An Experimental Study of Natural Convection Heat Loss from a Solar Concentrator Cavity Receiver at Varying Orientation.

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Abstract

Convection losses are an important determining factor in the performance of solar thermal power systems with cavity receivers such as those used in paraboloidal dishes. An experimental investigation based on an isothermal electrically heated model receiver, is in progress. The convection loss of the model receiver has been measured at inclinations varying from 0^o (cavity aligned horizontally) to 90^o(cavity facing straight down). The results show that the maximum convection loss occurs at 0^o and is a minimum at 90^o. Numerical analysis of the problem shows good agreement while most previous empirical correlations over predict the losses.

1 INTRODUCTION

In solar thermal systems, heat loss can significantly reduce the efficiency and consequently the cost effectiveness of the system. It is therefore vital to fully understand the nature of these heat loss mechanisms. With paraboloidal dish cavity receivers, conduction and radiation can readily be determined analytically, however the complexity of the temperature and velocity fields, in and around the cavity makes it considerably harder to determine the convection loss.

The Australian National University (ANU) has been involved with the investigation of solar thermal energy conversion using paraboloidal dish concentrators for many years. Currently the team is working with a 400 m^2 concentrator fitted with a monotube boiler cavity receiver for superheated steam production and a 20 m^2 concentrator that operates a cavity receiver lined with reactor tubes for ammonia dissociation for energy storage (Johnston *et al*, 2001 and Lovegrove *et al*, 2001).

To better understand the thermal losses from such receivers, a small electrically heated, laboratory simulation of a solar cavity receiver has been constructed to measure losses directly. The results from this system have then been used in comparison with the predictions obtained from Computational Fluid Dynamics (CFD) calculations, which are described in a parallel paper also presented in these proceedings (Paitoonsurikarn *et al*, 2002).

1.1 Previous investigations

There have been several previous investigations of convection losses from cavity receivers. An analytical model of large cubical central receivers was proposed by Clausing (1981), based on the local convective heat transfer coefficients inside the cavity, determined from standard semi-empirical correlations and the energy transferred by the air through the aperture due to buoyancy and wind effects. This model was later refined and verified by the same author, Clausing (1983) with experimental results from a 2.7m square aperture receiver and good agreement found.

Empirical correlations proposed by Koenig and Marvin (1981) cited in Harris *et al* (1985) and Stine and McDonald (1989) cited in Leibfried *et al* (1995), includes parameters such as inclination angle and aperture size in their models.

Leibfried *et al* (1995) carried out experimental studies on both upward and downward facing receivers. This study used electrically heated spherical and hemispherical receivers with a diameter of 400mm. The aperture for these receivers ranged from 60 to 195mm in diameter and was adjusted by adding insulated disks of different inner diameters. Correlations developed from this study were a modification of Clausing's (1981) and Stine and McDonald's (1989) models.

With all these studies the range of applicability beyond the receiver geometry directly examined remains unclear and therefore caution should be used when using them for different geometries and operating conditions.

2 LABORATORY MEASUREMENT OF CONVECTION LOSSES

2.1 Experimental apparatus:

An electrically heated experimental simulation of a cavity receiver has been constructed to allow direct measurement of losses under laboratory conditions. The details of the model receiver are shown in Fig. 1 and the arrangement in the laboratory in Fig. 2. The model receiver consists of a mild steel tube cavity with a "Pyrotenax" mineral insulated electrical heater cable wound around it as a source of heat input. The cavity interior surface has been painted with high temperature resistant black "Pyromark" 2500 paint. The steel tube is mounted in a framework of Calcium Silicate insulation board. A sheet metal casing covers the entire structure and all internal spaces are filled with "Kaowool" ceramic insulation material.
The model receiver is attached to the end of a support frame on a trolley by a hinged angle adjustment mechanism to enable testing at different angles. There are 7 K- type thermocouples that measure the cavity surface temperature, 8 on the exterior surface of the model, plus a further 8 measuring various temperatures within the model. These thermocouples are logged with a Datataker 600. The temperature of the cavity is controlled by a self-tuned Eurotherm 808 PID temperature controller that regulates the power level to the heating coil. A host computer, not shown in Fig. 2, acquires both the data from the Eurotherm 808 PID temperature controller and the Datataker 600.

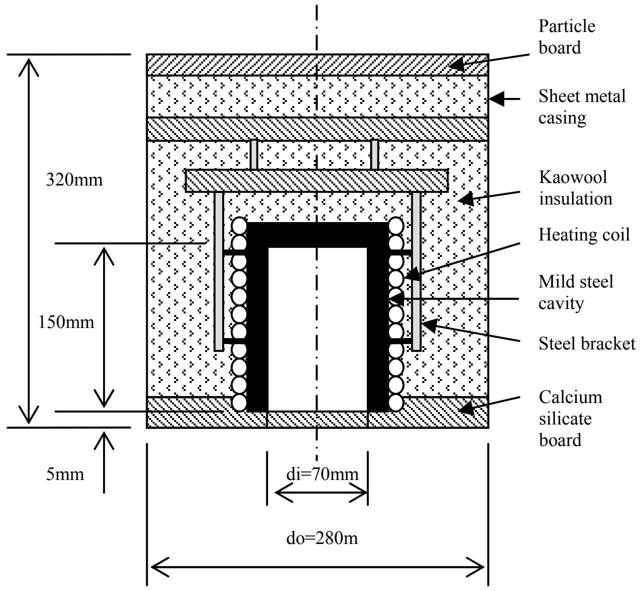

Fig. 1 Cross section sketch of model receiver.

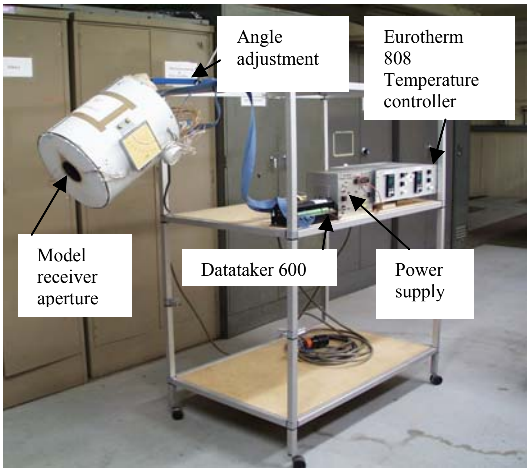

Fig. 2 Experimental setup.

During operation, a time interval of approximately one hour is required for the system to reach steady state. Temperatures are logged at 30 second intervals while the power level is logged every second for a period of 30 minutes, to provide the data for a reliable steady state data point. A "Fluke 83" multimeter is used to measure the supply voltage V, and heater resistance R, and in conjunction with the regulated power level p_L, the total heat loss rate q_t from the receiver can be calculated by Eq. (1).

$$q_t = p_L \frac{V^2}{R} \qquad (1)$$

2.2 Determination of the energy balance

The experimental arrangement provides a direct measurement of overall thermal losses from the cavity. The energy balance of the model receiver is shown in Fig. 3, where convection loss, q_{conv} and radiation loss, q_{rad} are modes of heat loss through the aperture, while conduction loss, q_{cond} is through the walls of the receiver.

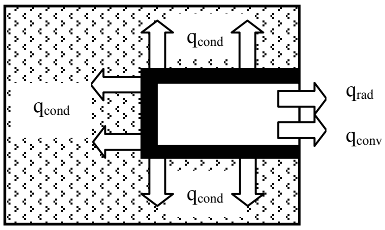

Fig. 3: Energy balance of model receiver.

Since it is convection loss that is of interest, conduction and radiation contributions need to be accounted for in Eq. (2).

$$q_{conv} = q_t - q_{cond} - q_{rad} \tag{2}$$

2.2.1 Conduction loss measurement

To determine the conduction heat loss, measurements of loss were made with the cavity at 90^0 and with an insulated plug in the aperture. The internal and external temperatures of the plug were measured and used to determine the plug conduction loss. It is assumed that conduction is the same for all inclination angles, with the thermal resistance associated with the boundary layer on the outside of the casing being considered negligible.

Finite element analysis of the conduction problem using STRAND 7 release 1.03 has also been carried out. The construction of the mesh for the conduction model comprises of three dimensional brick elements, where experimentally measured temperatures were used as boundary conditions. Agreement to within 10% was found and the difference attributed to the uncertainty in the actual effective conductivity of the insulation material.

2.2.2 Radiation loss calculation

Radiation loss has been determined analytically with the network method described by Holman (1997) where the surface is assumed to be grey and radiation is diffuse. The cavity is divided into 5 sections as shown in Fig. 4 and experimentally measured temperatures for each section are used to determine the net radiation from each section.

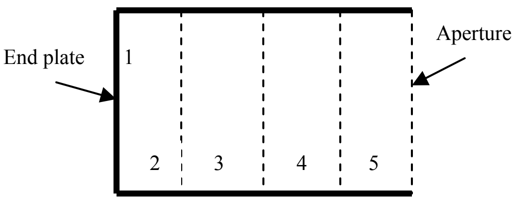

Fig. 4 Cavity division for radiation calculation.

A radiation energy balance is carried out for the i^{th} section with Eq. (3), where J_i is the radiosity, F_{ij} is the fraction of radiant energy leaving surface i and reaching surface j, ε_i is the surface emissivity and E_{bi} is the black body emissive power.

$$J_i = \frac{1}{1 - F_{ii}(1-\varepsilon_i)} \left((1-\varepsilon_i) \sum_{j \neq i} F_{ij} J_j + \varepsilon_i E_{b_i} \right) \tag{3}$$

Having set up an equation for each surface, a set of 5 equations is then solved simultaneously to calculate the radiosities. Eq. (4) is then used to determine the radiation transfer rate for each i^{th} surface having area A_i. The radiation loss through the aperture is then obtained from the sum of individual radiation losses.

$$q_i = \frac{\varepsilon_i A_i}{1-\varepsilon_i} \left(E_{b_i} - J_i \right) \tag{4}$$

An emissivity of 0.93 was used for the "Pyromark" painted cavity surface. With the high emissivity of the paint, the uncertainty in the effective emissivity at the aperture is negligible. Therefore the uncertainty in the radiation loss calculation is mainly due to the error from the experimental temperature measurements.

3 RESULTS AND DISCUSSIONS

3.1 *Experimental Results*

Fig. 5 presents the results of heat loss measurements using the model receiver operating at a set point temperature of 450°C, where the average experimental temperature values for the cylindrical section is 445°C and the end plate section is 408°C. Conduction losses were measured to be constant at 66.4 ± 6.0 W and radiation losses calculated at 57.9 ± 1.3W. The maximum convection loss occurs at 0° when it represents 45.5% of the total heat loss. With increasing inclination the convection loss reduces to a minimum at 90° representing 4.2% of the total heat loss. This trend is to be expected since as the inclination increases, more high temperature buoyant air remains stagnant within the cavity.

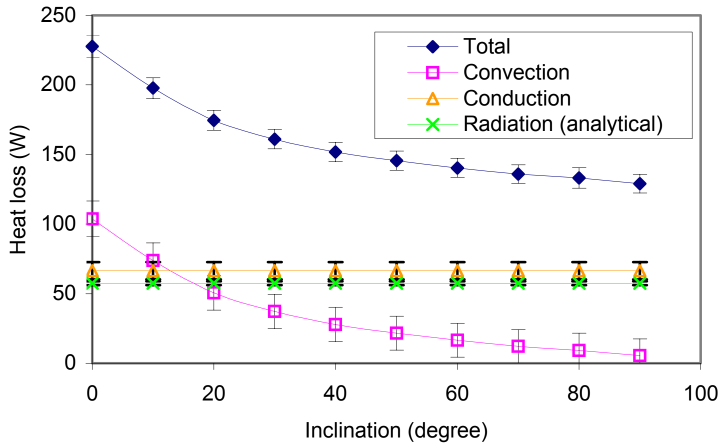

Fig. 5 Experimental heat loss for a cavity temperature of 450°C.

Convection loss for three cavity temperatures is compared in Fig. 6. They all show a similar dependence on inclination as that described for the convection loss in Fig. 5. It is also evident that the losses increase with higher cavity temperatures throughout all inclinations, as expected.

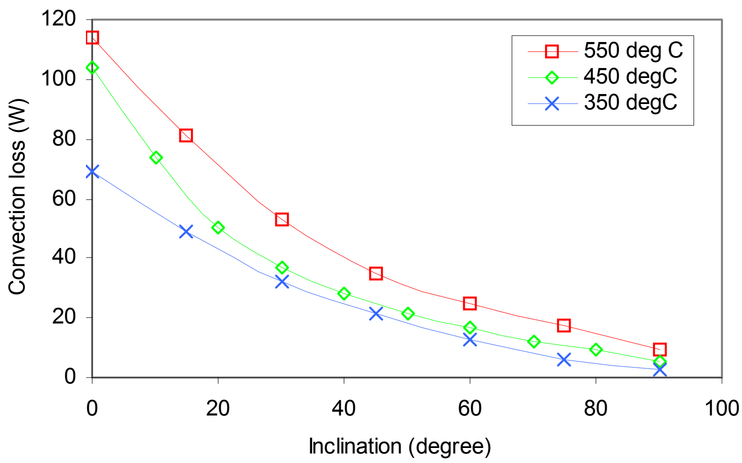

Fig. 6 Convection loss at various cavity temperatures

3.2 Comparison between experimental results and other correlations.

The experimentally measured convective heat loss from the model receiver at a cavity temperature of 450^0C is plotted in Fig. 10 together with the results from the CFD calculations of Paitoonsurikan *et al* (2002) and the values calculated from correlations presented by the various authors discussed in section 1.1.

The CFD calculations show good agreement at 0^0 and 90^0 with the experimental results while it slightly over predicts at intermediate angles.

The Clausing (1981) correlation shows the best agreement with the experimental results despite its derivation for large central receivers. The Modified Clausing and Modified Stine and McDonald correlations proposed by Leibfried *et al* (1995) are of similar magnitude and slightly over predict the experimental results. There is a further over prediction of the experimental results by the Koenig and Marvin (1981) and Stine and McDonald (1989) correlations, which may be due to the larger scale receivers that their studies were based on.

All the correlations show a similar tendency of decreasing natural convection loss with increasing inclination until there is no natural convection loss at 90^0. This is physically unrealistic and it is worth noting that with the experimental and CFD results that this is not the case.

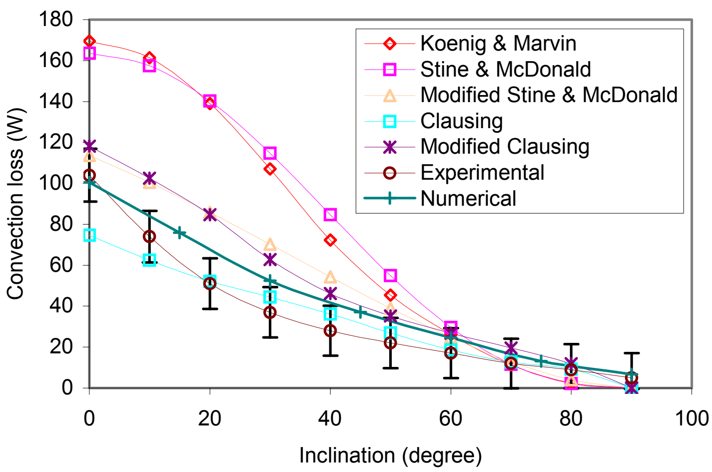

Fig. 6 Comparison of experimental convection loss at a cavity temperature of 450^0C with other correlations.

4 CONCLUSION

With a small-scale experimental receiver, it has been proven that a simple experiment can be built to quantify the convection losses from a cavity receiver. The experimental system has proven to be reliable and convection losses have been determined with good accuracy. Experiments with a larger size cavity need to be carried out in order to verify the CFD calculations for full size cavity receivers.

The numerical results obtained are qualitatively in good agreement with those predicted by various previously proposed correlations. The Clausing (1981) correlation shows the closest prediction to both numerical and experimental results despite its original use for bigger-scale central receivers. The discrepancy of convective heat loss at an orientation of 90^0 between the present results and the predictions of correlations taken from the literature requires further investigation.

5 REFERENCES

Clausing A.M. (1981). *An Analysis of Convective Losses From Cavity Solar Central Receiver*, Sol. Energy 27, 295-300.

Clausing A.M. (1983). *Convection Losses From Cavity Solar Receivers-Comparisons Between Analytical Predictions and Experimental Results,* Journal of Solar Energy Engineering 105, 29-33.

Johnston G., Burgess G., Lovegrove K., and Luzzi A. (2001), *Economic Mass Producible Mirror Panels for Solar Concentrators*, Proceedings of ISES World Congress, Adelaide, Australia.

Harris J.A. and Lenz T.G. (1985). *Thermal performance of concentrator/cavity receiver systems,* Solar energy 34, 135-142.

Holman J.P. (1997) *Heat transfer*, 8th edition, New York: McGraw-Hill Companies.

Koenig A.A. and Marvin M. (1981). *Convection heat loss sensitivity in open cavity solar receivers*, Final report, DOE contract No. EG77-C-04-3985.

Leibfried U. and Ortjohann J. (1995), *Convective Heat Loss from Upward and Downward-Facing Cavity Solar Receivers: Measurements and Calculations*, J. Sol. Eng. 117, 75-84.

Lovegrove K., Luzzi A., Soldiani I., and Kreetz H. (2001), *Developing Ammonia Based Thermochemical Energy Storage for Dish Power Plants – Smelly Experiments, Good Technology*, Proceedings of ISES World Congress, Adelaide, Australia.

Paitoonsurikarn S. and Lovegrove K. (2002). *Numerical Investigation of Natural Convection Loss in Cavity Type Solar Receivers*. In Proceedings of Solar 2000 - Australian and New Zealand Solar Energy Society, Newcastle, Australia.

Stine W.B. and McDonald C.G. (1989), *Cavity Receiver Heat Loss Measurements,* presented at ISES World Congress, Kobe, Japan.