

Experimental determination of the temperature variation across the flow channel in a natural convection solar air heater.

Ong K. S.¹, Kenny Tan, Tee W. N. and Chandok, S.

¹Prof., Monash University Sunway Campus, Jalan Lagoon Selatan, 46150 Bandar Sunway, Malaysia, Tel: +603 55146000, Fax: +603 55146215, Email: Ong.Kok.Seng@eng.monash.edu.my

ABSTRACT: An experimental investigation was conducted to measure the temperature variation across the flow channel and to determine the performance of a natural convection solar air heater at various tilt angles from 15, 30 and 45°. The results of the temperature profile across the air gap showed that heat transfer from the absorber plate to the air stream was mainly by convection. At a particular section, mean air temperature could be calculated from the arithmetic mean of the temperature profile across the air gap to within $\pm 2^\circ\text{C}$. The axial air temperature distribution was non linear and did not increase much beyond 1 m of collector length. It tended to decrease towards the end of the collector. Overall glass, absorber plate and mean air temperatures over the entire length of the solar air heater could be determined by averaging the mean axial temperatures to within $\pm 2^\circ\text{C}$. The heater performed better as inclination increased.

Keywords: Solar air heater, natural convection, inclination effects, temperature profile across air gap, axial temperature distribution

NOMENCLATURE

C_p specific heat of air [J/kg K]

d air flow channel depth [m]

L length of collector [m]

H_0 solar radiation heat flux on bottom plate [W/m²]

T_a overall mean absorber plate temperature [C]

T_{amb} ambient air temperature [C]

T_f overall mean induced air temperature [C]

T_g overall mean glass surface temperature [C]

T_o, T_i outlet and inlet air temperature [C]

u induced air velocity [m/s]

W width of collector [m]

x axial distance along collector [m]

y distance across air gap collector [m]

γ constant in mean temperature approximation

ρ air density [kg/m³]

θ collector tilt angle [°]

η_i instantaneous collector efficiency [%]

1. INTRODUCTION

Most natural convection solar air heater models assumed one dimensional air flow through the air channel with uniform air temperature across the duct gap. However, the temperature profile across the induced air stream is not uniform. For a top glass covered solar collector with a bottom absorber plate, the temperature decreases rapidly from the absorber surface to the top glass surface. Such a temperature distribution could affect the theoretical model postulated. The overall performance of the solar air heater could be determined from the quantity of induced air flow and the air temperature rise across the collector. The performance is dependent upon the angle of tilt or inclination of the collector and the amount or degree of incident solar radiation on the surface. As a solar air heater is increasingly tilted to the vertical, the surface area exposed to solar irradiation becomes less resulting in a lower induced air mass flow rate. However, by increasing the tilt, the effective chimney height is increased leading to increased flow rate. Hence, an optimum tilt angle for optimum performance would depend largely on where the geographical location of the air heater. An instantaneous efficiency measurement would enable optimum performance to be determined.

There are numerous theoretical and experimental studies on the buoyancy driven or the natural convection solar air heater. Most models assumed one dimensional air flow through the air channel and uniform air temperature across the duct gap. Burek and Habeb [1] measured the temperature and velocity profiles across the depth of the air gap in a small scale, glass covered, vertical solar air heater model with various air gaps using an electrically heated back plate. Thermocouples measured the temperature profiles across the depth at six sections centrally along the air heater. At each section there were 4 thermocouples in the

air stream and 1 each on the cover and the heater plate. Velocity profile of the induced air flow across the depth was measured using a hot bead anemometer at the inlet. Five heat inputs were studied, from 200 – 1000 W in 200 W steps. They found that temperature profiles were fairly flat across the main part of the channel with the heater plate being at the highest temperature followed by the glass cover and then the air. They also confirmed what others have observed, that the glass, plate and air temperatures increased and then decreased towards the end of the air heater. This phenomenon has not so far been explained. They presented a set of empirical equations for the flow Reynolds number and collector efficiency similar to the experimental studies of Pica et. al. [2]. As a solar air heater is increasingly tilted to the vertical, the surface area exposed to solar irradiation becomes less resulting in a lower induced air mass flow rate. However, by increasing the tilt, the effective chimney height is increased leading to increased flow rate. Hence, an optimum tilt angle for optimum performance would depend largely on where the geographical location of the air heater. Sakonidou et. al. [3] presented a mathematical model that could be employed to determine the optimum tilt of a solar chimney to maximise the induced air flow rate in a solar chimney at different periods of the year and found it to be around 60 degrees. Das and Chakraverty [4] suggested a local tilt angle of 30 degrees. Prasad and Chandra [5] presented a method to determine the optimum tilt for maximum flow rate.

2. OBJECTIVE

The objective of the present investigation is to determine the temperature profile across the duct gap and to gauge the effects of the angle of inclination on the performance of the natural convection solar air heater operating under outdoor conditions.

3. EXPERIMENTAL APPARATUS

The 2.4 m long x 0.35 m wide x 0.105 m high solar air heater is shown in Fig. 1. Side and bottom insulations were 25 mm thick polystyrene sheet. The 1.0 mm thick aluminium absorber plate was painted matt black and covered with 2 mm thick glass sheet leaving an air gap 80 mm deep. External casing was formed using 1.0 mm thick aluminium sheet. The solar air heater was supported on a metal frame oriented facing south as shown in Fig. 2. It could be tilted to any required angle.

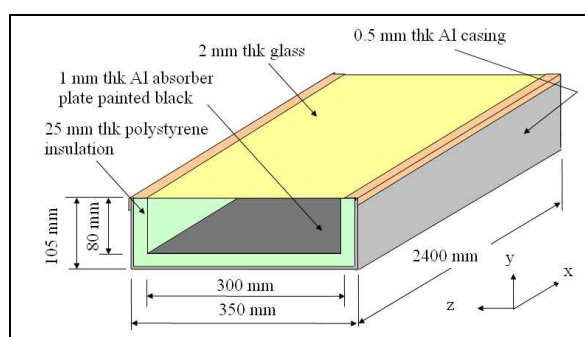


Fig. 1. Schematic diagram of experimental solar air heater.

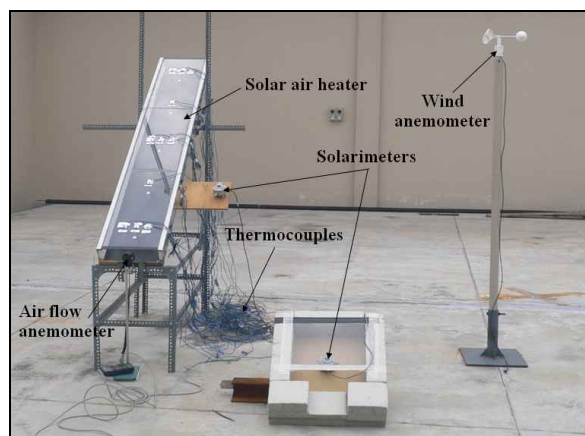


Fig. 2. Experimental setup.

The locations of 37 (11 each on the top glass and absorber plate and 15 in the air stream) copper-constantan thermocouples ($\pm 0.5^\circ\text{C}$) employed to measure glass, absorber plate and air temperatures are shown in Fig. 3. An anemometer was used to measure the induced air velocity ($\pm 3\%$) at the entrance

of the air heater. Two Kipp and Zonen solarimeters tilted at the same angle as the solar air heater were employed to measure the instantaneous solar radiation normal to and before and after the glass sheet. The results showed that the glass transmissivity varied from about 0.73 – 0.81. Ambient temperature was measured with another copper-constantan thermocouple located in the shade around the air heater. All output data were recorded on a data logger every minute. A wind anemometer was employed to measure the wind velocity throughout the study. Experiments were conducted at inclination angles from 15° to 45° about the solar noon from around 11 am to 1 pm.

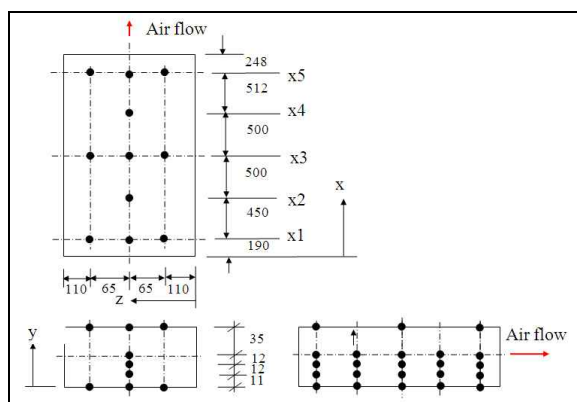


Fig. 3. Locations of thermocouples.

4. EXPERIMENTAL RESULTS

4.1 Uniformity of glass and absorber plate temperature across the air heater.

Preliminary observations showed that the glass and absorber plate temperatures across the width of the air heater at sections x1, x3 and x5 were uniform to within $\pm 1.5^\circ\text{C}$. The mean glass and absorber plate temperatures at each of these 3 sections along the solar air heater were determined by taking the average values of the 3 probes each across that particular section.

4.2 Experimental results obtained throughout the day.

A typical set of results showing the daily variation of solar radiation (H_0), ambient temperature (T_a), mean air temperature at section x5 (T_{x5}), induced air velocity and instantaneous efficiency between 11 am and 1 pm is shown in Fig. 4. The highly fluctuating nature of solar radiation recorded is typical in the tropics. It is virtually impossible to obtain steady conditions. The mean air temperature ($T_{f,x5}$) at section x5 was calculated from the arithmetic mean of the glass, absorber plate and the 3 thermocouples in the air stream.

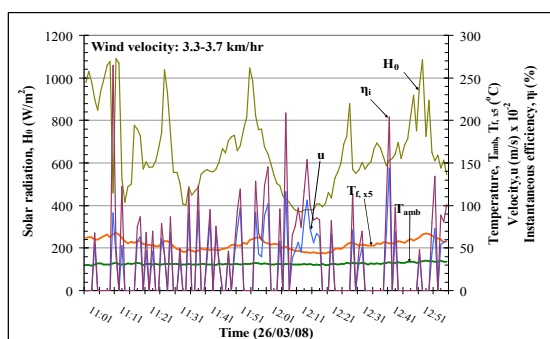


Fig. 4. Typical daily fluctuations of solar radiation, ambient temperature, induced air temperature and velocity and efficiency.

4.3 Temperature profile across air gap and section mean air temperature.

Typical results showing the induced air temperature profile (T_y) across the air gap at the 5 sections (x1 - x5) at 3 different times of the day are shown in Fig. 5 for 15° tilt. As expected, the absorber surface showed the highest temperature and the top surface temperature of the glass was lowest. The difference between absorber plate and the glass varied between 10 - 30°C, depending upon solar radiation and axial distance along the air heater. The air temperature was very nearly uniform across the upper half of the air gap. The steep gradient of the profile adjacent to the absorber plate indicated that heat transfer to the air was mainly by convection from absorber plate to the air stream. By assuming that the air temperatures at the bottom of the glass and

top of the absorber plate could be represented by the glass upper surface and the absorber plate temperatures, mean temperature of the air flow at each section could be calculated by taking the arithmetic mean of the 3 air temperatures together with the glass and absorber plate temperatures. A bulk average air temperature at each axial section could be determined by computing the area under the temperature profile distribution. Representative comparisons between this bulk average temperature and the arithmetic mean temperature showed differences of about 1°C at temperatures around 40 - 50°C and about 2°C when around 60°C. The larger difference arose because of the steeper gradients of the temperature profiles near to the absorber plate especially at high absorber plate temperatures. The results showed that the mean induced air temperature at any axial distance along the air heater could be approximated by the arithmetic mean of the five measured temperature values, i.e. 3 within the air gap and 2 on the glass and the absorber surfaces to within $\pm 2^\circ\text{C}$.

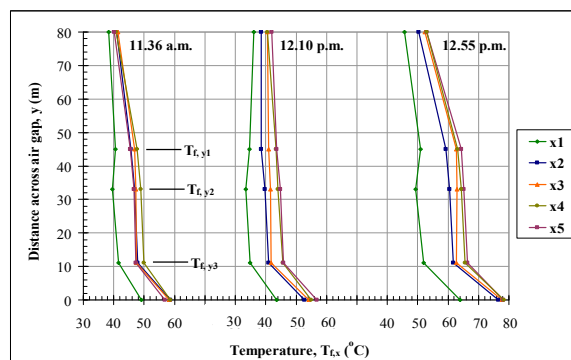


Fig. 5. Typical temperature variation across air gap at various axial distances along solar air heater.

4.4 Axial temperature distribution of glass, absorber plate and induced air flow.

A typical axial temperature distribution of glass, absorber plate and induced air flow is shown in Fig. 6 for a tilt angle of 15° and at a radiation level of 800 W/m². All

temperatures were observed to increase initially along the air heater and then tended to decrease towards the outlet of the air heater. These phenomena have also been observed by other investigators. It could be attributed to end cooling effects and mixing of the outgoing hot air with the ambient air due to recirculation.

4.5 Overall mean temperatures for glass, absorber plate and induced air flow.

Overall mean temperatures for glass, absorber plate and induced air flow could be approximated by taking the arithmetic average of the mean temperatures at the five sections (x1 – x5). The air temperature at the outlet of the air heater (T_o) was assumed equal to the temperature at the last section at x5. Bulk average temperatures could be determined graphically by considering the areas under the respective curves. Differences of about 1 - 2°C were obtained for the absorber plate, 0.5°C for glass and about 1°C for the induced air flow. The results showed that overall mean temperatures for glass, absorber plate and induced air flow could be approximated by the arithmetic mean measured at the five axial stations to within ± 0.5 , 1.0 and 2.0°C for glass, induced air and absorber plate, respectively.

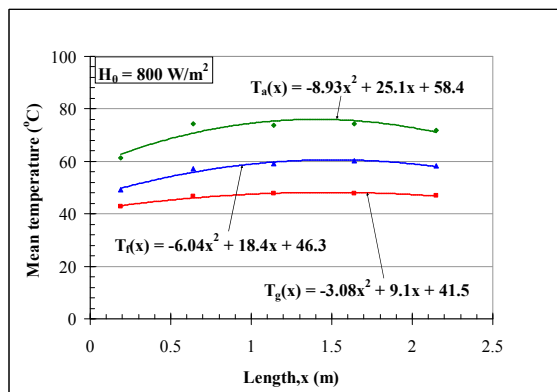


Fig. 6. Typical axial distribution of induced air temperature along solar air heater.

4.6 Effect of solar radiation.

Figure 7 shows typical overall mean temperatures for glass, absorber plate and induced air temperatures plotted against solar radiation for the 15° tilt angle. The results show that all the temperatures increase with solar radiation as expected. The absorber plate exhibited the highest temperature followed by the air and then the glass surface. The mean air temperature varies non-linearly along the collector. The non-linear effect could be gauged from γ , calculated according to the expression given by Ong [6], viz.,

$$T_f = \gamma T_o + (1 - \gamma) T_i \quad (1)$$

and shown in Fig. 7. Here, the inlet air temperature of the solar air heater (T_i) was assumed equal to ambient temperature and the outlet temperature equal to the mean value at section x5 ($T_{f,x5}$). The results showed that the average value of γ varied from 0.95 at 15° to 0.82 at 45°.

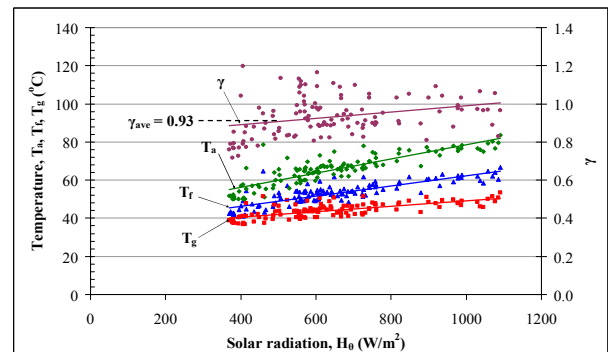


Fig. 7. Effect of solar radiation on glass, absorber plate and air temperatures.

4.7 Overall performance of the solar air heater.

The overall performance of the air heater could be determined from the instantaneous efficiency defined as

$$\eta_i = \frac{\rho u d C_p (T_o - T_i)}{L H_\theta} \times 100\% \quad (2)$$

Typical air temperature rise, induced air velocity and instantaneous efficiency against

solar radiation are shown in Fig. 8 for 15° degrees tilt angle. Here, the exit air temperature (T_o) was assumed equal to the air temperature at the section x5. It could be seen that induced air velocity measurements fluctuated greatly. This was attributed to its low magnitude and wind effects. With this wide fluctuation it would not be possible to have an accurate determination of both velocity and hence efficiency. The temperature rise was observed to vary linearly with solar radiation.

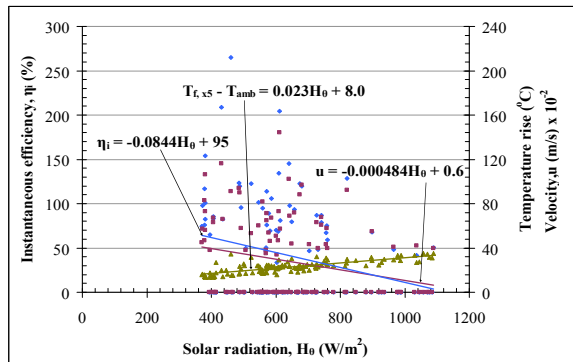


Fig. 8. Effect of solar radiation on induced air temperature rise, velocity and efficiency.

4.8 Effect of angle of inclination on the performance of the solar air heater.

Figure 9 shows the effect of angle of inclination on the induced air temperature rise along the solar air heater for 15° (Run #1), 30° (Runs #2 & 4) and 45° (Run #3). As expected, the higher the radiation the greater the temperature rise. We would expect air temperature rise to decrease as tilt angle increases. The present experimental results do not conclusively show this. More results are required in order to determine this effect.

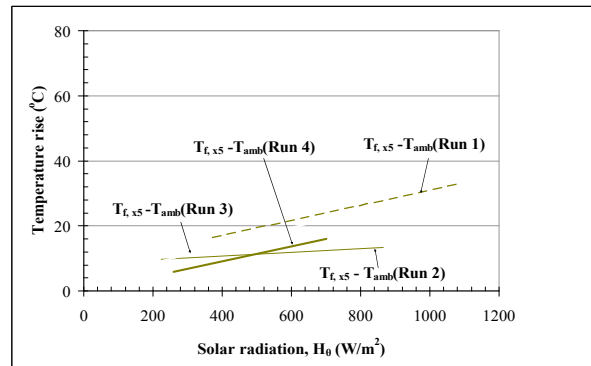


Fig. 9. Comparison of tilt angles on induced air temperature rise along solar air heater.

The effects of inclination on induced air velocity and collector efficiency are shown in Figs. 10 and 11. The downward trend in the velocity for Run #1 (15) is unexpected and attributed to wind effect. Generally, induced velocity and efficiency were seen to increase with solar radiation and tilt angle due to greater overall height of the collector.

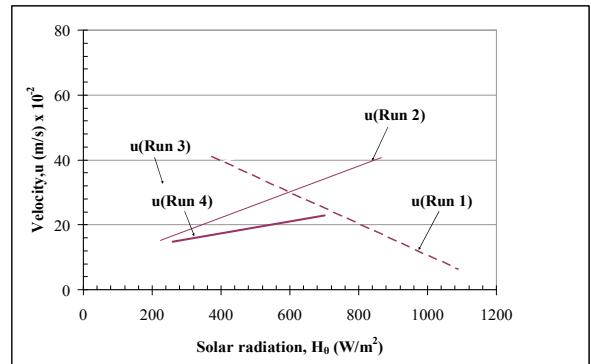


Fig. 10. Comparison of tilt angles on induced air velocity.

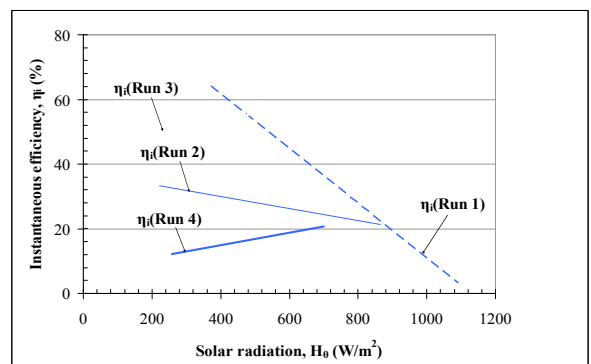


Fig. 11. Comparison of tilt angles on collector efficiency.

5. CONCLUSIONS

An experimental investigation was conducted to determine the performance of a natural convection solar air heater at tilt angles of 15, 30 and 45°. The temperature profile across the air gap indicated that a section mean air temperature could be calculated from the arithmetic mean of the temperature profile across the air gap. The axial air temperature distribution was non linear and did not increase much beyond 1 m of collector length. It tended to decrease towards the end of the collector. Overall glass, absorber plate and mean air temperatures over the entire length of the solar air heater could be determined by averaging the mean axial temperatures to within $\pm 2^{\circ}\text{C}$. The heater performed better as inclination increased.

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