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EXPERIMENTAL INVESTIGATION OF HEAT LOSS FROM HEMISPHERICAL SOLAR CONCENTRATOR RECEIVER

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ABSTRACT

Convection heat loss inevitably occurs in receivers of high concentrating solar concentrators. All the concentrators are need to be tack during the operation and hence the position of the receiver is changing continually. The angle of the receiver axis will then play an important role in the heat loss. Few researches were reported for the hemispherical cavity receivers numerically. The paper presented here is an experimental investigation natural convection heat loss from hemispherical cavity receiver. Cavity receiver of diameter 540 mm was tested. It is observed that the heat loss was minimum for 90^o and maximum for 0^o

Keywords: *Total Heat Loss; Natural Convection; Conduction and Radiation; Convection Zone; Stagnant Zone*

1. INTRODUCTION

Sun is an excellent source of radiant energy, and is the world's most abundant source of energy. It emits electromagnetic radiation with an average irradiance of 1353 W/m^2 on the earth's surface. The solar radiation incident on the Earth's surface is comprised of two types of radiation - beam and diffuse, ranging in the wavelengths from the ultraviolet to the infrared (300 to 200 μm), which is characterized by an average solar surface temperature of approximately 6000 K (Sukhatme and Nayak, 2008). The amount of this solar energy that is intercepted is 5000 times greater than the sum of all other inputs - terrestrial nuclear, geothermal and gravitational energies, and lunar gravit ational energy. To put this into perspective, if the energy produced by 25 acres of the surface of the sun were harvested, there would be enough energy to supply the current energy demand of the world. Concentrating solar collectors are used to achieve high temperatures and accomplish this concentration of the solar radiation by reflecting or refracting the flux incident on the aperture area (reflective surface), A_a onto a smaller absorber (receiver) area, A_r. The receiver's surface area is smaller than that of the reflective surface capturing the energy, thus allowing for the same amount of radiation that would have been spread over a few square meters to be collected and concentrated over a much smaller area, allowing for higher temperatures to be obtained. These concentrating solar collectors have the advantage of higher concentration and are capable of much greater utilization of the solar intensity at off-noon hours than other types of solar concentrators. However, one of the major problems of using a 'dish-type' parabolic collector is that two-dimensional tracking is required. Most concentrating collectors can only concentrate the beam normal insolation (the parallel insolation coming directly from the sun), otherwise the focal region becomes scattered and off focus therefore requiring the concentrator to follow the sun throughout the day for efficient energy collection.

Convection contributes a significant fractional loss in all concentrator solar systems. Concentrators are specially used for heating application at high temperature. Receivers are provided at the focal point of the concentrator that absorbs the heat energy and part of this heat energy is loss. Its heat loss characteristics hence need to be understood so that it can be effectively minimized in order to improve system efficiency. Heat loss characterization of solar receiver can accurately determine with the field test. However, heat loss from the receiver surface is a design input for concentrator area decisions. If heat loss from the solar receiver can be predicted well in advance then the concentrator area and the receiver aperture area can be analyze close to the required thermal application. Also, for a field test requires complete setup of concentrator that involves a cost and time. Present study is to develop a method and apparatus that can simulate field condition of receiver in laboratory and data so generated can be easily correlated to the field situation.

Fig. 1 the main features of a typical tilted hemispherical cavity. The rate of heat transferred from the cavity to the surrounding is influenced by the following geometrical parameters: the tilt angle u, the opening ratio $\left(OR = \frac{Dap}{Dcav}\right)$ which is the ratio of the opening diameter to the cavity diameter, and the opening displacement ratio $\left(DR = \frac{d}{Dcav}\right)$ which is the ratio of the distance from the centerline of the aperture to the base of the cavity, to the diameter of the cavity. Investigations were made to identify the convective heat loss for receivers. Leibfried and Ortjohann (1995) reported a combined numerical and experimental study of natural convection in a side-facing open cavity. Significant variations in the local Nusselt numbers along the cavity surfaces were predicted,

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these variations being correlated to features of the flow field. Correlating equations for the experimentally determined surface-average and cavity-average Nusselt numbers were developed in terms of a Rayleigh number based on the height of the cavity, the Rayleigh number ranging between 3.5×10^6 and 1.2×10^9. The surface-average Nusselt number for the back wall was found to be in qualitative agreement with an existing empirical correlation for an isothermal vertical plate, but was over-predicted by the correlation. For the bottom plate, good quantitative agreement was obtained between the experimental results and an existing empirical correlation for an isothermal horizontal flat plate. Agreement between the data and the existing correlation was relatively poor for the top plate. The numerical predictions, which covered the Rayleigh number range from $10^3 to 10^7$, were in good agreement with experimental data for the back plate, under-predicted the data for the bottom plate, and over-predicted the top-plate data. Clausing (1981) established a correlation based on the understanding of the physics of the convection heat loss associated with a large central cubical cavity. Laminar steady-state natural convection in a two-dimensional rectangular open cavity was investigated numerically by Chan and Tien (1985). Isotherms and streamline plots are obtained in a shallow open cavity with aspect ratio of 0.143 for Rayleigh numbers up to 10^6 using constant properties, by imposing approximate boundary conditions at the opening. This method has been tested and compared to cases where computations are carried out into an enlarged external domain. Results show that outgoing flow patterns and the heat transfer results are governed by strong characteristics of the heated cavity. These findings compare favorably with experimental results for Ra = 10^6. Five cavity geometries Cylindrical, Hetro-conical, Spherical, Elliptical and Conical was investigated Harrist and Terry (1985). Results indicated that Variations in concentrator rim angle and cavity geometry cause large variations in the power profiles produced inside the cavity; thus, a desired power profile may be achieved without significantly reducing thermal efficiency. Natural convection in a hemispherical enclosure heated from below was investigated by (Yasuaki *et al.*, 1994), and an experimental correlation was obtained. (Khubeiz *et al.*, 2002) carried out an experimental analysis of laminar free convection heat transfer from an isothermal hemispherical cavity. Two distinct receivers: semi-cavity and modified cavity were introduced for solar dish collector system Kaushika (1993). The modified cavity receiver (hemisphere with aperture plate) was found to be more efficient than the semi-cavity. The thermal performance characteristics and optimizations of cavity receiver of a low cost solar parabolic dish were presented, and it is concluded that the conventional cavity receivers are inadequate for fuzzy focal dish concentrator Kaushika and Reddy (2000). The modified cavity receiver is so designed to capture maximum reflected solar radiation at focal region of fuzzy focal dish concentrators with minimum heat loss. A comparative study was performed to predict the natural convection heat loss from the cavity, semi-cavity and modified cavity receivers. Among the three receivers, the modified cavity receiver was found to be the preferred receiver for a fuzzy focal solar dish collector system Sendhil-Kumar and Reddy (2008). Sendhil-Kumar and Reddy (2007) used a two dimensional model to investigate the approximate estimation of the natural convection heat loss from an actual geometry of the modified cavity receiver of a fuzzy focal solar dish concentrator. The total heat loss from the receiver has been estimated for both the configurations with insulation (WI) and without insulation (WOI) at the protecting aperture plane of the receiver. Also, they presented a numerical study of combined laminar natural convection and surface radiation heat transfer in a modified cavity receiver of solar parabolic dish collector. The influence of operating temperature, emissivity of the surface, orientation and the geometry on the total heat loss from the receiver has been investigated. Additionally, a numerical analysis of solar dish modified cavity receiver with cone, compound parabolic concentrator

The aim of the project is develop an experimental set up that will be used to simulate the receiver heat loss in the laboratory and to calculate the heat loss from hemispherical receiver in Natural convection mode Based on this aim following objectives are derived

- To develop hemispherical receiver and an experimental setup for determination of heat loss from solar concentrator hemispherical receiver.

- To measure the conduction and radiation heat loss from the receiver and separate it out from the total loss to calculate convection loss

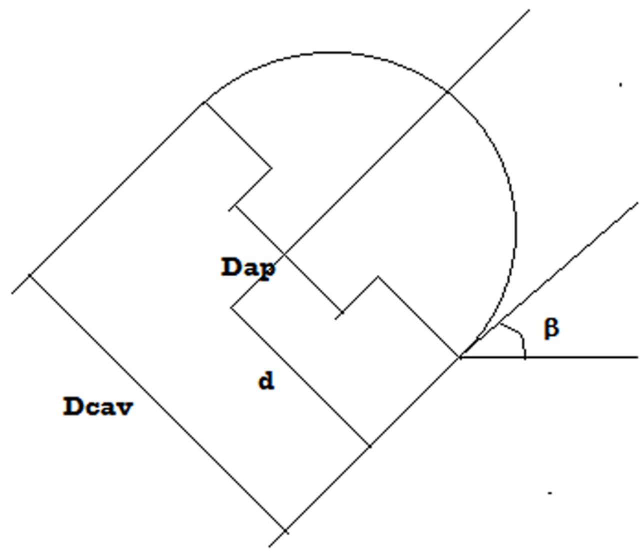

Fig. 1 Hemispherical Receiver

2. EXPERIMENTAL SETUP AND METHODOLOGY

Solar thermal applications with solar concentrators use receivers at focus of the concentrators. These receivers receive concentrated heat from the solar concentrators. Heat flux falling on to these receivers is partly absorbed and rest is lost by way of different thermal losses. To receive solar radiation at least one face of the solar receivers is to be kept exposed, other part of the receivers can be shielded with good insulation. This exposed face of the solar receiver looses heat primarily due to convective currents of the outside air. To understand the performance of the solar thermal system it is utmost important to understand that correct estimation of losses from the receiver are made. If the losses can be accurately measured then it is possible to establish performance or efficiency of the receiver at different operating conditions.

2.1. Experimental Setup

Fig.2 illustrates the test set up for heat loss measurements from the hemispherical receiver. Hemispherical receiver is provided on the stand as shown in figure. The receiver can be adjusted to the various angle with fulcrum arrangement provided with the stand. The details of the receiver are discussed in section 2.2. Water tank of a capacity 16 lit is manufacture. It is provided with an electrical heater of capacity 2 kW. Water from the tank is allowed to flow towards receiver naturally and constant head is maintained in the tank with float arrangement. Flow rate can be varied with the typical valve arrangement and measure as a time required to flow 1 lit of water. The temperature of water is controlled with temperature controller that controls the electrical heater. Once the temperature is reached to the set point controller puts off the heater. Temperature indicator and K-type thermocouple measures the temperature of water at inlet and exit.

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Fig. 2 Photograph of Experimental Setup

2.2. Receiver the Absorber

The receiver used in the current investigation is shown in Fig.3. It is a hemisphere with copper tube in its cavity. Overall dimensions of the receivers are 540 mm diameter and aperture of 270 mm dia. and height 0.5 m. No wind skirt arrangements are made. There are 19 turns along the circumference of the receiver. The copper tube has a diameter of 0.010 m (ID), the spacing between the coil turns is of the order of 2 - 3 mm. The coils are not coated and are bare surfaces. A layer of glass wool (35 mm thick) is provided on the outer side of the tube coils. It is supported by an aluminium foil.

Fig. 3 Photograph of Hemispherical Receiver

2.3. Experimental Methodology

Heat loss from the concentrator receiver can be determined on-flux or off-flux. On-flux is the mode where testing is carried at actual conditions and in off-flux mode it is determined experimentally. The schematic of the experimental set-up is shown in Fig.2. It consists of a downward facing hemispherical cavity receiver supported on a stand. The receiver can be inclined to various angles with respect to the horizontal in steps of 22.5. The hot water circulated in the receiver is supplied from a water tank of 40 lit capacity having one heaters (total wattage of 2 kW). The working fluid is circulated through the receiver tubes using a 0.18 kW pump. A liter flask measures the mass flow rate of hot water entering the receiver. The hot water is circulated at constant inlet temperature through the receiver. The temperatures of the fluid in the tube at four locations (including the outlet) are measured using K-type thermocouple. The system is operated under closed loop condition as the water exiting from the receiver flows back to the storage tank. Details of the instrumentation is as given below

1. *Digital Temperature Indicator (12 Channel)* Make - Eutech Systems; Sr. No - 123339; Model - DTI-112; Range - 0 to 600^oC; Resolution - 0.1^oC ;Calibrated on - 19 March 2012; Certificate No - LN/0312/783; Calibrations Standard - Universal Calibrator - ES/P/25; Certified by ERTL; Report No - 2011S&C756; Valid till 03/08/2012

2. *Digital Temperature Controller* Make - I-Therm; Sr. No - 2035237; Model - AI-5941; Range - 0 to 600^C; Resolution - 0.1^oC ; Calibrated on - 19 March 2012; Certificate No - LN/0312/771; Calibrations Standard - Universal Calibrator - ES/P/25; Certified by ERTL; Report No - 2011S&C756; Valid till 03/08/2012.

3. *Thermocouple - K SIMPLEX* Make - Eutech Systems; Sr. No - 111223416 to 111223425; Model - DTI-112; Range - 0 to 600^oC ; Output - mVDC; Calibrated on - 19 March 2012; Certificate No - LN/0312/783; Calibrations Standard - Universal Calibrator - ES/P/25; Certified by ERTL; Report No - 2011S&C756; Valid till 03/08/2012 & ; Thermocouple EPS/P/24, Certified by ARAI (I); Report No - ARAI/CAL/1107/899; Valid till 02/08/2012

The working fluid used for heat loss measurement was hot water and experiments with different inlet temperatures between 50^oC to 75^oC have been carried out. Hot water enters from the top of the receiver and leaves the receiver from the bottom This ensure temperature is high at top and low near the aperture. This is similar to the situation in the field operations. The flow rate of water is kept constant at 0.013 kg/s. For steady state operation experiment is continued till the outlet temperature remains steady for about half an hour. It takes a time of about 2 h. Heat loss is then measured.

3. TEST RESULTS AND DISCUSSION

Heat loss from the receiver at any angle β is calculated from the equation

$$Q_{total} = \dot{m}c_p(T_o - T_i) \tag{1}$$

Fig.4 represents Total heat loss Q_{total} with the temperature difference $(T_m - T_a)$. Where T_m is average temperature of $T_i \& T_o$. The total heat loss increases as the temperature difference increases while the loss decreases with increase in receiver angle as represented in Fig.5. Heat loss is maximum for 0 degree inclination and minimum for 90 degree inclination

3.1. Natural Convection Heat Loss

Natural convection loss at different angle are calculated by subtracting conduction and radiation losses at different angle from total heat loss Q_{total} Prakash M. (2009). Radiative loss is calculated theoretically from the equation

$$Q_{radiative} = \sigma.\epsilon.A.F.(T_m^4 - T_a^4) \tag{2}$$

For calculation of conductive losses aperture of the receiver is closed by wooden block insulated with glass wool. Every time the hot water is circulated in the temperature range of 50^oC to 75^oC For all fluid inlet

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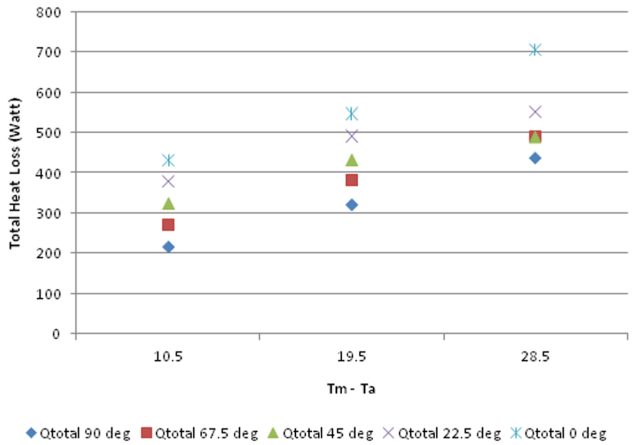

Fig. 4 Total Heat Loss with Temperature Difference $(T_m - T_a)$

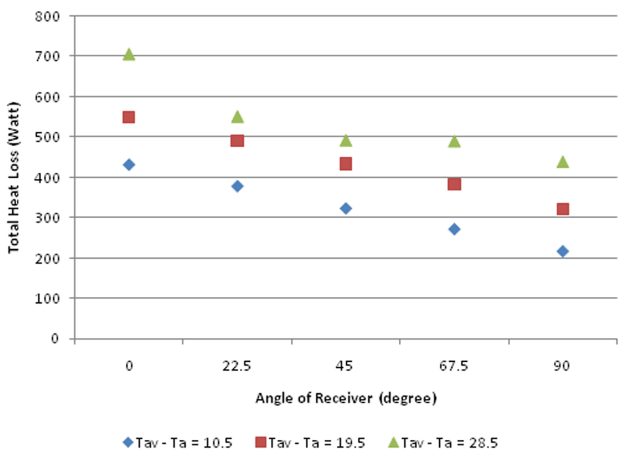

Fig. 5 Total Heat Loss with Receiver Angle(β)

conditions corresponding to five different angle of tilt of the receiver, the conductive and radiative losses are obtained. The convective loss for any inclination is obtained by subtracting the conductive and radiative losses from the total loss with the equation

$$Q_{convection} = Q_{total} - Q_{conduction} - Q_{radiation} \tag{3}$$

Fig.6 shows the variation of convective loss with (Tm-Ta) and Fig.7 shows convection heat loss with receiver angle. It is observed that as the temperature difference increases, the convective loss increases and has a linear trend. The convective loss increases with decrease in inclination. Heat loss by natural convection and total heat loss has the similar trend. At 90 degree inclination most os the receiver is in a stagnation zone and convective zone is only at aperture surface. Hence at 90 degree inclination convective heat loss is very small. As the angle of the receiver decreases convective zone is becoming significant and hence the heat loss increases. At 0 degree inclination natural convection heat loss is dominant while at 90 degree inclination conductive and radiative heat loss is dominant.

3.2. Uncertainty

Uncertainty of the measurement was carried by considering the variables and their absolute uncertainty. Experimental uncertainty is observed to be 2.18%

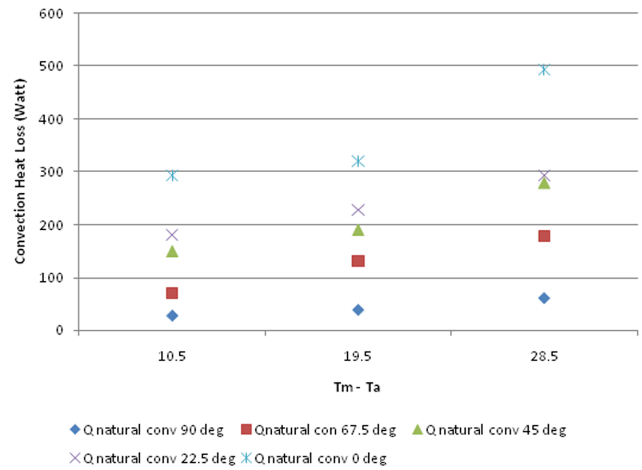

Fig. 6 Total Heat Loss with Temperature Difference $(T_m - T_a)$

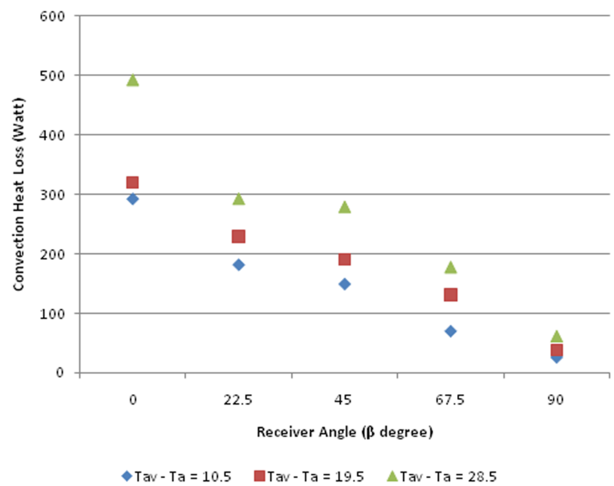

Fig. 7 Total Heat Loss with Receiver Angle(β)

4. CONCLUSIONS

Experimental heat loss from hemispherical receiver was determine. The aim of the project was to develop the setup that may be used to identify the total heat loss and convective heat loss from the receiver. Heat loss was observed to be minimum at 90 degree angle where as minimum for 0 degree angle. How ever it is the fact that the receiver in actual practice will not attend an angle of 0 degree. Concentrators are needed to be track where receiver can have maximum inclination of about 23.5 degree. Hence the use of hemispherical receiver may results in to minimum heat loss than that of cylindrical cavity receiver. However further studies are required for wind flow considerations and methodology to establish comparison of the receivers.

NOMENCLATURE

$\dot{m}$	mass flow rate (kg/sec)
c_p	specific heat (J/kg · K)
Q_{total}	total heat loss(W)
$Q_{conduction}$	conduction heat loss(W)
$Q_{convection}$	convection heat loss(W)
$Q_{radiation}$	radiation heat loss(W)
T	temperature (K)
D_ap	diameter of aperture(m)

D_cav diameter of cavity (m)
d distance from the center of the opening to the base (m)
DR opening displacement ratio of cavity (m)
β tilt angle of receiver (degree)
ε total emissivity
ρ density (kg/m^3)
σ Stefan-Boltzmann constant (W/m^{2}K^4)

Subscripts
i inlet condition
o exit condition
m mean average of the condition
a ambient condition

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