# HEAT LOSS ANALYSIS OF THREE COIL CYLINDRICAL SOLAR CAVITY RECEIVER OF PARABOLIC DISH FOR PROCESS HEAT

by

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*The share of solar thermal energy for process heat at sub cooled temperature is estimated about 30% of the total demand. The assessment of heat loss from tubular receiver used for the process heat is necessary to improve the thermal efficiency and consequently the cost effectiveness of the parabolic dish receiver system. The study considers a modified three coil solar cavity receiver of wall area three times (approximately) as compared to the existing single coil receiver and experimentally investigates the effect of increases in cavity inner wall area, fluid inlet temperature (50-75 ºC), and cavity inclination angle (θ = 0-90º) on the combined (total) heat loss from receiver under no wind condition. This paper also develops an analytical model to estimate the different mode of heat losses from the downward facing receiver. In the mean fluid temperature range of 50 ºC to 70 ºC, the total heat loss from three coil receiver is reduced up to 40.98% at 90º and 20% at 0º inclination, as compared to single coil receiver. The analytical modeling estimates very low heat loss from conduction (1-3%) and radiation (2-8%) and high heat loss from convection (97-89%). The heat loss by natural convection decreases sharply with increase in cavity inclination, while the heat loss by radiation and conduction increases slowly with inclination. A three coil cavity receiver might be considered in the design to reduce heat loss from parabolic dish receiver system to improve the thermal performance and cost effectiveness.*

Key words: *cavity receiver, cavity inclination angle, heat loss, thermal analysis, no wind test*

## Introduction

The concentrating solar technology is most efficient technology and it can be used for process heat applications as well as for power generation. Among four concentrating technology, parabolic dish-receiver system is the most efficient system. The system is generally designed of a collector in the form of a parabolic dish with downward facing receiver located at the focus point of the dish system.

A cavity type receiver is generally used since it absorbs maximum solar radiation flux with minimize heat losses from receiver. The heat losses in solar parabolic dish receiver system are convection and radiation losses through the opening of cavity and conduction through the solid structure and the insulation covering cavity exterior surfaces to reduce con-

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duction A detailed review on the convection heat loss from different shapes of cavity, normally used in different types of engineering systems, is available in literature [1].

The Australian National University (ANU) conducted series of experiments to study the convection heat loss of a cylindrical cavity with isothermal surface boundary [2]. Further investigation showed that for a vertically downward cavity, the convective heat loss from receiver was non-zero value [2, 3]. Numbers of experimental and numerical investigations were also carried out under constant heat flux boundary condition with non-uniform wall condition on model receiver [4, 5]. The heat loss by natural convection was observed to be more sensitive to the cavity inclination as compared to heat losses by radiation and conduction in constant heat flux boundary condition. Azzouzi *et al*. [6] also presented the experimental and analytical study on the helical coil cavity receiver with non-uniform high temperature wall condition. Most of the numerical and experimental studies on heat loss are performed on cylindrical cavity receivers, used for isothermal wall condition and high temperature applications (>400 °C) such as power generation, which cannot give accurate heat loss estimation for tubular cavity receivers for low and medium temperature process heat applications.

However, the potential of solar thermal energy for process heat is expected to be very large amount (5.6 EJ/year) by 2050 [7]. The demand for low temperature process heat (industries like: paper, pulp, food, textile, *etc*.) below 100 ºC is significant and share about 30% of the total demand [8]. Parabolic dish receiver systems for process heat has been least analyzed. The heat loss from receiver tubular assembly (generally used in process heat applications) determines the thermal efficiency as well as the cost effectiveness of the system.

The effect of increase of cavity inner wall to aperture area ratio is analyzed by researcher numerically. The analysis and correlations show that the total heat loss decreases significantly with the increase in area ratio *i. e.* receiver inner wall area to aperture area ratio [9]. An attempt has been made to reduce total heat loss from the cavity receiver by increasing the inner wall area.

This investigation consider a modified three coil cylindrical solar receiver of inner wall area of (approximately) three times of the single coil receiver and experimentally investigates the effect of increases in cavity inner wall area, fluid inlet temperature (50-75 ºC) and cavity inclination angle (0-90º) on the total (combined) heat loss from receiver under no wind condition. This paper also develops an analytical model to estimate heat losses from the downward facing receiver under various inclination of the receiver. Additionally, the convection heat loss Nusselt numbers is proposed. The analytical model can be used to estimate the different heat losses of the downward facing cavity receiver. The reduction in heat loss from modified receiver is experimentally investigated at low temperature, applicable for process heat applications. So the modified receiver design can be used to minimize the heat losses from the receiver and improve the thermal performance and cost effectiveness of the parabolic dish receiver system.

## Material and methods

### *Description of the receiver*

The three coil cavity receiver is made of a highly polished copper tube of outer diameter 11 mm and thickness 1 mm. The three coils are internally connected and the average clearance between the tubes is 2-3 mm, fig. 1(a). Ten thermocouples (K-type) are used for measuring fluid temperatures at the different locations of the receiver, fig. 1(b). The temperature is measured by 12 points manual temperature indicator. A 20 mm thick circular ceramic fiber insulation board of density 280 kg/m$^3$ and thermal conductivity 0.11 W/mK is used on the back side of the receiver. The receiver is covered from all sides (except aperture area), with 6 cm thick glass wool insulation, which minimizes the heat loss by conduction and maintains the outer layer of the insulation nearly adiabatic.

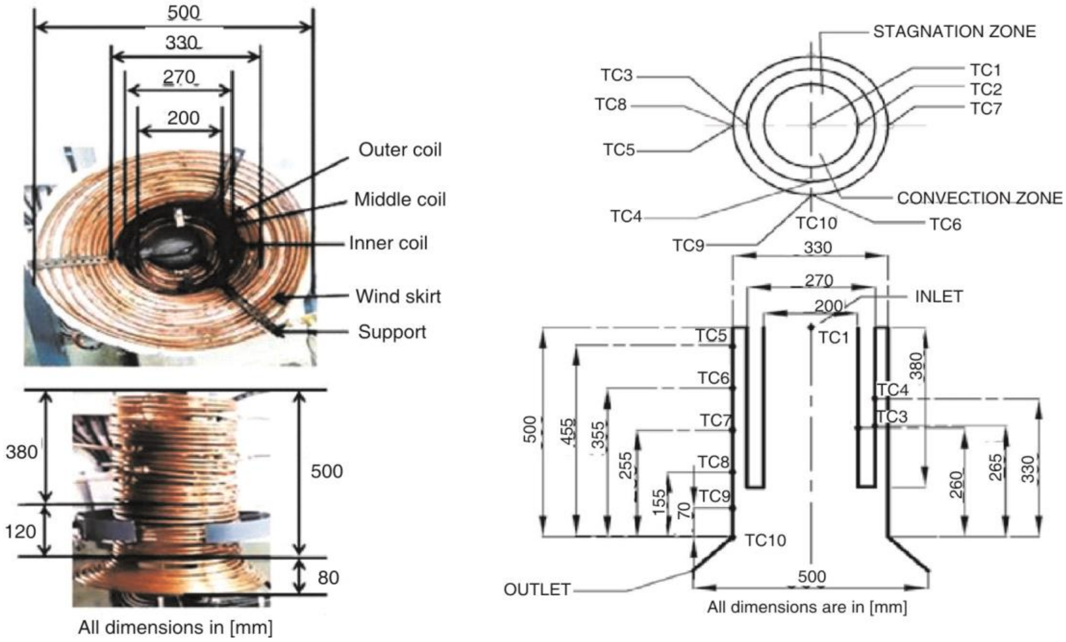


**Figure 1. Three coil cavity receiver; (a) actual front and side view, (b) thermocouples locations in receiver**

Material properties and cavity dimensions are given in tabs. 1 and 2.

**Table 1. Copper and glass wool properties at 100 ºC**

| Material | Copper Cu | Glass wool |
|---|---|---|
| Density, $\rho$, [kgm$^{-3}$] | 8933 | 120 |
| Thermal conductivity, $k$, [Wm$^{-1}$K$^{-1}$] | 395.7 | 0.04 |
| Emissivity | 0.03 | – |

**Table 2. Geometrical dimensions**

| | | |
|---|---|---|
| Outer coil mean diameter | $D_{icav1}$ | 0.33 m |
| Middle coil mean diameter | $D_{icav2}$ | 0.27 m |
| Inner coil mean diameter | $D_{icav3}$ | 0.20 m |
| Aperture diameter | $D_{ap}$ | 0.33 m |
| Length of outer coil | $L_{icav1}$ | 0.50 m |
| Length of middle coil | $L_{icav2}$ | 0.38 m |
| Length of inner coil | $L_{icav3}$ | 0.38 m |

### *Experimental investigation methodology*

The heat loss investigation of a receiver is generally conducted either in on flux mode (field test) or off flux mode (simulated laboratory experiments). To simulate with the field test in the actual condition, hot water at constant temperature (50-75 ºC) is supplied to the inlet of the cavity receiver from the top of the receiver, at constant mass-flow rate (0.02 kg/sec approximately) under different cavity inclinations (0º, 30º, 45º, 60º, and 90º). The hot water is supplied at the top of the inner coil and after passing through middle coil (upward), exit from the bottom of outer coil. Achieving steady-state takes 3-4 hours, when the outlet temperature remains steady for about half an hour to one hour. The rotameter uncertainty was in the range of about ±5% for 0.02 kg/s flow rate. The thermocouples have uncertainty of about 0.5 ºC in the temperature range of 50-75 ºC. The actual experimental set-up is shown in fig. 2.

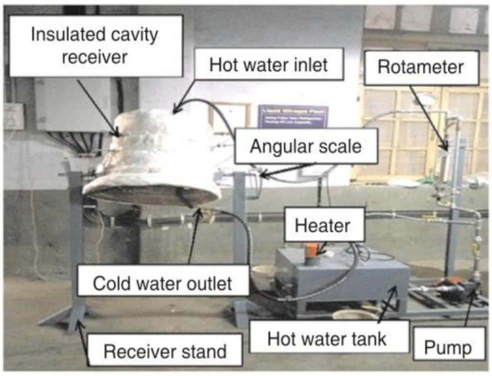


**Figure 2. Actual experimental set-up for heat loss investigation**

## Thermal analysis and analytical modeling

The heat losses (conduction, convection and radiation) between inside of the cavity and ambient air were estimated through thermal analysis of a solar cavity receiver. Based on thermal analysis, an analytical model is developed for three coil cavity receiver.

### *Receiver heat balance*

The convection and radiation heat loss, $Q_{\text{rcav}}$ and $Q_{\text{ccav}}$, is from the inner wall, $A_{\text{wicav}}$, of the three coil cavity receiver through opening of the cavity. The conduction heat loss is from back side, $Q_{\text{condb}}$, and cylindrical surface of the receiver, $Q_{\text{condr}}$, through insulation, as shown in fig. 3. In simulated experiment, solar flux is simulated with hot water supply at the inlet of receiver. The testing of a receiver is performed in a close loop where mass-flow rate of the fluid and fluid inlet temperature is maintained constant. In the steady-state condition useful heat gain is zero and heat received from solar radiation is total heat lost from the receiver, the heat balance is given by:

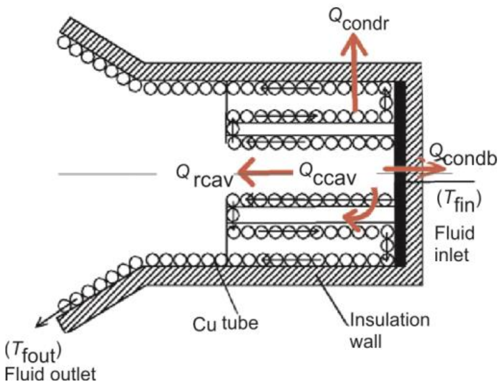


**Figure 3. Heat losses from three coil cavity receiver**

$$Q_{t\text{cav}} = Q_{c\text{cav}} + Q_{r\text{cav}} + Q_{\text{cond,r}} + Q_{\text{cond,b}} \tag{1}$$

### *Total heat loss estimation from experimental result*

$$Q_{t,\text{cav}} = \dot{m}C_p(T_{f\text{in}} - T_{f\text{out}}) \tag{2}$$

### *Radiation heat Loss through the receiver.*

For a very small size cavity as compared to the surrounding, the heat loss by radiation is given by Dehghan *et al*. [10]. The cavity wall temperature is taken as mean fluid temperature.

$$Q_{\text{r,acv}} = \varepsilon_{\text{ef}}\sigma(T_{\text{wicav}}^4 - T_{\text{amb}}^4) \tag{3}$$

$$\varepsilon_{\text{ef}} = \frac{\varepsilon_{w,\text{cav}}}{\left[1-(1-\varepsilon_{w,\text{cav}})\left(1-\dfrac{A_{\text{ap}}}{A_{w,\text{icav}}}\right)\right]} \tag{4}$$

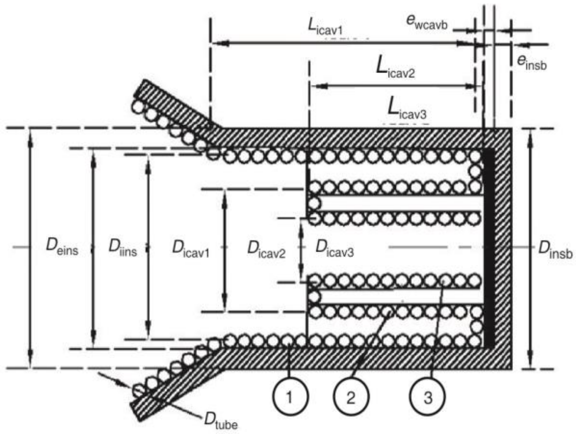


**Figure 4. Dimensional representation of the cylindrical cavity receiver**

Inner wall area for three cylindrical coils is calculated from the equations, fig. 4:

$$A_{w,\mathrm{icav}} = A_{w,\mathrm{icav1}} + A_{w,\mathrm{icav2}} + A_{w,\mathrm{icav3}} \tag{5}$$

$$A_{w,\mathrm{icav1}} = \pi D_{w,\mathrm{icav1}} L_{w,\mathrm{icav1}} \tag{6}$$

$$A_{w,\mathrm{icav2}} = 2\pi D_{w,\mathrm{icav2}} L_{w,\mathrm{icav2}} \tag{7}$$

$$A_{w,\mathrm{icav3}} = 2\pi D_{w,\mathrm{icav3}} L_{w,\mathrm{icav3}} \tag{8}$$

### *Conduction heat loss through the receiver wall*

Conduction heat loss from receiver is from bottom and curved surface (radial direction) of the receiver through the insulation. The conduction heat loss from the bottom and radial surface is estimated as [6]:

$$Q_{\mathrm{cond,b}} = U_{\mathrm{cond,b}} A_{\mathrm{eins,b}} (T_{w\mathrm{icav,b}} - T_{\mathrm{amb}}) \tag{9}$$

$$U_{\mathrm{cond,b}} A_{\mathrm{eins,b}} = \frac{1}{R_{\mathrm{wcav,b}} + R_{\mathrm{eins,b}} + R_{\mathrm{ext,r,b}}} \tag{10}$$

$$Q_{\mathrm{cond,r}} = U_{\mathrm{cond,r}} A_{\mathrm{eins,r}} (T_{w\mathrm{icav}} - T_{\mathrm{amb}}) \tag{11}$$

$$U_{\mathrm{cond,r}} A_{\mathrm{eins,r}} = \frac{1}{R_{\mathrm{tube}} + R_{\mathrm{eins,r}} + R_{\mathrm{ext,r}}} \tag{12}$$

The heat loss resistance from the bottom and radial surface of the receiver is shown in figs. 5 and 6.

### *Heat loss by convection*

The convection heat loss can be estimated either from available convection Nusselt number correlation or subtracting conduction and radition heat loss from total (combined) heat loss from experimental result:

$$Q_{c\mathrm{cav}} = Q_{t\mathrm{cav}} - (Q_{r\mathrm{cav}} + Q_{\mathrm{cond,r}} + Q_{\mathrm{cond,b}}) \tag{13}$$

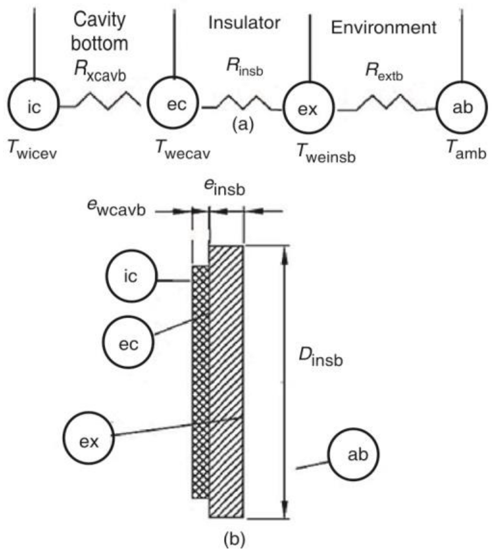


**Figure 5. Back side conduction heat loss resistance of receiver**

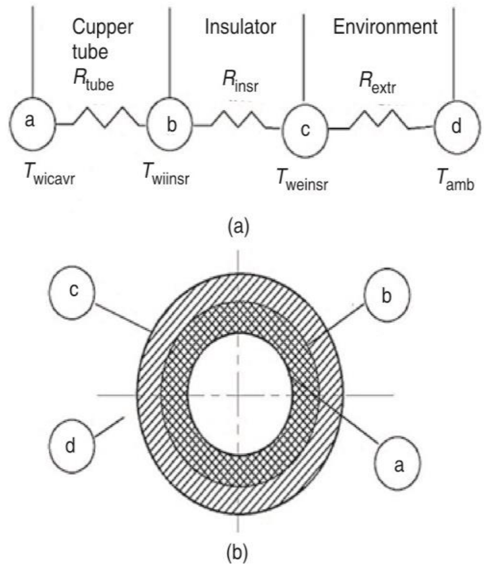


**Figure 6. Radial conduction heat loss resistance of receiver**

## Development of convection Nusselt number correlation from experimental result

Based on experimental result of convection heat loss, eq. (13), a convection Nusselt number correlation is developed, correlating parameters like: cavity inclination, temperature ratio, and Grashof number [3, 6]:

$$Q_{\text{ccav}} = A_{\text{wicav}} h_{\text{ccav}} (T_{\text{wicav}} - T_{\text{amb}}) \tag{14}$$

$$Q_{\text{ccav}} = \frac{(T_{\text{wicav}} - T_{\text{amb}})}{R_{\text{ccav}}} \tag{15}$$

$$R_{\text{ccav}} = \frac{1}{A_{\text{wicav}} h_{\text{ccav}}} \tag{16}$$

$$\text{Nu}_{\text{conv}} = \frac{h_{\text{ccav}} D_{\text{icav1}}}{K_{\text{air}}} \tag{17}$$

$$\text{Nu}_{\text{conv}} = 0.09927 \text{Gr}_{D_{\text{icav1}}}^{1/3} (1 + \cos\theta)^{1.5543} \left[ \frac{T_{\text{wicav}}}{T_{\text{amb}}} \right]^{-1.5} \tag{18}$$

$$\text{Gr}_{D_{\text{icav}}} = \left[ \frac{\text{g}\beta(T_{\text{wicav}} - T_{\text{amb}}) D_{\text{icav}}^3}{\nu^2} \right] \tag{19}$$

The fluid properties are taken at film temperature. The correlation is useful for the value of $T_m/T_{\text{amb}}$ varies between 1.1 and 1.14 and Grashof number in the range of $6.7 \cdot 10^7$ to $10.6 \cdot 10^7$. The developed convection correlation is suitable for medium temperature industrial process heat applications up to 70 °C fluid mean temperature suitable for inlet fluid temperature range 20-30 °C and outlet temperature 120-110 °C.

## Results and discussion

### *The convection heat loss Nusselt number from experimental result*

The relation between experimental and developed convection Nusselt number correlation, from eqs. (17) and (18) is shown in fig. 7. The experimental and correlated Nusselt number is found to be varies within ±15%.

As shown in fig. 8, the convection Nusselt number increases linearly with the increase in mean fluid temperature for all cavity inclinations (R-square > 0.88) and decreases with the increase in cavity inclination angle ($\theta$), when mean the fluid temperature is constant. This is because, when the cavity is horizontal ($\theta$ = 0°), the enhanced buoyancy force easily remove the heated air trapped inside the cavity and results in highest convection Nusselt number. For the vertical position of the cavity ($\theta$ = 90°), flow of hot air (convection flow) from inside of the cavity is difficult and lowers the convection Nusselt number. As can be seen from the slope of the curve, the Nusselt number increases at higher rate at ($\theta$ = 0°) and gradually decreases with increase in inclination at ($\theta$ = 90°).

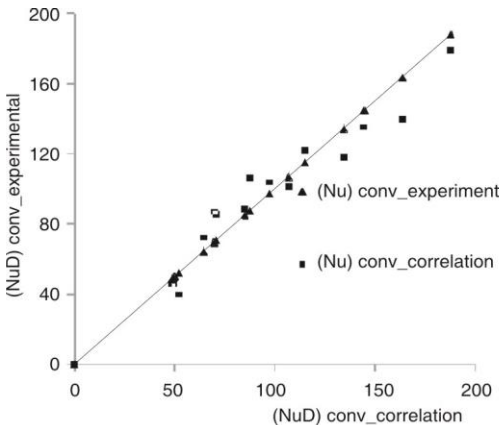


**Figure 7. Relation between experimental and correlated convection Nusselt number**

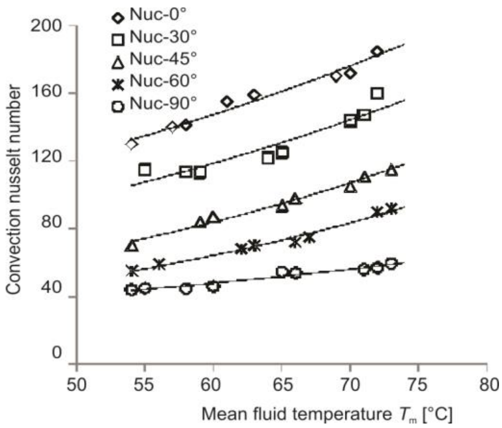


**Fig. 8. Variation of Nusselt number with mean fluid temperature**

### *Comparison of total loss from three coil cavity receiver with single coil receiver* [3]

The total heat loss from three coil receiver, from eq. (2) compared with sigle coil receiver at different mean fluid temperature and cavity inclination is presented in figs. 9 and 10 [3]. Heat loss from three coil cavity receivers is lower as compared to single coil receiver for all cavity inclinations. Heat loss increases with increase in mean fluid temperature. The heat loss rate is higher between 0-45°, fig. 9, as compared to 45-90° inclination, fig. 10.

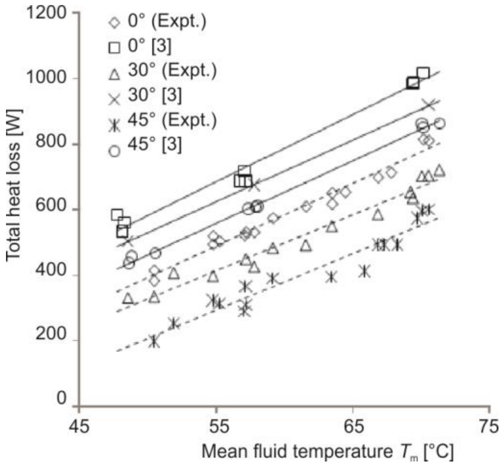


**Figure 9. Comparison of total heat loss with mean fluid temperature at $\theta$ = 0-45$^0$ [3]**

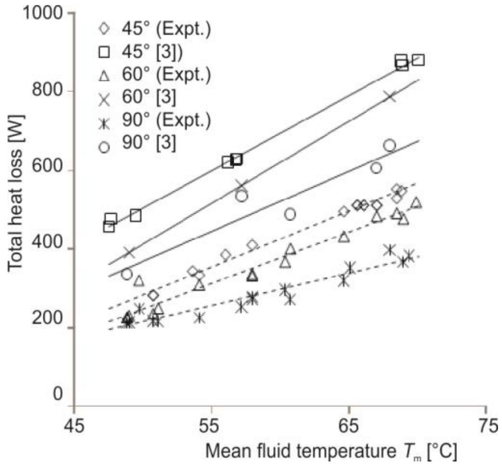


**Figure 10.Comparison of total heat loss with mean fluid temperature at $\theta$ = 45-90$^0$ [3]**

### *Different heat losses based on analytical modeling*

The convection heat loss decreases significantly with increase in cavity inclination for constant mean fluid temperature, fig. 11. The conduction and radiation heat loss increases slightly with increase in cavity inclination, $\theta$, for lower mean fluid temperature, fig. 12. In mean fluid temperature range 50-70 ºC the conduction and radiation heat loss percentage is very small (1-3% conduction and 2-8% radiation). The major heat loss is convection, which constitute 97-89% of total heat loss.

## Conclusions

The maximum heat loss from three coil receiver is 836 W at 0º cavity inclination and ~70 °C mean fluid temperature, which is 20% lower as compared to single coil receiver (1044 W), as can be seen from fig. 9 [3]. However, minimum heat loss from three coil receiver is 187 W at 90º cavity inclination and 49 °C mean fluid temperature, fig. 10, which is about

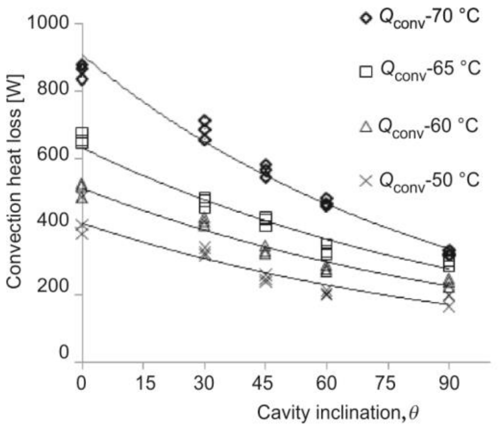


**Figure 11. Variation of convection heat losses with cavity inclination, $\theta$**

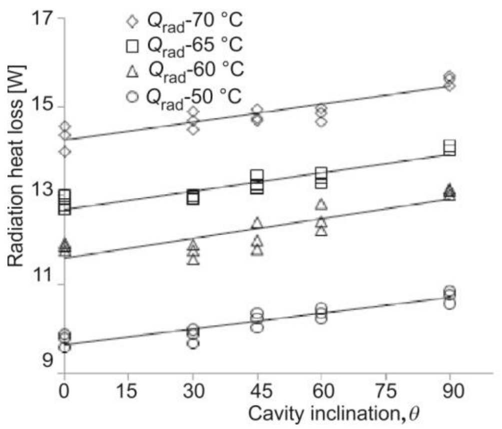


**Figure 12. Variation of radiation heat losses with cavity inclination, $\theta$**

41% lower as compared to single coil receiver (316 W). So, in the mean fluid temperature range of 50 ºC to 70 ºC, the total heat loss from three coils receiver is reduced by 41-20%, as compared to single coil receiver. A three coil cavity receiver might be considered in the design to reduce heat loss from parabolic dish receiver system to improve the thermal performance and cost effectiveness.

## Acknowledgement

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## Nomenclature

$A$ – area, [m$^2$]
$Cp$ – specific heat, [Jkg$^{-1}$K$^{-1}$]
$D$ – diameter, [m]
Gr – Grashof number, $\{\mathrm{Gr}_D=[g\beta(T_\mathrm{w}-T_\mathrm{amb})D^3/\vartheta^2]$
g – acceleration of gravity, [ms$^{-2}$]
$h$ – heat transfer coefficient, [Wm$^{-2}$K$^{-1}$]
$k$ – thermal conductivity, [Wm$^{-1}$K$^{-1}$]
Nu – Nusselt number, (=$hD/k$)
$L$ – length, [m]
$\dot{m}_f$ – mass-flow rate of fluid, [kgsec$^{-1}$]
Pr – Prandtl number, (=$Cp\mu/k$)
$Q_{c,\mathrm{cav}}$ – cavity convective heat loss, [W]
$Q_\mathrm{cond}$ – conductive heat loss, [W]
$Q_{r,\mathrm{cav}}$ – cavity radiation heat loss, [W]
$Q_t$ – cavity total heat loss, [W]
$R$ – thermal resistance, [KW$^{-1}$]
$U$ – overall heat transfer coefficient, [Wm$^{-2}$K$^{-1}$]
$T$ – temperature, [K]

*Greek Symbols*

$\beta$ – coefficient of thermal expansion, [K$^{-1}$]
$\varepsilon$ – emissivity of cavity material
$\theta$ – receiver inclination angle, [°]
$\mu$ – dynamic viscosity, [kgm$^{-1}$s$^{-1}$]
$\nu$ – kinematic viscosity, [m$^2$s$^{-1}$]

*Subscripts /superscript*

ap – aperture
b – bottom
cav – cavity
cond – conduction
conv – convection
ef – effective
ext – exterior
f – fluid
icav – interior
ins – insulation
t – total
$e$ – thickness, [m]
w – wall

*Acronym*

AR – area ratio, (=$A_{w,\mathrm{icav}}/A_\mathrm{ap}$)

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