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# Study of Solar Thermal Cavity Receiver for Parabolic Concentrating Collector and its Energy and Exergy Analysis

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**Abstract—***Solar energy is primary source of all type of energy which is present in nature i.e. all the energy derived from it. The parabolic concentrator reflects the direct incident solar radiation onto a receiver mounted above the dish at its focal point. The conversion of concentrated solar radiation to heat takes place in receiver. The heat transfer characteristics of the receiver changes during the rotation of the receiver which affects thermal performance. Thermal as well as optical losses affect the performance of a solar parabolic dish-cavity receiver system. The thermal losses of a solar cavity receiver include convective and radiative losses to the air in the cavity and conductive heat loss through the insulation used behind the helical tube surface. The convection heat loss from cavity receiver in parabolic dish solar thermal power system can significantly reduce the efficiency and consequently the cost effectiveness of the system. It is important to assess this heat loss and subsequently improve the thermal performance of the receiver. This study undertakes the theoretical investigation of heat losses from a cylindrical cavity receiver employed in a solar parabolic dish collector. Simultaneous energy and exergy equations are used for a thermal performance analysis of the system.*

**Keywords***: Energy, Parabolic collector, Energy analysis, exergy analysis, receiver, radiative heat loss, convective heat loss.*

## 1. INTRODUCTION

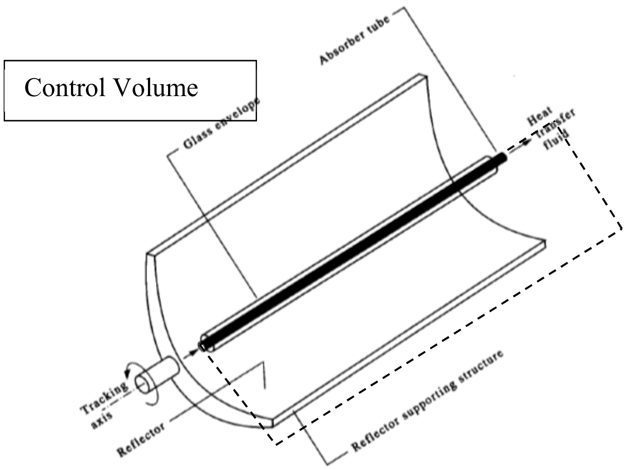
Solar energy is very large, inexhaustible source of energy. The power from the sun intercepted by the earth is approximately $1.8 \text{ X } 10^{11}$ MW which is many thousands of times larger than the present consumption rate on earth of all commercial energy sources. Thus, in principle, solar energy could supply all the present and future energy needs of the world on a continuing basis. This makes it one of the most promising of the unconventional energy sources. In addition to its size, solar energy has two other factors in its favour. First unlike fossil fuels and nuclear power, it is an environmentally clean source of energy. Second it is free and available in adequate quantities in almost all parts of the world where people live.

A cylindrical parabolic trough is a conventional optical imaging device used as a solar concentrator. It consists of a cylindrical parabolic reflector and a metal tube receiver at its focal plane. The receiver is blackened at the outside surface and is covered by concentrator and rotated about one axis to track the sun's diurnal motion. The absorber tube may be made of mild steel or copper and reflectors may be of anodized aluminium sheet, aluminium mylar or curved silvered glass. Also evacuated chamber is created to reduce the loss of heat and reduce the corrosion of concentrator surface The heat transfer fluid flows through the absorber tube, gets heated and thus carries heat. The temperature of the fluid reaches up to 400ºC. The thermal losses of a solar cavity receiver include the conduction heat loss through the cavity insulation and convection and radiation heat losses from the cavity to the ambient air. The conduction heat loss depends on the receiver temperature and the thermal properties of insulation material, the radiation heat loss depends on the receiver wall temperature, the shape factors, and emissivity of the receiver walls. There are too many factors that influence the convection heat loss of cavity receivers: the inclination and the geometry of cavity, the external wind conditions around the cavity, and the air temperature within the cavity.

Many experimental and analytical studies have been done on convection heat loss from cylindrical receivers.

A model was proposed by Koenig and Marvin [3], which was appropriate for a receiver temperature between 550 and 900 .C. Stine and McDonald [1] proposed an explicit model to consider the combined effects of operating temperature, tilt angles, and aperture size. Leibfried and Ortjohann [2] modified the Stine and McDonald model. In their study, the effect of wind on receiver losses for an upward-facing cavity is investigated. Lovegroveet al. [4] studied the heat losses from cavity receivers that are employed in solar parabolic dishes. A numerical investigation of natural and combined convection heat loss from cavity receivers was done by Paitoonsurikarn and Lovegrove [5]. Paitoonsurikarn et al. [6] accomplished a numerical investigation of natural and combined convection heat loss from cylindrical cavity receivers employed in solar parabolic dishesIn another research, Paitoonsurikarn and Lovegrove [7] studied the interaction between the wind and the dish structure.

## 2. EXPERIMENTAL SETUP AND DESCRIPTION :




The main components of parabolic trough solar collector system are:

1) **Reflector:** A parabolic reflector reflects and concentrates all the sun's rays to the receiver tube which is at the focal point of the parabola. The reflectors are parabolic shaped mirrors with a reflectivity of 96%.

2) **Absorber tube**: An absorber tube is a linear receiver located at the focus line of parabolic reflective surface at the focus line of parabolic reflective surface, with means of transferring the absorbed solar energy to a heat transfer fluid.

3) **Glass cover tube:** A concentric tubular glass cover surrounding the absorber with a gap of 1-2 cm with glass to metal seal to create vacuum so as to minimize the conduction, convection, and radiation losses. Evacuated glass tube also used which reduce heat losses more efficiently than the simple glass tube.

4) **Support structure:** Steel supported structure is there in the back of the reflector mirror so as to provide strength to the collector so as to provide mechanical strength to the collector to withstand the wind loads.

5) **Tracking mechanism:** In a Tracking mechanism the trough is usually aligned on a north-south axis, and rotated to track the sun as it moves across the sky each day. Alternatively the trough can be aligned on an east-west axis; this reduces the overall efficiency of the collector, due to cosine loss, but only requires the trough to be aligned with the change in seasons, avoiding the need for tracking motors.

## 3. ENERGY AND EXERGY ANALYSIS:

The direction of wind is an essential and important factor and plays a large role in determining the heat loss from solar receivers. For steady-state conditions, the energy balance for the cylindrical receiver (control volume shown in Figure) can be written as:

$$\eta_o I_b A_c + \dot{m} c_p (\text{Tin} - \text{Tout}) - Q_{l,conv} - Q_{l,rad} = 0 \quad (1)$$

For an isothermal wall condition, the receiver emissivity is constant and the entire inner surface of the receiver can be considered as a single surface and the surrounding as a second surface. The rate of radiation heat loss can be estimated from the following equation :

$$Q_{l,rad} = \epsilon_{eff}\, \sigma A_{r,ap} (T_w^4 - T_a^4), \quad (2)$$

The effective emissivity is based on the total surface area of the receiver and is given by [8]

$$\epsilon_{eff} = \frac{1}{1 + (\frac{1-\epsilon}{\epsilon}) \frac{A_{r,ap}}{A_{r,w}}} \quad (3)$$

By combining (1) and (2), the energy balance for receiver can be rewritten as

$$\eta_o I_b A_c + \dot{m} c_p (\text{Tin} - \text{Tout}) - U_l A_{r,ap} (T_w - T_a) + \epsilon_{eff}\, \sigma A_{r,ap} (T_w^4 - T_a^4) = 0 \quad (4)$$

Here, it is assumed that the receiver wall is isothermal and all elements of the receiver's inner surface have the same temperature. In (4), two unknown parameters exist: the receiver wall temperature Tw and the convection overall heat transfer coefficient $U_l$.So,to define the total rate of heat loss from the receiver, we need another equation. By applying the second thermodynamic law at steady-state condition for selected control volume shown in Figure, the rate of total convection heat loss can be defined. The steady-state exergy balance for the control volume is given by

$$\sum \dot{E}_{in} - \sum \dot{E}_{out} - \sum \dot{E}_{loss} - \sum \dot{E}_{des} = 0 \quad (5)$$

For the control volume shown in Figure, the input exergy rate includes the exergy flow rate coming from the Heat transfer fluid and exergy rate of solar irradiance that is re_ected from the concentrator to the receiver. The total rate of exergy input is

$$\sum \dot{E}_{in} = [\dot{m} C_p (T_{in} - T_o - T_o \ln \frac{T_{in}}{T_o}) + \frac{m \Delta \dot{P}_{in}}{\rho}] + \Psi \eta_o I_b A_C \quad (6)$$

Until now, many studies have been conducted to investigate the amount of work available from radiation reservoirs [9–14]. The Petela–Landsberg e_ciency corresponds to the fully concentrated radiation (i.e., a geometric factor of the radiation source $f_H$ = 1 in the notation of [10], which means the concentration ratio is about 46 000). The appropriate equation to calculate the amount of Ψ in this study is given by [10]

$$\Psi = 1 - \frac{4T_o}{3T_s} + \frac{1}{3f_H}\left(\frac{T_o}{T_s}\right)^4 \quad (7)$$

where Ts is the black-body sun temperature and is considered to be about 5800 K [15]. The geometric factor is given by the following equation [10]:

$$f_H = \frac{\Omega}{\pi}(1-\frac{\Omega}{4\pi})\cos(\theta_o), \quad (8)$$

The solid angle is given by [10]:

$$\Omega = 2\pi(1\text{-}\cos\delta), \quad (9)$$

where $\delta$ is the half-angle of the cone subtending the concentrator when viewed from the receiver.

The exergy output rate only includes the exergy rate of heat transfer fluid outflow from the solar receiver and is calculated by

$$\sum \dot{E}_{out} = \dot{m}C_p(T_{out}\text{-}T_o\text{-}T_o\ln\frac{T_{out}}{T_o}) + \frac{m\Delta\dot{P}_{out}}{\rho} \quad (10)$$

For the control volume shown in Figure 1, the rate of exergy losses is due to heat transfer losses from the solar receiver to the ambient. Therefore, the total rate of exergy losses is given by [27]

$$\sum \dot{E}_{loss} = \dot{Q}_{loss}(1\text{-}\frac{T_o}{T_w}), \quad (11)$$

In the solar receivers, the exergy destruction is caused by two mechanisms: exergy destruction due to heat transfer fluid pressure drop through the receiver and exergy destruction due to heat transfer from high to low temperatures[16]. The rate of exergy destruction due to heat transfer fluid pressure drop is as follows [17]:

$$\dot{E}_{des,\Delta p} = T_o\frac{\dot{m}\Delta p}{\rho}\frac{\ln(T_{out}/T_{in})}{T_{out}-T_{in}}, \quad (12)$$

In such systems, the exergy destruction due to heat transfer from high to low temperatures includes exergy destruction due to solar energy absorption by receiver and exergy destruction due to heat conduction from the receiver wall to the heat transfer fluid.

$$E_{des,abs} = \dot{m}C_p(T_{out} - T_{in})T_o(\frac{1}{T_W} - \frac{1}{T_S}) \quad (13)$$

$$E_{des,cond} = \dot{m}C_pT_o(ln\frac{T_{Out}}{T_{in}} - \frac{T_{out}-T_{in}}{T_W}) \quad (14)$$

By combining the energy equation (4) and exergy equation (5),(6),(10),(11),(12),(13) and (14) , two unknown parameters can be obtained: the average receiver wall temperature $T_w$ and the overall convective heat transfer coefficient $U_l$.

## 4. ENERGY LOSSES FROM SOLAR THERMAL CAVITY RECEIVER:

The thermal losses of a solar cavity receiver include convective and radiative losses to the air in the cavity and conductive heat loss through the insulation used behind the helical tube surface. Convective and radiative heat losses form the major constituents of the thermal losses. The radiative loss is dependent on the cavity wall temperature, the shape factors and emissivity/absorptivity of the receiver walls while conduction is dependent on the receiver temperature and the insulation material. The radiative and conductive losses are independent of the cavity inclination. The convective heat loss depends on the air temperature within the cavity, the inclination of the cavity and the external wind conditions, thus making the phenomenon complex.

## 5. CONCLUSIONS

Solar thermal cavity receiver is important component in cylindrical concentrating collector power system and subject to detailed research. The efficiency of the whole system depends on various parameters viz., type of cavity receiver, geometry of cavity receiver, the orientation of cavity, the size and position of cavity receiver etc.

One of the most important issues in thermal performance analysis of solar receivers is heat loss estimation, which plays a key role in accurate design of solar receivers and consequently system cost-effectiveness. The heat is lost from the receivers by three mechanisms: conduction through receiver insulation, convection, and radiation through the receiver's inner surface. In most cases, the conduction heat loss is negligible due to proper insulation and the radiation heat loss can be estimated analytically. The convection heat loss is the most complicated phenomenon in thermal analysis of solar receivers and yet is a major contributor for researchers. In presence of wind, it is more complicated and important.

In this study, the heat loss from a cylindrical receiver that is employed in a cylindrical parabolic concentrator was investigated. In thermal analysis, the isothermal receiver wall condition was assumed and the average receiver wall temperature was found by simultaneous energy and exergy analyses. The effects of operational parameters, such as heat transfer fluid mass flow rate and wind speed, and structural parameters, such as receiver geometry and inclination, on convective heat loss, were investigated.

## 6. NOMENCLATURE

$\eta_o$ Optical efficiency

A Aperture area ($m^2$)

$Q_l$ rate of total heat losses from receiver to the surrounding (W)

$I_b$ Global solar irradiance intensity per unit concentrator area (W/m2)

$\dot{m}$ Heat transfer fluid mass flow rate (kg/s)

$C_p$ Heat transfer fluid heat capacity (kJ/(kg - K))

T Temperature (K)

$T_S$ Black body temperature of the sun (K)

$\Delta P$ Pressure difference (Pa)

$\dot{E}$ Exergy rate (W)

$f_H$ Geometric factor

$U_l$ Overall heat transfer coefficient (W/(m2 - K))

*Subscripts*

t Thermal

r Receiver

ap Aperture

w Wall

a Ambient

out Outlet

in Inlet

eff Effective

0 Reference condition

rad Radiation

conv Convection

*Greek letters*

$\in$ Emissivity

$\sigma$ Stefan–Boltzmann constant (W/(m2 - K4))

$\Psi$ Maximum useful work available from radiation

$\theta_o$ Zenith angle (degree)

$\Omega$ Solid angle subtended by the mirrors

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