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# AN EXPERIMENTAL INVESTIGATION OF THE PERFORMANCE OF SEQUENTIALLY CONNECTED EVACUATED TUBES USING CONCENTRATED SOLAR POWER

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## ABSTRACT

Heated air has many applications including space heating, cooking, absorption refrigeration, curing of industrial products and drying of foodstuffs. Typically air heated using solar irradiance is achieved in a collector which incorporates absorber plates enclosed with a transparent surface to retain heat in the collector. The temperature of air heated in such collectors is limited to some 80 °C. An experimental investigation was carried out in which ambient air was passed through three sequentially connected evacuated tubes, each fitted with parabolic concentrator with a reflectance of 97%. Tests were carried out on 1 September when the maximum elevation of the sun was 56.7° corresponding to a required tilt angle at solar noon of 33.3°. The rig was set at a tilt angle of 30° and an azimuth angle of -12°. The effects of the irradiance angle of incidence on the outlet temperature of the air from the three tubes were evident with the maximum temperatures occurring at solar noon when the outlet temperatures of the air from the first tube was 151.2°C, from the second 221.0 °C, and from the third 250.1 °C. The flow rate of air was 0.00223 kg/s. Using a reflector cross sectional area of 0.51m$^2$ per tube the efficiencies of the tubes at solar noon based on the normal component of irradiance into the parabolic reflectors were for the first second and third tubes 42%, 24%, and 12% respectively with an overall efficiency of 28%. The results indicated that heating air to elevated temperatures using concentrated solar power evacuated tubes is feasible but it will be necessary to redesign the system to reduce the excessive energy loss to the atmosphere. This energy loss was found to be directly proportional to the temperature difference between the mean temperature of the air in a tube and atmospheric temperature.

## INTRODUCTION

Since the oil crisis in 1973 research into Solar Air Heaters (SAH) accelerated and many alternative configurations been developed and characterised [1], [2]. Generally the designs have included flat plate, or similar, collectors covered with a single or double pane of glass to retain irradiance within the SAH. The maximum air temperature attainable with these collectors is of the order of 80 °C. While hot air at these temperatures has many applications including space heating, absorption refrigeration, and drying of inorganic materials including foodstuffs [3]. The range of applications could be broadened if the temperature of the air could be increased to say 250 °C. Increasing air temperatures out of SAHs above 80 °C requires that some form of solar concentration be employed. Tests were carried out on three sequentially connected evacuated tubes fitted with parabolic reflectors. The concentration ratio was based on a glass tube outer diameter of 47 mm and a width of a parabolic concentrator of 395 mm [4]. A photograph of the rig is presented in figure 1.

**Figure 1** Photograph of evacuated tubes arrangement.

## NOMENCLATURE

| | | |
|---|---|---|
| $A$ | [º] | Solar azimuth angle in horizontal plane |
| $C_P$ | kJ/kg K | Coefficient of specific heat |
| $G$ | [kg/s] | Mass flow |
| $I_C$ | [W/m$^2$] | Irradiance normal to plane of rig |
| $I_N$ | [W/m$^2$] | Solar direct irradiance |
| $I_P$ | [W/m$^2$] | Irradiance of horizontal Pyranometer |
| $J$ | [d] | Julian day of the year |
| $J_0$ | [d] | Julian day of summer solstice in Southern Hemisphere |
| $L$ | [º] | Longitude |
| $L_{NST}$ | [º] | Longitude corresponding to local standard time |
| $M$ | [-] | Energy ratio |
| $n$ | [-] | Index constant |
| $S$ | [m$^2$] | Plane surface area of parabolic reflector |
| $t$ | [h] | Time |
| $T_a$ | [ºC] | Atmospheric temperature |
| $T_i$ | [ºC] | Inlet temperature |
| $T_o$ | [ºC] | Outlet temperature |
| **Greek Symbols** | | |
| $\alpha$ | [º] | Azimuth angle of rig normal in horizontal plane |
| $\beta$ | [º] | Tilt angle of rig relative to horizontal plane |
| $\delta$ | [º] | Solar declination relative to equatorial hemisphere |
| $\lambda$ | [º] | Solar elevation above horizontal plane |
| $\eta$ | [%] | Efficiency |
| $\phi$ | [º] | Latitude |
| $\varphi$ | [º] | Angle between test rig normal and sun vector |
| $\omega$ | [º] | Hour angle |
| $\omega_L$ | [º] | Adjustment to hour angle for local longitude |

## EXPERIMENTAL APPARATUS

Three Alpha Omega borosilicate glass evacuated tubes with an outer diameter of 47 mm, an inner tube diameter of 37 mm, and a length of 1542 mm, were interconnected in series as shown in figures 1 and 2. The absorber coating used was AIN/AIN-SS/Cu. The maximum operating temperature of the evacuated tubes was 380 ºC [5]. The flow path for the air comprised of a copper tube running down the centre of an inner tube. Air entered the evacuated tube through a cast aluminium connecter and flowed through the inside of the copper tube to the bottom of the copper tube and then back to the top of the evacuated tube in the space between the copper tube and the inner glass tube as shown in figure 2. The air then flows out of the aluminium connector into the copper inner tube of the following evacuated tube and through the rest of the system. All aluminium connectors and pipes between the connectors were insulated to reduce heat loss to the atmosphere. The air flow through the rig was measured using a specially manufactured Venturi tube fixed to the inlet of the first evacuated tube. The pressure drop across the Venturi tube was measured using an inclined manometer. Temperatures were measured at the inlet and outlet of each tube using K-type thermocouples. Atmospheric pressure was measured using a Druck DPI 142 Precision Barometer with a precision of 0.01% FS. The three evacuated tubes were mounted horizontally on a wooden moveable base, shown in figure 1, which allowed the tilt angle to be adjusted to suit the current solar declination angle. The direction of solar North was measured using a vertical pole and the time on which the sun would be at solar North. Irradiance was measured using a calibrated Lambrecht Pyranometer model 16103 with a stated error of $\pm$ 2.5 % at < 1000 W/m$^2$. The Pyranometer for the tests used was mounted horizontally.

A cross-section of the three tubes is shown in figure 2 and a cross-section of a tube and its parabolic reflector in figure 3.

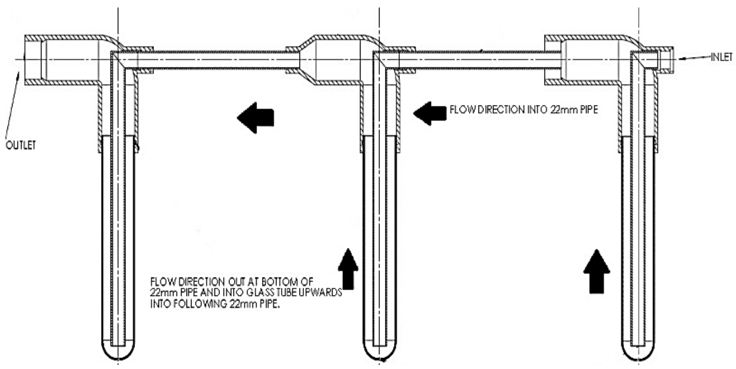


**Figure 2** General arrangement of three connected evacuated tubes [4].

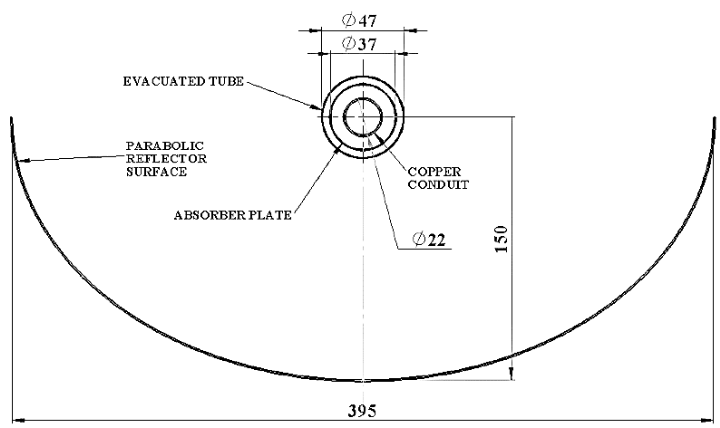


**Figure 3** Cross-section of a tube and parabolic reflector [4].

## EXPERIMENTAL METHODOLOGY

Tests were carried out on various days at latitude -26.2º South from 10h00 to 15h00 with temperature and irradiance measurements being recorded every minute. Results presented were recorded on 1 September 2014 which was Julian day 244. On that day the Equation of Time [6] and hence the error in the hour angle was negligible and was ignored in the analyses. Only data recorded at 15 minute intervals were used in the analyses as all required characterisations and trends were clearly indicated by the data. The tilt angle of the rig was based on the maximum elevation of the sun which on Julian day 244 was 56.7º giving a tilt angle of 33.3º. The tilt angle of the rig was set at 30º.

The component of irradiance normal to the plane containing the three evacuated tubes was based on the measured global irradiance adjusted using the tilt and azimuth angles of the rig and calculated solar angles. The calculated angles included the solar angle of elevation [6], the hour angle in the equatorial plane [6] and the azimuth angle of the sun in the horizontal plane at the location of interest [6].

## ANALYSIS

Apart from the objective of elevated temperatures the efficiency of the individual tubes and combination of the three tubes is relevant to their performance. The efficiency is related to the component of irradiance parallel to the centre lines of the parabolae and the plane of the rig. Calculation of the normal component of irradiance requires the elevation of the sun, azimuth angle of the sun, tilt and azimuth angles of the rig all relative to a reference system centred at the rig and the horizontal plane at the location of interest with solar North being one of the reference axes. Solar angles relative to solar North and the normal to the plane at the location of interest are readily calculated. Figure 4 illustrates the coordinate system and may be referred to.

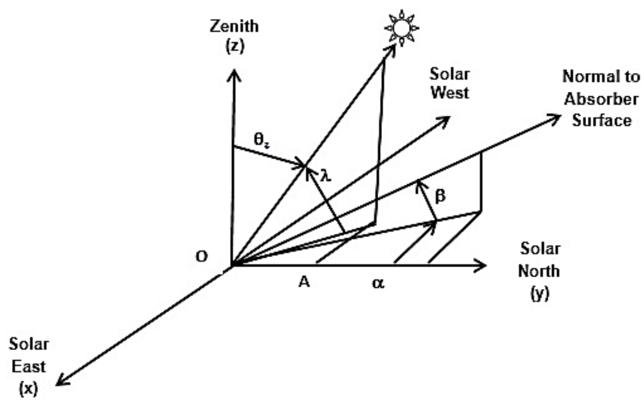


**Figure 4** Coordinate system with origin at location of interest.

The elevation of the sun is given by [6]:

$$\sin(\lambda) = \cos(\omega)\cos(\delta)\cos(\phi) + Sin\,(\delta)Sin\,(\phi) \qquad (1)$$

The hour angle measured on the equatorial plane is [6]:

$$\omega = 15\,(t-12)\,deg \qquad (2)$$

The adjustment to the hour angle for local longitude is [6]:

$$\omega_L = \frac{L_{NST}-L}{15}\,h \qquad (3)$$

The declination or tilt of the equatorial plane relative to the ecliptic plane is [6]:

$$\delta = \delta_0 \cos[\frac{2\pi(J-J_0)}{365.25}] \qquad (4)$$

The solar azimuth angle referred to the horizontal plane at the location of interest is [6]:

$$\sin(A) = \frac{\cos(\delta)\sin(\omega)}{\cos(\lambda)} \qquad (5)$$

Care should be taken in calculating $A$ due to angles exceeding $90^o$. Refer to the references for adjustments.

It may be shown that the angle between the vector joining the rig and sun and a normal to the plane of the rig is given by:

$$\cos(\varphi) = \cos(\lambda)\sin(A)\cos(\beta)\sin(\alpha) + \cos(\lambda)\cos(A)\cos(\beta)\cos(\alpha) + \sin(\lambda)\sin(\beta) \qquad (6)$$

For a Pyranometer placed on a horizontal plane the direct component of irradiance from the sun, including a small diffuse component is given by:

$$I_N = \frac{I_P}{\sin(\lambda)} \qquad (7)$$

The irradiance normal to the surface of the rig is:

$$I_C = I_N cos(\varphi) = I_P \frac{\cos(\varphi)}{\sin(\lambda)} \qquad (8)$$

### Data Correlations

It is postulated that the mean temperature of the air in an evacuated tube above atmospheric temperature will be a function of the inlet temperature to the tube, the normal solar irradiance, the plane area of the concentrators, the mass flow of air, and the specific heat of the air. A dimensional analysis yielded:

$$\frac{T_i+T_0}{2} - T_a = T_i(\frac{I_N S}{T_i G C_P})^n = T_i(M)^n \qquad (9)$$

It was found in the correlation that this equation needed to be adjusted to:

$$\frac{T_i+T_0}{2} - T_a = C + T_i(M)^n \qquad (10)$$

The additional constant may be attributed to the movement of the sun vector from the plane of the centre of a horizontal parabola as the hour angle increases in magnitude either side of solar North for the case where the tilt of the rig was set to be normal to the sun vector at solar noon. As the deviation from solar North increases the reflection of irradiance from the parabola onto the evacuated tube will be reduced increasing the rate of mean temperature reduction with reduction in M resulting in a mean temperature difference of less than zero at $M = 0$.

The efficiency of a tube is given by:

$$\eta_T = \frac{C_P G(T_0 - T_i)}{I_C S} \qquad (11)$$

for a single tube and:

$$\eta_{3T} = \frac{C_P G(T_0 - T_i)}{3\,I_C S} \qquad (12)$$

for three connected tubes.

## RESULTS

### Temperature Variations

Variation of the outlet temperature of the air from each of the tubes with time over the test day are presented in figure 5.

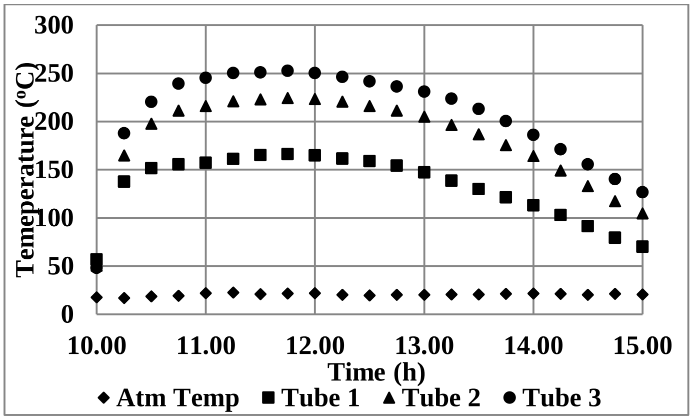


**Figure 5** Variation of temperature with time.

The effect of the variation of solar irradiance with time is evident in figure 5. Also evident is the reduction in temperature increase in successive tubes. This indicates an increase in heat transfer to the atmosphere with an increase in tube temperature.

The temperatures of the air entering the first tube and exiting each of the three tubes connected in series are presented in figure 6 for 11h00, 12h00, 13h00, and 14h00. The decrease in temperature relative to the maximum temperatures for each of the curves is due to the reduction in normal irradiance incident on the concentrators combined with the sun vector moving away from the normal plane to the parabolic collectors.

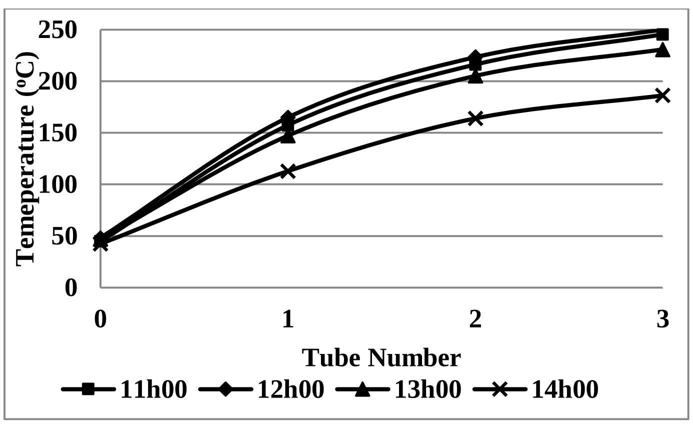


**Figure 6** Temperature variations across connected tubes.

Figures 5 and 6 demonstrate the reduction in temperature increase of the air as it passes through successive tubes. From figure 6, it appears that there is a temperature reduction as the temperature increases in a tube. This indicates that there would be no benefit of adding a fourth tube to the series.

### Efficiency

The variation of tube and system efficiencies with mean temperature difference is presented in figure 7. Only data recorded between, and including, 11h00 to 13h00, are presented. Outside of this time interval the movement of the sun vector from the concentrator centre lines influenced the data and hence were ignored.

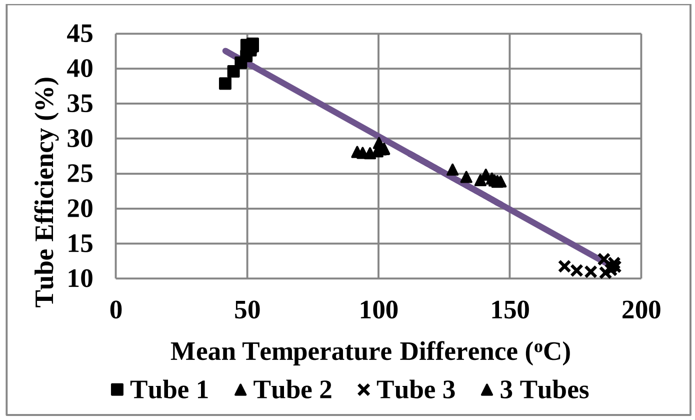


**Figure 7** Variation of tube efficiency with mean temperature difference.

As may be seen in figure 7 efficiency is directly influenced by the mean temperature difference indicating that heat losses are a strong function of the temperature indicating heat losses to the atmosphere.

### Correlation of All data

The data for all three tubes, as well as the three tubes acting as a single unit are presented in figure 8 using equation 10.

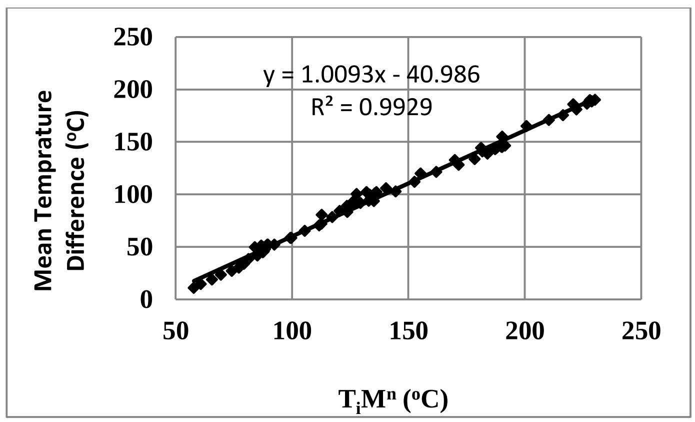


**Figure 8** Variation of mean temperature difference with $T_iM^n$ (all tubes).

Based on the correlation presented in figure 7:

$$\frac{T_i+T_0}{2} - T_a = -40.986 + T_i(M)^{0.385} \qquad (10)$$

The index 0.385 was adjusted by maximising the $R^2$ value for the data set presented in figure 7. The reason for the negative mean temperature difference of 40.97 °C at zero solar irradiance was presented above.

## CONCLUSIONS

Preliminary results for a method of heating air to temperatures of 250 ºC in evacuated tubes typically used in solar water heaters using solar irradiance were presented.

The design of the evacuated tubes would give high thermal efficiencies at typical geyser hot water temperatures of 70 ºC. For this arrangement however, the thermal efficiencies are reduced. Losses occur at higher temperatures and limits the maximum air temperature attainable.

Heat lost to the atmosphere increased with increasing air temperature limiting the maximum air temperature attainable with the current arrangement to not much more than 250 ºC.

Increasing the temperature of the air to higher temperatures would require a significant reduction in heat losses to the atmosphere at elevated air temperatures.

Tests were carried out with parabolic reflectors with a concentration ratio of 8.4 based on evacuated tube dimensions.

All the mean temperature difference data were correlated using dimensional analysis methods. These results showed the effects of the motion of the sun on the heating characteristics of stationary tubes which do not track the sun. Improved power absorption could be obtained by tracking the sun with the parabolic reflectors.

## FUTURE WORK

The effect of flow rate and in particular lower flow rates should be investigated as it may be possible to heat the air to similar temperatures in a single tube with much reduced heat losses to the atmosphere at greater efficiencies. It would then be useful to investigate the effects of the higher temperature which may occur in tube.

Evacuated tubes should be designed with much lower thermal loss coefficients. This could involve redesigning the evacuated tubes and their methods of interconnection.

The effects of higher concentration ratios could be examined.

Detailed investigations of the temperature distribution along the tube collector length as well as the effects on irradiance concentrations around the collector could provide essential insight into the design of evacuated tubes.

Computational Fluid Dynamics could be used to characterise details of the thermal field in an evacuated tube subject to concentrated solar power to aid future developments.

## REFERENCES


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