Comparison of Thermal Performances between Low Porosity Perforate Plate and Flat Plate Solar Air Collector

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Abstract. Flat plate solar air collector is the most common collector design, which is relatively simpler to fabricate and lower cost. In the present study, perforated plate solar collector was developed to improve the system thermal performance. A glazed perforated plate of 6mm holes diameter with square geometry was designed and installed as the absorber of the collector. The influences of solar radiation intensity and mass flow rate on the thermal performance were investigated. The perforated collector was compared with the flat plate solar collector under the same operating conditions. The highest values of thermal efficiency in this study for the perforated plate (PP) and the flat plate (FP) solar collectors were 59% and 36% respectively, at solar radiation intensity of 846 Wm⁻² and mass flow rate of 0.02 kgs⁻¹. Furthermore, PP collector gave better thermal performance compared to FP collector; and compared to previous studies, the present perforated design was compatible with the flat plate with double pass designs.

1. Introduction

The over-exploit of fossil fuel based energy resources such as crude oil, natural gas, coal and nuclear energy inevitably led to global energy crisis. Considering this, a great research endeavor has been committed to develop renewable and sustainable energy technologies. Among all of the available renewable energies, solar energy is one of the best alternatives owing to its source longevity and especially in recent years, solar based applications have been attracting immense research interests. One of the useful solar applications is solar air heater which harvests solar energy and transforms it into thermal energy. Furthermore, solar air heater is one of the most cost-effective systems that can be applied in both industry and domestic sectors, such as drying agricultural products and space heating [1-3].

There are various types of solar air heaters and the most conventional design for space heating belongs to flat plate (FP) solar air collector which exhibits advantages such as design simplicity and low fabrication cost [4]. FP solar collector consists of: glass, absorber plate and solar absorber plate mounted on insulated back surface, as shown in figure 1a. A number of investigations have been carried out to study and improve the performance of FP solar air collectors in the past [5-9]. Apparently, the thermal performance of FP solar collector in still inadequate due to the significant heat loss and high thermal resistance which in turn, decreases the heat transfer capability between absorber and working fluid [10]. In view of this, various enhancement techniques have been reported and discussed to address the shortcomings of FP solar collector [11-15], e.g. glazed, unglazed, single pass, double pass, perforated solar air collector, etc. There
are two known techniques of perforated solar air collector, namely transpired solar collector and impinging jet solar collector.

A simple impinging jet collector model was first developed by Choudhury and Garg [16] and Rask et al. [17]. From the studies, they found an increase in efficiency compared to flat plate solar collector between 10% and 20% depending on the collector configuration and other parameters. Beluko et al. [12] modeled an unglazed impinging jet solar collector and found an increase of efficiency by 21%. There also a study found that jet impingement solar collector can transfer thermal energy with a heat transfer efficiency three times higher than that of FP system [18]. Along with it, there also many studies of transpired solar collector have been reported [19-20]. Despite that, from all the previous studies it is clear that the collector performance of both techniques is affected on many different parameters, such as porosity, geometry of the holes, hole spacing, solar intensity, mass flow rate, surface coating, the collector configurations, etc [21-25]. These indicates that it is a feasible approach to enhance the heat transfer coefficient between the working fluid and plate surface, which will then reduce heat losses and increase the thermal efficiency of the system [26].

In present work, a low porosity perforated plate (PP) was used as the absorber of the solar collector which consists of: glass, absorber plate, perforated plate, and back insulation. The objective of this research is to investigate and study the thermal performance of a glazed perforated plate compared to the flat plate (FP) collector. Our results demonstrated that the present perforated design gave better thermal efficiency compared to the flat plate and it was compatible with the flat plate with double pass designs.

2. Experimental setup and procedure

Solar collector was constructed and indoor experiments were carried out under indoor conditions by using solar simulator as shown in figure 1. The collector was located approximately 1 m below the solar simulator. The collector was built with several slots to have several plate distances (X) where the top slot used to place a standard sheet tempered glass as the cover. The outer side of the collector was fully insulated and the back of the collector was insulated with polyurethane slab to prevent the heat loss from the back of the collector. The aluminum perforated and absorber plates were fabricated and painted with black colour as shown in figure 2, and the configuration is as shown in figure 3. Pyranometer CMD3 was used to determine the intensity of the solar simulator. K-type thermocouples and an AM-4214 anemometer were used to measure the temperature and the air flow rate. The specification of the solar collector and the operating condition were shown in tables 1 and 2.

![Figure 1. Experimental set up for PP and FP solar collectors.](image-url)
**Figure 2.** Perforated plate design.

**Figure 3.** Schematic of glazed a) flat plate and b) perforated solar collectors.

**Table 1.** Dimensions of the perforated solar collector components

| Components            | Dimensions      |
|-----------------------|-----------------|
| Collector frame       | 100.5 cm x 69.5 cm x 34 cm |
Table 2. Operating conditions of the experiment

| Parameters                  | Properties                        |
|-----------------------------|-----------------------------------|
| Solar intensity             | 350 Wm$^{-2}$ to 1050 Wm$^{-2}$   |
| Mass flow rate              | 0.06 kgs$^{-1}$ to 0.02 kgs$^{-1}$|
| Inlet temperature           | 30°C                              |

3. Data analysis
The following assumptions were used in this study analysis:
(i) the systems were assumed in steady state
(ii) the heat transfer from the sides and bottom of the collector were neglected.
Equation (1) shows the equation of an average thermal efficiency of the solar air collector system [7].

$$\eta = \frac{\dot{m}c_p(T_o - T_i)}{I A_c}$$

whereby $c_p$ is the specific heat of air [J kg$^{-1}$ K$^{-1}$]; $\dot{m}$ is the air mass flow rate [kgs$^{-1}$]; $T_o$ and $T_i$ are the inlet and outlet air temperature respectively; $I$ is the solar radiation intensity [Wm$^{-2}$]; and $A_c$ is the area of the collector.

4. Results and discussions
The performance of both PP and FP solar collector were evaluated through the values of temperature difference between the inlet air and out air ($\Delta T$), and the thermal efficiency ($\eta$) of the collectors. The influences of solar intensity ($I$) and mass flow rate ($\dot{m}$) were investigated.

4.1 Effects of solar radiation intensity
The effects of solar radiation intensity on the thermal performance of PP and FP solar collectors were illustrated in figure 4. The values of temperature difference are increasing with solar intensity, which the highest values of temperature difference at 1059Wm$^{-2}$ for PP and FP collectors are about 31°C and 22°C, respectively. While the effect of solar radiation intensity on thermal efficiency is relatively small compared to temperature difference. The highest and lowest thermal efficiency in this study range from 42 to 44% for PP collector, and 30 to 32% for the FP collector. This indicates that in terms of efficiency, solar radiation intensity is not a critical factor, however the impact would be more on the air temperature, which higher radiation intensity gives higher outlet temperature and hence the temperature difference. In addition, results also found that at the same solar radiation intensity, the perforated design has higher thermal performance compared to the flat plate collector.
4.2 Effects of mass flow rate

Figure 5 shows the effects of mass flow rate on the thermal performance of PP and FP solar collectors. The temperature difference is decreasing while the thermal efficiency is increasing with the mass flow rate. At the highest thermal efficiency value of 59%, the temperature difference value is 17°C for the PP collector, with outlet air temperature of 48°C. The PP collector also shown a better thermal performance compared to a FP collector, whereby at the highest thermal efficiency value for FP is only about 36%, with the temperature difference value of 10°C and outlet air temperature of 42°C.

This is due to the fact that the perforated design is able to enhance the heat transfer between the air and the absorber (PP). The heated air was drawn through the holes of the plate and this has minimized the convention heat loss between the glass and PP, and further drawing the heat from the PP. Moreover, the
enhanced heat transfer rate through PP design has also reduce the surface temperature of the PP and hence, reduce the radiation heat loss. Apart from that, results also showed that mass flow rate is a key factor in determining the system thermal performance, both the temperature difference and efficiency. Higher mass flow rate gives lower value of outlet temperature. Thus, depend on the applications, the required outlet temperature of the system could be adjusted by controlling the mass flow rates.

4.3 Comparisons with previous studies
Table 3 shows the comparisons of the values of thermal efficiency of solar collectors between present work and other flat plate solar collectors. The comparisons were compiled according to mass flow rate at 0.02 kgs\(^{-1}\). Results showed that the present design of perforated plate gave better thermal efficiency compared to the flat plate with single and double passes, and also better than the vertical transpired solar collectors. However, it is lower than flat plate collector with double pass airflow that consisted matrix layer.

Table 3. Comparison of thermal efficiency of the present study with other flat plate solar collector at mass flow rate of 0.02kg/s

| Solar collector type                                      | Thermal efficiency | Reference   |
|----------------------------------------------------------|--------------------|-------------|
| Present Glazed Perforated Solar                          | 59%                | Present Study|
| Flat Plate                                               | 36%                | Present Study|
| Flat Plate (double pass without matrix)                  | 56%                | [27]         |
| Flat Plate (double pass with matrix)                     | 63%                | [27]         |
| Glazed Transpired Solar Collector (Vertical)             | 38%                | [26]         |

5. Conclusion
In this study, the thermal performance of PP and FP solar collectors were investigated. The experiments were carried out in a laboratory under the operating conditions of solar radiation intensity ranged from 350 Wm\(^{-2}\) to 1050 Wm\(^{-2}\) and mass flow rate ranged from 0.006 kgs\(^{-1}\) to 0.02 kgs\(^{-1}\). Present study has found that the thermal efficiency of both PP and FP solar collectors were increasing with solar radiation intensity and mass flow rates. The highest and lowest thermal efficiency under different intensities in this study range from 42 to 44\% for PP collector, and 30 to 32\% for the FP collector. Whereas, under different mass flow rates, the highest thermal efficiency value for PP and FP was measured 59\% and 36\%, respectively. While the temperature difference between the inlet and outlet air were increasing with solar radiation intensity and decreasing with mass airflow rate. However, relatively mass flow was the key factor that would influence the system performance and outlet air temperature. Furthermore, PP collector gave better thermal performance compared to FP collector.

6. References
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