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THERMAL ANALYSIS OF A PENTAGONAL SOLAR AIR COLLECTOR

ODAY **A**DNAN **A**BO[*] and **L**OKMAN **H** **H**ASSAN[**]
[*]Dept. of Mechanical Engineering, University of Duhok, Kurdistan Region-Iraq
[**]Dept. of Electrical and computer Engineering, University of Duhok, Kurdistan Region-Iraq

ABSTRACT

In this paper, a pentagonal shaped Solar Air Collector (SAC) is proposed. The pentagon design is used to improve the incident radiation angle. The SAC is tested in University of Duhok campus, Kurdistan Region, Iraq in a stand facing south. The absorber made from the sandwich steel panel plate with an area of 0.9*1.5 m^2 and thickness of 0.4 mm. The collector is covered with a Plexiglas of thickness 5 mm. The effect of the air flow channel on the collector efficiency is studied. Experimental studies are carried out for different tilt angles to show the improvement in the collector performance. The collector is tested for four sunny days in the same atmospheric conditions in December as the worst month. The results demonstrate that the optimum tilt angle of the day will substantially enhance the thermal efficiency comparing to latitude tilt angle. In addition, the proposed SAC with closed channel and open channel shows different performance during the day time.

KEYWORDS: Solar Air Collector, Heat Transfer, Tilt Angle, Renewable Energy

1. INTRODUCTION

Flat-plate collectors as type of heat exchangers are used to produce heat from solar radiation energy (Duffie & Beckman, 2013). Solar flat-plate collectors are categorized into low and medium temperature (i.e. up to 100 ^{o}C) collectors and they are commonly used to heat air or water (Duffie & Beckman, 2013). In general, the efficiency of flat-plate air collectors is less than the liquid collector models.

Many researchers studied performance of various types of solar flat-plate collectors over the world. Most of studies are focused on improving the thermal performance of the collectors (Pandey & Chaurasiya, 2017). A solar air collector is developed by Y. Cengel, *et al.* (Hematian, Ajabshirchi, & Bakhtiari, 2012) and its efficiency is measured experimentally in the natural and forced convection. The absorber is designed in the form of window shade to increase the air contact area.

An experimental comparison study is carried out by F. Chabane, *et al.* (Chabane, Moummi, Benramache, Bensahal, & Belahssen, 2013) to assess the efficiency of a solar air collector without and with using fins attached at the back of the absorber plate. The collector is tested in Biskra city of Algeria. The results showed that the fins enhance efficiency of the collector with a tilt angle of 45°.

A single pass solar air heater is developed in (Chabane, Moummi, & Benramache, 2014) with five fins in form of semi cylindrical longitudinal under absorber plate. The collector is compared with a solar air collector without fins. The effect of tilt angle and mass flow rates on thermal efficiency is experimentally verified.

A dynamic analysis model in the form of series expansion is developed by Deng et al. (Deng, Xu, & Yang, 2015) to analyze thermal performance of flat-plate collectors. In addition, the collected data from solar air collector experimentally utilized to confirm the model.

Recently, solar chimney is widely used for generating power, air conditioning and ventilation systems. By adjusting the stack pressure for these systems, total efficiency can be increased (Hung, et al., 2017). To increase the bouncy force and the air stream velocity, different solar collectors during the last years are developed by researchers. These collectors increase radiant energy absorption and convective heat transfer coefficients.

A comparison study between two normal flat types with and without the wavy absorber using CFD theoretical model is carried out by Varol and Oztop (Varol & Oztop, 2008). The study includes Rayleigh number, tilt angle, wave length and aspect ratio parameters.

Karmare and Tikekar (Karmare & Tikekar, 2010) discussed the effect of ribs with different shapes and size on the thermal performance. The results revealed that the maximum heat transfer can be obtained using the square cross-section ribs with 58 degree incident angle.

Amori and Mohammed (Amori & Mohammed, 2012) implemented a solar chimney with side inlet of air to improve thermal performance. The effect of adding paraffin on the chimney's heat transfer characteristics is also presented.

The study of the geometry of collector and its effect on thermal performance is another important category. A numerical model was developed for a mechanical ventilation of solar air collector with internal baffles is proposed by Hu et al. (Hu, Sun, Xu, & Li, 2013).

Lee et al. (Lee, Hung, Lin, & Zhao, 2015) studied the effect of tilt angle black polish surface and high transmissivity of glass on the heat transfer performance and exist temperature of solar chimneys.

In this paper, a new Solar Air Collector (SAC) approach is proposed using a pentagon design to improve the incident radiation angle. The proposed study is based on the experimental method. The new design will increase the rate of radiation by increasing the availability of exposure. In this study, used two tilting angle with open and closed channel are used. The proposed collector is designed to be suitable for producing generating power. The rest of the paper is organized as follows: In Section 2, the proposed SAC is described. Experimental setup is explained in Section 3. Results and discussion are presented in Section 4. Finally, the conclusions and contributions of the paper are summarized in Section 5.

2. DESCRIPTION OF THE PROPOSED SOLAR AIR COLLECTOR (SAC)

A pentagon shape is selected to design the proposed SAC in order to improve the incident radiation angle. The collector design with dimensions is shown in Fig. 1. The length, width and height dimensions of the collector are 150 cm, 90 cm and 10 cm respectively. The proposed collector is covered with a Plexiglas. The sun light radiation passes through Plexiglas and re-radiated as long wave from the absorber. Thus the absorber heats up and transfers its heat to the air.

The absorber is a sandwich panel plate with a thickness of 8 cm painted with black color to absorb the maximum radiation of the sun. It consists of double plates and separated by an isolator. The isolator is Polyurethane foam that used to insulate the absorber plate. The properties of SAC material are given in Table 1 (Jack, 2010).

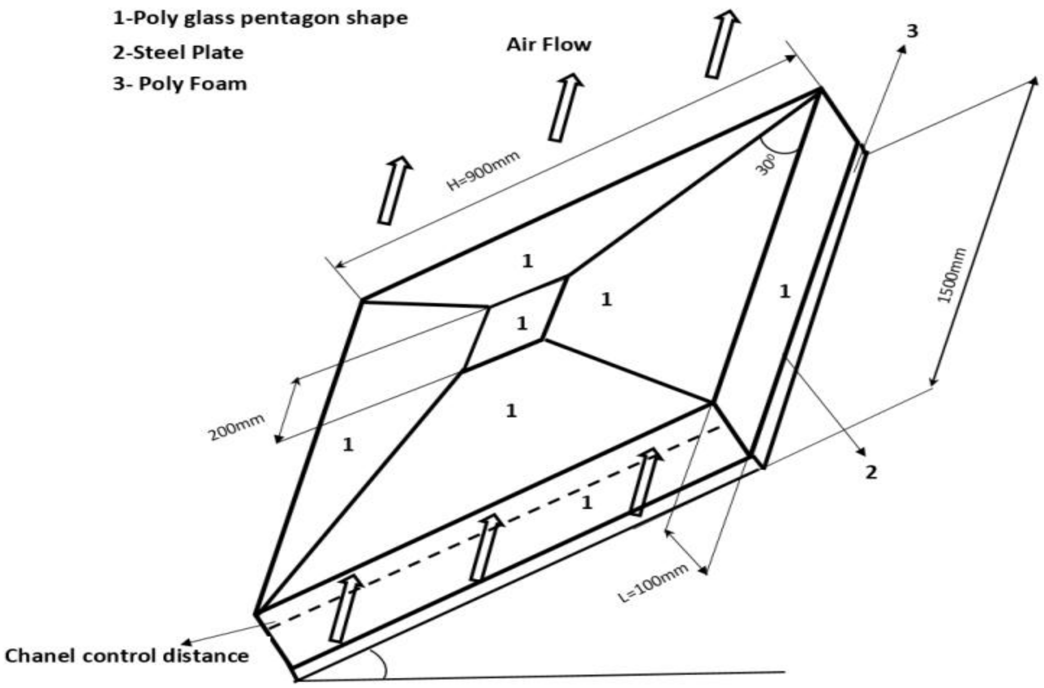

Fig.(1): Collector Design with Dimension

Table (1): Properties of the SAC materials at 20 C^{o}

Material	$\rho\ (\mathbf{kg/m^3})$	$k\ (\mathbf{W/m - C^o})$	$C_p\ (\mathbf{J/kg - C^o})$
Absorber plate (steel plate)	7833	54	0.465
Plexiglas (i.e. Poly(methyl methacrylate))	1200	0.2	1.5
Polyurethane foam	-	0.017	1.2

3. EXPERIMENTAL VALIDATION

3.1. Experimental Setup

The experiment data are measured using three instruments to measure the Plexiglas temperature, absorber and sunlight intensity. The measuring instruments used in this study with their specifications are shown in Table 2. All measuring instruments are calibrated to increase the accuracy of the instruments. The data are captured once every 15 minutes from 8.00 am to 4.45 pm on the campus of Duhok University. For accuracy, five points (top and four sides) are selected to measure Plexiglas and absorber plate temperatures. Then the average value of the five records is obtained. The fixed solar air collector is tested with two tilt angles of 60^{o} and 36.8^{o}. The first tilt angle is daily optimum tilt angle for the worst month during the year. The second one is yearly-average optimum tilt angle (i.e. Latitude angle) of Duhok city. The collector is tested for four sunny days in the same atmospheric conditions (i.e. sunlight intensity and air speed). A photograph of the experimental setup is shown in Fig. 2.

Table (2): Specifications of measuring instruments

Instrument	**Radiation Intensity of Solar Irradiation**	**Infrared Thermometer**	**Anemometer**
Image			
Output physical quantity	Intensity of Sun-Beams (W/m²)	Temperature (ºC/ºF)	Temperature (ºC/ºF)
Range	0 - 1999 W/m²	-50~550oc	-10ºC~45ºC
Accuracy	5 %	± 2%±2ºC	±2ºC

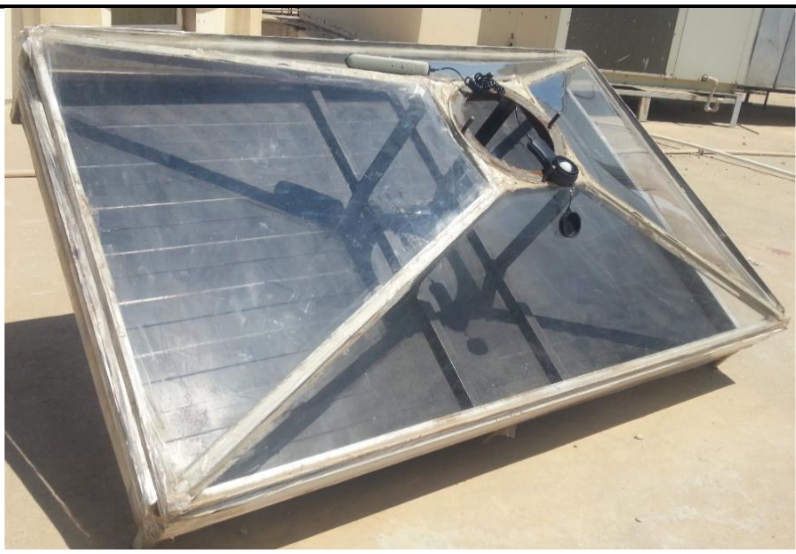

Fig.(2): photograph of the experimental setup

3.2.

3.3. Calculation of Thermal Heat Efficiency

3.4.

In order to determine the heat transfer between the Plexiglas cover and the absorber plate, heat aspect ratio (H/L) and the tilt angle should be considered.

At $\mathrm{H/L} < 12$ the natural convection inside enclosure can be determined (Catton, 1978) as

$$Nu = Nu_{\theta=0^o}\left(\frac{Nu_{\theta=90^o}}{Nu_{\theta=0^o}}\right)^{\frac{\theta}{\theta_{cr}}} (sin\theta_{cr})^{\frac{\theta}{\theta_{cr}}} \qquad 0^o < \theta < \theta_{cr} \qquad (1)$$

where θ is the tilt angle and θ_{cr} is the critical tilt angle from horizontal and Nu the Nusselt number.
For horizontal enclosures at $\theta = 0^{\text{o}}$, the Nusselt number is determined (Cengel, Turner, & Cimbala, 2016) as

$$Nu_{0^{\text{o}}} = 1 + 1.44\left[1 - \frac{1708}{Ra_L}\right]^{+} + \left[\frac{Ra_L^{1/3}}{18} - 1\right]^{+} \qquad Ra_L < 10^8 \qquad (2)$$

where Ra_L is the Rayleigh number for an enclosure.
The Rayleigh number can be calculated as

$$Ra_L = \frac{\text{g}\beta(T_1 - T_2)}{\nu^2} P_r \qquad (3)$$

where P_r is Prandtl number, g is gravitational acceleration in $\mathrm{m/s^2}$, β is the coefficient of volume expansion ($\beta = \frac{1}{T_f}$), T_f is the actual temperature of the fluid in K, ν is the kinematic viscosity of the fluid, $\mathrm{m^2/s}$ and T_1 and T_2 are the absorber plate temperature and the Plexiglas surface temperature respectively in C$^{\text{o}}$.
For vertical enclosures at $\theta = 90^{\text{o}}$ and $2 < H/L < 10$, the Nusselt number is determined (Cengel, et al., 2016) as

$$Nu_{\theta=90^{\text{o}}} = 0.22\left(\frac{\text{Pr}}{0.2 + \text{Pr}} Ra_L\right)^{0.28} \left(\frac{\text{H}}{\text{L}}\right)^{-1/4} \qquad Ra_L < 10^{10} \qquad (4)$$

where $\beta = \frac{1}{T_f}$

Then the rate of heat transfer to the air can be computed (Cengel, et al., 2016) as

$$\dot{Q}_{usful} = kNuA\frac{(\text{T}_1 - \text{T}_2)}{L}\text{Pr} \qquad (5)$$

where k and L are the thermal conductivity and thickness of the collector respectively.
The incident solar energy is

$$\dot{Q}_{total} = AI \qquad (6)$$

where A is the cross section area of the absorber in $\mathrm{m^2}$ and I is the intensity of sunlight in $\mathrm{W/m^2}$
The heat transfer to the air (i.e. useful energy) can be compared to the incident solar energy to determine the efficiency of the solar collector as

$$\eta = \frac{\dot{Q}_{usful}}{\dot{Q}_{total}} \qquad (7)$$

4. RESULTS AND DISCUSSION

The proposed SAC is exposed to solar intensity during December and January for four days. Temperature of the plate, Plexiglas and ambient are measured as depicted in Figs. 3-6. The SAC is tested keeping the channel closed at tilt angle 60$^{\text{o}}$ and 36.8$^{\text{o}}$. The tests are repeated when the channel is open at tilt angle 60$^{\text{o}}$ and 36.8$^{\text{o}}$. Solar radiation is measured during the tests for the four cases as shown in Table 3.

Table (3): Solar radiation measured during the tests for four cases

Time	Case 1 Closed channel at 60° Jan 2 2017	Case 2 Closed channel at 36.8° Jan 12 2017	Case 3 Open channel at 60° Dec 28 2016	Case 4 Open channel at 36.8° Dec 27 2016
8.00	105	190	180	340
9.00	215	247	300	475
9.30	340	350	420	580
10.00	460	480	520	690
10.30	600	695	605	765
11.45	800	810	700	815
12.30	945	806	780	870
13.30	1000	956	890	950
14.30	995	980	910	900
15.30	870	900	810	750
16.00	737	745	710	650
16.30	558	600	640	560
16.45	380	390	418	375

The effect of the tilt angle in increasing the temperature of the absorber plate for closed channel is observed in Fig. 3 and Fig. 4. Higher temperature degrees are recorded for the absorber plate at tilt angle 60° compared to tilt angle 36.8°. However, for open channel the effect of the tilt angle in increasing the temperature of the absorber plate is less compared to the closed channel as shown in Fig. 5 and Fig. 6.

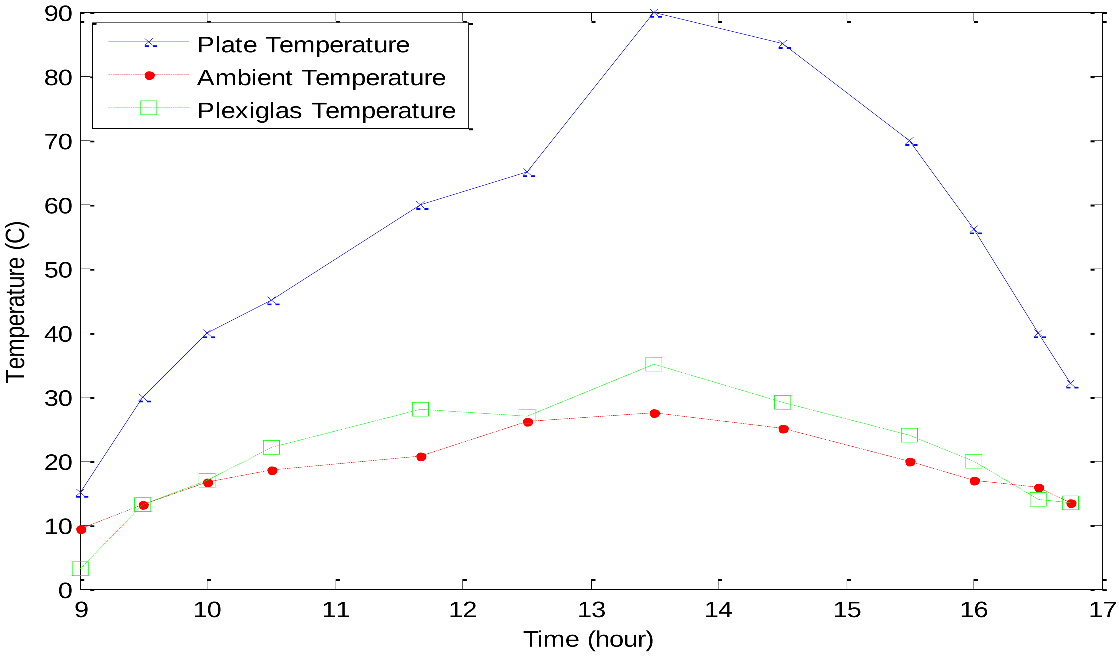

Fig. (3): Temperature measured during the test for closed channel and at tilt angle 60°

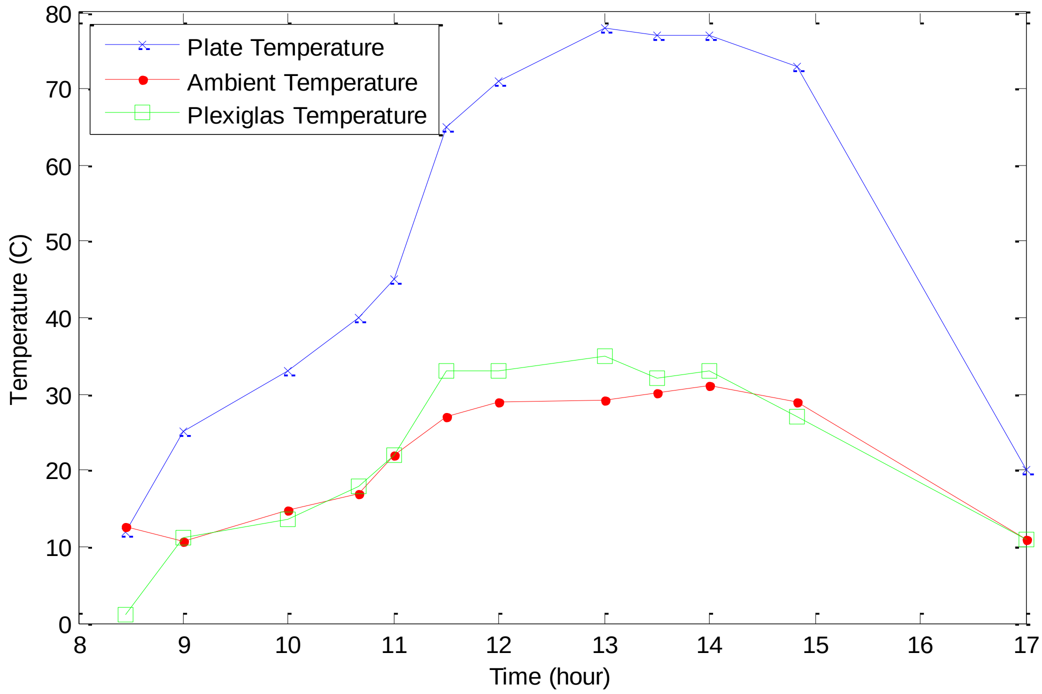

Fig. (4): Temperature measured during the test for closed channel and at tilt angle 36.8°

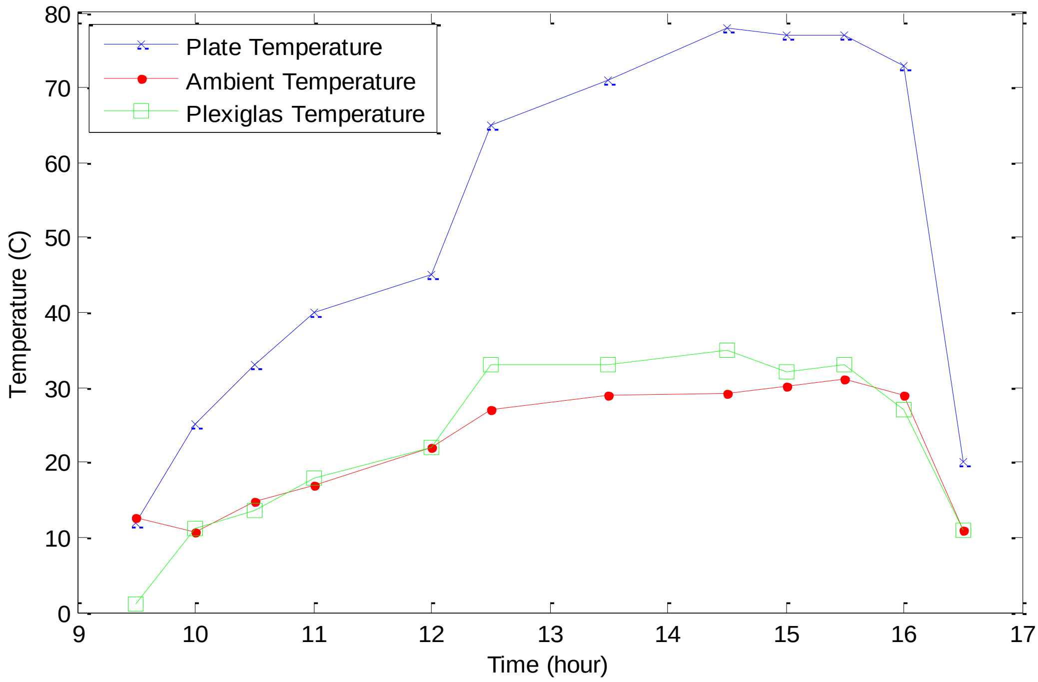

Fig. (5): Temperature measured during the test for open channel and at tilt angle 60°

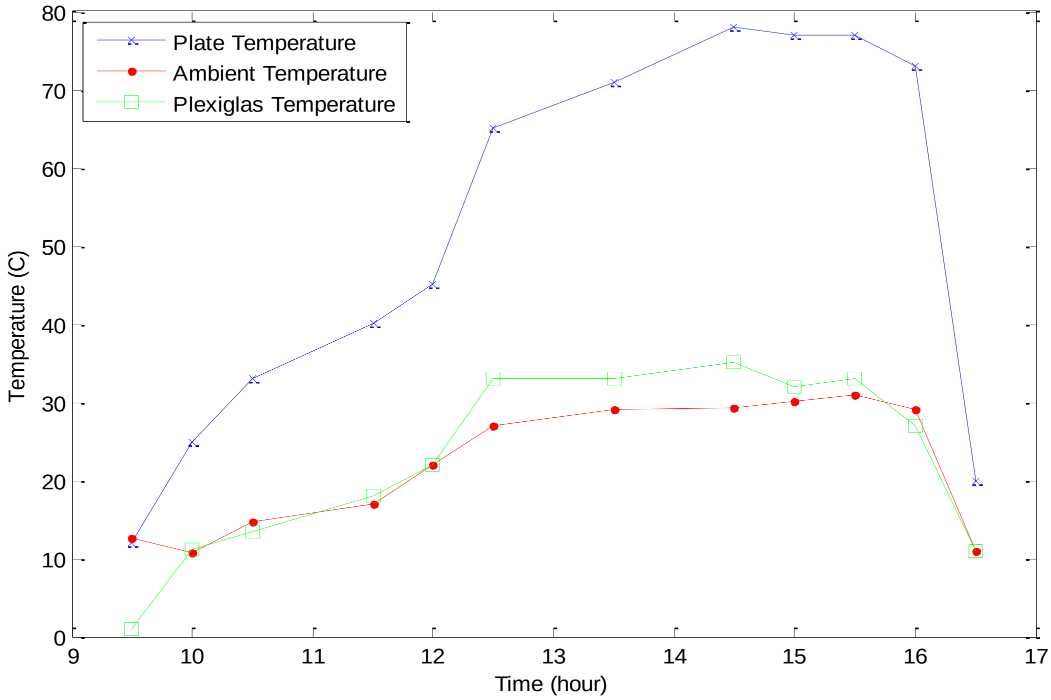

Fig. (6): Temperature measured during the test for open channel and at tilt angle 36.8°

The SAC heat losses are calculated in terms of the temperature difference between the air flow temperature (Tav) and the ambient temperature (Tam). Fig. 7 shows that the SAC at the optimum tilt angle during the day (i.e. 60°) has less heat losses comparing to the SAC at Latitude angle (i.e. 36.8°) of Duhok city.

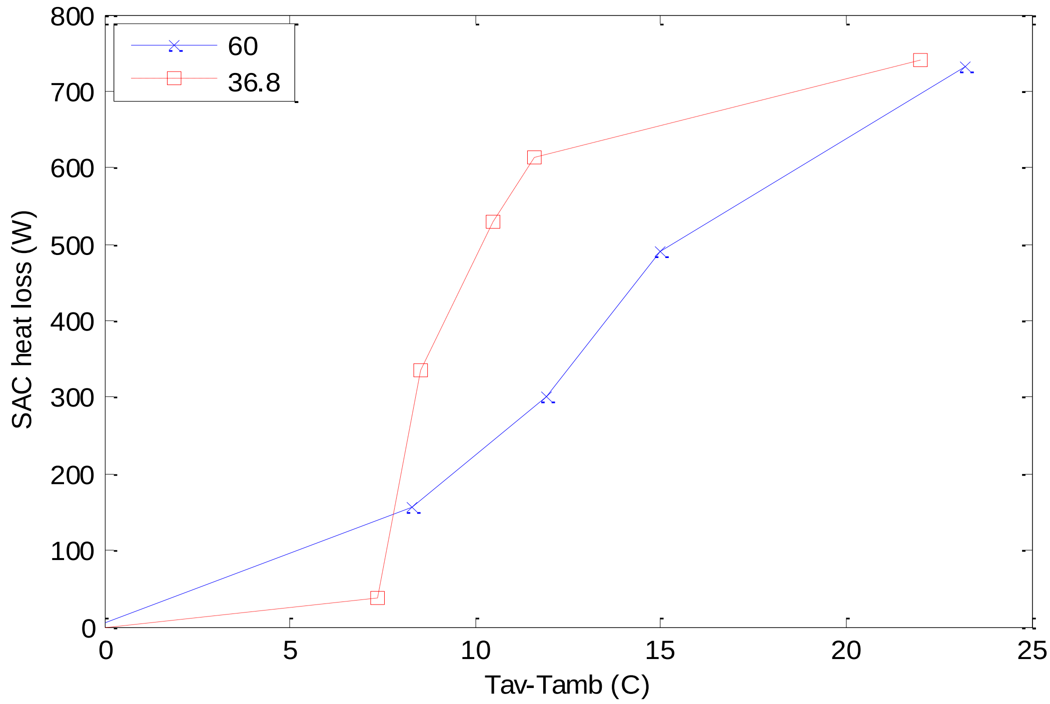

Fig. (7): Heat loss curve of the SAC for closed channel at different tilt angles.

Efficiency of the SAC is computed using (1) to (7). Fig. 8 shows the efficiency of the SAC at tilt angle 60° for open channel and closed channel. In Fig 7, it is observed that from 9.00 am to 12.30 pm the efficiency is increased and decreased frequently between open and closed channel. From 12:30 pm to 15:00 pm the SAC gives same efficiency using both scenarios. After 15.00 pm, the SAC with closed channel provides 25% higher efficiency than open channel.

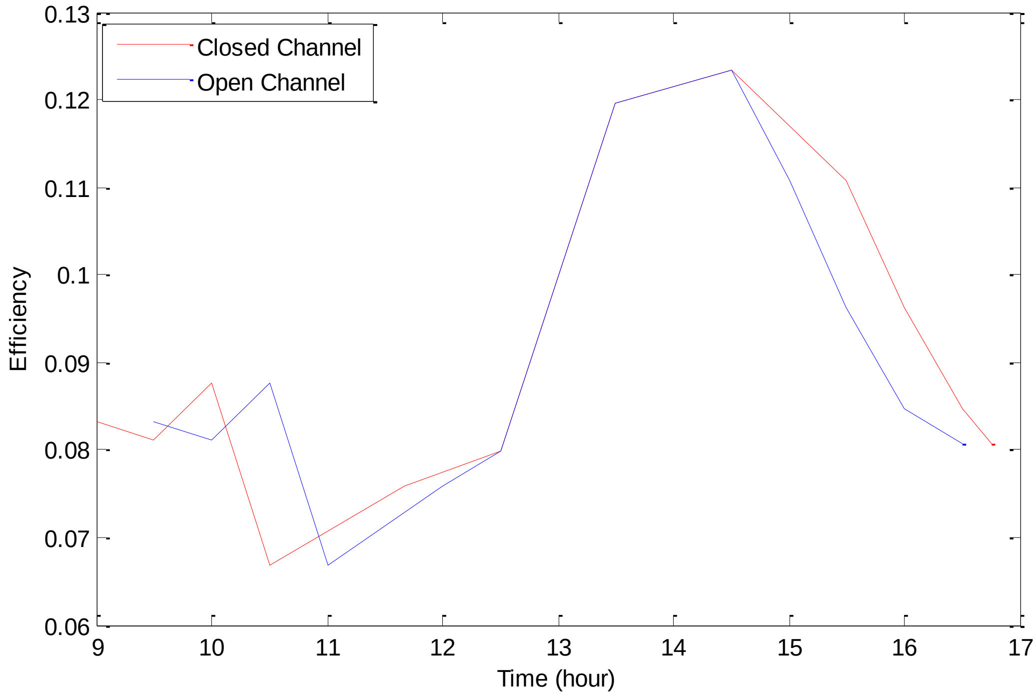

Fig. (8): Efficiency of the prototype at tilt angle 60°

In Fig. 9, when the latitude angle (i.e. 36.8°) is used, the open channel efficiency shifted one hour toward right. It is concluded that the channel size plays an important role in changing the efficiency of the SAC during the day time. From 13:30 pm to 16.00 pm, SAC with open channel provides better performance than the collector with closed channel. That means during that time an amount of air inside channel, which is produced from circulation of bouncy force during its stream motion, replaced with amount of air from outside channel. A new momentum produced due to the air inter through the open channel. Thus the heat transfer coefficient, Nusalt number and efficiency is increased.

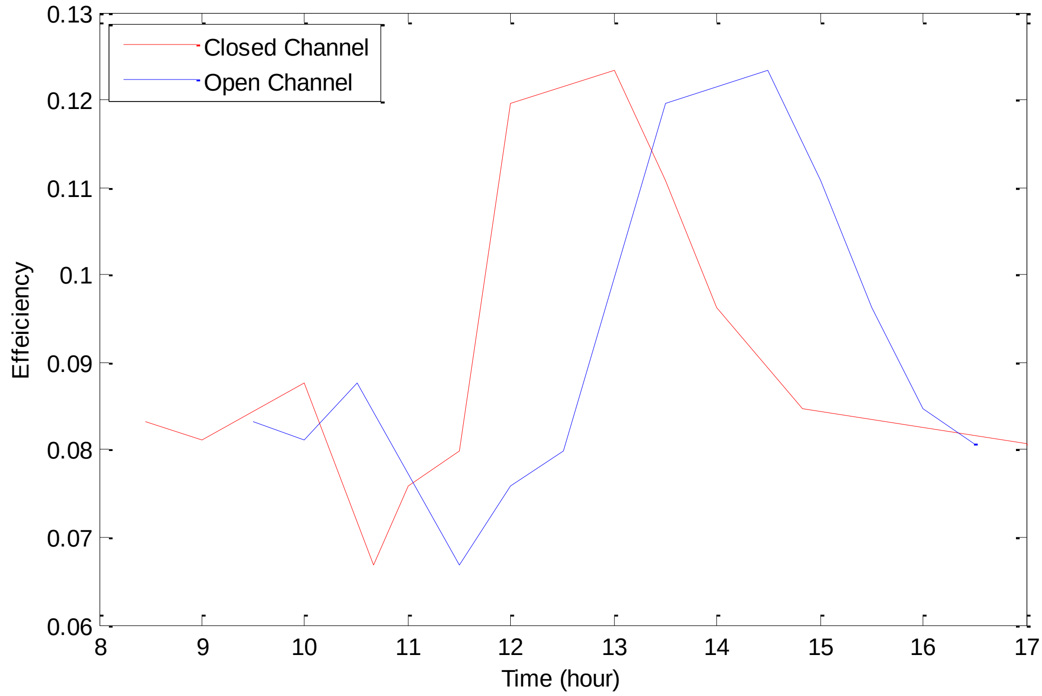

Fig. (9): Efficiency of the prototype at tilt angle 36.8°

Fig. 10 shows the efficiency of the SAC for closed channel at different tilt angles. The results in Fig. 10 show that the overall efficiency of the SAR at optimum tilt angle (i.e. 60°) is higher than the efficiency of the collector at latitude angle.

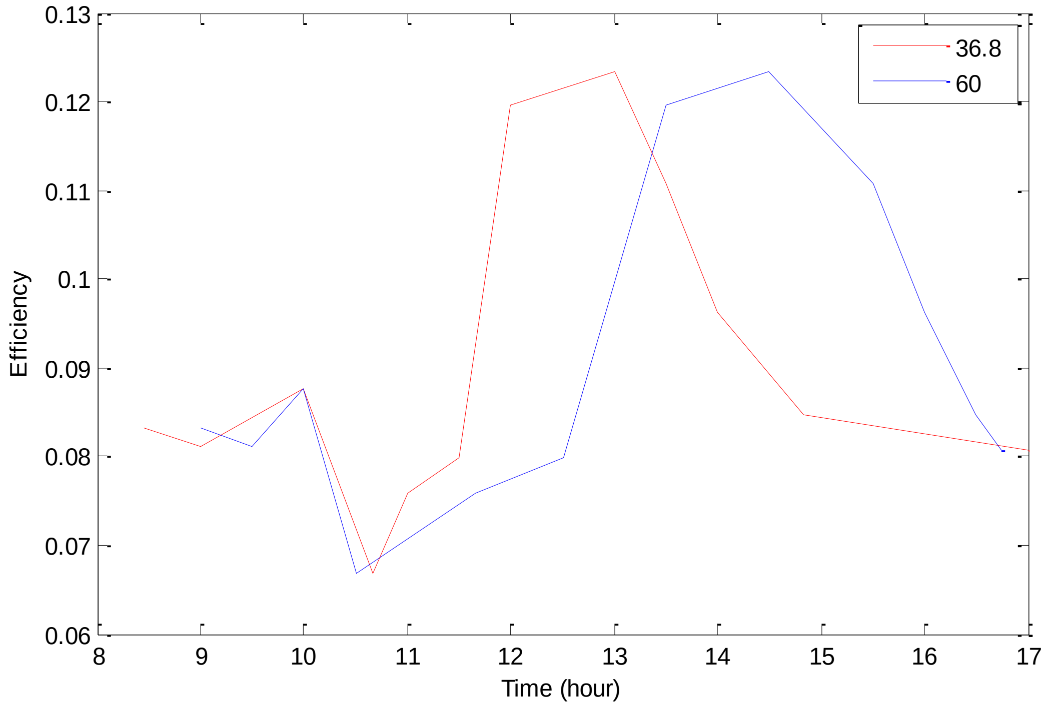

Fig. (10): Efficiency of the prototype for the closed channel at tilt angle 36° and 60°

5. CONCLUSION

A Solar Air Collector (SAC) based on the experimental method was presented in this paper using a pentagon design. The new design was used to increase the rate of radiation by increasing the availability of exposure. The sandwich steel panel plate with an area of 0.9*1.5 m^2 and thickness of 0.4 mm was selected as the absorber. A Plexiglas of thickness 5 mm was used to cover the SAC. The SAC was tested in University of Duhok campus in a stand facing south. The collector was tested for four sunny days in the same atmospheric conditions in December. The effect of the air flow channel on the collector efficiency was discussed. Experimental studies were carried out for latitude angle and optimum tilt angle. The results showed improvement in the thermal efficiency when the optimum tilt angle is used. However, the efficiency is increased and decreased frequently between open and closed channel during the day time.

REFERENCES

- Amori, K. E., & Mohammed, S. W. (2012). Experimental and numerical studies of solar chimney for natural ventilation in Iraq. Energy and Buildings, 47, 450-457.
- Catton, I. (1978). *Natural Convection in Enclosures.* Paper presented at the Sixth International Heat Transfer (pp.13–31). Toronto: Canada, 7-11 August.
- Cengel, Y., Turner, R., & Cimbala, J. (2016). Fundamentals of Thermal-Fluid Sciences: Mc Graw Hill.
- Chabane, F., Moummi, N., & Benramache, S. (2014). Experimental study of heat transfer and thermal performance with longitudinal fins of solar air heater. Journal of Advanced Research, 5(2), 183-192.
- Chabane, F., Moummi, N., Benramache, S., Bensahal, D., & Belahssen, O. (2013). Collector Efficiency by Single Pass of Solar Air Heaters with and without Using Fins. [Design of experiments, efficiency, solar energy, fins, temperature, heat transfer, ambient temperature.]. 2013, 17(3), 13.
- Deng, J., Xu, Y., & Yang, X. (2015). A dynamic thermal performance model for flat-plate solar collectors based on the thermal inertia correction of the steady-state test method. Renewable Energy, 76, 679-686.
- Duffie, J. A., & Beckman, W. A. (2013). Solar Engineering of thermal processes (4th ed.). NewJersey: John Wiley & Sons.
- Hematian, A., Ajabshirchi, Y., & Bakhtiari, A. A. (2012). Experimental Analysis of Flat Plate Solar Air Collector Efficiency. [Flat Plate Collector, Solar Radiation, Efficiency]. Indian Journal of Science and Technology, 5(8).
- Hu, J., Sun, X., Xu, J., & Li, Z. (2013). Numerical analysis of mechanical ventilation solar air collector with internal baffles. Energy and Buildings, 62, 230-238.
- Hung, T.-C., Huang, T.-J., Lee, D.-S., Lin, C.-H., Pei, B.-S., & Li, Z.-Y. (2017). Numerical analysis and experimental validation of heat transfer characteristic for flat-plate solar air collector. Applied Thermal Engineering, 111, 1025-1038.
- Jack, P. H. (2010). Heat Transfer (10th ed.): McGraw-Hill.
- Karmare, S. V., & Tikekar, A. N. (2010). Analysis of fluid flow and heat transfer in a rib grit roughened surface solar air heater using CFD. Solar Energy, 84(3), 409-417.
- Lee, D.-S., Hung, T.-C., Lin, J.-R., & Zhao, J. (2015). Experimental investigations on solar chimney for optimal heat collection to be utilized in organic Rankine cycle. Applied Energy, 154, 651-662.
- Pandey, K. M., & Chaurasiya, R. (2017). A review on analysis and development of solar flat plate collector. Renewable and Sustainable Energy Reviews, 67, 641-650.
- Varol, Y., & Oztop, H. F. (2008). A comparative numerical study on natural convection in inclined wavy and flat-plate solar collectors. Building and Environment, 43(9), 1535-1544.