AN EXPERIMENTAL & NUMERICAL INVESTIGATION OF HEAT LOSSES FROM SPHERICAL CAVITY SOLAR RECEIVER

C.Sreerag[1], P.Sachin[1], K.C.Shyamraj[1], P.Aswin[1], K.Akhil[1], P.C.Saishyam[1], B.C.Anilkumar[2]

1. Students, B TECH, Dept. of Mechanical Engineering, LBSCE Kasaragod

2. Asst. Prof. Dept. Of Mechanical engineering, LBSCE kasaragod

ABSTRACT

Different shaped cavity receivers of solar collectors and heat loss in them are always been an interesting topic for the researchers. Experimental and numerical observation on this field has always been a tool for technologies utilizing solar energy. A numerical & experimental analysis was conducted on a spherical cavity solar receiver to analyze its losses. Numerical analysis was carried out using ANSYS FLUENT software. Heat losses are analyzed with and without glazing at the opening and also by varying the inclination angles (0^o, 45^o, 90^o). The cavity receiver was made of copper tube of 6mm inside diameter winded in the form of a sphere with an opening ratio 0.5. In the numerical analysis the inner wall was assumed to be isothermal and adiabatic condition was given to the outer wall and also boussinesq approximation was assumed. The exhaust to the surrounding is taken as pressure outlet. The flow was taken laminar and effect of radiation is neglected. In the experimental analysis constant heat source is obtained by allowing water at different temperatures to pass through the copper tube and readings are taken using thermocouples fitted inside. From the analysis maximum heat loss was observed at 0^o inclination of the spherical cavity receiver and minimum loss at 90^o inclination. The stagnation temperature is lesser at 0^o and larger at 90^o. Also, experimental and numerical investigation has been conducted to study the effect of glazing and it is found that flux rate through glazing material is much lesser than the unglazed model.

Keywords: *Open ratios, Glazing, Stagnation point, Inclination angle, Spherical cavity receiver*

1. INTRODUCTION

A solar thermal collector collects heat by absorbing sunlight. A collector is a device for capturing solar radiation. The receiver is that element of the system where the radiation is absorbed and converted to some other energy form; it includes the absorber, its associated covers, and insulation. Cavity receiver is a key component of any solar system and the efficiency of solar system mainly depends on the performance of cavity receiver. The efficiency of solar receiver is an important factor affecting the total temperature obtained. Therefore the efficiency of cavity receiver can be improved by minimizing the losses of cavity receiver of solar concentrator. For many applications it is desirable to deliver energy at temperatures higher than those possible with flat-plate collector. Energy temperatures can be increased by decreasing the area from which heat losses occur. This is done by interposing an optical device between the source of radiation and the energy-absorbing surface. It includes the absorber, its associated covers, and insulation. The concentrator or optical system, is the part of the collector that directs radiation onto the receiver. The aperture of the concentrator is the opening through which the solar radiation enters the concentrator. Concentration ratios which are the ratios of collector aperture area to absorber area can vary over several orders of magnitude. Concentrators are treated in two groups: non imaging collectors with low concentration ratio and linear imaging collectors with intermediate concentration ratio. Receivers can be Cylindrical, hemispherical, spherical or other convex shaped and cavity receivers may also be used. Glazed systems usually have a transparent top sheet and insulated side and back panels to minimize heat loss. The efficiency of a solar collector is defined as the quotient of usable thermal energy versus received solar energy. Besides thermal loss there always is optical loss as well Open ratio, inclination angle, sun angle, glazing material, aperture area, absorber area etc are some of the factors affecting the efficiency of solar collector. This paper is a software analysis that gives an idea of heat loss in a single cavity spherical receiver and the effect due to few of the above mentioned factors.

2. LITERATURE REVIEW

A.M.Clausing's [1] analytical model which enables the estimation of convective losses show that the influences of the wind & effective buoyant force are minimal but the internal thermal resistances are of greatest importance. According to him the orientation of the aperture is critical. According to Harris & Lenz [2] System efficiency is defined as the power absorbed by the working fluid circulating in the cavity divided by the solar power falling on the concentrator aperture. Steinfeld & Schubnell [3] summarise that sunshape decreases the optimum operating temperature and the overall efficiency, and increases the dimension of the optimum aperture radius of a cavity receiver. Schubnell [4] states that the maximum overall energy conversion efficiency only depends the three parameters such as the circumsolar ratio, the operating temperature and the receiver aperture. A numerical study has been carried out by Bilgen & Oztop [5] on inclined partially open square cavities and finds that heat transfer can be maximized or minimized by selecting appropriate parameters, namely aperture size, aperture position and inclination angle at a given operation Rayleigh number. K.S.Reddy and N. Sendhil Kumar [6] founds that the convective heat loss is significantly influenced by the inclination of the receiver whereas the radiation heat loss is considerably affected by surface properties of the receiver. Bellel [7] studied on types of cylindrical absorber and spherical concentrator & finds that the lower the temperature of the absorber is the better the thermal output of the concentration M.Prakash et al. [8], studied the natural convection occurring from open cavities in various geometries & concluded that the presence of stagnation and convection zones and their relative areas play an important role in the convective loss mechanism. Mahdi et al. [9] developed a system for collecting solar energy at high temperature and their study highlighted the importance of the cylindrical receiver position, the optimal geometry of the spherical reflector and the cylindrical receiver position. R D Jilite et al. [10] studied the natural convection and radiation losses for seven different shape and sized cavity receiver used with dish concentrator and finds that radiative loss is dependent on aperture area and effective emissivity of cavity rather than the shape of the cavity. It is observed from the literature by M.Prakash [11] that the convective heat transfer constitutes a major share of the thermal losses & it is dependentent on various parameters like receiver inclination (θ),receiver wall boundary condition, aspect ratio(L/D),opening ratio(d/D) and external wind. Shewale et al. [12] carried out an experimental study on spherical cavity receiver & found that as operating temperature increases, total heat loss also increases for different cavity inclination angles & the convection loss is found to increase with an increase in open ratio. Vahid Madadi et al.[13] investigate on a cylindrical cavity and found that by increasing receiver average temperature, due to decreasing in HTF mass flow rate, the convective heat loss increases & with increase in wind velocity the convection heat loss increases and this effect is more significant for smaller wind velocities. E.Abbasi et al. [14] states that temperature distribution along the cavity walls is seen to vary naturally because of local radiative and convective heat transfer, and is a function of cavity inclination. Rubén Gil et al. [15] shows a thermal model for a dish Stirling cavity based on the finite differences method. It is concluded that a short aperture radius and high receiver absorptivity make the cavity become much more efficient. The effect of glazing is not mentioned in any above literatures and thus we would like to give a try in our analysis to study the effect of glazing at the opening of the cavity receiver.

3. NUMERICAL ANALYSIS ON SPHERICAL SINGLE CAVITY SOLAR RECEIVER

The 2D analysis done using ANSYS FLUENT, a heat source of 325K and 330K is alternatively given to the inner wall of the spherical cavity solar receiver. The inner wall material is of copper which is an isothermal wall having 330K. The ambient temperature is taken as 300K. The heat loss through convection is calculated for open ratio 0.5 at inclination angles 0^o, 45^o, 90^o. The inner diameter of the receiver is taken as 24 cm, outer diameter of the outer wall is 26 cm and heat source having 5 cm diameter was taken. The model is meshed with quadrilateral dominant method in an element size of 0.1cm. The inner wall is assumed as isothermal wall having 330K, the heat source is also isothermal source having 330K. The outer wall is assumed as adiabatic wall with 300K. The heat exhaust is defined as pressure outlet having 0 gauge pressure. The radiation losses are neglected because the effects of convection and radiation losses are independent of inclination angles. The fluid flow is assumed as laminar flow and boussinesq approximation is done because the density variation is significant for heat transfer problems.

ASSUMPTIONS AND APPROXIMATIONS

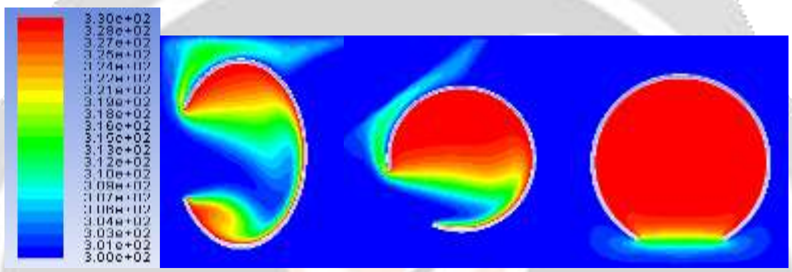
- ✓ Inner wall is taken as isothermal having 330K
- ✓ Outer wall is taken as adiabatic having 300K
- ✓ Heat exhaust from the surrounding is as pressure outlet(0 gauge pressure)
- ✓ The air flow is assumed as laminar
- ✓ Boussinesq approximation

Glazed covering of diameter 13cm for open ratio 0.5, having thickness of 4mm are placed at the opening of the receiver. This analysis using glazed covering was done using ANSYS steady state thermal.

4. RESULTS AND DISCUSSION OF NUMERICAL ANALYSIS

4.1 EFFECT OF INCLINATION ANGLE

The analysis is done for inclination angles 0°, 45°, 90°. It is found that the convective losses are maximum at 0° and minimum at 90°. The temperature profiles within the cavity receiver with opening ratio 0.5 in fig.4.1 are the results obtained by numerical analysis of the cavity receiver by varying the inclination angles.



0° 45° 90°

Open Ratio 0.5

Fig.4.1. Temperature profile in the cavity receiver at different inclination angle

The wall temperature is given as 300K. The highest temperatures are indicated by red shades while the lowest temperatures are indicated by dark blue shades. The stagnation zone which is indicated by red shade goes on increasing when the inclination angle of cavity receiver increases from 0° to 90° inclination. Maximum heat loss at 0° is obtained around 100 to 120W and minimum heat loss is obtained at below 40W. These values will be slight different from those obtained using theoretical calculation of convective losses. From fig.4.1 it is seen that at zero degree the stagnation zone is less and thus heat loss is more. At horizontal inclination, the incoming stream of ambient air experiences a decrease in density as it flows along the hot bottom wall. This results in the air rising towards the top surface, and leaving from the top of the aperture. At an angle of 45°, a stagnation zone forms along the top surface of the cavity. The reduced displacement of this volume of air allows the temperature in this region to rise. The inclination angle has no effect on radiation and conduction losses.

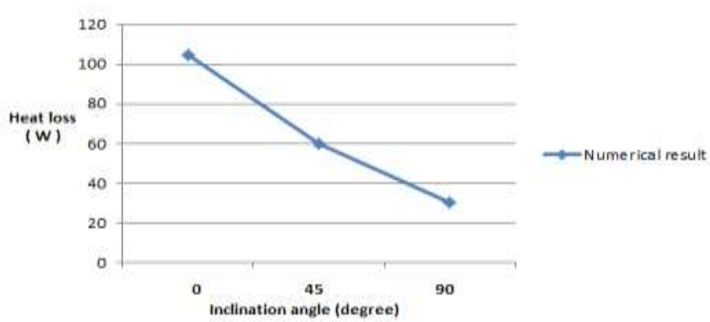


Fig.4.2. Graphical representation of heat loss at various inclination angles

The fig.4.2 shows the graphical representation of heat loss vs. inclination angle. It can be clearly observed that heat loss decreases with increase in inclination. The maximum heat loss is at 0^o and minimum is at 90^o inclination.

4.2 EFFECT OF GLAZING

The model was analyzed with glazed and unglazed opening with same conditions and assumptions and it was found that the heat loss decreases when the opening was given a glazed covering. The effect of convection loss is negligible due to glazing and only conduction loss is prominent. This conduction loss is much lower than the convection loss at unglazed opening. Therefore total loss at glazed model is lower than that of unglazed model Glazing can also partially polarize the radiations and it also absorbs, transmit and reflect the radiations. So glazing has prominent effects on heat loss in a receiver.

Fig.4.3 Heat flux on the glass plate used for glazing (W/m^2)

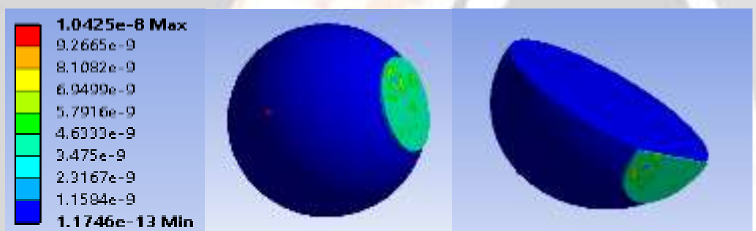


Fig.4.4 Flux distribution in a glazed model

The figure 4.3 shows the flux distribution in the glass plate of 4mm thickness and 13cm diameter. The maximum heat flux is around $5.7*10^{-9}$ W/m^2 and minimum flux is around $1.7*10^{-10} W/m^2$. Since the thickness of glass plate taken is so small the value obtained is very less. Fig 4.4 shows the flux distribution in glazed model. It can be see that the flux distribution inside the model is almost constant and it is much lesser than the maximum heat flux.

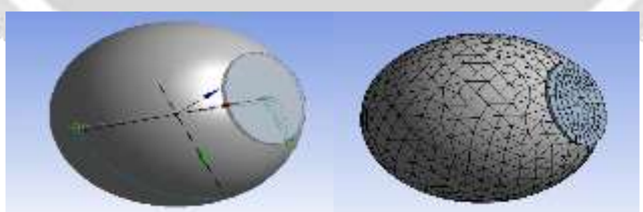


Fig.4.5. Glazed mesh model

It is clear that, providing a glazing at the opening reduces the heat loss and increases the absorption. Variation occurs depending on the thickness of glass plate used. Further observation on the effect of glazing is made through experimental analysis.

5. EXPERIMENTAL ANALYSIS

5.1 DETAILS OF CAVITY RECEIVER

The spherical cavity receiver used in the present analysis is made by copper tube material winded in the form of a spherical cavity receiver. The opening ratio of the model is taken as 0.5. The internal diameter of cavity receiver is 0.24m & opening diameter is 0.12m. The model has 30 numbers of turns of copper tubes in it. The inner diameter of copper tube is 0.009m. The spacing between the two coils is from 0.001 m to 0.005 m. A layer of glass wool insulation 50 mm thick is provided on the outer surface of cavity receiver to reduce the heat losses. The whole receiver is then enclosed by insulation tape to reduce heat losses further.

Fig.5.1. Cavity receiver

5.2 EXPERIMENTAL SETUP

Experimental analysis of spherical cavity receiver is done by pumping hot water at source temperature through the copper tube winded in the form of a single cavity spherical receiver. The schematic diagram of experimental setup is shown in the fig 5.2. The set up mainly consists of a downward facing spherical cavity receiver supported by a stand and angle adjustment mechanism is provided to incline the cavity at inclination angles 0°, 45°, & 90° with respect to horizontal. It is used for low temperature test at 60°C. The hot water is used as a working fluid into the receiver tubes and a tank having two heater (1.5 KW each) used for storage of hot water. A pump of capacity 0.25 HP is used for circulating the hot water through the cavity receiver tubes and the mass flow rate of water, which enters in to the cavity is measured with the help of measuring jar and stop watch. The tube temperature of cavity receiver and air temperature inside cavity receiver are measured with 4 K-type thermocouples at different locations in to the cavity receiver. The fluid inlet & outlet temperatures are measured with the use of thermometer. The hot water circulated through the receiver at constant inlet temperature & constant mass flow rate during the period of experimental run and the water from the outlet of cavity receiver again returned to the storage tank.

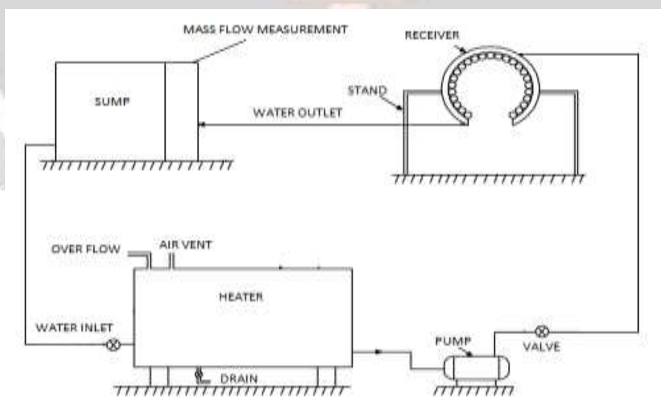


Fig 5.2 schematic diagram of experimental setup

The inlet of working fluid is at the top of cavity receiver and exit of working fluid is at the opening of cavity receiver so that the highest temperature is at the top and lowest temperature is at the aperture side of cavity receiver. Temperature is measured varying the inclination angle of the receiver and the readings are taken when steady state has reached and the heat losses are calculated at steady state condition. Glazing setup was made by using a glass plate of 13cm diameter and 4mm thickness. The glass plate is attached at the opening of the receiver and 2 thermistors are attached at the inner and outer surface of the glass plate to indicate the temperature at the glass surface.

5.3 MATHEMATICAL MODELING

The energy balance of spherical cavity receiver is shown by equation (1) in which conduction loss, convection loss and radiation loss are the three modes of heat losses. The convection losses and radiation losses are through the opening of cavity receiver while the conduction loss is through the surface of cavity receiver. The energy balance equation used for the heat loss calculation of cavity receiver is given by,

$$Q_{tot/\Theta} = Q_{cond/\Theta} + Q_{conve/\Theta} + Q_{rad/\Theta} \quad (1)$$

Where $Q_{tot/\Theta}$, $Q_{cond/\Theta}$, $Q_{conve/\Theta}$, $Q_{rad/\Theta}$ are the total, conduction, convection and radiation heat loss for cavity inclination angle θ respectively. The total heat losses can be finding out by using the following equation

$$Q_{tot/\Theta} = mC_p(T_{fi}-T_{fo}) \quad (2)$$

Where, 'm' is mass flow rate of water, 'C_p' is specific heat of water, and T_{fi} & T_{fo} are the temperatures of water at the inlet and outlet of receiver. For finding conduction loss, the opening of cavity receiver was closed with glass plate. Then the tests are conducted for fluid inlet temperature 60°C at various inclination angle of cavity receiver such as 0^o, 45^o, 90^o. The loss obtained from these tests is the conductive loss at these inclinations for cavity receiver.

$$Q_{cond\ /opening\ closed} = mC_p(T_{fi}-T_{fo}) \quad (3)$$

The Radiation loss through the opening of cavity receiver is calculated theoretically by using the following equation at various inclination angles (0^o, 45^o, 90^o) cavity receiver.

$$Q_{rad/theoretically} = \epsilon A_{op} \sigma (T_m^4 - T_a^4) \quad (4)$$

Where, 'ϵ' is emissivity of cavity surface, 'A_{op}' is opening area of cavity receiver. As there is no effect of inclination angle of cavity on conductive & radiative losses, therefore conductive & radiative losses are constant for all inclination angle of cavity receiver. Therefore the convective heat losses can be finding out by using the following equation

$$Q_{conve/\Theta} = Q_{tot/\Theta} - Q_{cond/\Theta} - Q_{rad/\Theta} \quad (5)$$

6. RESUTS AND DISCUSSION OF EXPERIMENTAL ANALYSIS

6.1 EFFECT OF INCLINATION ANGLE

Spherical cavity receiver is inclined at various angles such as 0^o, 45^o, 90^o and temperature at various points inside the cavity receiver is obtained using thermocouples. Open ratio was fixed at 0.5. As obtained in the numerical analysis maximum heat loss is obtained at 0^o and minimum heat loss was obtained at 90^o. The source temperature given was 333K and the inner wall temperature obtained is 335K. Temperature readings obtained at various points are shown in the fig 6.1 below.

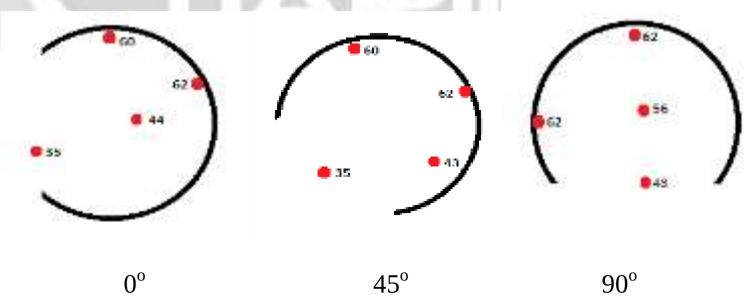


Fig 6.1 Temperature readings obtained by thermocouples (°c)

The temperature obtained at higher points in the receiver is more than that obtained at lower areas and this is to because of the formation of stagnation zone due to density variation. A graph is obtained after doing the calculations using the selected correlations. The depicted graph shows that the heat loss decreases with increase in inclination angle. The stagnation zone increases with increase in inclination angle and this is due to the density variation and this cause the decrease in the heat loss. The obtained graph is shown below.

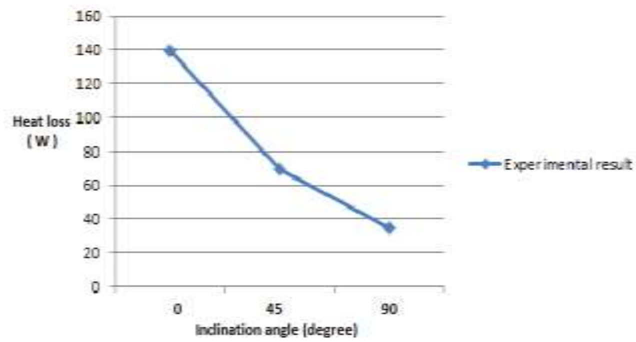


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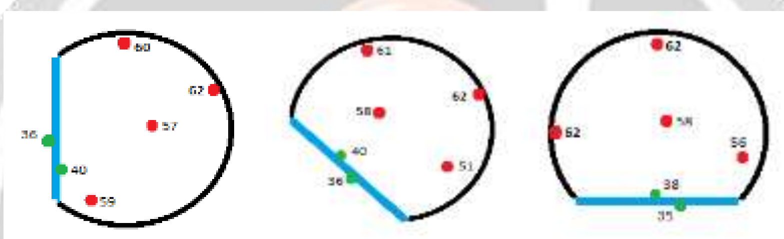
Fig 6.2 Graphical representation of Heat loss vs. Inclination angle

6.2 EFFECT OF GLAZING

Glazing was given to the opening of the receiver and temperature is measured using thermocouples. Temperature reading obtained at various points is shown in fig 6.3.



0°　　45°　　90°

Fig.6.3. Temperature reading obtained

Graphs are plotted after doing the calculations using the correlations selected. The depicted graph shows that heat loss decreases with increase in inclination angle. The value of heat loss when compared with unglazed model is found to be very much lesser in the case of glazed model. Convection loss is minimum and conduction losses are prominent. Variation will occur depending on the thickness of glass plate used.

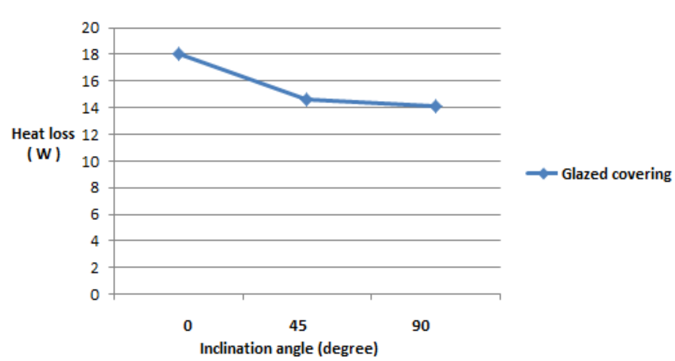


Fig 6.4. Graphical representation of heat loss vs. Inclination angle of glazed model

7. CONCLUSION

Numerical & experimental analysis of a single cavity spherical receiver has been conducted and effect of receiver inclination angle on heat loss is studied. The model was also analysed numerically and experimentally by giving glazed and unglazed opening. The inclination angle was varied from 0^o to 90^o and it was found that maximum heat loss is at 0^o and minimum heat loss is at 90^o. There is a decrease in the convective loss as the cavity inclination angle increases. This is due to the increase in stagnation zone which reduces the convection losses. Inclination angle has no effect on conduction and radiation losses. The glazing given at the opening reduces the convection loss. Conduction losses are observed at the glazing and this has much lower effect than that of the convection losses. The heat flux rate through glazing material is found to be very less. Glazing covers are also able to partially polarize the radiations and absorb the radiation. Variation occurs based on the thickness of glass plate used. A spherical cavity receiver with due considerations to the effects of these factor can be an efficient asset in various applications.

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