Experimental study on the thermal performance of a solar collector and the effect of the tilt angle on the collector efficiency

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Abstract. Effect of inclination of the absorbent metal plate on the thermal performance and instantaneous efficiency has been investigated in a solar heating system using solar collectors. Two various metallic plates had been designed for experimental research, In the first type (Type I) flat plate is used with (90°) inclination angle from horizon, while (60°) inclination angle from horizon is used in the second type (Type II) flat plate. The experimental study and the collectors was manufactured in Tikrit (34° 35 N, 43° 73 E), Iraq. Results of the experimental study show that inclination angle (60°) is the best compared with (90°) to absorb largest amount of solar radiation intensity. The optimum value of thermal performance and instantaneous efficiency was determined in (Type II). The effect of the changing air flow rate was also investigated. Three different air flow rates had been studied (0.2, 0.4, 0.6 m/sec). The results showed that the efficiency increases with increasing air flow rate, temperature difference decreases with increasing air flow rate.

1. Introduction

There are many ways of utilizing the solar energy. Solar heaters are one of the important applications currently used for heating buildings and natural ventilation [1]. Solar air heaters are utilized for many purposes, such as drying agrarian products [2], and heating buildings to maintain a comfortable climate particular in the winter season [3]. Solar air heaters are classified according to of the collector coating, absorber materials, form of absorbing surface, absorber flow style, flow shape, and the applications of the solar collectors [4]. Flat-plate solar air heaters are the easiest type of solar heaters [5]. experiments calculated the heat transfer in solar air heater duct roughened with detached W-shaped roughness and progressing correlations for heat transfer as a function of roughness and stream parameters [6]. The thermal performance of a solar collectors consisting of a corrugated metal sheet was studied. The results showed that the corrugated metal panel had little effect on the thermal performance of the system compared to the flat metal plate [7]. The effect of the velocity of the flowing air on the thermal performance of the solar collector has been studied. The results showed that the increase in the speed of the flowing air prevents the loss of heat from the metal plate to the air flowing in the gap. Subsequently there are slightly difference between the temperature of the air outside the solar collector and the ambient temperature [8]. The thermal performance of the glazed cover collectors is better than the non-glazed collectors. Thermal losses in the plate using glazed cover collectors are limited, and the effect of the drag velocity in efficiency is not as large as in non-glazed collector [9]. The difference in temperature has been shown to increase by increasing the glass cover at the front of the solar collector [10]. Putting in mind the economic side when constructing the solar collectors. The cost of solar panels with multiple glass interfaces is higher than the cost of solar collectors with a single glass cover [11]. Deniz et al. [12] studied the effect of mass flow rate, they
showed that the efficiency increases with increasing air flow rate. Difference in temperature decreases with increasing air flow rate. Kadir Bakirci [13] identified the ideal angle of solar panels used in different regions of Turkey. The experiments were conducted for several angles between (0°) and (90°) throughout the year. It was found that the ideal angle verified between (0°) and (65°). In addition, it was discovered that the ideal angle increases during the winter months and decreases during the summer months. The value of energy collected by a solar collector and thus transformed to thermal energy is extremely influenced by its orientation and inclination angle. Whoever designs solar systems that use flat-plate collectors, need to know the value of solar energy catch by a sloped surface. It is mostly known that in the northern hemisphere, the ideal collector orientations south-facing, and the optimum inclining angle counted on the latitude and the day of the year [14]. A significant parameter in the optimum employment of solar panels is their tilt angle with the horizon. This changes the value of solar radiation that arrives the solar panels. The optimal tilt angle of a solar collector is attached to the regional climatic condition, the geographic latitude, and the duration of its use. Therefore, various locations will have various optimal tilt angles for solar collectors. [15]. Kaldellis and Zafirakis [16] conducted a practical study in the Athens area on the date of determining the performance of the solar collectors using different angles during the summer. The results showed that a (15°) angle is the ideal angle during this time. The optimal angle of tilt of a solar collector to the south was determined to maximize the thermal performance of the system. The equations needed to calculate the solar radiation falling on an inclined surface were determined to obtain the optimum angle during the month over one year. On the other hand, by using maximum solar energy through the optimum tilt angle, we are capable to use the desired energy without polluting the environment. It minimizes the CO2 emissions in the external surrounding, by decreasing CO2 emissions in the external surrounding, carbon credit ability also gained, which is presently an international issue. The results showed that the ideal tilt angle changes from (1°) in June to (65°) in December during the same year in Antalya [17]. Tsalides and Thanailakis [18] studied the effect of the azimuth angle on the ideal inclination. They found that the ideal inclination reduced gradually as the azimuth angle was deviate from the south. While Gunerhan and Hepbasli [19] found that the ideal tilt angle yearly in Izmir, Turkey was equal to the site latitude. Khatib [20] indicated that the optimum tilt angle was smaller in summer season and larger in winner season. It can be distinctly seen that the intensity of solar radiation reduces with rise inclination. Due to the impact, a metallic sheet with low inclination hold additional radiation as compared with more inclined. On the other side, the effect of reduce in inclined angle is minimize in value of the air flow rate. As a result of these adverse effects, angle 45° can be considered the ideal angle. This is because angle 30° achieves as much absorbed radiation as possible and minimum mass flow of air. Angle 60 achieves the minimum amount of absorbed radiation and maximum mass flow [21]. Ramadan and Nader [22] found that the chimney inclination angle is a key parameter that highly impact space flow style and ventilation. The effect of chimney inclination angle on air flow rate and indoor flow style was investigated. A numerical simulation results were compared with experimental results. The study was conducted for angles of inclination between (45°) and (70°) at (28.4°) latitude and at a solar radiation rate higher than (500 W/m²). The ideal angle of tilt and azimuth angle was calculated by Zhenghao [22], to increase the thermal performance of the system, as the angle of tilt has a significant impact on the capture of solar radiation. The ideal azimuth angle is determined by the location and duration of experimental data. The results indicated that the ideal azimuth angle ranges from (-20°) to (20°) and the ideal angle of inclination depends on the location of the system. The maximum amount of solar energy not absorbed by the solar collector can reach
(29.5%) and (6.5%) azimuth angles when using the angle of inclination inaccurately. It has been shown in this research that the ideal angle of inclination and the azimuth angle affect the location of the solar collectors.

The main objective of this study is to find a suitable system for heating, and this is done by conducting thermal equilibrium equations for each part of the solar collector, such as glass cover and heat absorbed by the metal panel, and determining the design variables in terms of the interface area of the system and the type of metal plate, and measuring the variables of non-changeable weather, such as solar radiation and show effect of the tilt angle of the absorbent metal plate (60°-90°) on the thermal performance of the system.

2. Experimental

Fig (1) shows the location of thermocouples in the room, the gap, and mechanism of air flow through the plenum. Fig (2) shows solar air heater prototype and the room that we want to heat.
The photographs of the two different absorber plates of the solar air heater (SAH) collector and the absorber plates in the collector are shows in Fig (3). The solar collector was directed toward the south to collect the maximum amount of solar radiation through daylight hours. We summarize its major components as follow:

- A thin absorber plate made of steel coated in black with (1 mm) thickness. The absorber plates in the collector flat plate is used with inclination angle (90°) from horizon, dimensions (1×1.2 m) (type I), flat plate is used with inclination angle (60°) from horizon, dimensions (1×1.3 m) (type II).
- One layer of glass covered with (4 mm) thickness.
- A (1×1×1.2 m) room made of a (20 mm) layer of wood with a gap of the collectors also made of wood.
- The distance between transparent glass and absorber plate is: (1.2 m, 1 m, and 20 mm).
- A layer of glass wool is placed behind the absorbent metal plate to complete the heating process and prevent the occurrence of thermal losses.
- On the lateral sides, there are four top slots to enter the air into the solar collector with dimensions (14*10 cm), two of them at the bottom of the gap to enter the air from the surroundings, and the others at the bottom of the metal plate to return the hot air from the room and are mixed equally to increase the thermal performance of the solar collector. In addition, there is a top slot at the top of the metal plate with dimension (24*24 cm), which used to enter the heated air into the room by fan (50 W).

The experimental process results include:

- Measuring the intensity of solar radiation by using Solar meter device.
- Measuring the ambient temperature, air flow rate through the gap, room temperature, glass cover, and plate temperature by thermocouples (Type K).
- Measuring the speed of air flowing through the gap by using anemometer device.

Noting that the experimental study and the collectors was manufactured and taken in Tikrit (34°35 N, 43°73 E), Iraq, and all tests began at (9 am) and finished at (4 pm).
Analytical part

The thermal efficiency of the solar collectors ($\eta$) is defined as the ratio of the energy acquired and solar radiation absorbed by the collector [19]

$$\eta = \frac{\dot{m} C_p (T_{\text{out}} - T_{\text{in}})}{I A_c}$$

When: $\dot{m} = \rho V A_c$

Where:
- $A_c$ : surface area of collector (m$^2$)
- $C_p$ : specific heat of air at constant pressure (kJ/kg K)
- $\rho$ : air density (kg/m$^3$)
- $V$ : air velocity (m/s)
- $I$ : solar radiation (W/m$^2$)
- $\dot{m}$ : mass flow rate (kg/s)
- $M$ : mass (kg)
- $T$ : temperature (°C)
- in : inlet
- out : outlet
- $\eta$ : thermal efficiency (—)

3. Results and Discussion

Fig (4) shows that the hourly difference of the room temperatures (outlet collector temperature) of Type I for different air flow rates (0.2, 0.4, 0.6 m/sec). The results show that the outlet air temperature of Type I collector is calculated as (51, 40, 32 °C) at (0.2, 0.4, 0.6 m/sec), respectively. The highest daily solar radiation is gained as (800 W/m$^2$). As expected, it increases in the morning to a maximum amount of (800 W/m$^2$) at (12:30 pm) and begins to reduce in the afternoon.

Fig (5) shows that the hourly difference of the room temperature (outlet collector temperature) of Type II for different air flow rates (0.2, 0.4, 0.6 m/sec). The results show that the outlet air temperature of Type II collector is calculated as (54, 48, 44 °C) at (0.2, 0.4, 0.6 m/sec), respectively. The highest daily solar radiation is gained as (1022 W/m$^2$). As expected, it increases in the morning to a maximum value of (1022 W/m$^2$) at (12:30 pm) and begins to reduce in the afternoon. The results show that the room temperatures increases with increasing air flow rate and solar radiation $I$.

By comparing Fig (4) with Fig (5), we can find that the outlet air temperature of Type II collector is greater than the outlet air temperature of Type I collector due to the absorption of high solar radiation by the metal plate at type I of solar collector due to the incidence of solar radiation almost perpendicular to the metal plate. In addition, the angle of inclination (90°) showed high flow resistance and less absorption of solar radiation than in type II. It is also shown that the inclination angle of the solar collector has a significant effect on the thermal performance of the collector, because the amount of solar radiation obtained in type II is higher than the amount of radiation obtained in type I.
Fig (6) shows the hourly variation of the outlet air temperature of Types (I-II) collectors are calculated as (51, 54 °C), respectively at (0.2 m/sec) air flow rate. Fig (7) shows the hourly variation of the outlet air temperature of Types (I-II) collectors are calculated as (40, 48 °C), respectively at (0.4 m/sec) air flow rate, while Fig (8) shows the hourly variation of the outlet air temperature of Types (I-II) collectors are calculated as (32, 44 °C), respectively at (0.6 m/sec) air flow rate. By comparing Fig (6) with Fig (7) and Fig (8), we found that the air temperature outside the solar collector at the flow rate of (0.2) is greater than the air temperature outside the solar collector at flow rates (0.4, 0.6 m/sec). The rise in air flow rate leads to increase the speed of the air inside the collector channel, with the constant amount of heat absorbed in the surface of the metal plate, which leads to that the outlet air temperature from the gap is not heated well. This agrees with (Chan, et al, 2013) [23], and they found that the difference in temperature increases with the increase of the intensity of solar radiation.
Fig (6) Temperature versus time of collector types at (V= 0.2 m/sec)

Fig (7) Temperature versus time of collector types at (V= 0.4 m/sec)
Efficiency versus time of type I at different air flow rates is shown in Fig (9). As can be seen from Fig (9) the efficiencies increase to a maximum value at (12:30–13:30 PM) at noon, then they start to decrease in afternoon. The mean efficiencies in type I are calculated as 34%, 39% and 51% for different air flow rates (0.2, 0.4, 0.6 m/sec), respectively. Fig (10) shows the hourly variation of the efficiency of Type II, for different air flow rates (0.2, 0.4, 0.6 m/sec). The mean efficiencies in type II are calculated as 39%, 44% and 56% for (0.2, 0.4, 0.6 m/sec) air flow rate, respectively. We conclude that the mass flow rate of air in gap has an important influence in collector efficiency. The results show that the collector efficiency rises with increasing the air flow rate and solar radiation I. This agrees with (A.P. Omojaro, L.B.Y. Aldabbagh, 2010) [24], where the efficiency increases with the increase in air flow rate.
Figure (11) shows the variation in the efficiency of the collectors, Where the efficiency of type II is higher than the efficiency of type I at the same air flow rate (0.2 m/sec) due to the increase in the amount of radiation absorbed by the metal plate in type II. This proves that the intensity of solar radiation has a significant impact on the efficiency of the compound, where the efficiency increases by increasing the intensity of solar radiation absorbed by the metal plate.

4. Conclusions
A detailed experimental research was conducted to evaluate the thermal performance and instantaneous efficiencies of two types of solar air collectors under a wide domain of operating
conditions. The optimal value of collector efficiency had been obtained for type II at 0.6 m/sec air flow rate. Testing results always record higher efficiency values of the Type II (tilt angle equal to 60°) than that of the Type I (tilt angle equal to 90°), since, in flat plate collector (Type I) only a little part of solar energy absorbed by the collector can be used to determined thermal performance of solar air collectors.

Consequently, the possibility of different planning of the experimental part due to different atmospheric and operation conditions during the experimental process to determine the effect of different variables on the thermal performance and the efficiency of the solar collectors, such as speed of air flow, intensity solar radiation and inclination angle of flat plate.

References
[1] Shukla A D, Nchelatebe N, Cho Y J, Stevenson V and Jones Ph 2012 Renewable and Sustainable Energy Reviews 16 3975-85
[2] Chakraverty A and Das S K. 1992 Energy Conversion and Management 33 183-190.
[3] Zhao D L , Li Y, Dai YJ and Wang RZ. 2011 Energy Conversion and Management, 52 2392-400.
[4] Hakan F. O, Fatih B and Arif H. 2013 Renewable and Sustainable Energy Reviews 21 59-83
[5] Ho C D, Yeh C W and Hsieh S M 2005 Renewable Energy 30 1601-1621
[6] Arvind K, Bhagoria J L and Sarviya R M 2009 Energy Conversion and Management 50 2106-17
[7] Wenfeng G, Wenxian L, Tao L, Chao Feng X. 2007 Applied Energy 84 425-441
[8] Ahmad A. P and Keith B. W 1994 Solar Energy 52 419-427
[9] Lixin Gao, Hua Bi and Shufeng Mao 2014 Energy Conversion and Management 77 690-99
[10] Naiem A and S.C. M 2012 International Journal of Heat and Mass Transfer 55 125-32.
[11] Gill R S, Sukhmeet S and Parm P S 2012 Energy Conversion and Management 57 131-42.
[12] Deniz Aa, Emin B, Ertekin C and Osman Y 2010 Applied Energy 87 2953-73
[13] Kadir B 2012 General models for optimum tilt angles of solar panels Renewable and Sustainable Energy Reviews 16 6149-59
[14] [14]Tiris M and Tiris C 1998 Optimum collector slope and model evaluation Energy Conversion and Management 39 167-72
[15] Benghanem M 2011 Optimization of tilt angle for solar panel: case study for Madinah Applied Energy 88 1427–33
[16] Kaldellis J and Zafirakis D 2012 Experimental investigation of the optimum photovoltaic panels tilt angle during the summer period Energy 38 305–14
[17] Kocer A, Yaka, I F, Sardogan GT and Gungor A 2015 Effects of Tilt Angle on Flat-Plate Solar Thermal Collector Systems Brit J Appl Sci Technol 9 77-85
[18] Tsalides Ph and A. Thanailakis 1985 Direct computation of the array optimum tilt angle in constant-tilt photovoltaic systems Solar Cells 14 83-94
[19] Huseyin G and Arif H 2007 Building and Environment 42 779-83
[20] Khatib T, A. Mohamed and K. Sopian 2012 On the monthly optimum tilt angle of solar panel for five sites in Malaysia IEEE International Power Engineering and Optimization Conference Melaka Malaysia 7-10 Jytirmay M, Sanjay M, Anupma, Energy and Buildings 38 1156-63
[21] Ramadan B, Nader S.A. K 2009 Energy and Buildings 41 190-96
[22] Zhenghao J, Kuo X, Yin Z, Xuefei X, Jing Z and Enshen L 2017 Procedia Engineering 205 2995-3002.
[23] Chan HnY, J. Zhu and Riffat S 2013 Energy Procedia 42 2013 123-132
[24] Omojaro A P and Aldabbagh, L B Y 2010 Applied Energy 87 3759- 65