Influence of bladed and glazed entrance on the performance of solar air heater

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Abstract

The performance of a flat plate single-pass Solar Air Heater (SAH) modified at the entrance region was experimentally investigated. This entrance region was covered with glass cover instead of steel. Using glass at the entrance region increases the heating area exposed to solar radiation and avoids the restriction of solar radiation from reaching this area as in case of steel cover. Also, guide blades were placed in the entrance region to ensure well air distribution on the absorber surface and hence enhancing the thermal performance of SAH. The modified SAH was compared with another of conventional entrance. The experiments were performed at four air flow rates ranged from 0.013 to 0.04 kg/s. The modifications led to good enhancement in both the air temperature difference and the efficiency. For the daily efficiency, the maximum values are 43.43, 40.48 and 32.92 % for the glazed-bladed entrance SAH, glazed entrance SAH and conventional SAH, respectively, at the rate of 0.04 kg/s. The glazed-bladed SAH showed a good improvement in the daily thermal efficiency by 6.72 to 10.5 % over the conventional heater and by 2.16 to 3.25 % over the glazed SAH.

Keywords: Single-pass solar air heater; Entrance region; Glass cover; Guide blades; Daily efficiency.
1. Introduction

SAHs are used in many applications such as, space heating, drying applications and water desalination. They have more advantageous than liquid heaters because the used fluid, air, is not as freezable or stagnant as liquids and has no environmental or health hazards [1]. Moreover, SAHs have a simple construction of thermally insulated duct covered with glass cover. The main component is the absorber plate which has heating capacity to store the heat gained from the sun and heats the flowing air. As the heat transfer between the flowing air and the absorber plate is low, many investigators aimed to use many modifications on the absorber plate for enhancing the performance of SAHs.

Many researchers studied the different parameters affecting the performance of the simplest configurations of SAHs, flat plate SAH, such as mass flow rate ($\dot{m}$), solar radiation ($I_0$), number of glass covers, tilt angle, number of passes and absorber configurations with various corresponding attachments. Sharma et al. [2] aimed to optimize analytically set of different operating parameters affecting smooth flat plate SAH which are glass cover number, plate emissivity, mean temperature, temperature rise, tilt angle and solar radiation intensity at different Reynolds number. Also, dimensionless models were presented for optimizing the aspect ratio of flat plate SAH and the outlet temperature ($T_{out}$) [3,4]. In addition, different cross-sections and geometries of the SAH duct and absorber were studied by some researchers such as the experimental investigation performed by Abdullah et al. [5] on three SAHs having different cross sectional shapes (circular, semi-circular and half-circle plus isosceles triangle) with an absorber identical with a half-circle shape. The value of thermal efficiency ($\eta$) reached 80, 64 and 48 % for the circular, half-circle plus isosceles triangle and semi-circular shapes, respectively.

The improving methods aim essentially to improve the thermal and thermo-hydraulic performance which depends essentially on enhancing the heat transfer characteristics. One of these methods is attaching fins to increase the heat transfer area. Different shapes of fins have been studied. First, longitudinal fins which was studied by many researchers either experimentally [6–8] or theoretically [9,10]. The results of such studies confirmed that attaching fins to the absorber plate improves the performance of SAH as they have higher heat transfer area and lower irreversibility compared to flat plate SAH. Decreasing fins spacing and increasing fins height enhances the thermal and thermohydraulic efficiencies by 114.1 and 112.65 %,
respectively as concluded in [9]. Also, recycling process with various reflux ratios was studied to obtain the ratio which achieves the best performance of finned SAHs [11–13]. Furthermore, Other shapes of fins can also be used to enhance the performance of SAHs like wavy fins [14,15] and v-corrugated fins [16,17] with enhancement in efficiency for both single and double pass SAHs.

Improving the heat transfer can be accomplished by improving thermo-hydraulic performance by creating a turbulent flow using artificial roughness. Many works proved the significance of using artificial roughness at different geometries such as different shapes of ribs [18–21], obstacles [22,23] and arc wires and protrusions [24,25]. Furthermore, artificial roughness can be added to the sides of SAH which give more enhancement according to [26,27].

Using energy storage, absorbers coating and packed bed enhances the performance of energy systems in addition to its role in conservation the energy. Energy storage are commonly utilized in areas with variation in solar energy and areas having high temperature variation between day and night. The most common energy storage materials are Phase Change Materials (PCMs) which proved their ability to enhance the performance of SAHs according to the studies made by many researchers such as Krishnananth and Kalidasa Murugavel [28], Sohif M [29] and Moradi et al. [30]. Using PCMs material affects well on the performance of finned [31] and corrugated plate SAHs [32]. In addition, the absorbing efficiency depends on the absorber plate coating which states the absorptivity of the absorber plate as ensured by El-Sebaii and Al-Snani [33] compared to the results reported in [34] which stated that nickel–tin (Ni–Sn) achieved the best performance. Also, using different beds on the absorber improves the performance. According to Ramani et al. [35], double pass SAH with porous material has $\eta$ about 20–25 % and 30–35 % higher than that of double pass SAH without porous material and single pass SAH, respectively. Dissa et al. [36] designed and experimented a SAH with a composite absorber of a non-porous corrugated iron sheet and a porous mesh of aluminum. The value of midday $\eta$ reached 61 %. The results were ensured by an unsteady state model. In addition, using steel wire mesh as beds showed good enhancements in the SAHs performance [37,38]. Also, the metal corrugated packing SAH was ensured to be more appropriate for using in the cold regions rural buildings for its advantages of large heat transfer area, high heat transfer coefficient and good economic performance as studied by Zheng et al. [39].
A lot of researches made in the field of SAHs did not concern with the entrance region however its extreme importance as it has a heat gain not considered by their studies in the temperature rise when calculating of efficiency. So, the aim of the current study is to study the influence of modifications made at the entrance region on the performance of a flat-plate SAH of single-pass type.

The entrance region of some researches’ test-rigs had the shape of conical or divergent shape from opaque materials [17,31,32,40]. The present study aims to replace the opaque material or steel used at entrance by glass cover to increase the heating area exposed to solar radiation. Also, replacing the opaque or steel cover with glass avoids the restriction of solar radiation from reaching the area of the entrance region as in case of steel cover. As solar radiation restriction makes the entrance region have lower temperature than the absorber and hence heat is dissipated decreasing the absorber surface temperature and hence the outlet air temperature.

In addition, the heating efficiency depends on the distribution of the air through the whole area of the duct and eliminating dead zones. So, air distribution has an effective role to improve the performance of SAHs. Therefore, to ensure a uniformly air distribution and overcome the problem of pressure drop across the air distribution systems, simple fixed air directing blades are used in the present study. The blades are made of aluminum to have an additional role as fins at the entrance to enhance the heat transfer at heater entrance.

From the previous review, the effect of glazing the entrance region on the flat plate SAH is not recognized. In addition, the effect of attaching guide blades to the entrance region is not studied in details. So, the present work studies experimentally the performance of a flat plat SAH with new modifications at the entrance region (glazed-bladed entrance SAH) and compared with conventional SAH at the same time. In the present paper the following test cases are carried out:

1- The effect of glazing the entrance of a flat plate SAH (glazed entrance SAH) compared to another one with steel entrance (conventional SAH).

2- The effect of attaching guide blades to the glazed entrance SAH (glazed-bladed entrance SAH) compared to the conventional one.
2. Experimental set-up and procedure

Two SAHs are designed and fabricated from commercial available materials. One of them is the modified SAH and the other is the conventional SAH. Also, the SAHs are equipped with measuring instruments to measure the parameters affecting the thermal efficiency (solar radiation, air mass flow rate and both inlet and outlet temperatures).

2.1 Experimental set-up description

The test-rig consists of a conventional flat plate SAH and another modified one SAH. Each heater is made of galvanized steel having thickness of 1.5 mm. The dimensions of the heater duct are 200 cm length and 100 cm width with side-wall height of 10 cm. The whole internal surface is black painted to increase their absorptivity. Also, to avoid the heat loss to the surrounding, the heaters are well insulated with glass-wool insulation material. The heaters are tilted with approximately 30° on horizontal according to the latitude of Kafrelsheikh city, Egypt. Each SAH was covered with a sheet of commercial glass of 4 mm thick with silicon sealant to prevent any air leakage. Each heater is made of conical shape passage at entrance and exit of 40 cm length with passage variation from 10 cm till 100 cm with the same side-wall height of the duct. In modified SAHs, the entrance region is covered with glass cover as a first modification. Also, four guide blades made of aluminum are fixed at the entrance region as a second modification. While for the conventional SAH, the entrance and exit regions are covered with steel without using guide blades at the entrance region. Fig. 1 illustrates the tested SAHs. In addition, Fig. 2 shows a schematic diagram of the test set-up. Also, Table 1 summarizes the specifications of the SAH.

The air is being forced by a centrifugal air blower of a blade diameter of 30 cm connected to an AC electric motor powered by a photovoltaic (PV) system consisting of PV cell, battery, charger and converter (DC to AC). The used PV cell is a silicon solar panel 600 W with area of (1*1.6) m². A regulator is connected to the blower to obtain variable speeds of rotation and hence variable air flow rates according to the output voltage of the regulator. The air flow duct system consists of a main pipe branching into two air pipes. Each pipe is made of 4 inches made of PVC. Thermocouples of K-type are used for measuring the various temperatures either for the air flow or the absorber surface. The air flow temperatures are measured at entrance (T_{in}) and outlet (T_{out}). Also, the ambient temperature is measured. In addition, thermocouples are fixed at
different points on the surface of the absorbers to measure the variation of temperature. Finally, to measure the glass covers temperatures, thermocouples are fixed at the upper side of them. Fig. 3 shows the various positions of thermocouples along the surface of each SAH. As, $T_1$, $T_2$ and $T_3$ are the temperatures of the surface of the absorber along its centerline.

2.2. Experimental procedure

Two SAHs are experimentally tested in outdoor environment. The SAHs are installed facing south during the study. The measured quantities (solar radiation, air temperatures at different points, absorber surface temperature, ambient temperature and glass cover temperatures) are measured from 9 am to 5 pm at hourly interval for various air flow rates. The temperatures measurements are recorded using calibrated K-type thermocouples. The readout of the thermocouples is monitored by temperature readers (TC4M-24R, Autonics). The readers are connected to two manual selectors. The global incident solar irradiation on the surface is measured by means of data logging solar meter (TES-1333) with accuracy of $\pm 1\text{ W/m}^2$ and of range $0 – 5000\text{ W/m}^2$ and the speed of air is measured using a van type anemometer accuracy of $\pm 0.1\text{ m/s}$ and of range $0 – 30\text{ m/s}$. The experimental investigations are carried out on each modified SAH and the conventional at the same time.

2.3 The thermal efficiency of heaters

The thermal efficiency of the SAH can be defined as reported in [6,41]:

$$\eta = \frac{\text{useful energy gained}}{\text{total solar incident on the SAH absorber}} = \frac{Q_u}{I_{(s)\times A}}$$  \hspace{1cm} (1)

Where, the useful energy gained can be defined by:

$$Q_u = \dot{m} \ \ C_p \ (T_{out} - T_{in})$$  \hspace{1cm} (2)

2.4. Experimental error analysis

During designing and planning of experiments, uncertainty analysis is an effective and a powerful tool. For estimating the uncertainty of the measured parameters and resulted data, the method reported in [42] is used. Consider a measurement set is conducted to measure variables of “n” number. Let the result $R$ is a function of independent variables. Thus,

$$R = R \ (X_1, X_2, X_3, ................., X_n)$$  \hspace{1cm} (3)
Let the uncertainty in the result be $W_R$ and the uncertainties in the independent variables be $W_1, W_2, W_3, \ldots, W_n$. Regarding the uncertainties in the independent variables, uncertainty in the result can be calculated by:

$$W_R = \left[ \left( \frac{\partial R}{\partial X_1} W_1 \right)^2 + \left( \frac{\partial R}{\partial X_2} W_2 \right)^2 + \cdots + \left( \frac{\partial R}{\partial X_n} W_n \right)^2 \right]^{\frac{1}{2}} \quad (4)$$

By knowing the relation between the measured quantities and the uncertainties of each quantity, the uncertainty $W_R$ is calculated from Eq. (4).

Table 2 presents an example of the experimental data measured of the glazed-bladed SAH. Uncertainty of the measured parameters is given in Table 3. The minimum error equals the ratio between its least count and minimum value of the output measured, as defined by [43]. From these measured data, $\eta$ can be calculated.

From the equation of $\eta$:

$$\eta_{th} = \frac{Q_u}{A_h I_R} = \frac{m c_p \Delta T}{A_h I_R} \quad (5)$$

Since $A_h$ is constant and assuming $C_p$ is constant for the range of measured temperatures, then,

$$\eta_{th} = f(m, \Delta T, I_R) \quad (6)$$

Following Eq. (6), total uncertainty for $\eta$ can be derived as,

$$W_{\eta_h} = \left[ \left( \frac{\partial \eta_{th}}{\partial m} W_m \right)^2 + \left( \frac{\partial \eta_{th}}{\partial \Delta T} W_{\Delta T} \right)^2 + \left( \frac{\partial \eta_{th}}{\partial I_R} W_{I_R} \right)^2 \right]^{\frac{1}{2}} \quad (7)$$

The uncertainty of $\Delta T$ is:

$$W_{\Delta T} = \left[ \left( \frac{\partial \Delta T}{\partial T_{in}} W_{T_{in}} \right)^2 + \left( \frac{\partial \Delta T}{\partial T_{out}} W_{T_{out}} \right)^2 \right]^{\frac{1}{2}}$$

$$W_{\Delta T} = [ (\pm 1 \times -1)^2 + ((\pm 1 \times 1)^2)]^{0.5} = \pm 1.414 \degree C$$

Then, the relative error is:

$$E_{\Delta T} = \frac{1.414}{28} = 5 \%$$
For $\dot{m}$, the uncertainty can be calculated as follows:

$$\dot{m} = \rho \cdot V_{\text{air}} \cdot A_p$$

Let, $\rho = 1.2 \text{ kg/m}^3$ and $A_p = 0.00784 \text{ m}^2$

$$\dot{m} = 0.009408 \cdot V_{\text{air}}$$

$$\dot{m} = 0.009408 \times 4.5 = 0.04 \text{ kg/sec}$$

Then, the uncertainty is:

$$W_m = \left( \frac{\dot{m}}{V_{\text{air}}} \right)^2 \left[ \frac{1}{2} \right]$$

$$W_m = [ (\pm 0.1 \times 0.009408)^2 ]^{0.5} = \pm 0.0009408 \text{ kg/s}$$

Then, the relative error is:

$$E_m = \frac{0.0009408}{0.04} = 2.352 \%.$$  

iii- The uncertainty of the solar radiation is:

$$W_{I_R} = \pm 1 \text{ W/m}^2$$

Then, the relative error is:

$$E_{I(\%)} = \frac{1}{1128} = 0.0886 \%$$

Then, the uncertainty of $\eta$ can be calculated as follows:

$$W_\eta = [(\pm 0.0009408 \times \frac{1005+28}{2.2+1128})^2 + (\pm 1.414 \times \frac{0.04+1005}{2.2+1128})^2 + (\pm 1 \times \frac{-0.04+1005+28}{2.2+1128})^2 ]^{0.5} = \pm 2.5 \%$$

Then,

$$E_\eta = \frac{2.5}{40.8} = 6.13 \%$$

Accordingly, the resulting errors of the calculated $\eta$ of the solar air heater are about $\pm 2.5 \%$.

3. Results and Discussion

The tested heaters were studied experimentally under Kafrelsheikh, Egypt weather, ($31^\circ 05' 54''$ N and $30^\circ 57' 00''$ E). The experiments were performed to study the influence of glazed entrance and guide blades on a single-pass SAH performance at various air flow rates. The tested SAHs differ in the configurations of the entrance region (glazed entrance, glazed entrance with
blades and steel entrance). Also, the experiments were carried out at four various flow rates of air ranged from 0.013 to 0.04 kg/s.

3.1. Effect of entrance modifications on the temperatures of both absorber surface and air flow

Solar intensity ($I(t)$) influences the SAH performance through the day. Fig. 4 indicates the variation of $I(t)$ during the day time of the experiments of the two cases of study at the different values of $\dot{m}$. As expected, $I(t)$ varies during the day as it increases from the day early hours till its peak value and then decreases later. The daily average value of solar radiation shows its stability due to the close range of the measured values. The stability of $I(t)$ can be noticed from the affinity or semi-congruent curves especially at the late hours of the day as obviously shown in Fig. 4(b). The mean average value of solar radiation is 790.4 W/m$^2$ for all days of the experiments. While the maximum recorded value is 1212 W/m$^2$.

Fig. 5 shows the variations of the conventional SAH temperatures during the day time at $\dot{m} = 0.013$ kg/s. From the results, the mean temperatures of the absorber surface during the day are 26.7, 59.6 and 65 °C for $T_1$, $T_2$ and $T_3$, respectively. While the mean value of temperature difference of the air flow is 26.3 °C at the same flow rate of 0.013 kg/s. Moreover, the maximum values of surface temperatures are 35, 82 and 88 °C for $T_1$, $T_2$ and $T_3$, respectively. While, the maximum value of temperature difference ($\Delta T$), $T_{out} - T_{in}$, is 42 °C.

While, Fig. 6 shows the variation of the glazed entrance SAH temperatures versus the experiment time at the same value of $\dot{m} = 0.013$ kg/s. It is noticed that, the mean temperatures on the absorber surface during the day are 45.4, 64.6 and 71.1 °C for $T_1$, $T_2$ and $T_3$, respectively. While the mean value of $\Delta T$ is 31.1 °C. Also, the maximum values of temperatures are 61, 85 and 93 °C for $T_1$, $T_2$ and $T_3$, respectively. While the maximum value of $\Delta T$ is 46 °C.

On the other side, for glazed-bladed entrance SAH, Fig. 7 illustrates the variation of its temperatures versus time at the same value of $\dot{m} = 0.013$ kg/s. The mean temperatures of the surface during that day are 44.8, 63.8 and 70.33 °C for $T_1$, $T_2$ and $T_3$, respectively. While the mean value of $\Delta T$ is 33.1 °C. Also, the maximum values of temperatures are 60, 84 and 92 °C for $T_1$, $T_2$ and $T_3$, respectively. While, the maximum value of $\Delta T$ is 47 °C. The results show that the mean temperatures on the absorber surface of the glazed-bladed entrance SAH during the day are
approximately the same for the glazed entrance SAH as the blades gain low value of heat from the entrance besides the close-range of the solar radiation during the days of the experiments.

Comparing the results, both surface temperatures and $T_{\text{out}}$ of the modified SAHs are higher than their values at the conventional SAH. This may be due to the restriction of solar radiation from reaching the entrance occurred because of the steel entrance. So, the entrance temperature decreases. Hence, the absorber losses heat to the entrance resulting in decrease of the absorber temperature. Moreover, using glass cover at the entrance of the modified SAHs increases the area exposed to the solar radiation which in-role increases the surface temperature and hence $T_{\text{out}}$. In addition, it is noticed that the $T_{\text{out}}$ in case of the glazed-bladed entrance SAH is higher than that of the glazed entrance SAH without blades. This may be due to the good distribution of air through the heater surface which-in-turn enhances the heat transfer process. Hence, in case of using entrance without blades allows low air distribution and low heat transfer area, for the same value of $\dot{m}$, and hence low value of $T_{\text{out}}$.

3.2. The temperature difference of the air flow

The temperature difference ($\Delta T$) is one of the parameters must be considered during describing or stating the performance of SAHs. The modifications made on the entrance region led to good enhancement in $\Delta T$ for each value of $\dot{m}$. For example, at 0.022 kg/s, glazing the entrance led to enhancing $\Delta T$ by 2 to 8 °C over the conventional SAH as shown in Fig. 8a. On the other side, the glazed-bladed entrance SAH overcomes the conventional one by 4 to 9 °C as shown in Fig. 8b.

Fig. 9 shows the daily temperature difference ($\Delta T_d$) versus the air flow rate for each case-study. The results show that $\Delta T_d$ decreases as $\dot{m}$ increases. At constant value of $\dot{m}$, the results show that the modifications made on the entrance led to good enhancement as the glazed-bladed entrance SAH leads both the glazed entrance and conventional SAHs. The glazed entrance SAH also has higher values than the conventional one at each value of $\dot{m}$. The achieved enhancements may be due to the increasing of the area exposed to solar radiation by glazing the entrance as it became 2.2 m$^2$ instead of 2 m$^2$ in case of conventional SAH besides eliminating the heat lost from the absorber to the entrance. Moreover, using guide blades allows good air distribution in both the entrance section and the absorber plate and reduces the dead zones in the heater. The
good distribution of air enhances the heat transfer process as mentioned before. In addition, the guide blades act as fins, thus enhance the heat transfer at entrance of heater.

From Fig. 9a, it is noticed that the maximum values of ∆Td are 33.07 and 25.9 °C for the glazed-bladed entrance SAH and conventional SAH, respectively, at \( \dot{m} = 0.013 \) kg/s. Also, From Fig. 9b, the maximum values of ∆Td are 31.11 and 26.3 °C for the glazed entrance SAH and conventional SAH, respectively, at \( \dot{m} = 0.013 \) kg/s.

### 3.3. The heater efficiency

The efficiency \( (\eta) \) of SAHs is the most important parameter for stating their performance. For all values of \( \dot{m} \), each case of modified SAH has values of \( \eta \) higher than the conventional one. Also, the glazed-bladed entrance is more efficient than the conventional one. That can be noticed from Fig. 10 which indicates the thermal efficiency at air flow rate of 0.022 kg/s, as example, for both the modified and conventional SAHs. From the figure, it is noticed that \( \eta \) of the conventional SAH obviously decreases at the day late-hours in opposite manner to the increase occurred for the modified SAHs. According to equation (5), this notice may be because that the decrease in ∆T is in small rate during the decrease of \( I_{R(\theta)} \) in case of the modified SAHs in opposite to its rate in case of conventional SAH. The slow rate of decrease of ∆T in case of modified SAHs backs to the modifications made to the entrance which increased the area exposed to solar radiation and eliminated the dead zones of air through the SAH. Moreover, at 0.022 kg/s, the glazed-bladed entrance SAH overcomes the conventional SAH by 3.71 to 27.12 % while the glazed entrance SAH is higher than the conventional SAH by 1.87 to 24.47 %.

Fig. 11 illustrates the influence of air mass flow rate on the daily thermal efficiency \( (\eta_d) \) for the tested SAHs. The values of \( \eta_d \) vary proportional to \( \dot{m} \) due to the enhancement in the heat transfer characteristics. Also, the modifications made at the entrance showed good improvement in the thermal efficiency due to avoiding the mentioned problems of steel entrance and distribution of the air by the blades. In addition, the figure clearly shows that the glazed-bladed entrance SAH is more efficient than the glazed entrance and the conventional SAHs over the entire range of \( \dot{m} \). The enhancement in the values of \( \eta_d \) increases as \( \dot{m} \) increases. From the figure, the maximum values of the \( \eta_d \) are 43.43, 40.48 and 32.92 % for the glazed-bladed entrance, glazed entrance and conventional SAHs, respectively, at \( \dot{m} \) of 0.04 kg/s. As a result,
the glazed-bladed SAH showed a good enhancement in $\eta_d$ by 6.72 to 10.5% over the conventional SAH and by 2.16 to 3.25% over the glazed SAH.

4. Cost estimation for the gained heat

For estimating the average cost of the gained heat, the total cost (C) for the assumed number of life time years ($n_y$), fixed cost (F) and variable cost (V) is to be calculated as $C = F + V$. The value of the variable cost (V) can be assumed to be (V = 0.15 F) per year without the price of PV-system. The cost of PV-system is 300 $. The fixed cost of the components of the fabricated SAHs is illustrated in Table 4. If $n_y = 25$ year and number of days is 350 day/year, the following cost estimation can be calculated:

For the glazed-bladed entrance SAH, at $\dot{m} = 0.04$ kg/s, $F = 366$, then, then $C = 366 + (0.15 \times 66 \times 25) = 613.5$. Then, $C_{\text{year}}$ is 24.54 $. For average heat production of the glazed-bladed SAH of 2378 kW/year, then the cost of one kW is 0.01032 $.

Similarly, considering the corresponding values of fixed cost, the cost of one kW is 0.01099 $ and 0.01351 $ for glazed entrance and conventional SAHs, respectively.

5. Conclusion

The present experimental study aims to enhance the performance of flat plate SAH by modifying the entrance region. The entrance region was covered with glass cover instead of steel cover. In addition, guide blades were placed in the entrance region to ensure well air distribution on the absorber surface. The experiments were performed at four various air flow rates between 0.013 kg/s and 0.04 kg/s. The performance of the modified SAHs is compared with a conventional SAH. The results showed good enhancement in both the efficiency and the air temperature difference. The maximum values of the daily efficiency are 43.43, 40.48 and 32.92% for the glazed-bladed entrance SAH, glazed entrance SAH and conventional SAH, respectively, at air flow rate of 0.04 kg/s. The glazed-bladed SAH showed a good improvement.
in the thermal efficiency by 6.72 % to 10.51 % over the conventional heater and by 2.16 % to 3.25 % over the glazed SAH.

References


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### Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$A_h$</td>
<td>Surface area of SAH ($m^2$)</td>
</tr>
<tr>
<td>$A_p$</td>
<td>PV pipe cross-sectional area ($m^2$)</td>
</tr>
<tr>
<td>$C$</td>
<td>Total cost ($)</td>
</tr>
<tr>
<td>$C_p$</td>
<td>Air specific heat ($J/kg K$)</td>
</tr>
<tr>
<td>$F$</td>
<td>Fixed cost ($)</td>
</tr>
<tr>
<td>$I_{(t)}$</td>
<td>Solar radiation intensity ($W/m^2$)</td>
</tr>
<tr>
<td>$\dot{m}$</td>
<td>Air mass Flow rate (kg/s)</td>
</tr>
<tr>
<td>$N$</td>
<td>Number of variables</td>
</tr>
<tr>
<td>$n_y$</td>
<td>Number of years</td>
</tr>
<tr>
<td>PV</td>
<td>Photovoltaic</td>
</tr>
<tr>
<td>PCM</td>
<td>Phase change material</td>
</tr>
<tr>
<td>$Q_u$</td>
<td>Useful heat gained (W)</td>
</tr>
<tr>
<td>SAH</td>
<td>Solar air heater</td>
</tr>
<tr>
<td>$T_{in}$</td>
<td>Inlet air temperature ($^\circ C$)</td>
</tr>
<tr>
<td>$T_{out}$</td>
<td>Outlet air temperature ($^\circ C$)</td>
</tr>
<tr>
<td>$T_1$, $T_2$, $T_3$</td>
<td>Temperatures at different positions on the absorber ($^\circ C$)</td>
</tr>
<tr>
<td>$\Delta T$</td>
<td>Temperature difference of air flow ($^\circ C$)</td>
</tr>
<tr>
<td>$\Delta T_d$</td>
<td>Daily temperature difference of air flow ($^\circ C$)</td>
</tr>
<tr>
<td>$V$</td>
<td>Variable cost ($)</td>
</tr>
<tr>
<td>$V_{air}$</td>
<td>Air velocity (m/s)</td>
</tr>
<tr>
<td>$\eta$</td>
<td>Thermal efficiency</td>
</tr>
<tr>
<td>$\eta_d$</td>
<td>Daily thermal efficiency</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Density of air ($kg/m^3$)</td>
</tr>
</tbody>
</table>
List of figures

Fig. 1 Photos of the tested heaters.
Fig. 2 A schematic diagram of the test set-up.
Fig. 3 Positions of thermocouples.
Fig. 4 The hourly variations of $I(t)$ during the days of experiments.
Fig. 5 The hourly Variations of the conventional SAH temperatures at 0.013 kg/s.
Fig. 6 The hourly Variations of the glazed entrance SAH temperatures at 0.013 kg/s.
Fig. 7 The hourly Variations of the glazed-bladed entrance SAH temperatures at 0.013 kg/s.
Fig. 8 Variations of the temperature difference at 0.022 kg/s.
Fig. 9 Daily temperature difference versus air flow rate.
Fig. 10 The thermal efficiency of tested heaters at 0.022 kg/s.
Fig. 11 Daily thermal efficiency versus air flow rate.

List of tables

Table 1 Specifications of the SAH.
Table 2 Sample of experimental data
Table 3 Measurements uncertainties and relative errors
Table 4 Cost of fabricated SAHs
Figures

a- Flat plate SAH with glass cover at entrance

b- Flat plate SAH with directing blades (unpainted)

c- Flat plate SAH with steel cover at entrance

Fig. 1 Photos of the tested heaters.
Fig. 2 A schematic diagram of the test set-up.

Fig. 3 Positions of thermocouples.
(a) Days of glazed entrance SAH experiments.

(b) Days of glazed-bladed entrance SAH experiments.

Fig. 4 The hourly variations of $I(t)$ during the days of experiments.
Fig. 5 The hourly Variations of the conventional SAH temperatures at 0.013 kg/s.

Fig. 6 The hourly Variations of the glazed entrance SAH temperatures at 0.013 kg/s.
Fig. 7 The hourly Variations of the glazed-bladed entrance SAH temperatures at 0.013 kg/s.
a - Glazed entrance vs. conventional

b - Glazed and bladed entrance vs. conventional

Fig. 8 Variations of the temperature difference at 0.022 kg/s.
a- Glazed entrance vs. conventional

b- Glazed and bladed entrance vs. conventional

Fig. 9 Daily temperature difference versus air flow rate.
Fig. 10 The thermal efficiency of tested heaters at 0.022 kg/s.

Fig. 11 Daily thermal efficiency versus air flow rate.
### Tables

#### Table 1 Specifications of the SAH.

<table>
<thead>
<tr>
<th>Component</th>
<th>Type and specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAH duct</td>
<td>Galvanized steel of 200 ×100×10 cm</td>
</tr>
<tr>
<td>Entrance and Exit</td>
<td>Divergent (entrance) and convergent (exit) ducts 100 cm for one end till 10 cm at the other end with 40 cm length</td>
</tr>
<tr>
<td>Blades</td>
<td>4 aluminum blades oriented at nearly 24° in-between angle</td>
</tr>
<tr>
<td>Coating</td>
<td>Industrial matt black (absorptivity of 0.95)</td>
</tr>
<tr>
<td>Back and Side</td>
<td>Glass-wool (5 cm thickness)</td>
</tr>
<tr>
<td>Insulation</td>
<td>Glazing Single glass cover (0.4 cm thickness) (absorptivity of 0.05) (emissivity of 0.85)</td>
</tr>
<tr>
<td>Tilt Angle</td>
<td>30° with the horizontal</td>
</tr>
<tr>
<td>Outer Frame</td>
<td>Wooden Frame</td>
</tr>
<tr>
<td>Sealant</td>
<td>Thermal Silicon</td>
</tr>
</tbody>
</table>

#### Table 2 Sample of experimental data

<table>
<thead>
<tr>
<th>Time and Day</th>
<th>$T_{in}$</th>
<th>$T_{out}$ (°C)</th>
<th>$V_{air}$ (m/s)</th>
<th>$I_0$ (W/m$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12:00</td>
<td>23</td>
<td>51</td>
<td>4.5</td>
<td>1128</td>
</tr>
<tr>
<td>13/2/2017</td>
<td>± 1</td>
<td>± 1</td>
<td>± 0.1</td>
<td>± 1</td>
</tr>
</tbody>
</table>

#### Table 3 Measurements uncertainties and relative errors

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Uncertainty</th>
<th>Relative error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air temperature difference (°C)</td>
<td>± 1.414</td>
<td>5 %</td>
</tr>
<tr>
<td>Air mass flow rate (kg/s)</td>
<td>± 0.0009408</td>
<td>2.352 %</td>
</tr>
<tr>
<td>Solar radiation (W/m$^2$)</td>
<td>± 1</td>
<td>0.0886 %</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>± 2.5</td>
<td>6.13 %</td>
</tr>
</tbody>
</table>

#### Table 4 Cost of fabricated SAHs

<table>
<thead>
<tr>
<th>Unit</th>
<th>Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metal sheet</td>
<td>25</td>
</tr>
<tr>
<td>Glass cover</td>
<td>8</td>
</tr>
<tr>
<td>Blower</td>
<td>15</td>
</tr>
<tr>
<td>Thermal insulation</td>
<td>4</td>
</tr>
<tr>
<td>Connection pipes and valves</td>
<td>8</td>
</tr>
<tr>
<td>Paint and silicon</td>
<td>5</td>
</tr>
<tr>
<td>Blades</td>
<td>1</td>
</tr>
</tbody>
</table>