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Experimental Thermal Analysis of a Solar Cavity Receiver

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Abstract – *In this communication, an experimental thermal analysis of a solar cavity receiver is reported. The cavity receiver is made up of helically coiled copper tube. The experiments are conducted in a dry test mode wherein the coiled tube of the receiver is heated electrically and no fluid is circulated through the receiver coil. A special heating set-up is designed so as to replicate the actual heating of the tubes by solar insolation. The temperature variations in the cavity receiver are studied at receiver orientations of 45° and 90° (downward facing cavity) for power input values of 0.33, 0.5, 0.667 and 1kW. The results suggest that the air and tube temperatures are higher at 90° inclination when compared to 45° inclination. The temperatures are higher near the back wall of the receiver and are lower at the receiver aperture. The difference in temperatures at the inner most regions of the receiver and at the aperture are low for the 90° receiver inclination when compared to the 45° inclination. This indicates the presence of a large stagnation zone for the 90° receiver inclination when compared with that of 45° inclination.*

Keywords – Cavity receiver, heat losses, solar concentrator, temperature distribution.

1. INTRODUCTION

A point focus solar dish concentrator system consists of a paraboloid reflector dish, receiver, tracking system and storage systems [1], [2]. The receiver is a key component of such unit. Receivers of different types are used. In this paper, a cylindrical cavity receiver formed from helical coiled tube is studied. The downward facing cavity receiver has higher efficiency than an external receiver because of process of multiple reflections and re-absorption within the cavity as well as reduced convection losses due to the presence of a stagnation zone within the receiver. The other advantages of a cavity receiver include compactness, ease of manufacturing and cost effective design [3]. At temperatures of about 400° C, the cavity receiver can be used to minimize the heat losses [4]. Different cavity shapes such as cylindrical, heteroconical, spherical, elliptical and conical were studied and it is found that the losses from the cavity receiver are of the order of about 10% of the energy falling on the concentrator aperture with optical losses of about 2% [4]. The convective loss study is reported to be highly complicated due to the large characteristic lengths of the receivers, large temperature distributions and complex flow patterns within and outside the cavity [5]. The heat transfer losses in the solar cavity receiver were mathematically modelled [5], [6]. Experimental convective heat losses analysis for receiver inclinations between 0 and 90 degree inclination were performed [7]. The experimental studies include the variation of total losses with inclination and temperature. The total losses decrease with increase in inclination and increase with temperature increase. The variation of air and tube temperatures with inclination at different loss values are not reported in literature.

In the present study, the losses within a cavity receiver are studied in the off-flux mode. The cavity receiver is heated by an electrical heater placed inside the cavity and dry test is carried out i.e. no fluid is circulated through the receiver coil. The effects of orientation and power input on the air temperatures and tube temperatures within the cavity are studied.

2. EXPERIMENTAL SET-UP

The experimental setup is shown in Figure 1. It consists of open mouth cylindrical cavity receiver, mild steel stand, cylindrical electrical heating unit, thermocouples and measuring instruments.

Receiver

The receiver is cylindrical in shape formed from a single helical coiled copper tube as shown in Figure 2. It has a skirt of conical shape as shown. The copper tubes of about 10 mm diameter are wrapped helically with a pitch of about 13 to 14 mm. The receiver is coated with black polyurethane coating of 2 micron thickness to enhance heat absorption by increasing emissivity. A thin aluminum cladding and insulated layer of mineral wool of 75 mm thick is wrapped around this receiver coil.

The receiver is mounted on stand made up of mild steel angle. The receiver could be inclined at any angle in steps of 15^{o} and locked to any position using a locking pin. The inclination of the receiver axis is measured from the horizontal as shown in Figure 3. The stand is designed to maintain the mouth of the receiver at the minimum distance of 600 mm above ground.

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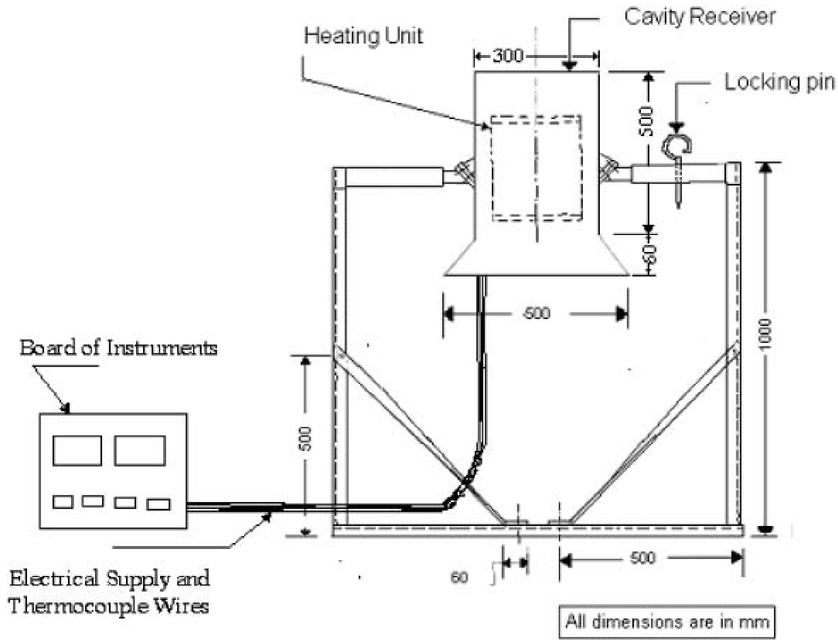

Fig. 1. Schematic of the experimental set-up.

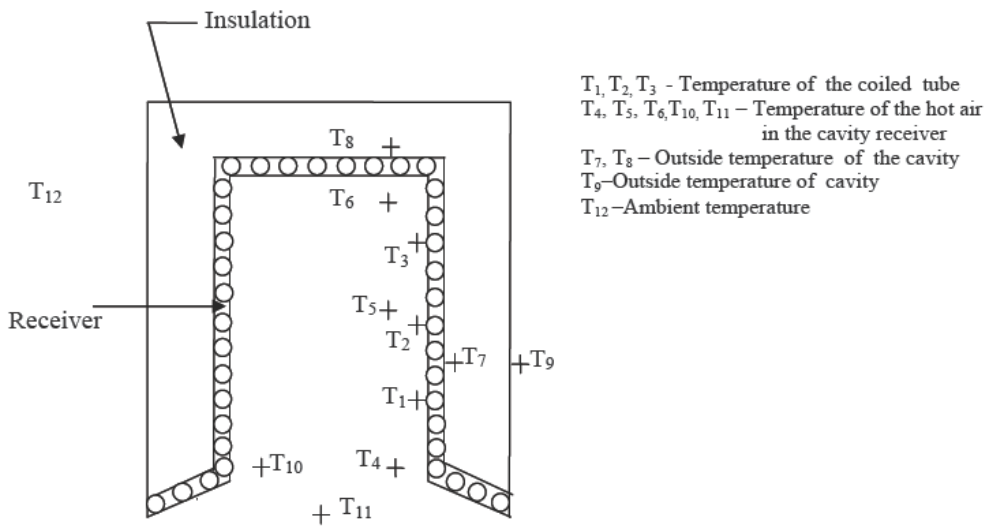

Fig. 2. Schematic of the cavity receiver showing position of thermocouples.

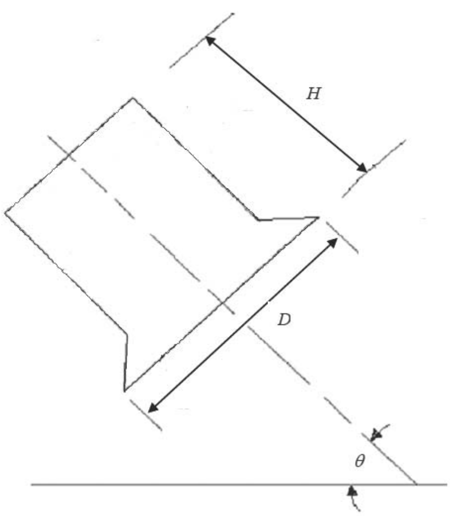

Fig. 3. The cavity receiver at an inclination angle θ.

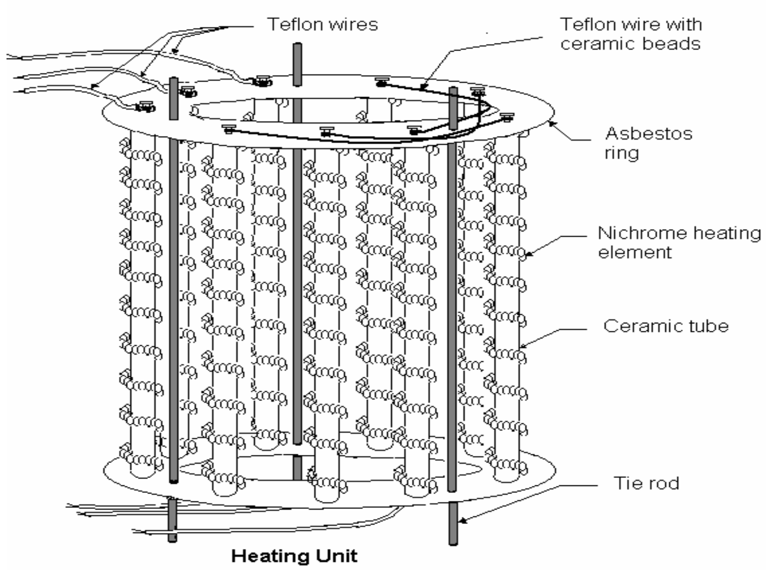

Fig. 4. Electrical heating unit of 3 kW capacity used in the dry test of the cavity receiver.

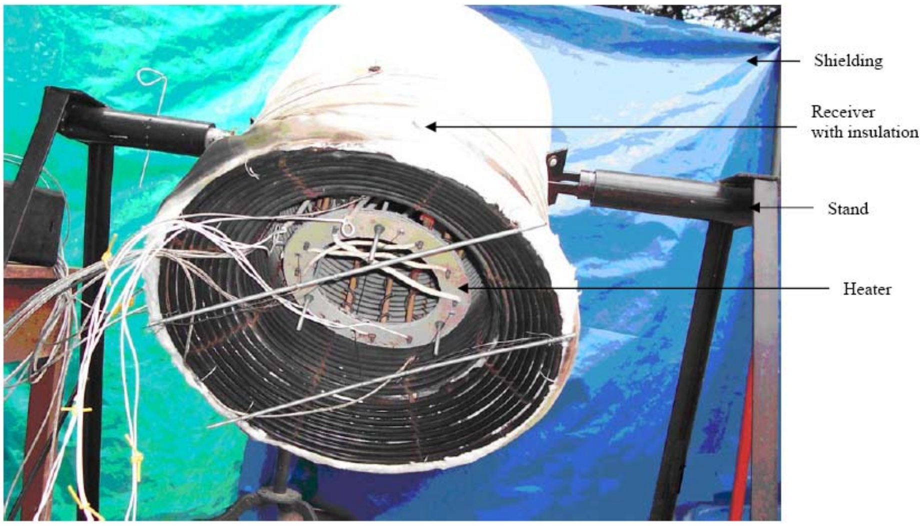

Fig. 5. The open mouth cylindrical cavity receiver with electrical heating unit.

Heating Unit

In a solar concentrator, concentrated radiation is focused inside the cavity receiver. This situation is simulated in the experiment by electrical heating unit designed to give heat fairly uniformly to the cavity receiver as shown in Figure 4. The cylindrical heating unit consists of two asbestos rings held 200 mm apart by three threaded mild steel tie rods of 6 mm diameter. Nichrome heating elements are arranged between two asbestos rings as shown in Figure 4. Heating elements are connected to the supply of 230V AC. Each nichrome heating element was supported by ceramic tube of 10 mm diameter and 200 mm length to avoid their sagging in hot condition. This cylindrical heating unit of maximum 3 kW capacity is placed at the center of the receiver as shown in Figure 5. Three heater wires of 1 kW each are used to obtain the heating capacity as 1 kW, 0.667 kW, 0.5 kW or 0.33 kW by arranging a number of them in series or in parallel circuit.

It is expected that the receiver tubes will be heated by radiation from the electrical heater coils, thus simulating the concentrated radiation. However, as the heater is placed within the receiver, the convective loss could be affected.

Thermocouples

Chromel-Alumel (K type) thermocouples are provided at 12 different positions in and out of the cavity receiver as shown in Figure 2 to study temperature distribution. Thermocouples T_1, T_2 and T_3 are used to measure temperature of the coil tube. Thermocouples T_4, T_5, T_6, T_{10} and T_{11} are used to measure temperature of the air inside the cavity. Thermocouples T_7 and T_8 measures the outside temperature of the coiled tube and T_9 measures temperature outside the insulation. The ambient temperature (T_{12}) is measured at a shaded region some distance away from the receiver in order to ensure that it is not affected by the set-up. All K-type thermocouples used are calibrated up to 100^{o}C. Above 100^{o}C, the behavioral graph of K-type [8] is assumed to be applicable.

Procedure

The receiver cavity is heated by heating coil, till steady state was reached. At steady state, as there is no energy withdrawn from the receiver, the electrical input energy is same as the thermal energy lost by the receiver. The testing of the receiver is done to measure the tube and air temperatures at different locations within the receiver at various power input values and inclination angles. Tests are carried out at 45^o and 90^o inclination for four power input levels of 0.33, 0.5, 0.667, 1 kW. Typically, the steady state is attained after about 3 to 6 hours depending upon inclination and input power. The test set-up is surrounded by an enclosure made of tarpaulin sheets. This is to ensure that the external air currents do not affect the experiments. Therefore the tests here are conducted in the shielded condition.

3. RESULTS AND DISCUSSIONS

The thermal analysis of the cavity receiver is studied on the basis of the losses within the receiver and the temperature variation inside the cavity.

Temperature Variations

The receiver is heated at power input of 0.33, 0.5, 0.667, and 1 kW for 90^o and 45^o inclination angle of the cavity axis. Tube temperatures and air temperatures at different points of the receiver are recorded in the experiment. Typical variations of air temperatures and tube temperatures are presented here. These experimental results are compared with those based on the simulation model [9]. In the simulation model, the receiver coil is divided into smaller elements and an energy balance of each element is carried out. The concentrated solar radiation is the input to the tube element and the heat is lost from the element by radiation, convection and conduction heat transfer.

i. 90^o Inclination of the Cavity Receiver

The variation of air and tube temperatures within the receiver with time for power inputs of 0.5 KW and 0.667 kW at 90^o inclination for cavity receiver is shown in Figures 6 and 7. Initially tube and air temperature inside the cavity increase rapidly. They slowly attain steady state after 2 to 4 hours of continuous heating. It can be noticed that the air temperatures T_6 and T_5 are the highest air temperature values and they are close to one another. This indicates that at this region the heat loss is low and a kind of stagnation is achieved. The presence of the heating coil also contributes to this. The values of T_4 and T_{10} being near to the mouth are close to each other and are lower than T_6 and T_5. T_{11} represents the lowest air temperature. The tube temperatures are close to one another throughout the test period, T_3 being the highest temperature while T_1 being the lowest. Due to small disturbances from the external wind, a highly stable temperature value is difficult to attain.

ii. 45^o Inclination of the Cavity Receiver

Figures 8 and 9 show variation of temperature with time for power input of 0.5 kW and 0.667 kW at 45^o inclination for shielded cavity receiver. During the tests, the air and tube temperatures rise rapidly and then stabilises after about 2 hours. The temperature values are more stable here unlike the 90° inclination tests. T_6 is the highest air temperature while T_{11} is the lowest air temperature. T_{10} is also at a higher temperature when compared to T_4 as thermocouple T_4 is vertically below the thermocouple T_{10} in the plane of the aperture. T_4 is observed to be constant and near the ambient temperature. The difference between the highest and the lowest tube temperatures are high when compared to the results at 90° inclination.

iii. Analysis of the Tube Temperatures at 90^o and 45^o Inclination Angle

The temperature of the tube at 90^o inclination of the cavity axis with horizontal is plotted against heating power of the coil representing losses (kW) from the cavity receiver. In Figure 10, the dotted lines representing T_1, T_2 and T_3 are experimental values of temperature at tube and the solid lines represent the results calculated from the simulation model. At 90^o inclination the cavity is in stagnant condition as per the simulation model. Hence T_1, T_2 and T_3 are nearly equal as per the calculations from the simulation model. The temperatures obtained from the simulation model matches with measured temperature values for lower values of heating power or losses but exceeds measured temperature at higher power. However, temperature increase with heat losses is observed in both the simulated and experimental results. The discrepancy between the values of temperatures is due to the disturbances produced by wind which may have caused some convective currents in the cavity during experiment. These disturbances are more dominant at high losses and higher temperatures. Hence the discrepancy is greater at higher loss values and higher temperatures. Temperature variations plotted against power of electrical heating for the cavity receiver at 45^o inclination with horizontal is shown in Figure 11.

It can be seen from Figure 11 that at low power input, temperature measured was above the calculated temperature and after 0.5 kW input, the calculated temperature from the simulation model exceeds the measured temperature. However they are comparable within about 10 to 30%. In this case, measured value of T_3 is less than T_2. This may be due to presence of heating coil. The electrical heaters of limited height are used in this experiment instead of concentrated solar radiation. This heater is closer to the tube points T_2 and T_3 when compared to T_1. Hence, temperature of T_2 and T_3 is higher than T_1. T_2 is more exposed to the heating coils hence its temperature is greater than even T_3 in the experiment. At 45^o inclination, convective flow is set-up due to buoyant forces and wind caused entry of the cold air in the cavity from lower portion and exit from the upper portion. Hence T_1 measured being near the mouth is expected to be lower than T_2 and T_3.

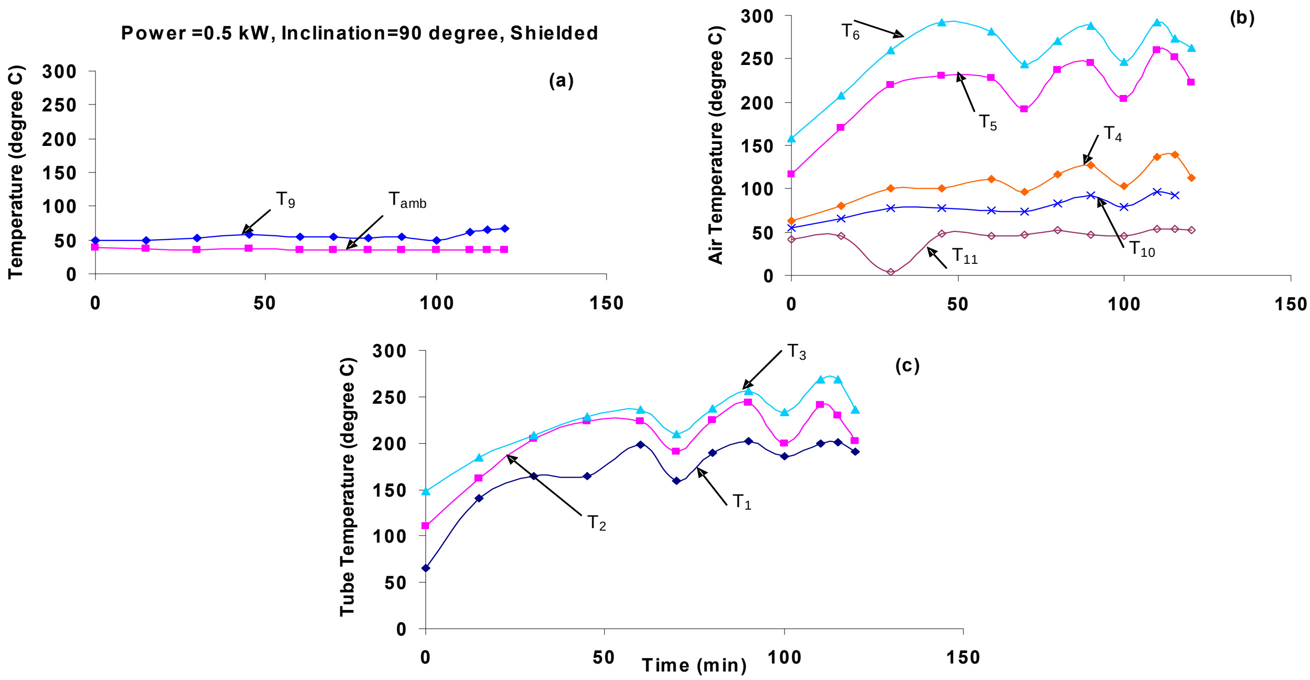

Fig. 6. Variation of measured temperature with time, (a) T_9 and T_{amb}, (b) air temperatures, and (c) tube temperatures.

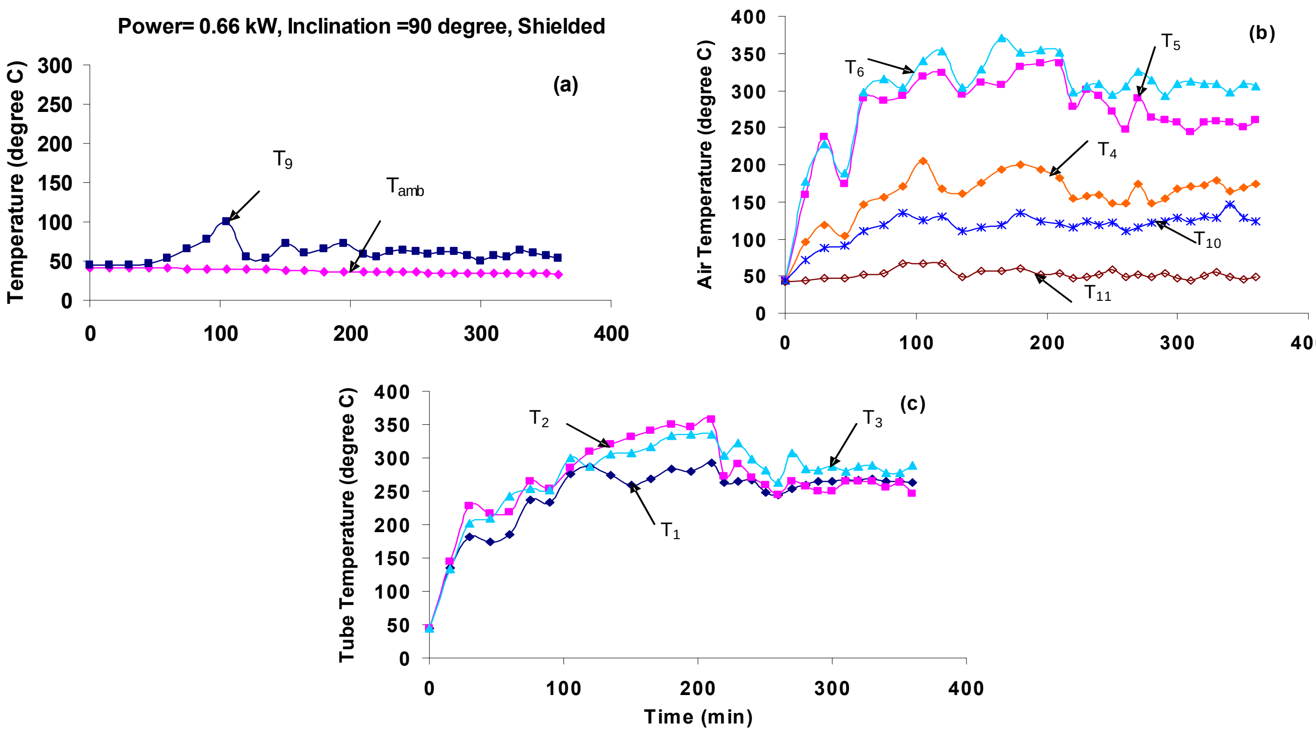

Fig. 7. Variation of measured temperature with time, (a) T_9 and T_{amb}, (b) air temperatures, and (c) tube temperatures.

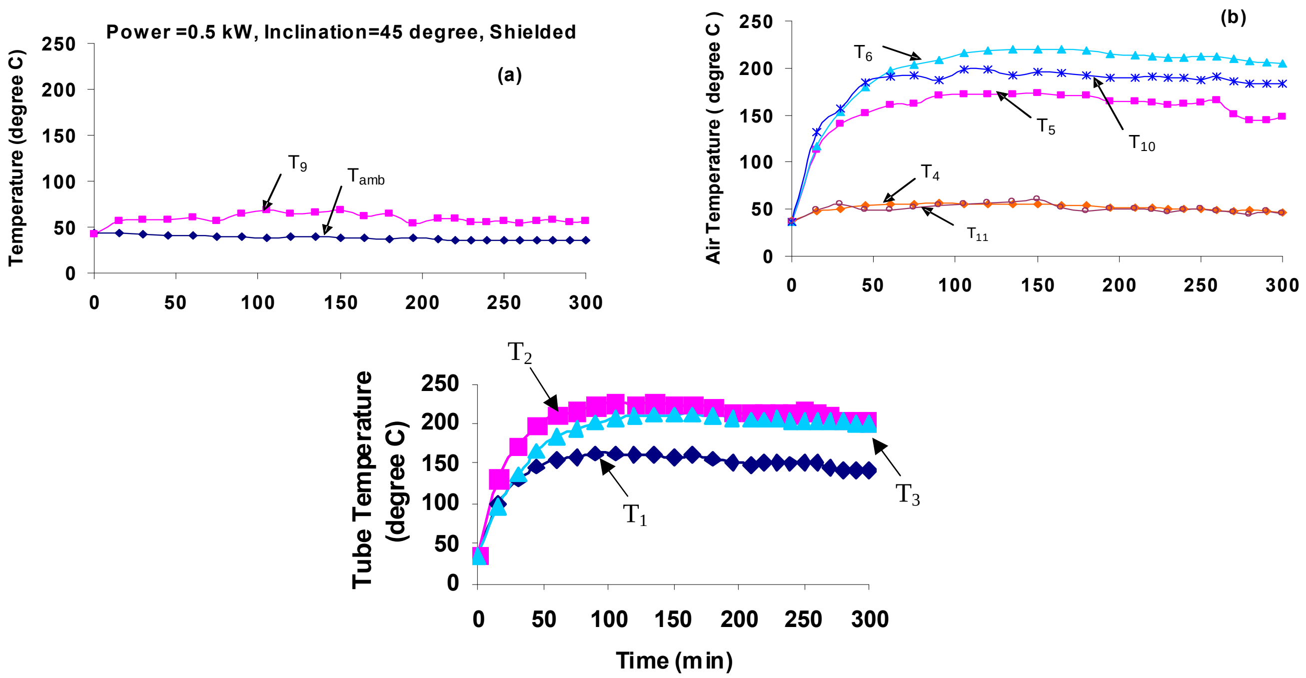

Fig. 8. Variation of measured temperature with time, (a) T_9 and $T_{amb,}$ (b) air temperatures, and (c) tube temperatures.

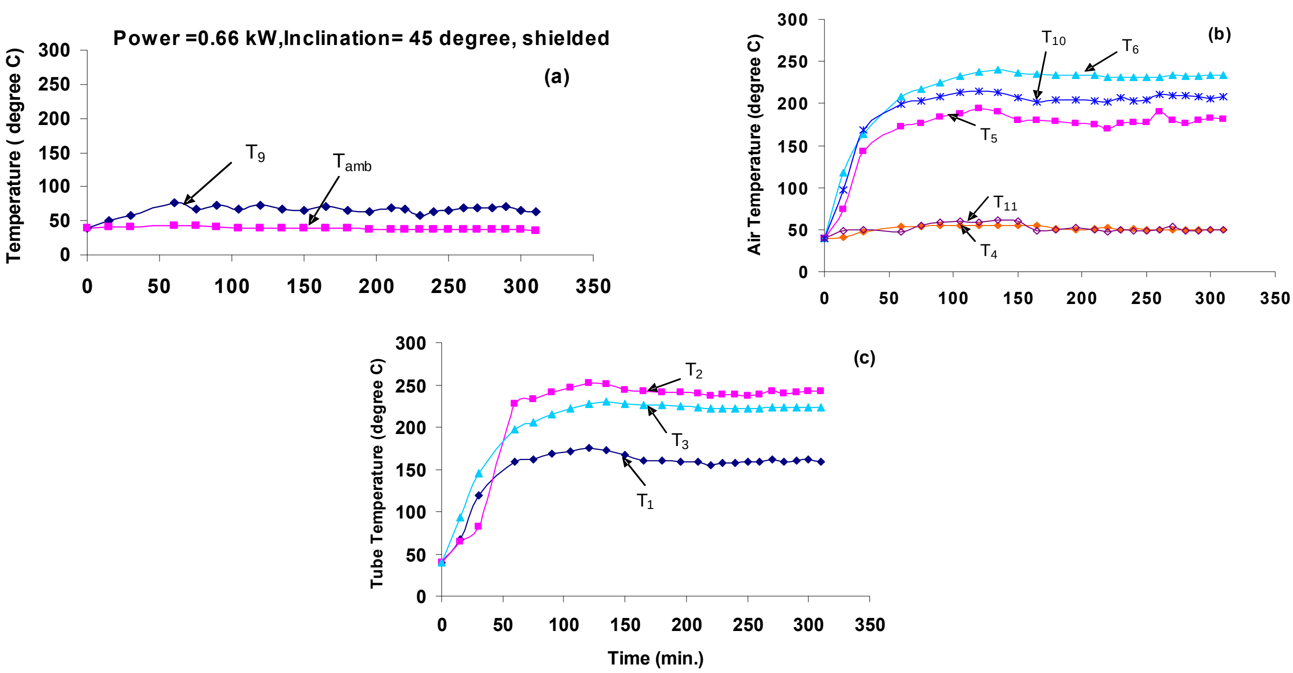

Fig. 9. Variation of measured temperature with time, a) T_9 and $T_{amb,}$ (b) air temperatures, and (c) tube temperatures.

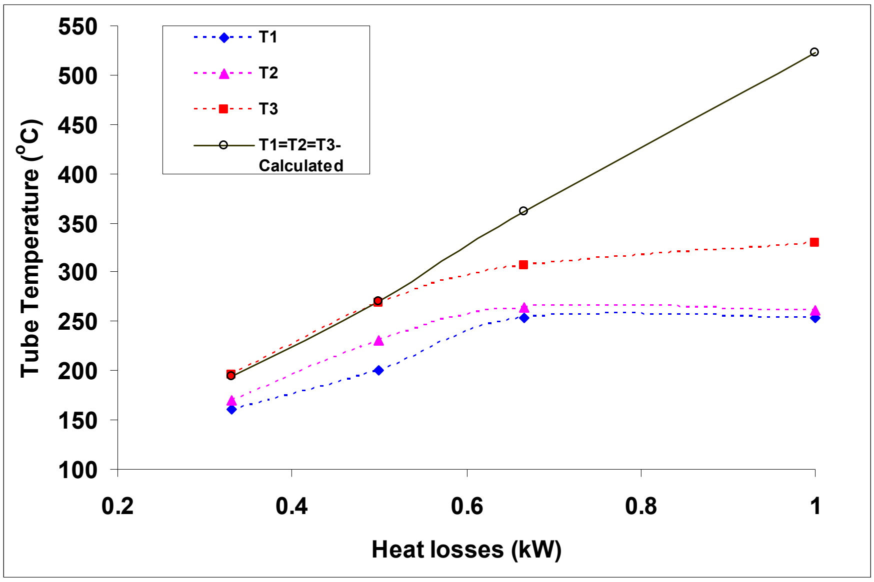

Fig. 10. Variation of measured and calculated tube temperature with heat losses at 90° inclination of the shielded cavity receiver.

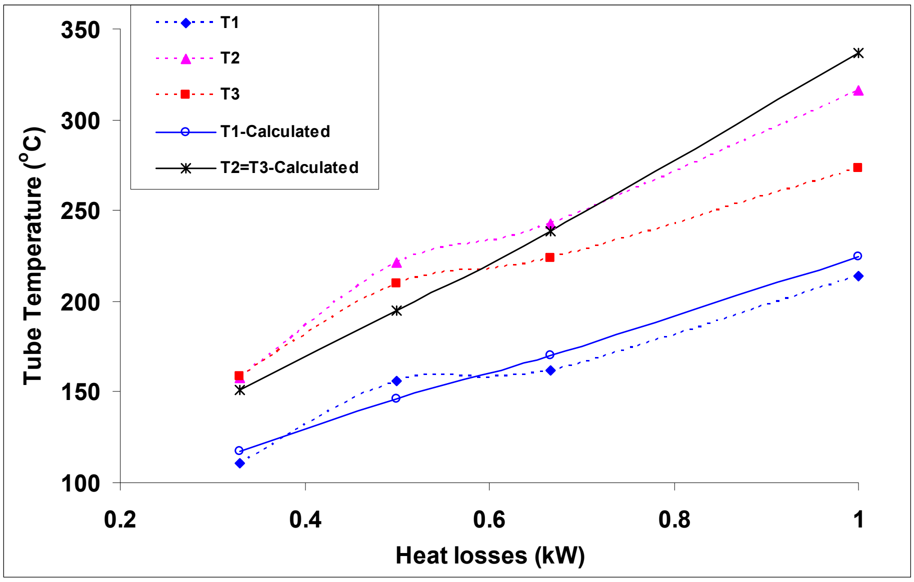

Fig. 11. Variation of measured and calculated tube temperature with heat losses at 45° inclination of the shielded cavity receiver.

iv. Air Temperatures Variation with Power Input

Figure 12 shows the variation of the air temperature with the power input at 90° inclination angle. The values of T_4 and T_{10} being near to the mouth are close to each other and are the lowest. The values of T_5 and T_6 are also close to each other but at higher temperature, temperature of air at aperture (T_4) increases continuously with heating power implying higher losses from the mouth region.

At 45° inclination, with varying power input it can be noticed that the air temperature increase with increase in power input. The value of T_4 is found to be near the ambient temperature value and the value of T_{10} is observed to be significantly higher than T_4 as shown in Figure 13. This suggests that the heat is flowing out of the cavity due to buoyancy effect, with ambient air entering near the T_4 location, getting heated and leaving the cavity near the T_{10} location. This trend is observed for all input power values.

Overall Heat Loss Coefficient Based on Aperture Area

Overall heat loss coefficient is function of operating and design parameters of the cavity receiver. Experimental heat loss coefficients are compared with those obtained theoretically using the simulation model. The heat loss coefficients are based on aperture area of the cavity receiver. The overall heat loss coefficient can be calculated using Equation 1.

$$U_{loss} = \frac{Q_{loss}}{A_{ap}\,\Delta T} \quad (1)$$

Where Q_{loss} is the total heat loss occurring from the receiver, A_{ap} is the aperture area and ΔT is the difference between the receiver temperature (T_{rec}) and ambient temperature (T_{amb}). T_{rec} is calculated as an average of T_1, T_2 and T_3. Figure 13 shows variation of experimental and calculated overall heat loss coefficient (U_{loss}) values with ΔT. At 90° inclination angle, calculated loss coefficient (U_{loss}) is observed to be constant at all power inputs. It is noticed from the experimental values at 90° inclination that the U_{loss} values increases slowly and later steeply with ΔT as shown in Figure 14. This is due to convection current set-up at high temperature. The simulated and experimental U_{loss} values at 90° inclination are found to match well for temperature differences upto 250°C. At higher temperature differences above 250°, the values vary greatly. At 45° inclination, the calculated and experimental overall heat loss coefficients are found to match well. The U_{loss} values from these experiments are found to be lower owing to the fact that the heater setup placed in the middle of the receiver enhances the stagnation zone and decreases the convective losses occurring from the receiver.

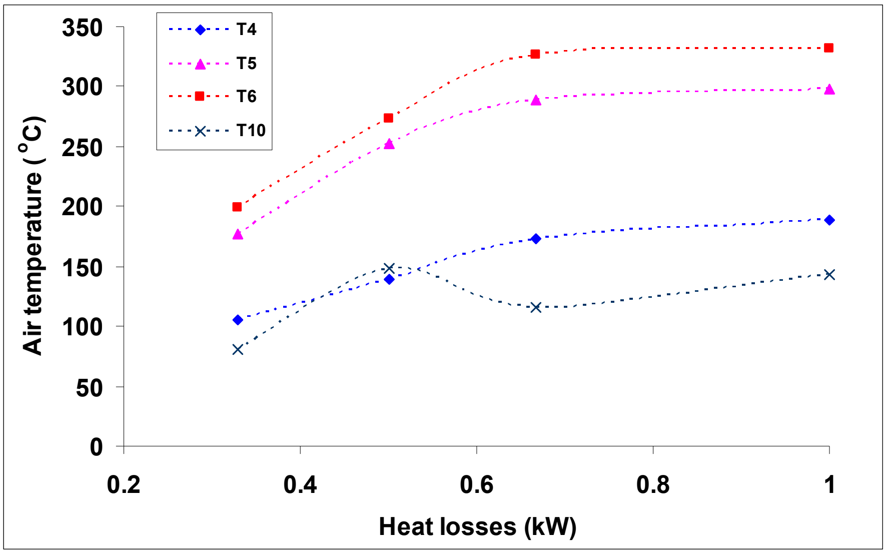

Fig. 12. Variation of experimental air temperature with heat losses at 90° inclination of the shielded cavity receiver.

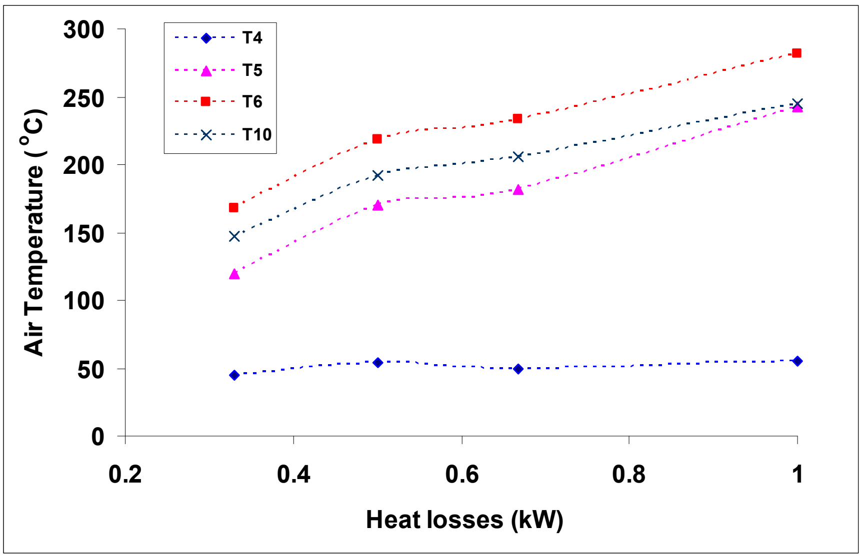

Fig. 13. Variation of experimental air temperature with heat losses at 45° inclination of the cavity receiver.

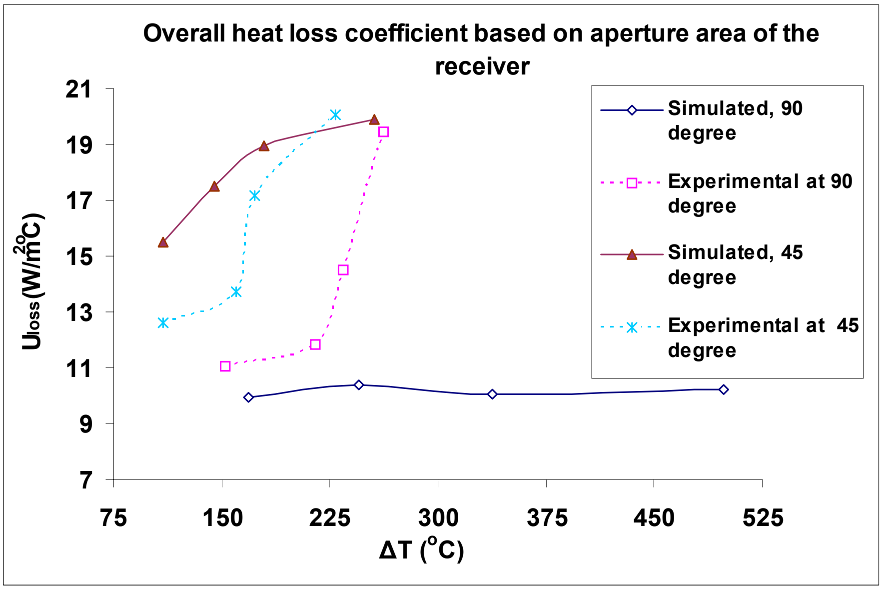

Fig. 14. Comparison of experimental and simulated overall heat loss coefficient.

4. CONCLUSIONS

The air and tube temperatures within the receiver are studied for power inputs of 0.33kW, 0.5kW, 0.66kW and 1kW. The following conclusions are derived from the experimental analysis:

1. The air and tube temperatures increase with input power and inclination. The highest tube and air temperature is observed at 90° inclination angle and power input of 1 kW.
2. At 45° inclination angle, tube temperature values obtained experimentally and from the simulation model matches well for all power inputs of heating coil unit. At 90° inclination, these temperatures matches well at 0.33 and 0.5 kW power of heating of coil. Tube temperatures estimated from the simulation model are higher than experimental tube temperatures at 0.667 and 1 kW.
3. The tube temperature measured at the innermost region of the cavity and at the aperture does not differ much for the 90° inclination. This is due to the fact that the stagnation zone covers majority of the cavity at the 90° inclination thus decreasing the convective losses.
4. The overall heat loss coefficients are obtained experimentally and estimated using the simulation model. The simulated and experimental values match well for the 45° inclination. At 90° inclination, the values match well up to 250°C and then they vary greatly as the temperature difference is increased.
5. The U_{loss} values from these experiments are found to be low due to the fact that the heater setup placed in the middle of the receiver decreases the convective losses occurring from the receiver. The U_{loss} is mainly based on the radiative and conductive losses.
6. The experimental methodology can also be adopted to evaluate the losses from a cavity receiver for a particular receiver mean temperature value.

NOMENCLATURE

A_{ap}	Aperture area (m^2)
D	Aperture diameter (m)
H	Length of cavity (m)
Q_{loss}	Total loss (W)
T_{amb}	Ambient temperature (°C)
T_1-T_{12}	Temperature readings (°C)
T_{rec}	Receiver mean temperature (°C)
U_{loss}	Overall heat loss coefficient (W/m^2-°C)
ΔT	Temperature difference (T_{rec}-T_{amb})
θ	Receiver inclination (degrees)

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