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Study of Heat Losses from Cylindrical Cavity Receiver of Solar Concentrator

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Abstract. In this paper heat losses from cavity receiver of solar concentrators are presented. Convective and radiative losses for specified cavity receiver are estimated by MATLAB programming and effect of the various parameters is studied. Radiation losses are analyzed for operating temperature in range of $127^{o}C$ to $527\ ^{o}C$ and aspect ratio of 0.5 to 2.5. Convective losses are investigated for operating temperature in range of $127^{o}C$ to $527\ ^{o}C$, inclination angle from 0 to 90^{o}, aspect ratio of 0.5 to 2.5 and wind effect for 0 to 10 m/s. Radiation losses and convective losses increases as operating temperature of cavity receiver increases. The convective losses are more for sidewise facing cavity (0^{o} inclination) and less for downward facing cavity (90^{o} inclination). As aspect ratio and wind velocity increases, convective loss increases.

Introduction

The performances of cavity receiver of solar concentrator are studied by various authors. Clausing has developed analytical model to estimate convective losses. Clausing analyzed cavity receiver and suggested that buoyancy effect plays important role and wind velocity also affects convective losses[1]. Harris and Lenz have presented six loss mechanisms for the concentrating solar collector system with cavity receiver. These loss mechanisms were losses due to reflection from reflector, spoilage losses from the cavity, losses due to shadowing, reflection and thermal radiation losses from the cavity, convective and conductive losses from the cavity. Harris and Lenz have tested cylindrical, heteroconical, conical, spherical and elliptical cavities. A well designed cavity receiver will lose only about 12% of energy entering its aperture [2]. Stine and Mc Donald developed the correlation for convective losses experimentally using full size cavity receiver by considering effect of cavity temperature, tilt and geometry [3]. Leibfriend and Ortijohann have studied convective heat loss from upward and downward facing spherical and hemispherical receivers for different aperture diameters. Poitoonsurikaran and Lovegrove had simulated the ANU dish receiver to estimate convective losses by using fluent 6 and the results are compared with all available models for convective heat losses. Kedare had designed and set-up 'ARUN 160'dish concentrator of 160 m^2 with cylindrical solar cavity receiver and studied performance of system[4]. Barahate had studied heat losses and factors affecting it experimentally [5, 6].

In this paper cylindrical cavity receiver specified below is analyzed to investigate convective and radiative losses by MATLAB programming. Radiation losses are estimated for operating temperature upto 800K and for aspect ratio of 0.5 to 2.5. Convective losses are studied for operating temperature upto 800K and inclination angle from 0^{o} (Horizontal position) to 90^{o}(Downward position) and aspect ratio of 0.5 to 2.5 and wind velocity upto 14m/s.

Methodology and Mathematical Model

The cylindrical cavity receiver is analyzed in this work with following details

- Cavity material: Cupronickel: Emissivity (ε) = 0.3
  Reflectivity (ρ_r) = 0.63

- Receiver Diameter(D) = 800 mm
- Receiver Length (L=H)= 1200 mm
- Concentration Ratio (C.R) = 20
- Operating Temperature Range : 373K TO 737 K

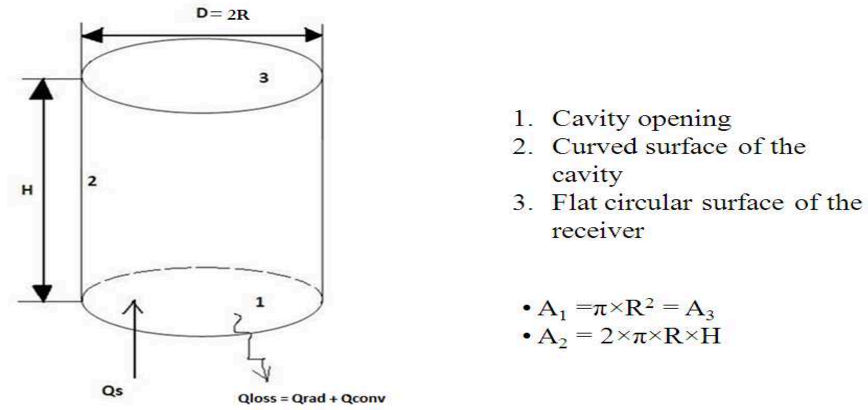


Fig.1 Cylindrical cavity receiver

Radiation losses

The cavity is considered of three surfaces for ease of radiation calculation i. e cavity opening (1), Curved surface (2) and flat circular surface (3) as shown in Fig.1. Radiative energy emitted by curved surface 2 is

$$Q_{e2}= \sigma\ \varepsilon\ A_2\ (T_2^4 - T_{amb}^4) \quad (1)$$

Energy leaving the surface 2 and passing through the opening

$$Q_{rad2}=Q_s F_{12}\rho_r\ F_{21} + Q_{e2}\ F_{21} \quad (2)$$

Radiative energy emitted by flat surface 3 is

$$Q_{e3}= \sigma\ \varepsilon\ A_3\ (T_3^4 - T_{amb}^4) \quad (3)$$

Energy leaving the surface 2 and passing through the opening

$$Q_{rad3}= Q_s\ F_{13}\rho_r\ F_{31} + Q_{e3}\ F_{31} \quad (4)$$

Total radiation loss trough opening of cavity

$$Q_{rad} = Q_{rad2} + Q_{rad3} \quad (5)$$

Convection losses

The convective losses are investigated by using correlation of Koenig and Marvin [7] and Stine and McDonald [3]. Koenig and Marvin [7] had suggested following correlation for average Nusselt Number for natural convection from cavity receivers.

$$\overline{Nu_L} = 0.78\ P(\theta)\ L_c^{1.75}\ (Gr_L\ Pr)^{0.25}$$

Stine and McDonald [3] had suggested following correlation for average Nusselt Number for natural convection.

$$Nu_L = 0.088 Gr_L^{\frac{1}{3}} (\frac{T_w}{T_o})^{0.18}\ (\cos\theta)^{2.47}\ (\frac{d}{L})^S$$

Results and Analysis

Effect of various parameter Radiation and convection losses for cylindrical cavity receiver are studied by using MATLAB programming. The effect of inclination angle, geometry, temperature, aspect ratio and wind velocity are studied.

Radiation Losses

The radiation losses are studied for different Cavity surface temperature and aspect ratio (L/d) of the cavity receiver.

Effect of cavity receiver surface temperature

Fig.2 shows variation of radiative loss from cavity receiver with cavity surface temperature.

In the cavity receiver radiative losses occur through small aperture area and due to reflection and thermal emission. Therefore it depends upon reflectivity, emissivity, view factor and temperature of hot parts and ambient temperature. At low temperatures, losses due to emission are small and only reflection losses are significant and at high temperatures both reflection and thermal emission becomes significant. Radiation losses become dominant becomes dominant at higher temperature because radiation losses are directly proportional to fourth power of absolute temperature. Above graph clearly shows the quartic i.e. 4^{th}degree nature of radiation loss.

Effect of aspect ratio (L/D)

Fig 3 shows effect of aspect ratio of cavity on radiation loss from receiver. Aspect ratio is varied from 0.5 to 2.5. Radiation loss is higher for low values of aspect ratio and it decreases with increase in aspect ratio. As we know, radiation losses are through the cavity opening. So, longer the cavity, longer will be the path that radiations have to cover to get emitted out of cavity opening. Also, larger diameter opening will facilitate more radiation loss. Low value of aspect ratio symbolize short length receiver, so radiations will readily leave the receiver giving high values of radiation losses. As the value of aspect ratio increases, receiver's length increases and radiation will have to travel a longer distance. It may get attenuated and absorbed by the receiver surface. Thus, radiation losses are less in case of receivers of higher aspect ratio.

Convection losses

The convection losses from cavity receiver are studied and presented for effect of various parameters i.e. temperature, orientation, aspect ratio (L/D) and wind and its direction.

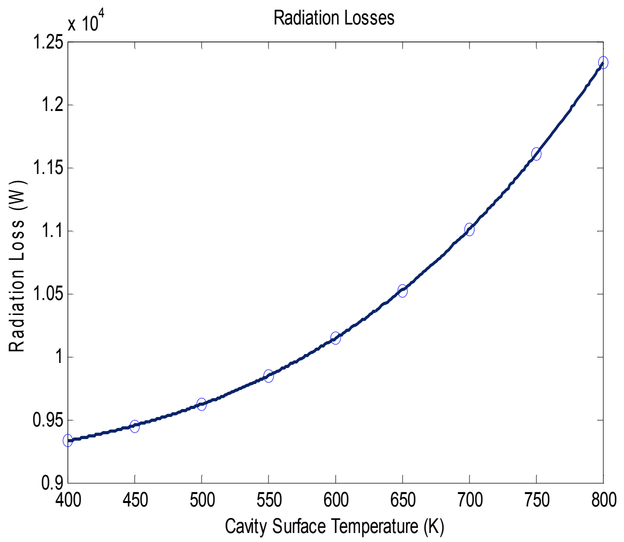


Fig.2 Radiation loss versus temperature

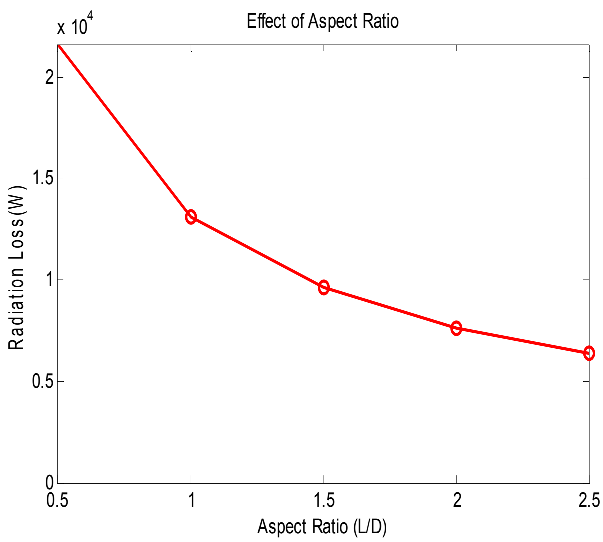


Fig.3 Radiation loss versus Aspect Ratio

Effect of Temperature

Fig.4 shows effect of cavity surface temperature on convection loss. Convection loss is calculated using two convection models namely Koenig & Marvin model and Stine & McDonald model. In both the cases, the convection losses increase linearly with the cavity surface temperature. This is because convection loss is directly proportional to the difference between cavity surface temperature and ambient temperature. It is also observed that at higher temperatures, convection loss as given by Stine & McDonald is more as compared to the loss given by Koenig & Marvin model. The reason of this variation is Nusselt number as given by Stine & McDonald varies with $(T_s/T_{amb})^{0.18}$ whereas Koenig & Marvin's model shows no such direct variation of Nusselt number with temperature.

Effect of Orientation

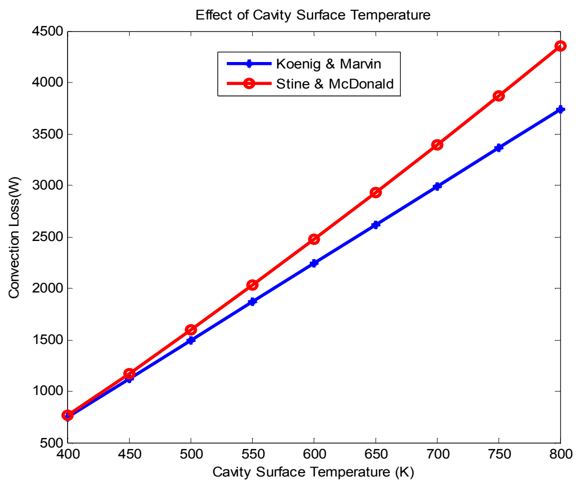
Fig.5. shows plot of cavity inclination Angle versus convective loss (W) of different models. The convective losses are more for sidewise facing cavity (0^o inclination) and less for downward facing cavities (90^o inclination). The decreased natural convective heat loss as the receiver is tilted downward is due to a larger portion of the receiver volume being in the stagnant zone, where convective currents are virtually non-existent and air temperature is high, and a smaller portion being in the convective zone,where significant air currents exist. In the present analysis, Koeing & Marvin and Stine & McDonald models are used to estimate convective losses from cylindrical cavity receiver.

Effect of Aspect Ratio

Fig 6. Shows effect of aspect ratio on convection loss from cavity receiver. Aspect ratio is varied from 0.5 to 2.5. It is clear from above plot that convection loss increases with increase in aspect ratio. As length of the receiver increases, the surface area, through which convection loss occurs, increases. Since, more surface is available for convection to take place, convection loss increases with increase in aspect ratio. For low values of aspect ratio, the surface available for convection loss will be less and hence the convection loss will be less. This variation is unlike that of radiation loss with aspect ratio. As aspect ratio increases, radiation loss decreases and convection loss increases. So, aspect ratio of cavity receiver should be such that it gives moderate or less values of both radiation loss and convection loss.

Effect of Wind

Effect of Wind for Side on Wind Condition. Fig.7 shows effect of variation in wind velocity on convective losses from cavity in side on wind case and Fig.8 shows variation of convection loss with cavity inclination at different wind velocities varying from 0 m/s to 10 m/s. It is observed that there is a significant effect of wind on convective losses. Convective losses increase with increase in wind velocity. Total convection loss is the sum of natural convection loss and forced convection loss. Loss due to natural convection depends upon cavity inclination whereas that due to forced convection is independent of cavity inclination and depends only upon wind velocity. For side on wind case, variation in convection loss with wind velocity is approximately parabolic because forced convection losses are directly proportional to square of velocity. This also explains the reason why convection loss increases with increase in wind velocity. The convection loss versus cavity inclination regime does not vary much with increase in velocity. Only the value of convection loss increases, regime remains the same.



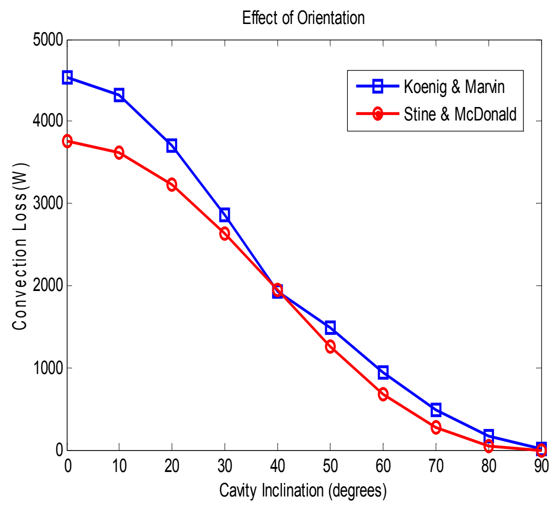


Fig. 4. Variation of convective losses with temperature **Fig. 5. Variation of convective losses with inclination**

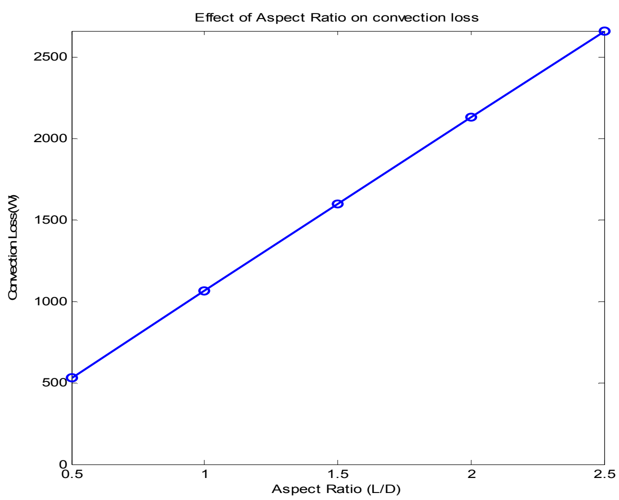
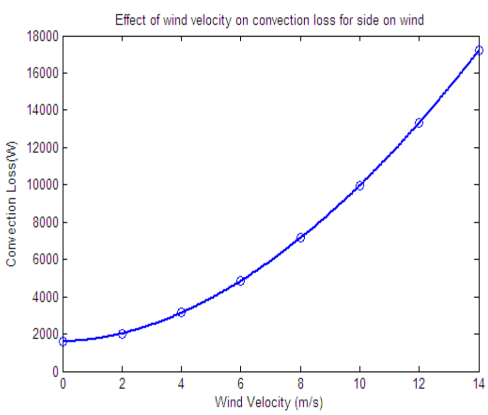


Fig.6. Effect of aspect ratio of receiver on convection loss



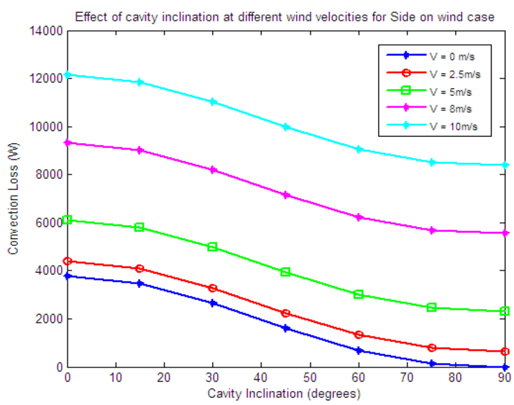


Fig.7. Variation of convection loss with wind velocities for Side on wind **Fig.8. Variation of convection loss with cavity inclination at different wind speeds for Side on wind**

Effect of Wind for Head on Wind Condition. Fig.9 shows effect of variation in wind velocity on convective losses from cavity in head on wind case and Fig.10 shows variation of convection loss with cavity inclination at different wind velocities varying from 0 m/s to 10 m/s. For head-on winds, unlike side on wind case, the amount of increase in convective heat loss varies as a function of receiver tilt angle. Increase in convective heat loss due to wind are minimal with the receiver facing horizontally however, with the receiver facing down, convective heat loss increases are large at high velocities. Convective heat loss versus wind speed appears to be well behaved for side-on winds, but is more erratic for head-on winds. Here, not only natural convection depends upon cavity inclination but forced convection also depends on inclination angle. Therefore, the regime of convection loss versus cavity inclination does not remain same. It varies for every wind velocity.

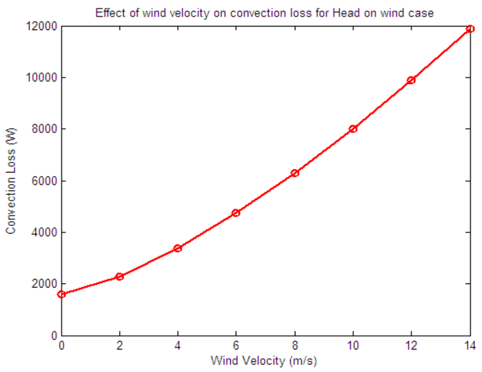


Fig.9. Variation of convection loss with wind velocities for Head on wind

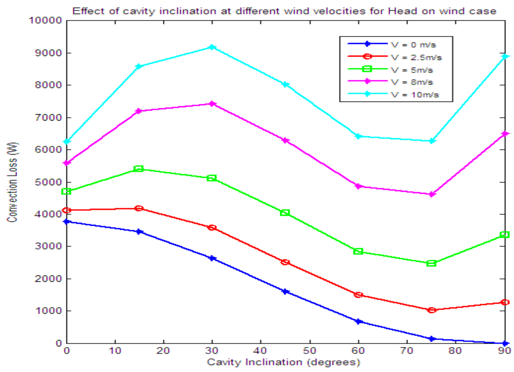


Fig.10. Variation of convection loss with cavity inclination at different wind speeds for Side on wind

Conclusion

Radiation loss increases as the receiver's operating temperature increases. However, with increase in aspect ratio, radiation loss decreases. Convective loss increases with increase in temperature. Convective loss decrease with increase in cavity inclination. It is minimum for downward facing receiver and maximum for horizontal receiver. As aspect ratio increases, convective losses increase. **5**. Losses due to convection increases with increase in wind velocity for both side on wind case and head on wind case. However, variation in convection loss with cavity inclination at different wind velocities is well behaved in case of side on wind while it is more erratic in head on wind case.

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