Energy Analysis of Solar Collector With perforated Absorber Plate

Dr. Ammar Ali Farhan
Lecturer
Energy Eng. Dept. – University of Baghdad
ammarali@uob.edu.iq

Hana Abdulhussien Sahi
M. Sc. Student
College of Engineering - University of Baghdad
musnew1@gmail.com

ABSTRACT

The thermal performance of three solar collectors with 3, 6 mm holes and without perforation absorber plate was experimentally assessed. The experimental tests were implemented in Baghdad during January and February 2017. Five values of airflow rates range between 0.01 – 0.1 m^3/s were used through the test with a constant airflow rate during the test day. The variation of the following parameters was recorded every 15 minutes air temperature difference, useful energy, absorber plate temperature, and collector efficiency. The experimental data reported that the number of absorber plate perforations with a small diameters is more efficient than increasing the hole diameters of the absorber plate with decreasing the perforation numbers. The maximum air temperature difference throughout the solar collector with 3, 6 mm perforations and without perforations were 17, 15, and 12 ^oC, respectively. Also, it can be conclude that the energy gained from the solar collector with 3 mm perforation absorber plate is 28.2 % higher than the energy gained from solar collector without holes per day for 0.1 m^3/s airflow rate. The maximum values of the thermal performance curves were 67 %, 64 %, and 56 % for the solar collector with 3, 6 mm, and without perforations, respectively.

Key words: Energy analysis, solar collector, perforated absorber plate, thermal performance.

تحليل الطاقة لمجمع شمسي ذو صفيحة امتصاص مثقبة

د. عمار علي فرحان
مدرس
قسم هندسة الطاقة – جامعة بغداد

هناء عبد الحسين ساهي
طالبة ماجستير
كلية الهندسة – جامعة بغداد

الخلاصة

تم تقييم الأداء الحراري عملياً لثلاثة مجمعات شمسية ذات لوح امتصاص تحتوي على ثقوب 3 و 6 ملم وبدون ثقوب .اجريت الاختبارات التجريبية في بغداد خلال شهري كانون الثاني وشباط لعام 2017. تم استخدام خمسة قيم لمعدلات تدفق الهواء تتراوح بين 0.01 – 0.1 م ^{3} \ ثانية خلال التجارب مع معدل تدفق هواء ثابت خلال الاختبار الواحد .تم تسجيل بيانات العناصر الآتية كل 15 دقيقة: الفرق في درجة حرارة الهواء، الطاقة المفيدة، درجة حرارة لوح الامتصاص، وكفاءة المجمع .اثبتت البيانات العملية أن زيادة عدد ثقوب لوح الامتصاص مع قطر صغير هو أحسن كفاءة من قطر كبير وعدد قليل من الثقوب في لوح الامتصاص . أقصى فرق في درجة حرارة الهواء خلال المجمع الشمسي ذو لوح امتصاص يحتوي على ثقوب 3 و 6 ملم وبدون ثقوب كانت 17، 15، و 12 درجة مئوية، على التوالي .أيضا، يمكن استنتاج أن الطاقة المكتسبة من المجمع الشمسي ذو لوح امتصاص يحتوي على ثقوب 3 ملم هي أكثر من الطاقة المكتسبة من المجمع الشمسي ذو لوح امتصاص بدون ثقوب بمقدار 28.2 ٪ في اليوم

لمعدل تدفق هواء بمقدار 0.1 م ^{3} /ثانية. كانت القيم القصوى لمنحنيات الأداء الحراري هي % 67، % 64، و % 56 لمجمع الشمسي ذو لوح امتصاص يحتوي على ثقوب 3 و 6 ملم وبدون ثقوب ، على التوالي.

الكلمات الرئيسية: تحليل الطاقة، مجمع شمسي، لوح امتصاص مثقب، الاداء الحراري.

1. INTRODUCTION

One of the weather features in Iraq is the clear sunny sky days for most year days. It encourages exploiting the solar energy and using it in different applications. The solar heaters are the devices that represent the best and simplest use of solar energy. It absorbs the solar radiation falling on the absorbent surface and then transfer the heat to the inside air of the solar collector. The hot air is used for different purposes such as heating buildings, agricultural drying and paper products **Joudi and Dhaidan 2001. Zomorrodian and Barati 2010,** investigated the effect of single glass cover of solar air collector with aluminum absorber perforated plate. They studied the effect of porosity of the plate absorber and the rate of airflow on the efficiency of the heater. They found that a maximum thermal efficiency of 84% was achieved for the most part of the porous absorber plate at the highest air mass flow rate.

Different ways were used by researchers to improve the thermal efficiency of the solar air heater. **Lizica et al. 2014** used good thermal insulation, cover with high permeability, and the use of high absorbency materials to enhance the thermal efficiency. The performance of solar heater affected by the turbulent flow generated as a result of the obstacles of fixed fins on the absorber board compared with the same solar heater without fins were implemented by **Pakadaman et al. 2011.** They concluded that the existence of the fins increasing the temperature of the absorber plate temperature whereas increasing the thermal exchange rates between it and the inside air compare to the same heater but without fins. The effect of artificial roughness (fins, baffles and ribs) attached at the absorber plate on the convective heat transfer between it and the working fluid were presented by **Gawande et al. 2014** and **Singh et al. 2014**. Thereby, the thermal efficiency will be increased as the turbulent convective heat transfer increases.

The use of matrix solar collector has more advantages than the traditional flat plate solar collector. Many researchers have studied the thermal performance of matrix solar air heater theoretically and experimentally **Rajarajeswari** and **Sreekumar 2016**. **Xu et al. 2007** studied numerically the effect of wire screen meshes on the thermal efficiency. They concluded that the thermal efficiency enhanced because of the improvement in the convective heat transfer. **Ramani et al. 2010** studied experimentally the effect of using double pass solar air heater with a porous material on the thermal efficiency. Clearly, the thermal performance was increased by 25 % as it compared with double pass solar air heater without porous material. In general, the uses of a matrix material as an absorber plate or a packed bed in the airflow duct produces a turbulent flow leads to improve the convective heat transfer. Thereby, there is a percentage improvement in the thermal efficiency of the matrix solar collector as compared to traditional type.

In this study, three solar air heaters with different absorber plate will be constructed and installed with the same dimensions. The first heater will contains a flat absorber plate while the second and third heaters will contain a perforated absorber plate with a different diameter. The study aim to identify the efficiency of the best heater among this group and determine the factors affecting this efficiency. Also, the effect of the perforated absorber plate on the pressure drop across the heater.

2. EXPERIMENTAL WORK

Three outdoor single glass cover solar collector was designed and installed according to the outlines states in **ASHRAE** recommendations **1977**. These collectors were assembled from an available local material. The experimental rigs composed of a centrifugal blower, glass cover, absorber plate, connection diffusers, and insulation on the sides and bottom. A wood frame was used to combine these components as shown in **Fig.1**. Each collector 120 cm (length) × 50 cm (width) × 21 cm (height) as shown in **Fig. 2**. An ordinary glass cover with 4 mm thickness was used. Three different absorber plate of 1 mm galvanized steel which were used in the study are shown in **Fig. 3**. The first plate was without perforations; the second and third plates were perforated with circular holes (3 and 6 mm) respectively.

Hourly solar radiation data was taken from the Iraqi meteorological organization and seismology. Absorber plate, air inlet, and air outlet temperatures of solar air heater were recorded every 900 s intervals using twenty-two integrated circuit sensors DS18B20, which has an accuracy of ± 0.5 ^{o}C over a range of - 55 to 125 ^{o}C. These integrated circuit sensors were coupled to a USB DAQ model ARDUINO MEGA 2560 device with 54 flexible input/output channels. Seven sensors were manipulated to measure the temperature of the absorber plate, inlet air, and outlet air for each solar air heater. One sensor was handled to measure the ambient temperature. Measurement of air flow rate was accomplished through a multi-function measurement instrument for air-conditioning, ventilation and indoor air quality manufactured by testo company, Lenzkrich, Germany, model 435. A handheld Extech HD350 Pitot Tube Anemometer and Differential Manometer made by Extech company, Nashua, USA, were used to compute the pressure drop through the solar air heater.

The experimental rig was installed in Baghdad (33 ^{o}N, 44 ^{o}E) with a tilted angle of 45^{o}. The experimental work was implemented in winter 2017. Experimental data was recorded from 9 AM to 4 PM. Five values of airflow rate were used through the solar air heaters ranging between 0.01 – 0.1 m^3/s. A constant airflow rate was used during the day for each test. A mean value of air flow rate uses was calculated from six measurements across the solar air heater outlet. The density variation was treated by ideal gas law to compute the mass flow rate from solar air heater.

3. THERMAL ANALYSIS

In steady state, the performance of a solar air collector is described by an energy balance that indicates the distribution of incident solar energy into useful energy gain, thermal losses, and optical losses. The absorbed energy (S) by an absorber plate is equal to the difference between the incident solar radiation and the optical losses. The thermal energy lost from the collector to the surroundings by conduction, convection, and infrared radiation can be represented as the product of a heat transfer coefficient U_L times the difference between the mean absorber plate temperature Tpm and the ambient temperature T_a **Duffie and Beckman 2013.**

The amount of solar energy incident on the heater is:

$$Q_i = IA_c \tag{1}$$

While the total losses energy from the collector are equall to the losses from the absorber plate, rear plate and from the sides of the collector then we can callculated the total energy losses from the equation below:

$$Q_L = U_L A_c (T_p - T_a) \tag{2}$$

In steady state, the useful energy output of a collector of area Ac is the difference between the absorbed solar radiation and the thermal loss **Struckmann 2008.**

$$Q_u = Q_i - Q_L = A_C [S - U_L (T_p - T_a)] \tag{3}$$

Where S is the absorbed energy by absorber plate, which is written as;

$$S = \alpha_s \tau_c I \tag{4}$$

The basic method of measuring collector performance is to expose the operating collector to solar radiation and measure the fluid inlet and outlet temperatures and the fluid flow rate **Duffie and Beckman 2013**. Then the useful energy gain is :

$$Q_u = \dot{m} c_p (T_{fo} - T_{fi}) \tag{5}$$

Thermal efficiency of the solar collector is defined as the ratio of the useful gain over some specified time-period to the incident solar energy over the same time-period **Duffie and Beckman 2013**.

$$\eta = \frac{Q_u}{Q_i} \tag{6}$$

4. RESULTS AND DISSCUSION

The testing work of the thermal performance of the three solar air heaters were occurred outdoor for the period between January and February 2017. The experiment day starts from 8:30 AM and ends at 4:00 PM. A constant air flow rate was used for each test. Five values of air flow rate were taken in this study ranging between 0.01 to 0.1 m^3/s.

The solar irradiance data collected by the Iraqi meteorological organization and seismology for experimental days is presented in **Fig. 4**. These data are measured for 45 ^{o} tilted surface and clear sky day. Clearly, the maximum value of solar radiation intensity was 960 W/m^2 occurred at the solar noon. In addition, the variation of ambient temperature that measured locally is also shown in **Fig. 4**. It is obvious; the ambient temperature is ranged between 10 to 19 ^oC during the experimental work.

Fig. 5 shows the variation of the absorber plate temperature for the three collectors with the time of day at 0.01 m^3/s flow rate. It seems that the behavior of the absorber plate temperature with time look like the behavior of solar irradiance with time as it is reported by **Joudi and Dhaidan 2001 and Farhan 2017**. The maximum value of the absorber plate temperature without perforation, 3 mm, and 6 mm perforation are 67, 50, and 34 ^oC, respectively. It is clear that the airflow across the perforated absorber plate reduces its temperature when it compares with the absorber plate without perforations. The temperature of the 3 mm perforated plate is higher than the temperature of the 6 mm perforated plate because of the different diameter and pitch for the holes. Also, the effect of airflow rate on the absorber plate temperature.

Hourly variation of the measured outlet air temperature for two different airflow rate 0.01 and 0.1 m^3/s is illustrated in **Figs. 6** and **7**. It is clear that the outlet air temperature increases with time till it reaches the maximum value at solar noon, then its decreases gradually when the value of solar irradiance decreases. The highest value of the outlet air temperature for solar collector without perforation, 3 mm perforation and 6 mm perforation are 26, 32, and 30 ^oC, respectively as shown in **Fig. 6**. A low value of airflow rate and small holes diameter make the convective heat transfer between the airflow and the absorber plate more efficient, which is explained why the solar collector with 3 mm perforation has maximum outlet air temperature. It can be conclude that increases the number of absorber plate holes with a small diameter is more efficient than increasing the hole diameter of the absorber plate with decreasing the perforation numbers. This conclusion is agree with the result obtained by **Zomorrodian and Barati 2010.**

A comparison between the maximum air temperature differences throughout the three collectors for various airflow rates is shown in **Fig. 8**. It can be conclude that the value of the air temperature difference across the collector depends strongly on the value of used airflow rate. The air temperature difference is proportional inversely with the value of airflow rate. Maximum air temperature difference throughout the solar collector with 3, 6 mm perforations and without perforations are 17, 15, and 12 ^oC, respectively. Based on the result presented in **Fig. 8** and according to the maximum air temperature difference throughout the collectors, it concludes that the solar collector with 3 mm perforation was more active than the other two collectors. This behavior is due to the turbulent flow accomplished by the small holes thereby, the convective heat transfer between absorber plate and the airflow is increasing. Also, the solar collector with perforation absorber plate has a larger contact area with the airflow due to the flow direction as shown in **Fig. 2b**, i.e. more heat transfer rate to the working fluid.

Distribution of the useful energy gained from the solar collector of 3 mm perforation absorber plate with time for different airflow rates is presented in **Fig. 9**. The energy obtained from the solar collector was proportional directly with the values of airflow rate. The useful energy rises with time from 9 a.m. to the solar noon due to the increasing in solar irradiance. After solar noon, it begins to reduce because of the decreasing in the solar irradiance. A comparison between the useful energy gained from solar collector with 3, 6 mm perforation and without perforation for 0.1 m^3/s airflow rate is plotted in **Fig. 10**. It can be seen that the maximum values of the useful energy are 703, 622 and 481 W, respectively. The reason beyond the higher value of useful energy obtained from the solar collector with 3 mm perforation absorber plate is mentioned in the discussion of **Fig. 8**. It can be conclude that the energy gained from the solar collector with 3 mm perforation absorber plate is 28.2 % more than the energy gained from solar collector without holes per day for 0.1 m^3/s airflow rate.

The thermal efficiency of a solar collector is expressed as the ratio of the useful energy gained in a given period to the solar irradiance during the same period **Duffie and Beckman 2013**. A comparison between the thermal performance curves for the three collectors in winter season is shown in **Fig. 11**. These curves are obtained from working data for clear sky days in winter. The scatter in experimental data points is due to the varying in operating conditions as it is reported by **Farhan 2017**. In addition, changes in wind velocity during the test time. Some extreme points have been omitted so as not to affect the curves behavior. The values of intersection points of thermal performance curves with the y-axes are 0.67, 0.64, and 0.56 for the solar collector with 3, 6 mm, and without perforations, respectively. The following equations represent the curves values illustrated in **Fig. 11** :

$$\eta = 0.67 - 11.15\,\frac{(T_{fo}-T_{fi})}{I} \tag{7}$$

$$\eta = 0.64 - 12.22\,\frac{(T_{fo}-T_{fi})}{I} \tag{8}$$

$$\eta = 0.56 - 15.40\,\frac{(T_{fo}-T_{fi})}{I} \tag{9}$$

These constants appear in the above equations are within normal values for similar solar collectors. Equations 7 – 9 are valid for airflow rate ranging between 0.01 – 0.1 m^3/s and ambient temperature not exceed 20 ^{O}C.

The Variation of static pressure drop as a function of the airflow rates for the three solar collectors is plotted in **Fig. 12**. It can be seen that the increases in the airflow rate lead to increase in the static pressure drop as expected. Clearly, the collector with 3 mm perforation has the larger value of pressure drop due to the small holes diameter thereby, the velocity is increasing which makes the existence of turbulence is dominant.

5. CONCLUSIONS

Three solar collectors with 3, 6 mm holes, and without perforation absorber plate were fabricated and investigated for different airflow rates in January and February 2017 in Baghdad, Iraq. The experimental data reported that the airflow across the perforated absorber plate reduces its temperature when it compares with the absorber plate without perforations. It can be conclude that increases the number of absorber plate holes with a small diameter is more efficient rather than increasing the hole diameter of the absorber plate with decreasing the perforation numbers. The maximum air temperature difference throughout the solar collector with 3, 6 mm perforations and without perforations were 17, 15, and 12 ^{o}C, respectively. Also, it can be concluded that the energy gained from the solar collector with 3 mm perforation absorber plate is 28.2 % more than the energy gained from solar collector without holes per day for 0.1 m^3/s airflow rate. The maximum values of the thermal performance curves are 0.67, 0.64, and 0.56 for the solar collector with 3, 6 mm, and without perforations, respectively. The value of pressure drop through the collector of absorber plate with 3 mm holes is greater than its value through the collector without perforation absorber plate by five times at constant air flow rate.

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NOMENCLATURE

A_c area of the solar collector, m^2

c_p specific heat of air at constant pressure, J/kg K

I solar irradiance, W/m^2

$\dot{m}$ air mass flow rate, kg/s

Q_i incident solar energy incident, W

Q_l total losses energy, W

Q_u useful energy, W

T_a ambient temperature, ^oC

T_{fi} inlet air temperature, ^oC

T_{fo} outlet air temperature, ^oC

T_p absorber plate temperature, ^oC

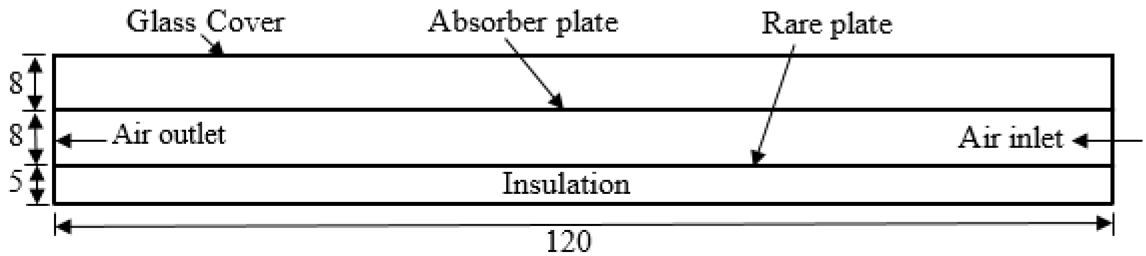
U_l overall heat transfer coefficient, $W/m^2 . K$

α_p plate absorptance, dimensionless.

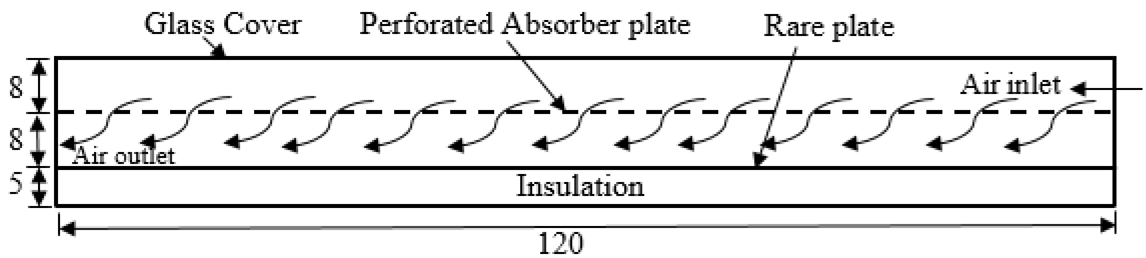
τ_g glass transmittance, dimensionless.

η instantaneous efficiency, %

Figure 1. Photograph of the experimental rig.

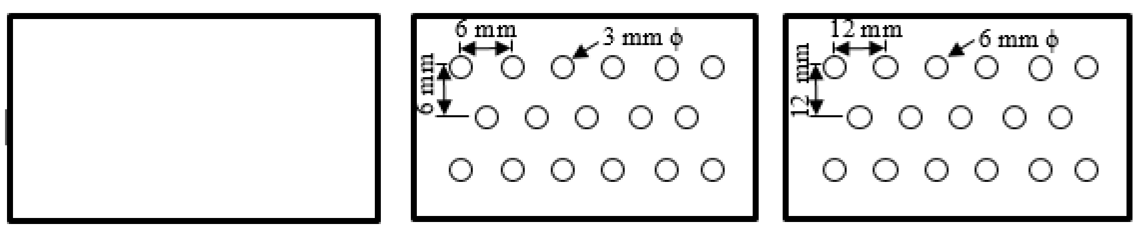


a. Flat plate collector with conventional absorber plate.



b. Flat plate solar collector with perforated absorber plate.

Figure 2. Schematic of solar collectors. All dimensions in centimeters.



a. Without perforations b. 3 mm perforations c. 6 mm perforations

Figure 3. Types of the absorber plates.

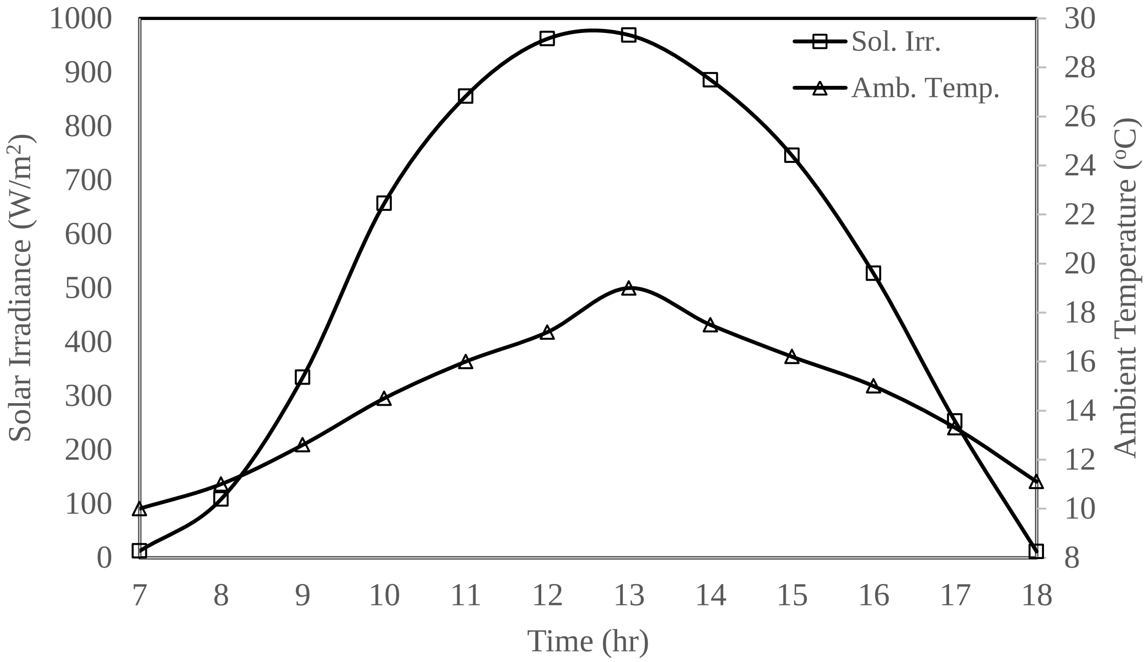


Figure 4. Variation of solar irradiance and ambient temperature with time for clear sky day in January 2017.

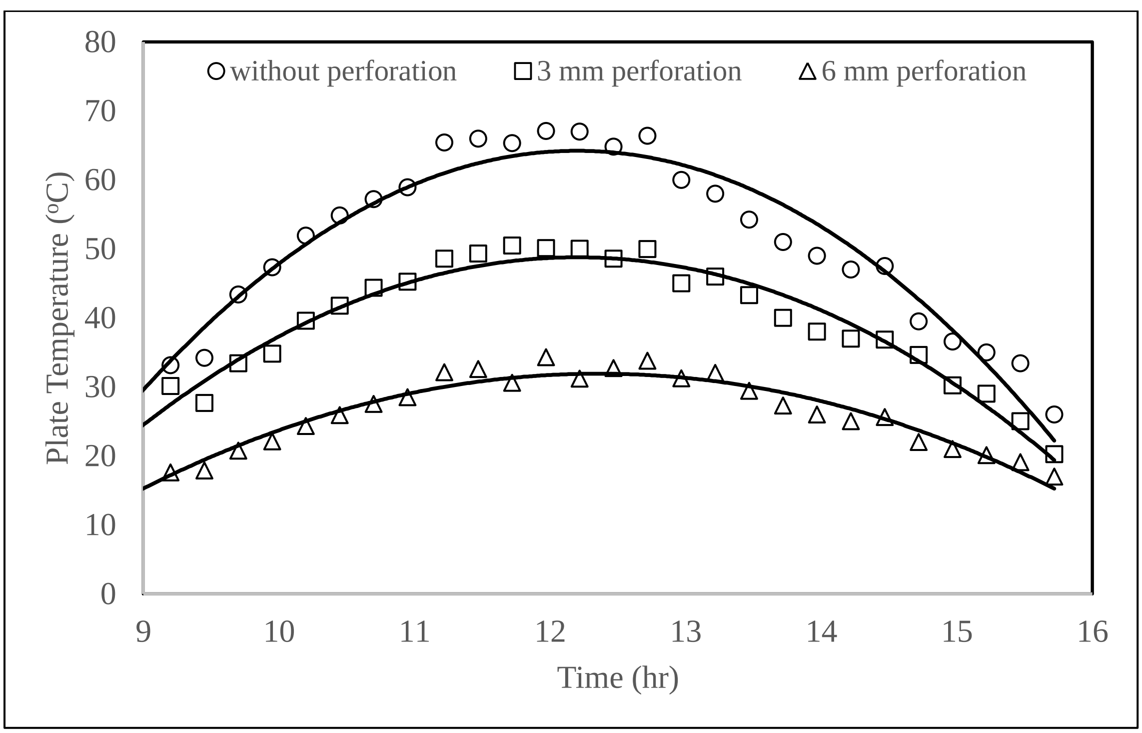


Figure 5. Hourly variation of the measured plate temperature with time for 0.01 m^3/s airflow rate.

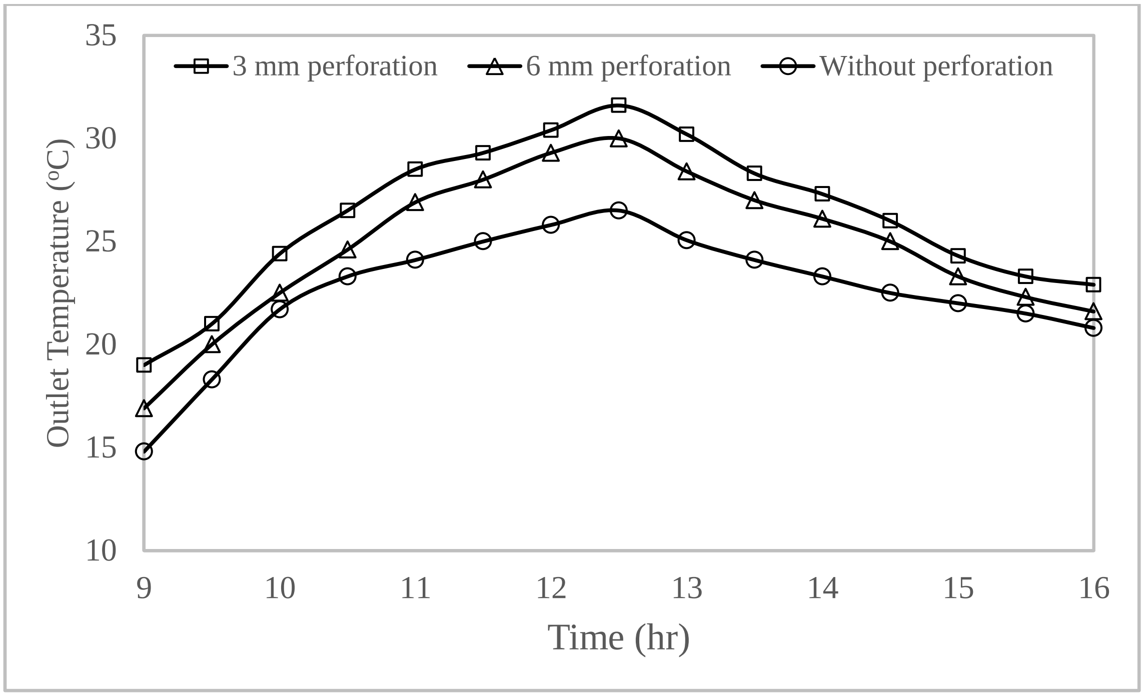


Figure 6. Distribution of the measured outlet air temperature with time for 0.01 m^3/s airflow rate.

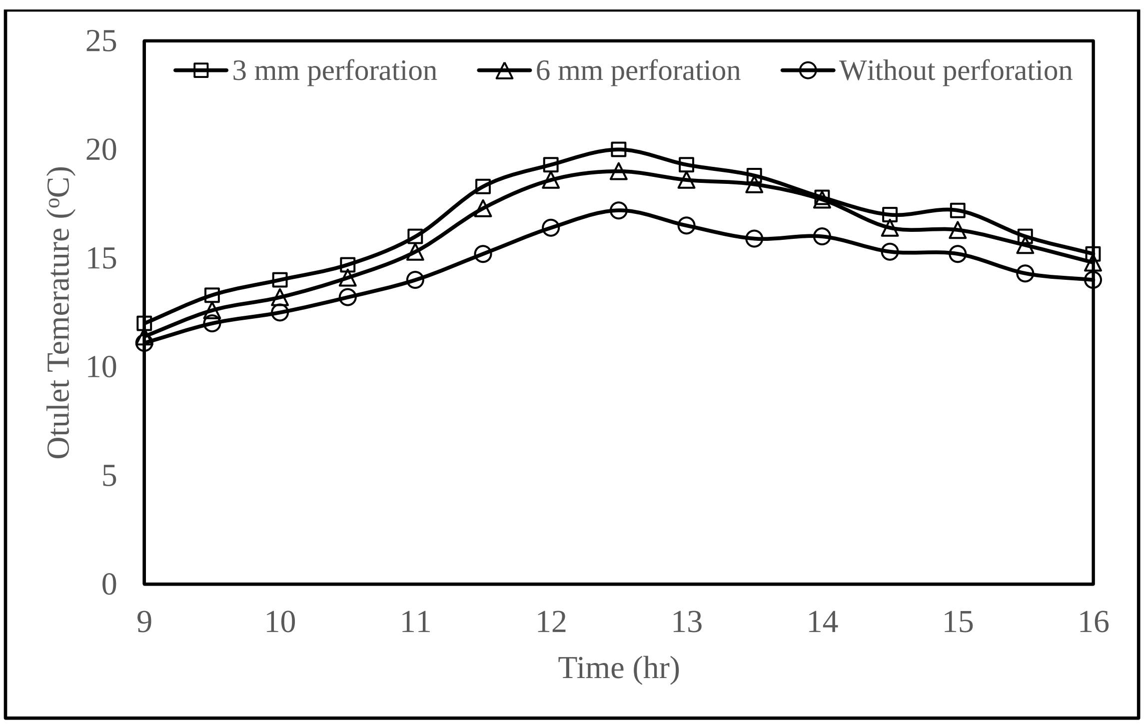


Figure 7. Distribution of the measured outlet air temperature with time for 0.1 m^3/s airflow rate.

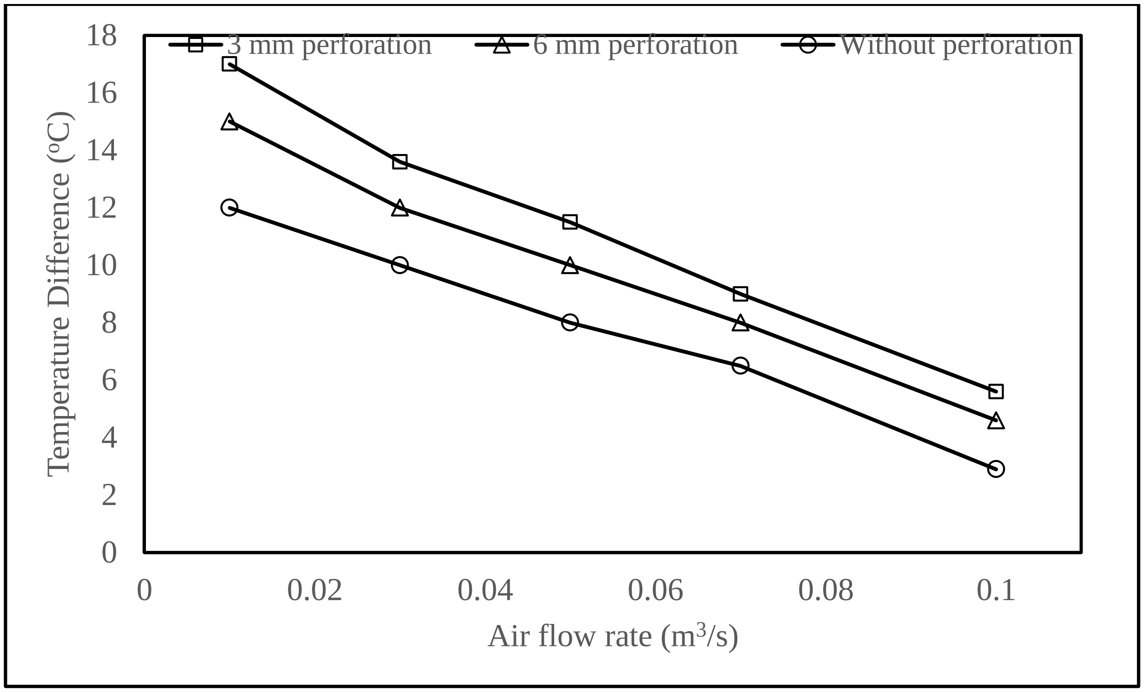


Figure 8. Maximum air temperature difference across the solar collector for different airflow rates.

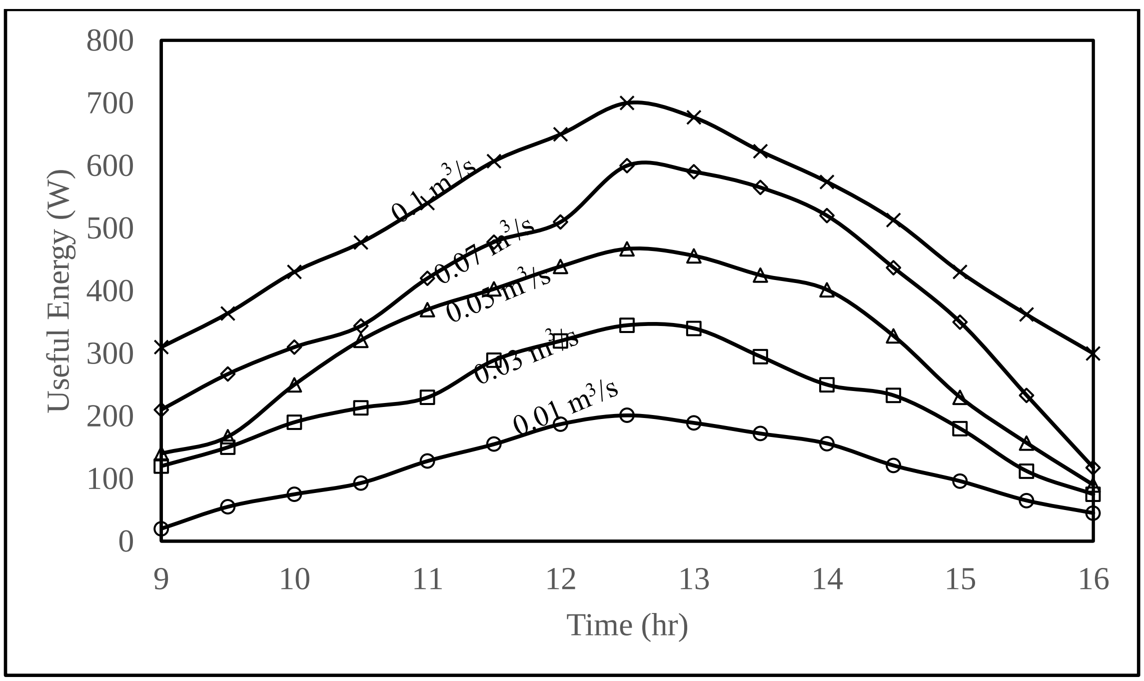


Figure 9. Distribution of the useful energy gained from solar collector of 3 mm perforation absorber plate with time for different airflow rates.

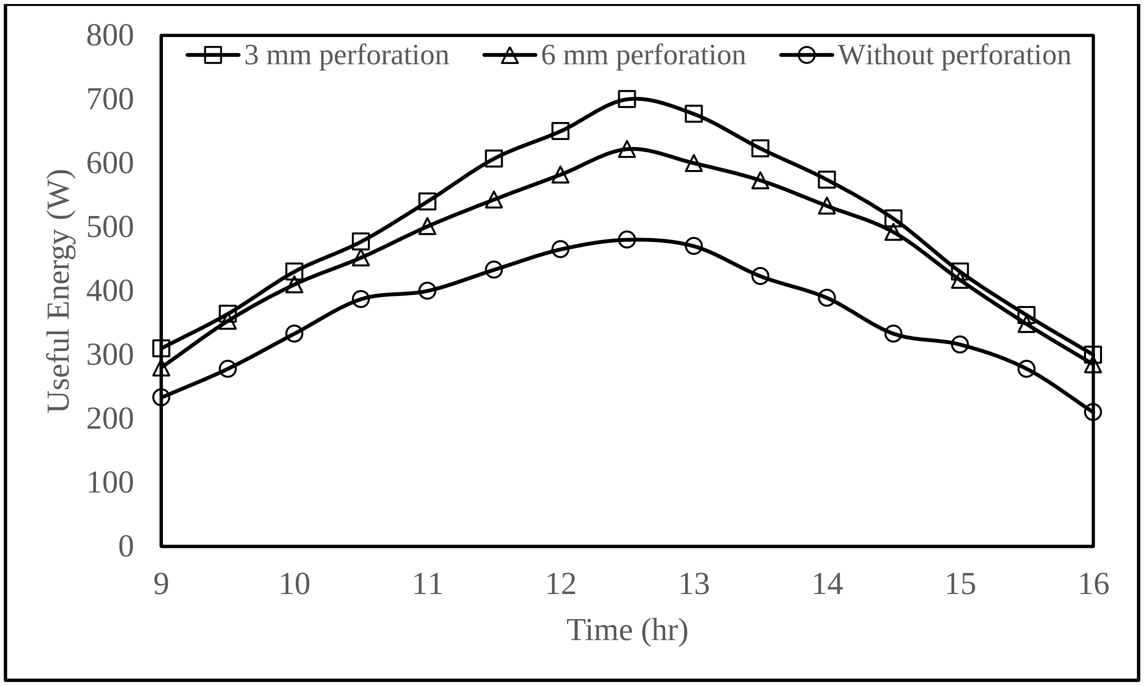


Figure 10. Distribution of the useful energy gained from solar collectors with time for 0.1 m^3/s airflow rate.

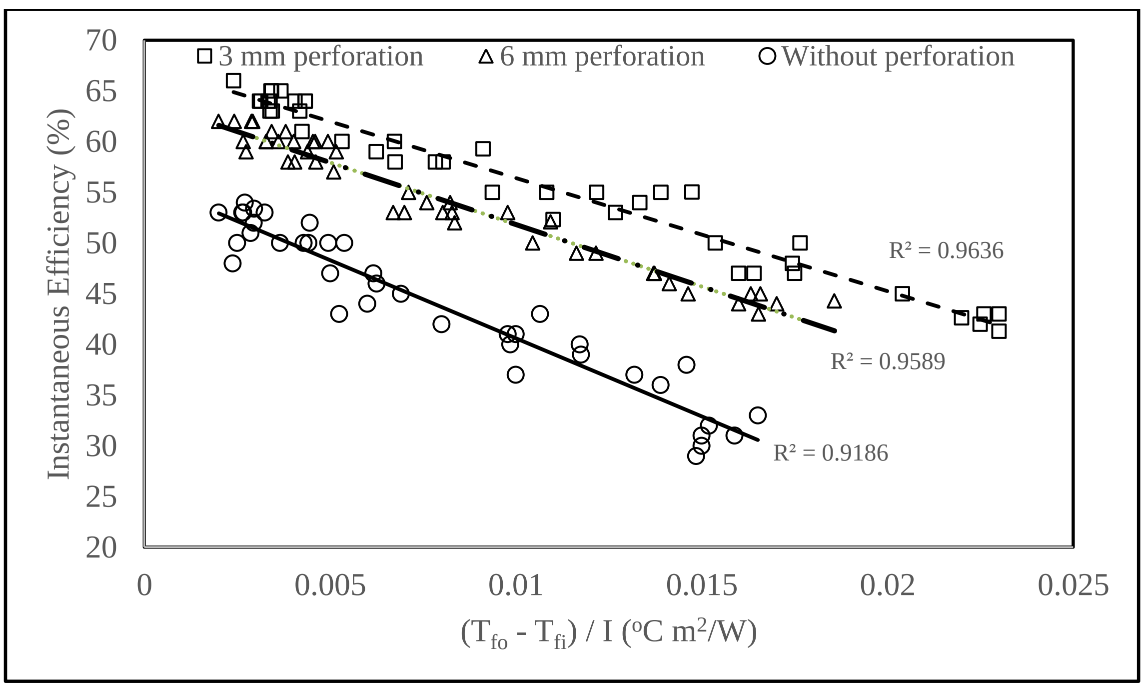


Figure 11. Operational efficiency curves for the three solar air heaters.

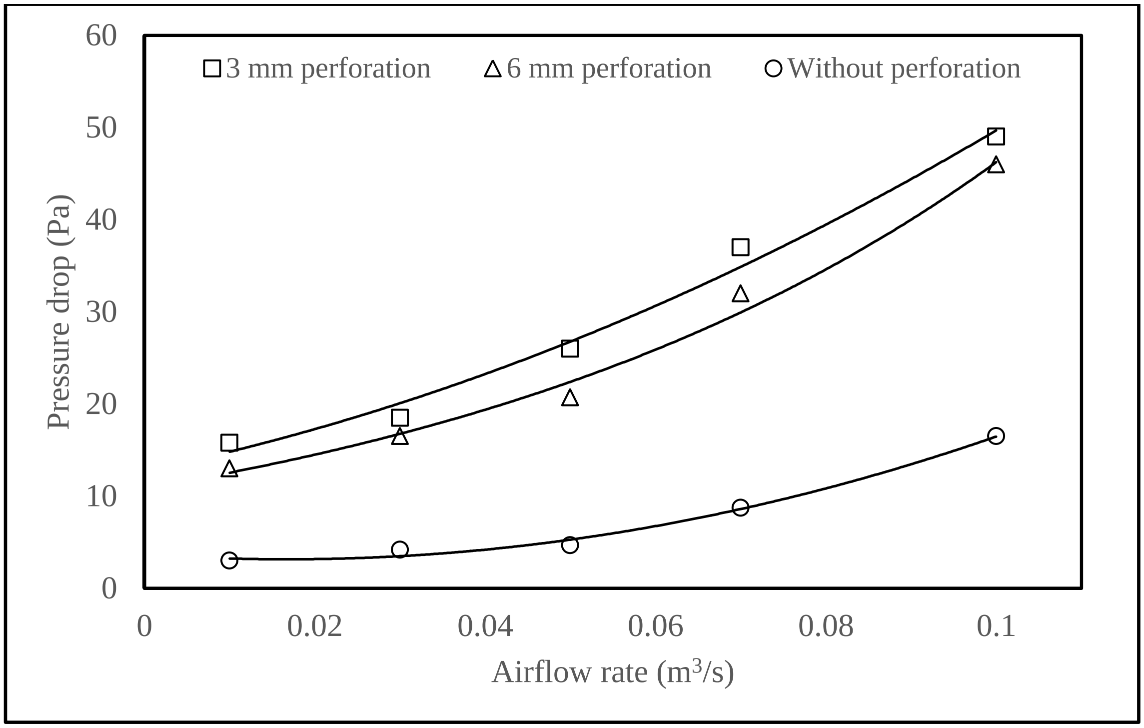


Figure 12. Variation of static pressure drop with different airflow rates.