Experimental performance of unglazed transpired solar collector for air heating

Hoy-Yen Chan[1,*], Saffa Riffat[1], Jie Zhu[1]

[1]Department of Architecture and Built Environment, University of Nottingham, Nottingham, UK
* Corresponding author. Tel: +44 115 951 3134, Fax: +44 115 951 31591, E-mail: laxhyc@nottingham.ac.uk

Abstract: Unglazed transpired solar collectors are usually mounted on the side of the building that receives the most sunlight. It is a fan-assisted system, whereby air is drawn through the holes into the plenum and the warm air is then ducted into the building. The primary reason for using the unglazed transpired metal plate as the solar collector is not only to absorb the solar heat but also to reduce the convection heat loss. These in return will have higher heat exchange effectives and heating efficiency. Though many research have been carried out to study the Nusselt number correlations, heat exchange effectiveness, wind effects and pressure drop, yet only hand full of research that involved heat transfer study that including the vertical airflow in the plenum. This paper is to assess the heating performance of this system through experimental tests which involve the study of temperature rise along the vertical air flow in the plenum. Results show that the temperature of the air flowing vertically is increasing gradually from the bottom to the top of the plenum. This is contrast with the previous studies which assumed that the temperature of the air in the plenum is constant and same as the outlet air temperature at the top of the plenum. The temperature rise is increasing with solar radiation intensity. Temperature rise along the plenum contributes between 30 to 60% of the total temperature rise at a constant suction velocity. On the other hand, temperature rise is decreasing with suction velocity. Values of temperature rise along the plenum are between 30 to 50% of the total temperature rise for suction velocity of 0.03 to 0.05 ms^{-1} at $600Wm^{-2}$ of solar radiation. Therefore, this study has proved that heat transfer of vertical airflow in the plenum has a crucial heating effect.

Keywords: *Unglazed transpired solar collector, Air heating, Solar façade.*

Nomenclature

d	*hole diameter*	*m*
D	*plenum depth*	*m*
ΔP	*pressure drop*	*Pa G*
H	*collector height*	*m*
I	*solar radiation intensity*	$W{\cdot}m^{-2}$
L	*collector width*	*m*
Nu	*Nusselt Number*	
Pit	*pitch*	*m*
Re	*Reynolds number*	
Ta	*ambiant temperature*	*K*
Ti	*air temperature at the bottom of the plenum also air temperature after pass through the hole*	*K*
Tout	*outlet air temperature (on top of plenum)*	*K*
Tp	*collector plate temperature*	*K*
U_w	*wind velocity*	$m{\cdot}s^{-1}$
v_s	*suction velocity*	$m{\cdot}s^{-1}$

1. Introduction

The heat transfer of the transpired plate occurs at the front-of-plate (the upstream-facing surface), the hole and the back-of-plate. The diameter, pitch and geometrical of the hole together with the porosity of the plate and suction velocity of airflow rate are the key factors for the heat transfer coefficient. However, there are limited studies on transpired plate heat transfer. Kutsher [1] has developed an empirical correlation of Nusselt number which is appropriate for thin transpired plates with porosity less than 2%, low suction flow rates and triangular hole arrays. To-date, this is the only study considering the porosity, hole diameter and crosswind conditions to reach the empirical correlation Nu. The correlation covers heat transfers from the front-of-plate, hole and back-of-plate but excludes the vertical airflow in the plenum. The author ignore heat transfer between the back surface and the vertical airflow because it is believed that the flow in plenum has little effect due to the injection effect on the back-of-plate side and the air laminarization induced by acceleration. The numerical results show that the heat transfer that occurs at the front surface dominates heat transfer in the hole and on the back surface at suction flow rates of 0.02 to 0.07 kg $s^{-1}m^{-2}$. The crosswind data for the narrow transverse spacing are correlated as $Nu=2.75[(Pit/d)^{-1.2}Re^{0.43}+0.011PRe(U_w/v_s)^{0.48}]$ with $0.001\leq P\leq 0.05$ and $100\leq Re\leq 200$ [1]. Augustus and Kumar [2] use the same Nu correlation in their mathematical modelling of transpired solar collector performance. The assumptions made are the same as Kutscher's [1, 3] and Dymond's [4] studies. The plate is a mild steel absorber coated with black paint with input parameters as follows: $400\leq I\leq 900 Wm^{-2}$, $0.02\leq v_s\leq 0.03 ms^{-1}$, $25\leq \Delta P\leq 80Pa$, $0.050\leq D\leq 0.150m$, $0.012\leq Pit\leq 0.024m$ and $0.00080\leq d\leq 0.00155m$.

Gunnewiek et.al have studied the airflow in plenum but only considering the vertical direction by using 2D CFD model. The transpiration of air through the plate is modelled as a process occurring through discrete holes. The collector height range is $3.0 \leq H\leq 6.0$ m, and the plenum aspect ratio range is $10 \leq H/D \leq 50$. The results show that different settings of parameters yield different airflow profiles. The nature of the profile depends on whether the flow is dominated by buoyancy or by the forced-flow produced by the fan. When the flow is non-uniform, the code predicts that an important amount of heat transfer can take place from the back-of-plate to the vertical air in the plenum. The non-uniform flow is favoured in flows that are buoyancy dominated. Besides improving the efficiency, non-uniform flow is also keeping the fan power at a minimum, so there is a dual benefit [5]. Poor flow distribution occur in large building applications; this has been shown by infrared photographs [4]. Such poor distribution would cause penalties in performance due to greater radiation and convective heat losses at hotter, flow-starved surfaces. In order to study the uniformity of the airflow, Dymond and Kutsher [4] have developed a computer program to allow designers to predict flow uniformity and efficiency by applying pipe networks concept. The studied range of plenum depth, D is between 5 and 30cm. In terms of the energy balance the authors acknowledge additional heat transfer from the plate to the air in the plenum is possible, which has been indicated by Gunnewiek et. al [5] simulation results. However this part of heat transfer is ignored due to the absence of heat transfer correlation between the back-of-plate and the vertical airflow. Hence, it is assumed that the air temperature leaving a junction is the same as the perfectly mixed temperature of the air entering the junction. The overall results show that the air inside the collector plenum experiences three plenum pressure drops, i.e. acceleration, friction, and buoyancy. The larger the air flow through the collector, the better the heat is transferred away from the collector, which results in a higher collector efficiency.

Though there are quite a number of studies that ignored the heat transfer from the back of the plate, study [5] has proved that this part of heat transfer is possible and the authors [4, 6] also acknowledge this possibility if the collector is vertically tall. Thus, this paper is to discuss the heating performance of this system through experimental tests which involve the study of temperature rise along the vertical air flow in the plenum.

2. Methodology

A chamber is built inside a laboratory. Fig. 1 illustrates the schematic view of the experimental system. The wall of the façade that contacts with the ambient is a black painted aluminium transpired plate which adjuncts with three other solid walls, and so they form a plenum. As shown in Fig. 1. The sandtile wall is made of eight sandtile blocks with the dimension of 0.25m x 0.25m x 0.06m for a single block. The other two adjunction walls that attached to both aluminium plate and sandtile wall are rigid polyisocyanurate foam boards with glassfibre of 0.07m of thickness and U-value of 0.023W $m^{-2}K^{-1}$. The opening of the air outlet is 0.23m x 1.0m. Two fans are installed at the air outlet. Nine K-type thermocouples are placed on each aluminium plate, the plenum and the sandtile wall as shown in Fig. 2. The locations of thermocouples between the wall and the plate (the plenum) are in line with the thermocouples on the sandtile wall except at the bottom they are in line with the first row of the holes from the bottom. The thermocouples are connected to a computer-controlled data logger. Temperatures data are started to be taken only after the test has begun for 2hours to reach a steady state. Air velocities are measured at the centreline of the plenum and at the outlet of the plenum.

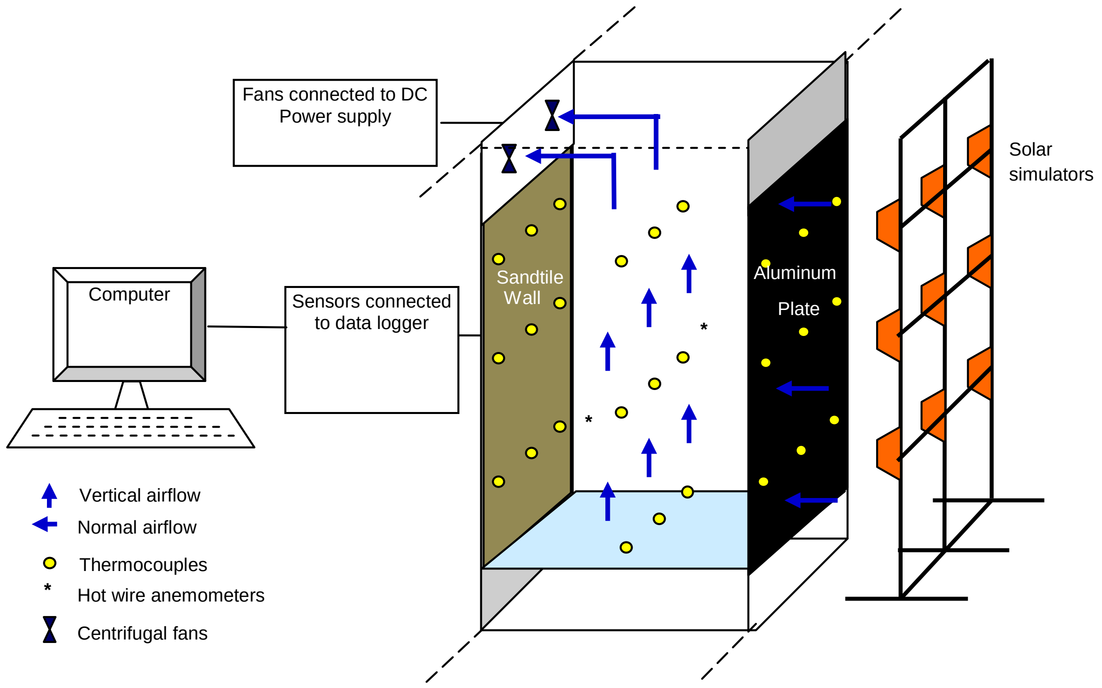

Fig. 1. Schematic view of experimental set up.

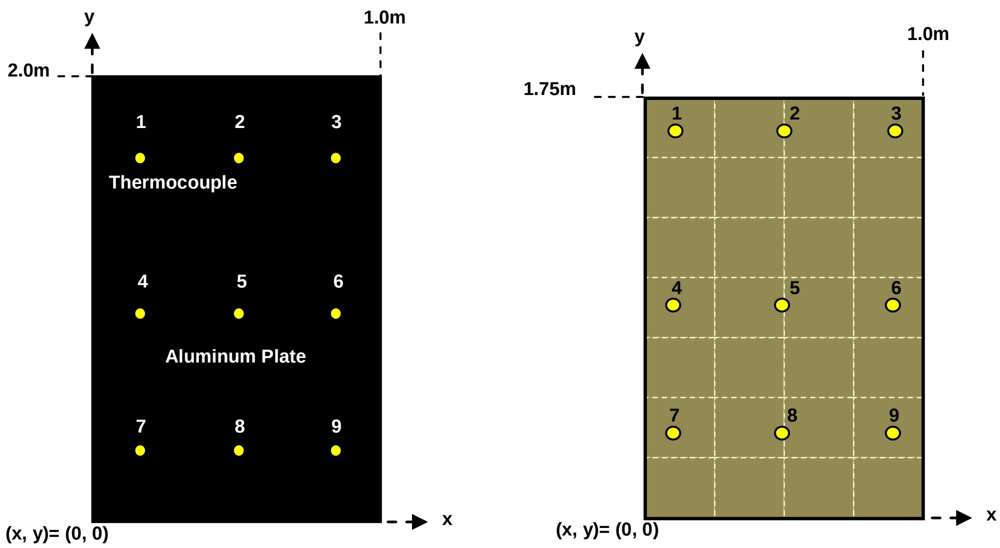

Fig. 2. Thermocouples' location on the plate and santile wall.

2.1. Test conditions and analytical parameters

The test conditions and some of the interested parameter to be investigated in this study are as shown in Table 1. The parameters that vary from one cycle to another of the tests are among solar radiation intensity and suction velocity. Only one design of the transpired plate is involved in this study, which the circular holes are arranged in triangular geometry. Pressure drops across the collector for all the tests are ensured to be at least 10 times greater than the pressure drops in the plenum and so as positive values of pressure coefficient. This step is to avoid outflow air from the plenum. The solar radiation that absorbed by the plate is assumed to be homogenous.

Table 1. Parameters for the experiment tests.

Parameter	Value/ range
Solar radiation intensity (I), Wm^{-2}	300-800
Suction velocity (v_s), ms^{-1}	0.03-0.05
Plenum depth (D), m	0.25
Pressure drop across the collector (ΔP), Pa	12-36
Pitch (Pit), m	0.012
Hole diameter (d), m	0.0012
Height of the collector (H), m	2.0
Width of the collector (L), m	1.0

3. Results

Effects of suction mass flow rate and solar radiation intensity have been studied and results are as discussed in the following sections.

3.1. Effect of suction airflow rate

Fig. 3 shows the temperature rise for different depths of the channel at different suction mass flow rates with a solar radiation intensity of 614Wm-2. The temperature rise of (Tout-Ta) is the overall temperature rise for the system, which is the temperature difference between the outlet air and the ambient air. The temperature rise of (Ti-Ta) is the temperature difference between the heated air after passing through the holes (normal flow) and the ambient air. Whereas the (Tout-Ti) is temperature change of the vertical flow from the bottom to the top of plenum. The values of these temperature rises decrease with the suction mass flow rate. Increasing the suction mass flow rate by about $0.02kgs^{-1}m^{-2}$, Tout-Ta decreases nearly 3K, while (Ti-Ta) and (Tout-Ti) decrease about 1K and 3K respectively. T he shares of temperature rises contributed from normal and vertical flows remain almost the same between 0.04 to $0.06kgs^{-1}m^{-2}$ (Fig. 3). The degrees of temperature decrease for the normal and vertical flows are about the same. Nonetheless, results shows that in term of percentage the vertical flow (Tout-Ti) contributes about 39-49% of the total air temperature rise (Tout-Ta). Thus the air temperature rise along the plenum should not be ignored.

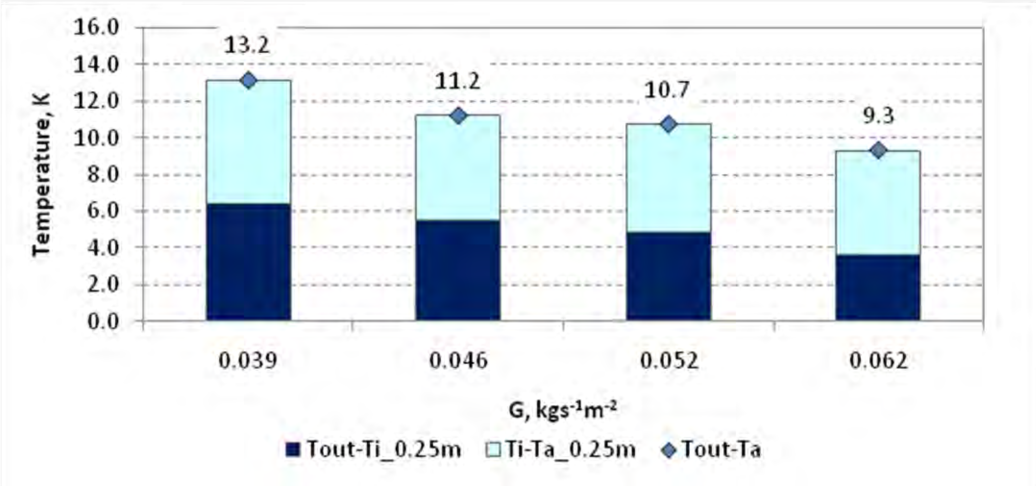

Fig. 3. Values of total, normal and vertical temperature rise at different suction mass flow rates.

3.2. Effect of solar radiation intensity

Fig. 4 shows the temperatures of the ambient, the plate and the air in the plenum for plenum depth of 0.20, 0.25 and 0.30m respectively, at a constant suction mass flow rate. The values of the temperatures increase with the solar radiation intensity and are as shown in Figure 8. The overall rise in temperature (Tout-Ta) from 307 t o 820Wm-2 is about 6 t o 18K, which approximately increases 3K for every increase of 100Wm-2. Thus, the solar radiation intensity plays an important role in the thermal performance of the system. Fig. 5 shows the shares of temperature rises contributed by the normal (Ti-Ta) and vertical (Tout-Ti) flows at constant suction mass flow rate and solar radiation intensity. In terms of percentage, vertical flow contributes 34% of total temperature rise at 307Wm^{-2} and increases to 58% at 820Wm^{-2}. Therefore, this indicates that the temperature rise in the plenum should not be ignored.

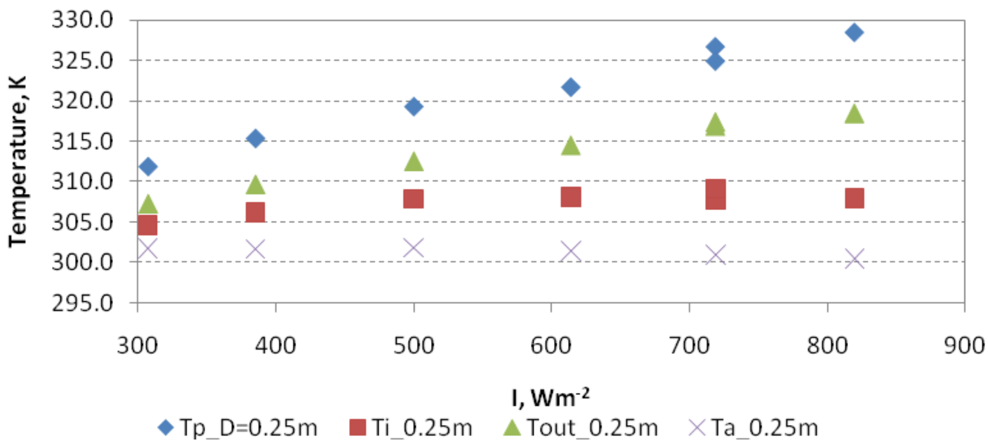

Fig. 4. Temperatures of ambient, at the plate, bottom of plenum and the outlet at a constant suction mass flow rate and different solar radiation intensities.

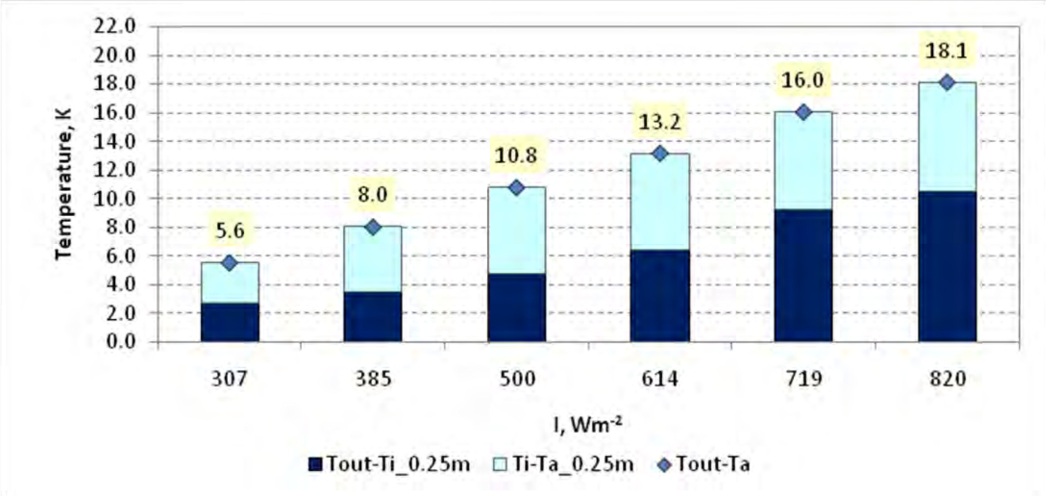

Fig. 5. Values of total, normal and vertical temperature rise at different solar radiation intensities.

4. Discussion and Conclusions

Experimental results show that the vertical flow contributes about 50% of the total air temperature rise. This is contrast with previous studies. As most of the transpired solar collector related studies adopt the same Nu heat transfer correlation [1] and lack of correlation between the plate and the air in the plenum, they accept the same assumption which is neglecting the heat transfer from the back of the plate to the air in the plenum. One of the possibilities for being disagreed with this assumption could be the height of the collector in Kutscher's study [6]. The height for the collector was 0.5m which is quarter of the height of present study. In the study, the author acknowledges that heat transfer from the back of plate might occur for tall vertical collector. Moreover, this could be due to buoyancy-dominated pattern of the vertical flow and causes heat transfer takes place from the back of the plate [5]. Present results show that vertical flow heat transfer is significant for the total air temperature rise. The air temperature rise from the bottom to the top of plenum is between 2 to 10K depends on the operating parameters. However the pattern of the vertical flow is beyond this study. A more precise correlation for vertically tall solar collector need to be developed which include the heat transfer along the plenum whether experimentally or through CFD simulation.

References

[1] Kutscher C. F, Heat exchange effectiveness and pressure drop for air flow through perforated plates with and without crosswinds, *J Heat Transfer* 116, 1994, pp. 391–9.

[2] M. Augustus Leon, S. Kumar, Mathematical modeling and thermal performance analysis of unglazed transpired solar collectors, *Solar Energy* 81, 2007, pp. 62-75.

[3] Kutscher, C.F., Christensen, C.B., Barker, G.M, Unglazed transpired solar collectors: heat loss theory, *ASME Journal of Solar Engineering* 115, 1993, pp. 182–8.

[4] Dymond C., and Kutscher, C., Development of a flow distribution and design model for transpired solar collectors, *Solar Energy* 60, 1997, pp. 291-300.

[5] L. H. Gunnewiek, E. Brundrett, K. G. T. Hollands, Flow distribution in unglazed transpired plate solar air heaters of large area, *Solar Energy* 58, 1996, pp. 227-37.

[6] Kutscher C. F., A n investigation of heat transfer for air flow through low porosity perforated plates, Colorado: University of Colorado, 1992.