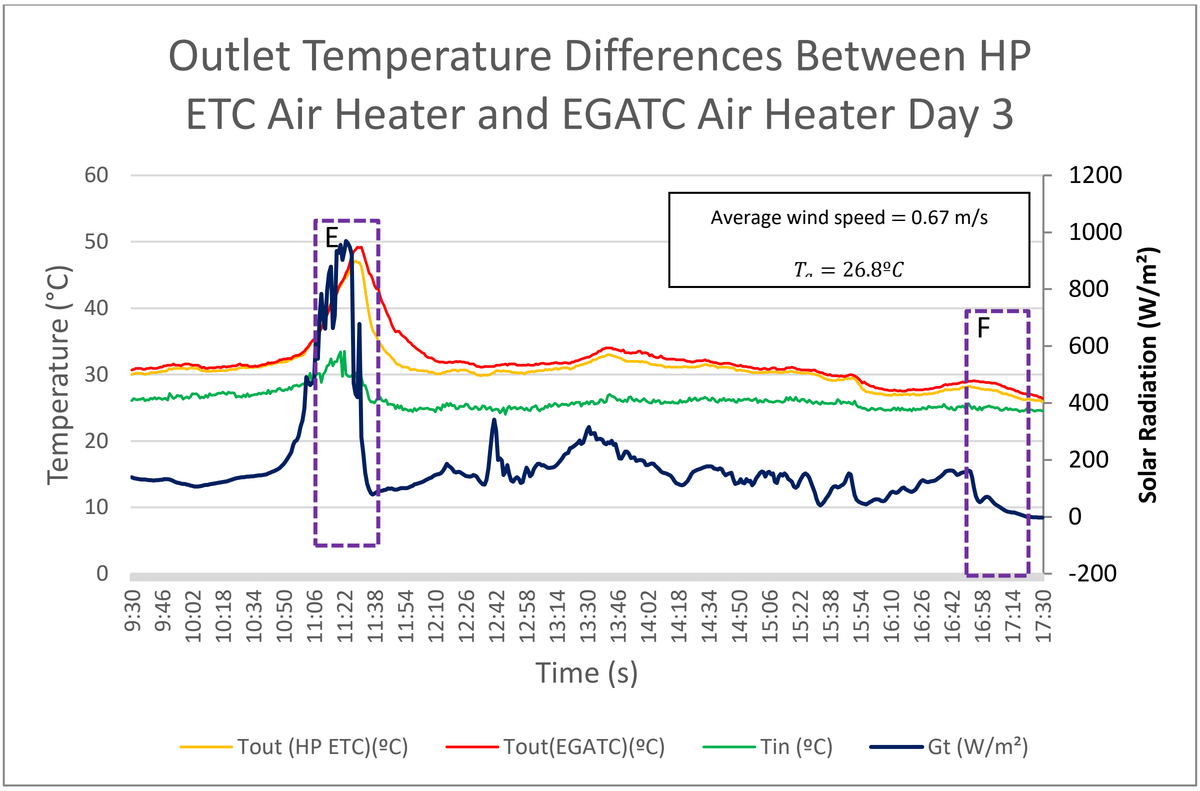


Fig. 7. Outlet temperature differences between HP ETC air heater and EGATC air heater on Day 3

Based on the outlet temperature differences between HP ETC air heater and EGATC air heater on each day, EGATC performance was better at initial outlet temperature with slightly higher temperature than the HP ETC. The initial outlet temperature was recorded early in the morning when the ambient humidity was high at low solar radiation. The low cumulative heat gain inside the evacuated glass able to increase the temperature of the EGATC thermal absorber but failed to do the same for HP ETC. As HP ETC working principle, the working liquid inside the heat pipe must be heated up to a boiling temperature to allow it to function properly.

While, for the maximum outlet temperature differences between HP ETC air heater and EGATC air heater on each day, EGATC attained slightly higher temperature compared to HP ETC at the medium range of solar radiation. Maximum outlet temperature produced by EGATC also good enough to ensure the perfect drying of agricultural products. Table 1 shows the summary of the calculated values of solar radiation range and temperature discharge rate obtained from the experimental run. Based on the result and observation, EGATC produce small value of temperature discharge rate compared with HP ETC when the solar radiation drops. In other words, EGATC has been release small amount of temperature in a second. The ‘-’ve signed of temperature discharge rate represent the direction of the graph gradient.

Table 1
Summary of the calculated values of solar radiation range and temperature discharge rate obtained from the experimental runs

Label	Parameters	HP ETC	EGATC
A	Solar radiation range, W/m^2	798.9 – 393.2	
	Solar radiation drops, W/m^2	405.7	
	Temperature discharge rate, °C/s	-0.0012	-0.0011
B	Solar radiation range, W/m^2	358.4 – 130.7	
	Solar radiation drops, W/m^2	227.7	
	Temperature discharge rate, °C/s	-0.0005	-0.0003
C	Solar radiation range, W/m^2	825.0 – 319.2	
	Solar radiation drops, W/m^2	505.8	
	Temperature discharge rate, °C/s	-0.0037	-0.0010
D	Solar radiation range, W/m^2	293.0 – 214.5	
	Solar radiation drops, W/m^2	78.5	
	Temperature discharge rate, °C/s	-0.0002	-0.0001
E	Solar radiation range, W/m^2	677.9 – 116.0	
	Solar radiation drops, W/m^2	561.9	
	Temperature discharge rate, °C/s	-0.0146	-0.0084
F	Solar radiation range, W/m^2	147.1 – 14.9	
	Solar radiation drops, W/m^2	132.2	
	Temperature discharge rate, °C/s	-0.0006	-0.0005

The thermal buffer effect is very useful for the air heating applications in the condition where there is intermittent solar radiation and during the unavailability of the solar radiation. Figure 8 shows the daily performance between HP ETC air heater and EGATC air heater. This outdoor experiment was done from 9.30 a.m. to 4.30 p.m. with average wind speed 0.28 m/s. At the beginning, the outlet temperature for both HP ETC air heater and EGATC air heater are 33.6 °C and 34.6 °C, respectively with solar radiation 431.0 W/m^2. Then, the solar radiation was fluctuated between 99.9 W/m^2 to 838.9 W/m^2 until 11.00 am before it continues decrease until afternoon. At 1.11 pm, those collectors were coverup to create diffuse solar radiation condition. During the time, the outlet temperature for both HP ETC and EGATC are 32.8 °C and 34.2 °C, respectively. After 30 minutes the outlet temperature for both collectors decrease to 32.5 °C for HP ETC and 33.8 °C for EGATC. In order to attain toward ambient temperature, T_a = 27.9 °C, HP ETC outlet temperature need 126 minutes while EGATC outlet temperature need 129 minutes.

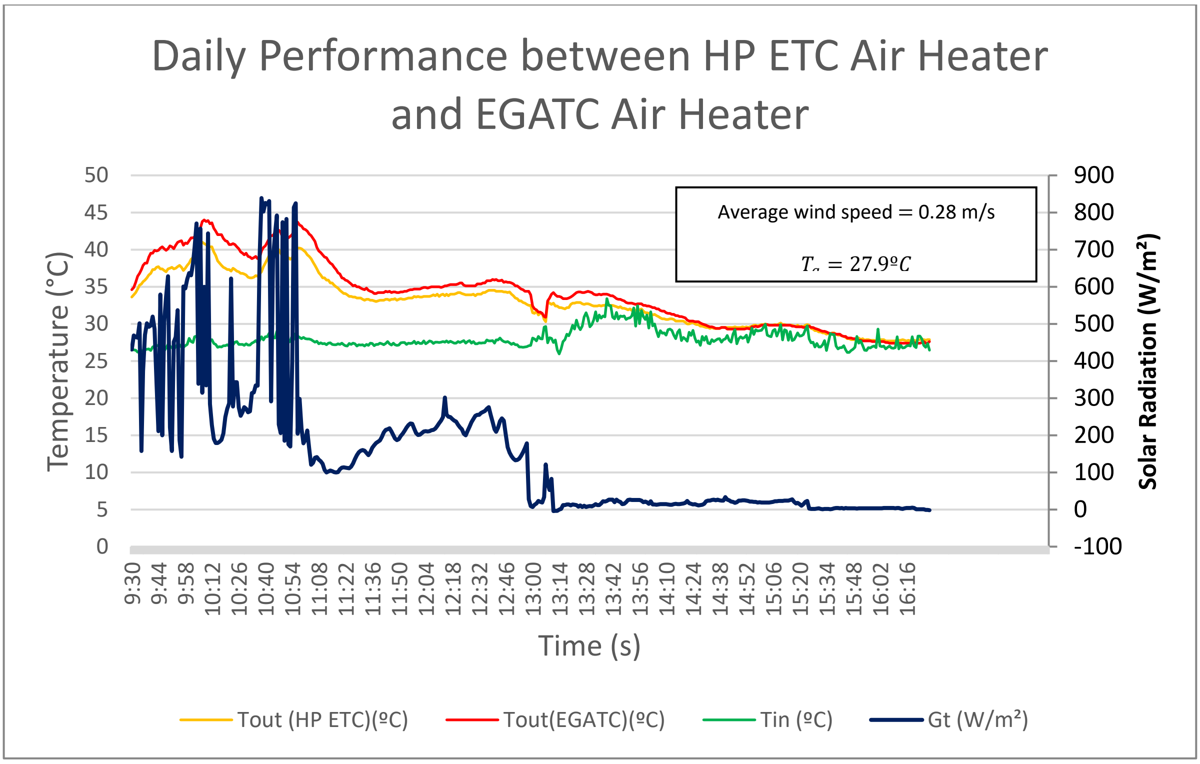


Fig. 8. Daily performance with total energy storage between HP ETC air heater and EGATC air heater

The thermal absorption respond time between HP ETC air heater and EGATC was shown in Figure 9. This outdoor experiment was done in duration of 30 minutes. The first 15 minutes was charging period with average solar radiation 570.9 W/m^2 and another 15 minutes the solar radiation had been remove to the null value to create the discharging period. Since the initial outlet temperature was recorded in the evening, the ambient humidity was low with intermediate solar radiation range. The intermediate solar radiation created cumulative heat gain inside the evacuated glass and heated up the working liquid inside the heat pipe. The working liquid experienced the phase change from liquid to superheated vapor thus condensed to the heat pipe condenser which is located on the top of the heat pipe. The heat pipe condenser produced the high temperature (superheated temperature) and attached to the plate as heat transfer medium to the outlet air. Therefore, HP ETC initial outlet temperature (32.2 °C) was slightly higher than EGATC (31.4 °C) in the evening. As the experiment going further, after 8 minutes the EGATC outlet temperature was increasing to 36.9 °C compared to the HP ETC 36.7 °C. At minutes 16, the discharging condition was created by cover up the both solar thermal collectors. EGATC outlet temperature was remained slightly higher than HP ETC which is 42.3 °C and 39.9 °C, respectively. The polar was continued until at the end of the experiment at minutes 30. For both EGATC and HP ETC, the outlet temperature is 41.1 °C and 37.2 °C, respectively.

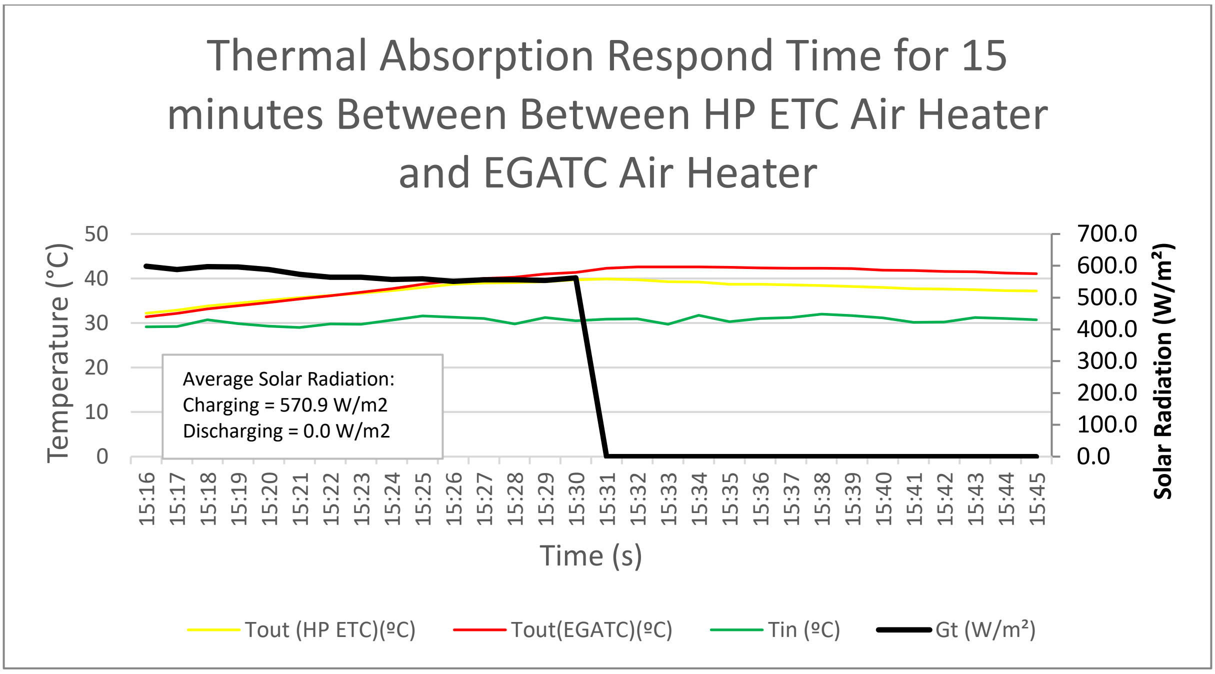


Fig. 9. Thermal absorption respond time for 15 minutes between HP ETC air heater and EGATC air heater while charging and discharging period

As for reference, the total maximum heat storage capability obtained from Eq. (2) for EGATC are 38.22 kJ at solar radiation 1025.9 W/m^2. This outdoor experiment was done under the real exposure of solar radiation with constant airflow from 09.30a.m to 5.30p.m. Based on the efficiency evaluation analysis, EGATC capable to store larger amount of heat compare to HP ETC as shown in Table 2. The data for the analysis was obtained from the outdoor experiment on outlet temperature differences between HP ETC air heater and EGATC air heater. The total daily collected energy from global solar radiation (G_t) by solar thermal collector, partially is converted into heat which increases the outlet temperature and at the same time it is used as the heat storage by the thermal absorber.

Table 2
Summary of the efficiency analysis obtained from the outdoor experiment

	DAY 1		DAY 2		DAY 3	
	G_t hour/day = 2.39 hour Average Airflow, V = 0.67 m/s		G_t hour/day = 2.98 hour Average Airflow, V = 0.67 m/s		G_t hour/day = 1.39 hour Average Airflow, V = 0.67 m/s	
	EGATC	HP ETC	EGATC	HP ETC	EGATC	HP ETC
E ($\boldsymbol{G_t A_c}$) (kJ)	247.59	247.59	308.81	308.81	143.856	143.86
E ($\dot{\boldsymbol{Q}}_{\boldsymbol{Collector}}$) (kJ)	130.76	104.52	148.84	124.06	70.03	57.93
Efficiency (Collector) (%)	52.8	42.2	48.2	40.2	48.7	40.3
$\boldsymbol{Q_{Store}}$ (Daily) (kJ)	2.06	1.29	7.35	4.39	1.60	1.13
Efficiency (Collector + Storage) (%)	53.6	42.7	50.6	41.6	49.8	41.1

As Day 1 with global solar radiation, G_t hour per day are 2.39 hour with average air flow, V are 0.67 m/s, total daily collected energy from global solar radiation (G_t) for area of collector (A_c) = 0.0288m^2, E($G_t A_c$) were 247.59 kJ for both EGATC and HP ETC collectors. Total daily energy gain produced by solar thermal collector E ($\dot{Q}_{Collector}$) for EGATC were 130.76 kJ and 104.52 kJ for HP ETC.

By implementation of Eq. (3), the collector's efficiency was 52.8% and 42.2% for EGATC and HP ETC, respectively. In addition, daily energy stored by thermal absorber, Q_{Store} by EGATC was 2.06 kJ whilst by HP ETC was 1.29 kJ. From Eq. (4), the efficiency of collector with storage ability were 53.6% and 42.7% for both EGATC and HP ETC, respectively.

On Day 2, the global solar radiation, G_t hour per day are 2.98 hour and average air flow, V are 0.67 m/s. For both EGATC and HP ETC, total daily collected energy from global solar radiation, E$(G_t A_c)$ was 308.81 kJ. Total daily energy gain produced by solar thermal collector E $(\dot{Q}_{Collector})$ for EGATC were 148.84 kJ and 124.06 kJ for HP ETC. The efficiency of collector obtains for EGATC and HP ETC were 48.2% and 40.2%, respectively. The daily stored energy by thermal absorber, Q_{Store} by EGATC was 7.35 kJ on the other hand by HP ETC was 4.39 kJ. For both EGATC and HP ETC, the efficiency of collector with storage ability obtains were 50.6% and 41.6%, respectively.

As on Day 3, total daily collected energy from global solar radiation, E$(G_t A_c)$ was 143.86 kJ for both EGATC and HP ETC collectors with global solar radiation, G_t hour per day are 1.39 hour and average air flow, V are 0.67 m/s. Total daily energy gain produces by solar thermal collector E $(\dot{Q}_{Collector})$ for EGATC were 70.03 kJ and 57.93 kJ for HP ETC. The obtained efficiency of solar collector was 48.7% for EGATC and 40.3% for HP ETC. The daily stored energy by thermal absorber, Q_{Store} by EGATC and HP ETC were 1.60 kJ and 1.123 kJ, respectively. The efficiency of collector with storage ability for both EGATC and HP ETC were 49.8% and 41.1%, respectively.

With the theoretical, experimental result and analysis support, it can be concluded EGATC have greater efficiency in term of heat storage capability, discharge rate and thermal absorption respond time as compared to HP ETC. EGATC will be introduced as the new design of solar thermal collector to strengthen the conventional HP ETC. EGATC is located under ETC section which is same group with HP ETC, Direct-Flow ETC and ETSC. EGATC is design purposely for air heating application while others especially Direct-Flow ETC is focusing on water heating and HP ETC is targeting for both, water heating and air heating with the usage of heat exchanger. Figure 10 shows the types of ETC and the location where EGATC is categorized.

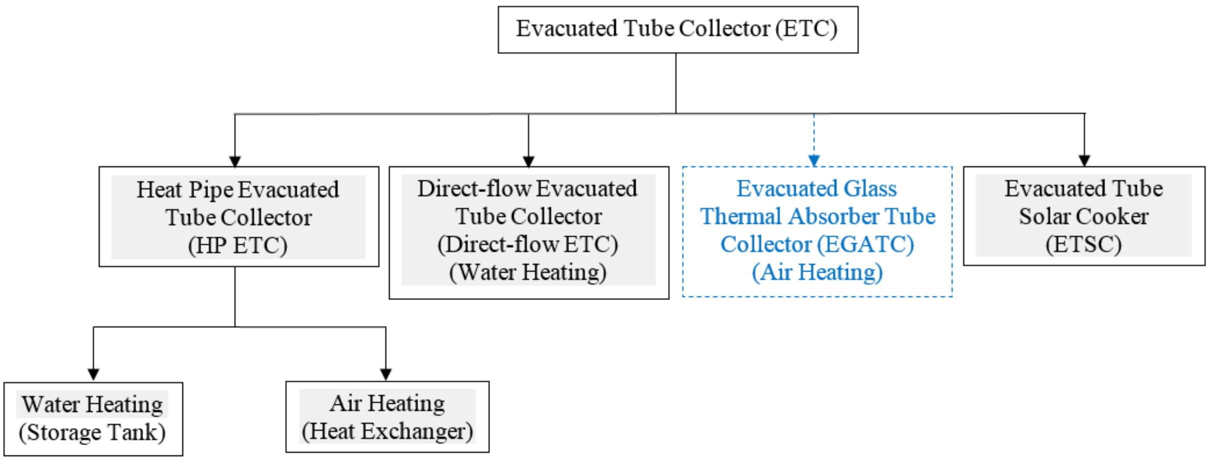


Fig. 10. Types of Evacuated Tube Collector (ETC). Blue dotted box shows where EGATC is put in place

4. Conclusion

Performance study of EGATC shows that this design proves better result compared to HP ETC on the outlet temperature and energy buffer storage for solar air heating applications. The analysis was carried out through outdoor experiment, by recorded solar charging and discharging heat rate between EGATC and HP ETC with responding to weather change such as diffuse solar radiation during clouds. Based on this experimental work, several conclusions are made, as follows

i. EGATC have better performances in term of air inlet and outlet temperature differences with high outlet temperature as compared to HP ETC.
ii. EGATC have greater efficiency with better solar heat absorption to energy conversion respond time and better thermal absorber heat storage which is provides consistent heat discharge rate as compared to HP ETC. Based on the obtained result, EGATC demonstrated more design flexibility in terms of thickness and selected material of the thermal absorber. Thicker thermal absorber with high heat capacity material can be selected for high heat energy storage applications.
iii. EGATC was designed to meet requirement of Good Manufacturing Practice (GMP) for drying food whereby selective surface could be coated outside on thermal absorber to avoid direct contact with drying material.
iv. The experiment was setup as the solar thermal collector in the flat orientation. The installation of EGATC does not required tilt angle and positioning of northern and southern hemisphere as compared to conventional HP ETC.
v. For air heating applications, EGATC provide direct heat conversion compare to HP ETC which is the system need working liquid to be assemble together with water tank as an energy storage and heat exchanger to operate.
vi. EGATC have broad surface area contact between thermal absorber and air which is the entire thermal absorber will convert the heat directly as compared to HP ETC rely on heat pipe condenser with small surface area.

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References
[1] Matuska, Tomas, and Borivoj Sourek. "Performance analysis of photovoltaic water heating system." *International Journal of Photoenergy* 2017 (2017). https://doi.org/10.1155/2017/7540250
[2] Sabiha, M. A., R. Saidur, Saad Mekhilef, and Omid Mahian. "Progress and latest developments of evacuated tube solar collectors." *Renewable and Sustainable Energy Reviews* 51 (2015): 1038-1054. https://doi.org/10.1016/j.rser.2015.07.016
[3] Fudholi, Ahmad, and Kamaruzzaman Sopian. "A review of solar air flat plate collector for drying application." *Renewable and Sustainable Energy Reviews* 102 (2019): 333-345. https://doi.org/10.1016/j.rser.2018.12.032
[4] Morrison, G. L., I. Budihardjo, and M. Behnia. "Water-in-glass evacuated tube solar water heaters." *Solar Energy* 76, no. 1-3 (2004): 135-140. https://doi.org/10.1016/j.solener.2003.07.024
[5] Zubriski, Stephanie Erin, and K. J. Dick. "Measurement of the efficiency of evacuated tube solar collectors under various operating conditions." *Journal of Green Building* 7, no. 3 (2012): 114-130. https://doi.org/10.3992/jgb.7.3.114
[6] Ayompe, L. M., Aidan Duffy, M. Mc Keever, Michael Conlon, and S. J. McCormack. "Comparative field performance study of flat plate and heat pipe evacuated tube collectors (ETCs) for domestic water heating systems in a temperate climate." *Energy* 36, no. 5 (2011): 3370-3378. https://doi.org/10.1016/j.energy.2011.03.034
[7] Mahdjuri, F. "Evacuated heat pipe solar collector." *Energy Conversion* 19, no. 2 (1979): 85-90. https://doi.org/10.1016/0013-7480(79)90004-4

[8] Saxena, Abhishek, and A. A. El-Sebaii. "A thermodynamic review of solar air heaters." *Renewable and Sustainable Energy Reviews* 43 (2015): 863-890. https://doi.org/10.1016/j.rser.2014.11.059
[9] Sharma, Neeraj, and Gerardo Diaz. "Performance model of a novel evacuated-tube solar collector based on minichannels." *Solar Energy* 85, no. 5 (2011): 881-890. https://doi.org/10.1016/j.solener.2011.02.001
[10] Kalogirou, Soteris A. Solar energy engineering: processes and systems (Second Edition). Academic Press, 2014.
[11] Tyagi, V. V., S. C. Kaushik, and S. K. Tyagi. "Advancement in solar photovoltaic/thermal (PV/T) hybrid collector technology." *Renewable and Sustainable Energy Reviews* 16, no. 3 (2012): 1383-1398. https://doi.org/10.1016/j.rser.2011.12.013
[12] Fudholi, Ahmad, Kamaruzzaman Sopian, Mohd Hafidz Ruslan, M. A. Alghoul, and Mohamad Yusof Sulaiman. "Review of solar dryers for agricultural and marine products." *Renewable and Sustainable Energy Reviews* 14, no. 1 (2010): 1-30. https://doi.org/10.1016/j.rser.2009.07.032
[13] Shafieian, Abdellah, Mehdi Khiadani, and Ataollah Nosrati. "Strategies to improve the thermal performance of heat pipe solar collectors in solar systems: a review." *Energy Conversion and Management* 183 (2019): 307-331. https://doi.org/10.1016/j.enconman.2018.12.115
[14] Ullah, Asad, Hassan Imran, Zaki Maqsood, and Nauman Zafar Butt. "Investigation of optimal tilt angles and effects of soiling on PV energy production in Pakistan." *Renewable Energy* 139 (2019): 830-843. https://doi.org/10.1016/j.renene.2019.02.114
[15] Shariah, Adnan, M-Ali Al-Akhras, and I. A. Al-Omari. "Optimizing the tilt angle of solar collectors." *Renewable Energy* 26, no. 4 (2002): 587-598. https://doi.org/10.1016/S0960-1481(01)00106-9
[16] Karmakar, Anjan, Agnimitra Biswas, Jibin T. Philip, and Basil Kuriachen. "Estimation of Heat Loss Factor with the Tilt Angle in a Solar Thermal Flat-Plate Collector." In *Green Buildings and Sustainable Engineering*, pp. 73-79. Springer, Singapore, 2019. https://doi.org/10.1007/978-981-13-1202-1_6
[17] Majid, Z. A. A. "Kajian prestasi sistem pengering pam haba terbantu suria dengan pengumpul suria multifungsi." *PhD diss., Bangi, Malaysia: Universiti Kebangsaan Malaysia* (2011).
[18] Fazlizan, Ahmad, Ahmed Abdulmula, Akmal Naim Amran, Chin Haw Lim, and Kamaruzzaman Sopian. "Performance evaluation of maximum light detection solar tracking system in the tropics." *Journal of Mechanical Science and Technology* 33, no. 3 (2019): 1391-1397. https://doi.org/10.1007/s12206-019-0240-2
[19] Ataer, O. Ercan. "Storage of thermal energy." *Energy Storage Systems in Encyclopedia of Life Support Systems (EOLSS)* (2006).
[20] Lane, George A. *Solar heat storage: Latent heat materials*. CRC Press (1st edition), 1983.
[21] Sharma, Atul, V. V. Chen Tyagi, and D. C. R. Buddhi. "Review on Thermal Energy Storage with Phase Change Materials and Applications." *Renewable and Sustainable Energy Reviews* 13 (2009): 318-345. https://doi.org/10.1016/j.rser.2007.10.005
[22] Fudholi, Ahmad, Kamaruzzaman Sopian, Mohamed Gabbasa, Ba Bakhtyar, M. Yahya, Mohd Hafidz Ruslan, and Sohif Mat. "Techno-economic of solar drying systems with water based solar collectors in Malaysia: a review." *Renewable and Sustainable Energy Reviews* 51 (2015): 809-820. https://doi.org/10.1016/j.rser.2015.06.059
[23] Steven, Vanessa, Colin Craven, and Bruno Grunau. "Thermal Storage Technology Assessment." *Cold Climate Housing Research Center (CCHRC)*, 2013.
[24] Elsheniti, Mahmoud B., Amr Kotb, and Osama Elsamni. "Thermal performance of a heat-pipe evacuated-tube solar collector at high inlet temperatures." *Applied Thermal Engineering* 154 (2019): 315-325. https://doi.org/10.1016/j.applthermaleng.2019.03.106
[25] Speyer, E. "Solar energy collection with evacuated tubes." *Journal of Engineering for Power* 87, no. 3 (1965): 270-276. https://doi.org/10.1115/1.3678243
[26] Kalogirou, Soteris A. "Solar thermal collectors and applications." *Progress in Energy and Combustion Science* 30, no. 3 (2004): 231-295. https://doi.org/10.1016/j.pecs.2004.02.001
[27] Duffie, John A., and William A. Beckman. *Solar Engineering of Thermal Processes, 4th Edition*. John Wiley & Sons, 2013. https://doi.org/10.1002/9781118671603

[28] ASHRAE. *1995 ASHRAE Handbook. HVAC applications. SI Edition*. American Society of Heating Refrigerating and Air-Conditioning Engineers, United States, 1995.

[29] Li, Qiong, Wenfeng Gao, Wenxian Lin, Tao Liu, Yougang Zhang, Xiang Ding, Xiaoqiao Huang, and Wuming Liu. "Experiment and simulation study on convective heat transfer of all-glass evacuated tube solar collector." *Renewable Energy* 152 (2020): 1129-1139. https://doi.org/10.1016/j.renene.2020.01.089