Double-Pass Solar air Heater (DP-SAH) utilizing Latent Thermal Energy Storage (LTES)

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Abstract. The solar air heater is a device rises air flowing temperature in numerous engineering applications as; heating of buildings, and agricultural crops drying. An indoor investigation was experimentally established using the solar simulator to test the flat plate double-pass solar air heater performance with and without paraffin wax-based on phase change material PCM. Although the temperature inside this collector is higher than the required temperature. Therefore, being a paraffin wax may be used as a heat storing material will enable the collector to work during the night. The tests were applied to evaluate the charge and discharge process of the new system and was performed under various air MFRs of (0.6, 0.9, 1.2, 1.5, and 1.8) kg/min and constant solar irradiation of 625 W/m². The results showed that the maximum thermal efficiencies obtained for the double-pass with and without PCM were 63.53% and 68.23%, respectively, for airflow rate of 1.8 kg/min and also the efficiencies is a strongly dependence on the air MFR. Also, the maximum air temperature rise was about 10.9°C, and 12.25 °C with and without PCM, respectively, above the inlet temperature at air MAF of 0.6 kg/min and solar irradiation of 625 W/m² during charging period and this leads to energy saving. The experimental tests showing reasonable agreement with the previous study with a maximum error of thermal efficiency was about (4.5%) at the same indoor conditions.

Keywords: Double-Pass Collector, Phase Change Material (PCM), Solar Thermal Storage.

Nomenclature

| Symbol | Description |
|--------|-------------|
| \( A_e \) | effective glazing area of DPSA-heater (m²) |
| \( A_o \) | outlet duct area of DPSA-heater (m²) |
| \( \dot{m}_a \) | the airflow rate (kg/min) |
| \( p_a \) | air specific heat at constant pressure (J/kg.K) |
| \( T_{\text{out}} \) | outlet fluid temperature (°C) |
| \( T_{\text{in}} \) | inlet fluid temperature (°C) |
| \( I_s \) | solar radiation intensity (W/m²) |
| \( V_m \) | mean velocity of airflow (m/sec) |
| \( Q_u \) | the useful energy of air (W) |

Greek letters

| Symbol | Description |
|--------|-------------|
| \( \rho \) | the density of air (kg/m³) |
| \( \Delta T \) | air temperature difference (°C) |
| \( \eta_{th} \) | thermal efficiency (%) |
1. Introduction

In the 21st century, latest studies indicate an increase in the atmospheric concentration of more toxic gases like carbon dioxide CO\textsubscript{2} and nitrous oxide N\textsubscript{2}O which are unprecedented in past decades. As a result of the consumption of fossil fuels like oil, coal, and gas to produce conventional energy in the world which cause a lot of serious lung diseases that threaten the life of mankind if it has not been seriously tackled this problem. Solar radiation is sourcing of renewable energy that contributes to the conservation of fossil energy and reduces pollution of the environment. Also, the energy of sunlight is the most abundant natural resource for humankind and is a promising source of unpolluted energy.

Therefore, it can be guided economically and practically in applications of non-concentrated solar thermal units as; a flat plate-solar air heater SAH which is the most common and used in a solar radiation applications, by converting collected energy into a hot air at a low-temperature applications for space heating of households and glasshouse, agricultural products drying for example grains crops, and various industrial drying purposes, which cannot effectively operate without some form of thermal stored energy, as reviewed comprehensively by authors, [1-4]. In general, the application of flat plate-solar air collector has two major problems that can be summarized as follows:

• Firstly, the main disadvantage of flat plate collector has a poor convective-coefficient between air flowing and absorber plate as well as energy loss to the atmosphere, so many researchers have improved the thermal efficiency of SAC by increasing convective area and creating turbulence flow which was achieved by various techniques as: extended surfaces i.e. obstacles or fins[5-13]; roughened absorber [14-19]; porous materials [20-25]; and corrugated or grooved absorber [26-29]. In the beginning, some authors [30, 31] researched and tested experiments of the simple double pass-SAC performance with the different construction and over a varied range of MFR of air. As well, a comparative study between single and two pass air collector systems was evaluated by Wijesundera et al. [32]. It was detected that a two pass-SAC performance is better than a single pass-SAC about 10–15\% under same operating conditions.

On the other hand, new technology contributes for reducing the energy losses by utilizing different methods such as double-glazed covers,[33]; and double pass flow of collector,[34, 35]. One of the recent techniques used to improve the collector performance by means of a double pass SAC which increases the total area by passing two channels. But low pressure is one of the main drawbacks of this method which can be reduced by the optimal design of collector dimensions.

• Secondly, the incompatibility between access to sunlight during the day and the need to request heat energy after sunset. Moreover, the intensity of solar energy in nature is intermittent at night and low intensity with the existence of the clouds. The best solution to overcome the problem by utilizing thermal energy storage technology directly or indirectly with the collector. Nowadays, latest research point remarkable in the literature studies focused on latent heat storage LHS technologies-based on stored energy that uses a solid/liquid phase change materials PCMs integrated with solar air collector systems to achieve optimum performance of thermal energy and provide energy during cloudy periods and at night for different engineering fields: e.g. thermal storage at heating of buildings or solar drying, [36, 37]. Most common, the latent thermal energy storage LTES utilizes instead of sensible thermal energy storage STES in the storage substance which is based on a latent heat of a solid/liquid phase change material PCM like a paraffin wax has the highest possible heat capacity. Such that a large quantity of absorbed energy can be stored in a storage substance when it is subjected by absorbed irradiation. On another hand, PCM has the technical reason to change from solid-to-liquid is achieved better than others phases changes like liquid/gas, solid/gas, and solid/solid.

Tyagi et al. [38] studied a solar collector performance without and with different thermal storage materials. They used three different models; PCM paraffin wax, without PCM, and hytherm oil as sensible heat-based energy storage. The results revealed that the higher efficiency of the solar heater with both storages was 20–53\% than a collector with non-storage, so the paraffin wax was best considerably as compared to hytherm oil. Charvat et al. [39] fabricated and tested the effect of PCM on a solar air collector SAC performance. The MATLAB code used for modeling SAC integrating with a paraffin wax as phase change material (PCM) has a melting point of 40\degree C. They observed that the lower exit air temperatures with energy storing during the charging period, and noted higher air temperatures at discharging period process. In particular, TES based on latent heat storage is a very
desirable technique in account of PCM involves a high capacity for storing energy. The suitability of the PCM depends on its thermo-physical properties at melting temperature. A paraffin wax is an available and safe form in the phase change material PCM, but it is a low-thermal conductive during the transition of solid, mushy, and liquid phase is a major disadvantage. Numerous research provided a range of technique resolutions to address this problem by means of nanoparticles technology or PCM encapsulation, as reviewed by authors,[40, 41], and also, the usage porous materials as graphite foams or carbon fibers and longitudinal fins in the PCM.[42, 43].

An experimental and theoretical analysis of a single-glazed-SAC united with NPCM was presented by Alkilani et al., [40]. They designed inline cylinders filled with nano-paraffin as an absorber-storage, NPCM consists of PCM and 5% nanoparticles of aluminum powder so as to develop the conductivity of PCM for different values of air MFR of 0.05 –0.19 kg/s. It was also observed that the optimal discharging period and the highest exit temperature of the system was reached of 8 hr and 42 °C for air MFR of 0.05 kg/s, respectively. The discharging time of the NPCM was correlated inversely to the air MFR under an indoor solar simulator and operating conditions.

Fath,[41] researched the conventional-SAC performance integrated with encapsulated PCM with melting temperature of 50 °C. A corrugated set of an encapsulated copper cylindrical was packed with paraffin wax as PCM and located as absorbent and container of the energy store. The system was taken a 1.0 m² of a collected area, and 7.5 cm of the height of the collector channel. The investigation showed that the daily efficiency of the staggered set tube with PCM is approximate of 63.35% which was under an air MFR of 0.02 kg/s. The tests detected that the exit temperature of air increased by 5 °C as compared to ambient temperature and extended for about 16 hr, whereas the daily efficiency of flat plate-SAC has 38.7% for 9 hr. El Khadraoui et al. [44] empirically investigated the influence of PCM combination on a solar air collector performance. They revealed that the higher daily efficiency of the SAC in presence of PCM was approximate of 33% than the system in absence of PCM had 17% which was under the same operating conditions.

Alkilani et al. [45] fabricated and verified of a solar heater with a built-in thermal storage unit of PCM paraffin wax. An indoor system has projectors simulator was used in performing tests within the laboratory to simulate the solar intensity. They conducted that the minimum period of charging of a composite NPCM was nearly 70% as compared to pure PCM due to the 0.5% mass of aluminum powder improves PCM conductivity. It was also observed that the optimal efficiencies of the solar collector were reached 71.9% and 77.18% which under an air MFR of 0.05 and 0.07 kg/sec for pure PCM and NPCM, respectively.

An experimental study of a two pass-SAC performance with thermal storage was tested by Krishnananth and Murugavel, [46]. They used aluminum capsulation filled with PCM as an absorbent and container of storage. The tests detected that the double pass-SAC with PCM supplies moderately high-temperature air during the day length. It was also showed that a two pass-SAC in the presence of PCM capsulation was more efficient than that other non-storage collector. An investigation of a solar dryer efficiency in the absence and presence of PCM was carried out by Shalaby and Bek,[47]. They indicated that the air temperature of drying collector by using the PCM was more than that outdoor temperature by 2.5–7.5 °C during nighttime for 7 hr. Moreover, the solar collector supplies an air temperature at 3.5–6.5 °C for drying, after 2:00 pm, which was more than the collector without paraffin wax.

Maitham and Mohammed, [48] investigated the heat conductivity enhancement of a paraffin wax in a vertical cylindrical capsule utilizing fraction volume of nanoparticles alumina in a range (0.5 % ≤ Φ ≤ 3%). The results stated that the decreasing melting and freezing rate period about (7, 15, 11, and 9%) and (4, 8, 6, and 5%), respectively as compared to pure paraffin.

In particular, thermal energy storage in solar heater uses was presently still under investigation and improvement. For the best of our knowledge, there is an indicated gap in the previous literature on an experimental study about a double pass-SAH performance utilizing PCM as thermal energy storage which requires to study this practice because it provides the superior thermal performance of collector during discharging period. An indoor, the present studied aims to manufacture and test the double-pass solar air heater (DP-SAH) performance with and without paraffin wax as PCM. Many variables were
studied experimentally which include the intensity of solar irradiation, air flow speed, and freezing time of paraffin wax PCM.

2. Experimental investigation
In this research, the effect of different parameters on counterflow in a double-pass solar air heater (DP-SAHP) performance with and without PCM paraffin wax was investigated experimentally. The experiment was situated indoors to preserve the solar irradiation and ambient temperature and to avoid different outdoor conditions. The test rig is assembled of two major units are DPSA-collector test platform and artificial solar simulator with a voltage supplied control. Firstly, air flows in the lower duct (1st pass flow) which is fabricated between the lower absorber surface and back plate of the heater. Secondly, recycle air flows through the upper duct (2nd pass flow) which is fabricated between the glass cover and the upper absorber surface and container of PCM. The experimental work is discussed below.

2.1. Experimental Setup
The experiment rig consists of the two main parts which are: a test section of a DPSA-collector incorporated with latent heat storage unit, and artificial solar simulator. Figures 1 and 2 show digital photographs and diagram outline of the experimental apparatus of DPSA-heater with a cover area 0.411 m². An indoor solar simulator utilizes six tungsten halogen lamps, each one consumes a maximum power of 500 W. The lamps were fixed perpendicularly at 700 mm from the glass cover of DPSA-heater such that the maximum average irradiation of about 825 W/m² was reached. Three VARIAC voltage regulators 1000VA capacity were used to control the solar intensity which was directed to the test heater. The fabrication of the double pass was constructed by utilizing a rectangular duct of 25 mm thick plywood has a cross section of 1284x320x84 mm.

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Figure 1. An indoor experimental apparatus diagram of DPSA-collector with LTES-unit.

Figure 2. Digital photographs of the experimental apparatus.

Figure 3. Configurations of container PCM (I) single capsules, and (II) multiple-capsules.
The current study contribution, due to the low conductivity for paraffin wax in the three transition phases, we used eight rectangle pipes of galvanized iron (GI) filled with RT42 paraffin wax were installed as multiple capsules of latent heat storage in the middle of a DPSA-collector height, see Fig.3. Each capsule of storage contains 0.625 kg of paraffin wax PCM which was placed parallel to the air stream and coated with black matte as an absorbent material. These storage capsules worked as an absorbent for solar irradiation so that the thermal energy is stored. The flow channel of experimental setup involves three units i.e. the entrance section consists of (900×320mm), test section consists of (1200×320mm) and exit section is (450×320mm), and also air gap of (84mm) which was left at the end for air flowing towards the upper channel. In addition, the aspect ratio (W/H) is kept as 10 for the lower and upper channel of the collector which is (32mm) gap height respectively, according to ASHRAE standards, [49]. The working medium was air supplied by a (65 W) axial fan. In operation, this fan pulls air through the collector at a volumetric flow rate up to 700 m³/hr. The flow rate was manually changed by controlling the fan voltage through a contact voltage regulator.

Table 1 and 2 contain the details about experimental rig and the thermo-physical properties of low melting paraffin wax which used into the DPSA-heater. A set of thirty-two calibrated thermocouples of K-type were located to monitor the temperatures of the DPSA-heater during the charge and discharge processes of the experiment. The thermocouples were mounted in a different locations which are: four thermocouples were installed in: a glass cover, lower and upper surface of absorbent, inside the center of PCM rectangular capsule, back plate surface, first pass of airflow, and second pass of airflow, all at the distances: 150, 450, 750, 1050 mm from entry edge. Also, two thermocouples were placed at both inlet and outlet air units. The temperature values from the thermocouples in the solar collector were recorded for every 60 sec during experiments by using data logger type AT-4532.

### Table 1. Specifications of a DPSA-heater with TES unit in the experimental rig.

| Parameter                   | Values       |
|-----------------------------|--------------|
| **DP-SA heater:**           |              |
| Length                      | 1284 mm      |
| Width                       | 320 mm       |
| Height                      | 84 mm        |
| Channel height              | 32 mm        |
| Effective glazing area      | 0.411 m²     |
| Glass thickness             | 3 mm         |
| Glass transmittance         | 0.83         |
| Galvanized iron absorbance  | 0.9          |
| Galvanized iron thickness   | 1 mm         |
| **PCM rectangular capsules:**|              |
| Number of capsules          | 8            |
| Length                      | 1200 mm      |
| Width                       | 40 mm        |
| Height                      | 20 mm        |
| Thickness                   | 1 mm         |
| Total weight of paraffin wax PCM | 5 kg        |
Table 2. Thermo-physical properties of paraffin wax-based on PCM, [53].

| Property                              | Values                      |
|---------------------------------------|-----------------------------|
| Melting temperature range             | 38–43 °C                    |
| Congealing temperature range          | 43–37 °C                    |
| Heat storage capacity                 | 174 kJ/kg                   |
| Specific heats in both solid and liquid states | 2 kJ. kg⁻¹. K⁻¹  |
| Density in solid state                | 880 kg.m⁻³                  |
| Density in liquid state               | 760 kg.m⁻³                  |
| Volume expansion (solid/liquid phase change) | 16%                     |
| Thermal conductivity in both solid and liquid states | 0.2 W.m⁻¹.K⁻¹  |

2.2. Experimental procedures

Before starting the experiments, all thermocouples which used in the collector should indicate same room temperature. The experiments were carried out in sequential steps as follow:

1- In the beginning, the solar simulator and axial fan were started in the desired range by means of voltage regulator control.

2- The test rig runs until the steady state was reached after 45 minutes and 90 minutes from the start of operation of the solar heater without and with PCM thermal storage, respectively.

3- Noting and recording the values of temperature was done by utilizing a data logger.

4- For DPSA-heater experiments without PCM, changing air mass flow rate and repeat the previous steps, it took about 30 min to reach steady condition.

5- For DPSA-heater experiments with PCM, changing the solar intensity of the charging period and repeat the previous steps except for the fourth step.

6- Finally, turn off solar simulator during the discharging period and repeat the third step until the air temperature difference becomes equal to zero.

2.3. Thermal efficiency analysis

The amount of useful energy (Q₁ua) to the air flowing in a DPSA-heater can be calculated by,[50]:

\[ Q_{1ua} = m_a C_p a (T_{out} - T_{in}) \]  

Where \( m_a \), \( C_p a \), and \( T_{out} - T_{in} \) were the air MFR, air specific heat, and the air temperature difference between outlet and inlet of the collector, respectively.

The thermal efficiency (\( \eta_{th} \)) of DPSA-heater can be calculated by:

\[ \eta_{th} = \frac{Q_{1ua}}{I_s A_c} \]  

Where \( I_s \), and \( A_c \) were the solar irradiation and collector area, respectively.

2.4. Uncertainty analysis

The uncertainty analysis in an experiment is used to indicate a possible value of an error in the measurement instruments. Typically, the error is a difference between an actual value and a measured value. Particularly, the analysis of uncertainty in the experiments measurement is a powerful tool and effective to apply the experiment design. The resulting uncertainty can be computed by a formula which is related between the dependent variable \( W_R \) and independent variables \( W_1, W_2, \ldots W_n \),[51]:

\[ W_R = \left[ \left( \frac{\partial R}{\partial X_1} W_1 \right)^2 + \left( \frac{\partial R}{\partial X_2} W_2 \right)^2 + \ldots + \left( \frac{\partial R}{\partial X_n} W_n \right)^2 \right]^{1/2} \]  

In this current work, the main parameters were measured in the DPSA-collector which are: solar irradiation, air mass flow rate, and temperatures by using appropriate tools. An airflow AM-4206M
anemometer was used to measure the air speed with an accuracy of (±4%) and of range (0.4–35 m/s) at the outlet DPSA-collector. K-type thermocouples with an accuracy of (± 0.4% °C) and temperature measuring range (-100–1300°C). Furthermore, TM-207 solar power meter with (± 5%) accuracy and of range (0 – 2000 W/m²) was used to measure a solar irradiation. From above equations (2.1 and 2.2) the thermal efficiency-based on the measured independent variables can be determined as follow:

\[ \eta_{th} = \frac{\dot{m}_a c_p a (T_{out} - T_{in})}{I_s A_c} \]  
(2.4)

The air mass flow rate can be determined by:

\[ \dot{m}_a = \rho_a A_o V_m \]  
(2.5)

Where, the \( A_o, A_c, \rho_a, \) and \( C_p_a \) were assumed constants in Eqs.(2.4 and 2.5), hence

\[ \eta_{th} = f(\dot{m}_a, \Delta T, I_s) \]  
(2.6)

The uncertainty of \( \eta_{th} \) can be found from Eq. (2.3) as follow:

\[ W_{\eta_{th}} = \left[ \left( \frac{\partial \eta_{th}}{\partial \dot{m}_a} W_{\dot{m}_a} \right)^2 + \left( \frac{\partial \eta_{th}}{\partial \Delta T} W_{\Delta T} \right)^2 + \left( \frac{\partial \eta_{th}}{\partial I_s} W_{I_s} \right)^2 \right]^{1/2} \]  
(2.7)

Then, the relative error percentage of \( \eta_{th} \) can be calculated:

\[ E_{\eta_{th}} = \frac{W_{\eta_{th}}}{\eta_{th}} \times 100\% \]  
(2.8)

Table 3 presents the uncertainties and error percent that occurred during the measurements.

| Parameters               | Uncertainty       | Error          |
|--------------------------|-------------------|----------------|
| Air temperature difference | ± 0.622           | 3.865 - 8.642% |
| Air mass flow rate       | ± 0.000485        | 1.578-4.734%   |
| Solar irradiation        | ± 0.5             | 1.379%         |
| Thermal efficiency        | ± 0.3-0.7         | 0.4-1.2%       |

2.5. Validation of experimental set up

To verify the accuracy of this work, current results data was validated based on similar application of an experimental study of a double-pass solar air heater that reported by P. Velmurugan and R. Kalaivanan, [52], at constant averaged solar energy and various air MFR. Figure 4 shows a good agreement of a comparison between thermal efficiencies of our results with the previous study with a maximum error of thermal efficiency was about (4.5%) at the same indoor conditions.

![Figure 4. The Thermal efficiency calculated in this investigation versus that of Ref.[53].](image-url)
3. Results and Discussions

An experimental investigation was achieved in an indoor environment at constant wind speed 1.5 m/sec and room temperature approximately 25°C, to investigate the DPSA-heater performance with and without paraffin wax-based on PCM. In this work, the lost energy in the collector to the atmosphere was neglected. Furthermore, various air mass flow rates of (0.6, 0.9, 1.2, 1.5, and 1.8) kg/min and constant average solar energy of 625 W/m² were applied in the present tests. Figure 5 displays the temperature variation of different positions in the collector at the same average solar energy of 625 W/m² and air MFR of 0.6 kg/min. All curves showed that the glass cover temperatures were higher than the back plate and air temperature but lower than the absorber plate temperatures of collector without thermal storage. Obviously, the DPSA-collector with thermal storage displays that the absorber temperatures dropped due to the absorbed heat by paraffin wax medium for storing energy. The influence of air MFR on the mean temperature for different points in the DPSA-collector with PCM at the solar intensity of 625 W/m² can be represented in Fig. 6. The tests revealed that a drop of the temperatures curves of (Tg, Tu, ab, Tl, ab, Tpcm, Tbp, Tf2, Tf1, and To) by increasing air MFR simultaneously. Figures (7 a, b, and c) represent the temperatures variation of air flowing along the first and second pass in a two-pass heater with and without PCM for various airflow rates of (0.6, 1.2, and 1.8) kg/min at a solar radiation of 625 W/m². Firstly, air flowing in the first pass between the lower absorbent surface and back plate. Secondly, the air recycles toward the second pass between the glass cover and upper absorbent surface. Generally, from the inlet to the outlet of DPSA-heater the temperature curves gradually increased, but outlet temperature of air in two passes was lower in DPSA-collector with PCM as compared to collector without PCM. In this case, absorbed energy by thermal storage PCM by heat conduction from the absorbent surface in the collector for storing energy. The results showed that the heat exchange between the absorbent surface and the air flow was reduced as air MFR increased. Figure 8 displays the air temperature difference versus air MFR of the DPSA-collector without and with PCM at constant solar energy of 625 W/m². It was noticed that the air temperature rise correspondingly decreases as the air MFR increases in both applications. This can be attributed to a decrease in the exchanging heat of the absorbent with air flowing when an increase in airflow flow rate. Also, the air rising temperature in collector with PCM was lower than the other due to heat absorbed by paraffin-based on PCM for storing energy. Therefore, the useful energy gain of air for a DPSA-heater with PCM was lower than the other heater, see Fig.9.

Finally, the thermal efficiency versus air MFR of the DPSA-heater without and with PCM at constant solar energy of 625 W/m² can be revealed in Fig. 10. Clearly, it can be detected that the increased thermal efficiency when the value of airflow rate was increased in both applications, and which has a strong dependence on the air MFR. It can be revealed from figure that the thermal efficiency curves dropped by (4 - 7%) as compared to another application without PCM. Because of the useful energy gaining of the DPSA-collector with PCM was lower than the gaining energy of another collector when the absorbent pipes with no PCM. Also, for various taking air MFR found the thermal efficiency of DPSA-heater with and without PCM is between 42.74 – 63.53 %, and 48-68.23%, respectively.

![Figure 5](image-url). The temperature variation in a different positions of a DPSA-collector: (a) without PCM, and (b) with PCM, at air MFR = 0.6 kg/min, and Is = 625 W/m².
Figure 6. The mean temperature with air MFR for a different positions in the DPSA-collector with PCM.
Figure 7. The temperature variation of air flowing along the first and second pass in a DPSA-heater with and without PCM for a different air MFR: (a) MFR =0.6 kg/min, (b) MFR =1.2 kg/min, and (c) MFR =1.8 kg/min, at solar intensity of 625 W/m$^2$.

Figure 8. Temperature rise of air versus air MFR for DPSA-heater with and without PCM, at constant solar irradiation of 625 W/m$^2$.

Figure 9. Useful energy rate versus air MFR for DPSA-heater with and without PCM, at constant solar irradiation of 625 W/m$^2$. 
4. Conclusions

Main important conclusions of current work can be identified as follows:

1. The outlet temperature of air in DPSA-collector with containing PCM was lower than the other collector without PCM. Because of the absorbed energy from the absorbent surface of the collector by the thermal storage material of PCM for storing energy and then heat was released at night.

2. The maximum values of air temperatures rise obtained across the double-pass solar air heater with and without PCM were 10.9°C, and 12.25 °C, respectively, at an airflow of 0.6 kg/min and irradiance of 625 W/m².

3. The maximum values of the efficiency obtained across the DPSA-heater with and without PCM were 63.53 %, and 68.23%, respectively, at an airflow of 1.8 kg/min and irradiance of 625 W/m².

4. The results represent that the energy efficiency was a strong dependence on the intensity of solar energy and air MFR. In addition, the thermal efficiency of DPSA-heater with PCM dropped by (4 - 7%) as compared to another heater. Because of the useful energy gaining of the DPSA-heater with PCM was lower than the gaining energy of another heater when the absorbent pipes with no PCM.

5. Finally, it can be detected that the higher efficiency when the value of airflow rate was increased in both applications, and which is a strong dependence on the air MFR.

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