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Thermal losses in central receiver solar thermal power plant

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Abstract. Central receiver solar thermal power plant with high temperatures is innovative technology for sustaining ecological thermal power generation. The mathematical modeling and simulation of central receiver solar power plant with cavity receiver is done in this paper to predict the thermal power losses from cavity receiver. Results obtained are verified with evidence from solar experiments. A tool is developed with the help of Visual basic to use weather data for simulation. Hitec salt is used as heat transport fluid to obtain high temperatures upto 550°C and is used to produce steam which drives the turbine. Simulation of plant allows to study the performance of entire power plant prior to its actual construction and is done for 10 MWe central receiver solar power plant. The receivers efficiency in absorbing and transferring solar energy to the working fluid is critical in the central receiver concept since plant performance, capital cost and ultimately the cost of energy produced are significantly affected by the receiver’s efficiency. The thermal losses including loss due to convection and radiation losses are considered in the cavity receiver of power plant. Results are obtained for generation of power with change in hourly weather data of Jaipur. From hourly simulation, the thermal losses throughout the day, i.e. in the morning, afternoon and evening are determined for the day receiving the highest solar radiation. Monthly thermal losses and hence power generation under the climatic conditions of Jaipur can be predicted throughout the year.

1. Introduction

In a central receiver solar thermal power plant, solar radiation is concentrated on a tower mounted receiver by the use of large mirrors called heliostats. Heat transport fluid flowing through the receiver tubes gets heated up by absorbing the incident energy on the receiver and is used to produce steam which drives the turbine. The individual thermal losses including conduction losses, radiation losses and convection losses play important role in determining receiver efficiency and hence annual power generation. A model is developed for simulation of central receiver power plant. The radiation and convection losses account for most of the receiver thermal losses resulting from the calculation. They are evaluated in the receiver simulation model. According to meteorological data [8], Rajasthan state receives with the highest value of solar radiation in India. Weather data of Jaipur, a city of Rajasthan is considered as input for simulation.
2. Cavity Receiver

Fig.1 shows the cavity receiver. In a cavity receiver, the solar radiation reflected from heliostats passes through an aperture into a close structure; this structure and aperture define the cavity [1]. The active heat transfer surfaces in cavity receiver are similar to those in external receiver; however, the panel arrangement, within a cavity is concave facing the heliostats. Other internal areas of the cavity, such as the roof and floor, do not normally serve as active heat absorbing surfaces. These areas are insulated to minimize heat losses. The active panel area and inactive internal surface area are each two to three times the area of aperture.

3. Modelling of cavity receiver

Model is developed for determining thermal performance of cavity receiver. It is assumed that incident solar radiation is distributed uniformly on the absorber tubes of cavity surface [4]. The thermal power losses by radiation and convection are determined using the formulae in coming section and hence net thermal power can be calculated by deducting from power absorbed by the receiver.

3.1. Thermal Power absorbed by receiver

Thermal Power absorbed by receiver is determined by the incident solar radiation falling on the area of heliostats and entering into the aperture of cavity receiver. Here, all the radiation is not absorbed. Optical efficiency and absorptivity of the receiver material are taken into consideration in determining the power absorbed by the receiver.

3.2. Thermal power loss by radiation from the receiver

The radiation loss is caused by infrared radiation, which is emitted from the receiver walls to the environment. Thermal power lost by radiation is determined by Stefan Boltzman equation

\[ P_{\text{RL}} = \varepsilon \sigma (T_R^4 - T_a^4)A \]

where, \( \sigma = \) Stefan Boltzman Constant = \( 5.67 \times 10^{-8} \) W/m².K⁴
\( \varepsilon = \) Receiver surface emissivity
\( T_R = \) Receiver surface temperature in K
\( T_a = \) Ambient air temperature in K
\( A_p = \) aperture area for cavity receiver in m²

Solar radiation is converted into heat by the solar receiver with efficiency \( \eta \). Fig. 2 shows that, efficiency of solar receiver does not increase steadily with receiver temperature continuously [7]. Receiver efficiency reaches a maximum value and then decreases after a certain point, as the amount of energy it cannot absorb (loss by radiation) grows by the fourth power as function of temperature. Hence there is a maximum reachable temperature. By means of fluid flow rate variation, the temperature of receiver can be adjusted to produce maximum work.
Fig. 2 Efficiency of solar receiver at different temperature for different concentration ratios

Efficiency is given by,

\[ \eta = \frac{P_R - P_L}{P_{in}} \quad \text{....(2)} \]

\[ \eta = \frac{\alpha P_{in} - P_L}{P_{in}} \quad \text{....(3)} \]

The losses are assumed to be only radiative losses as the temperatures are very high.

Applying Stefan-Boltzmann law, the thermal power reradiated is given by [2]

\[ P_{RL} = A_R \varepsilon \sigma T^4 \]

\[ \eta = \frac{\alpha \eta_{helio} ICA_R - A_R \varepsilon \sigma T^4}{\eta_{helio} ICA_R} \quad \text{......(4)} \]

Assuming emissivity and absorptivity to be maximum i.e. \( \varepsilon = 1, \alpha = 1 \) and also with maximum optics efficiency of 1, above equation is simplified, therefore

\[ \eta = \frac{ICA_R - A_R \sigma T_R^4}{ICA_R} \]

\[ \eta = \left(1 - \frac{\sigma T_R^4}{I_C} \right) \quad \text{...(5)} \]

From Fig. 2, it can be seen that, at maximum reachable temperature, efficiency is zero. Therefore,

\[ T_{Rmax} = \left( \frac{I_C}{\alpha} \right)^{0.25} \quad \text{...(6)} \]

There is a temperature, \( T_{opt} \) for which the efficiency is maximum, i.e. when the efficiency derivative relative to the receiver temperature is null [7].

\[ \frac{d\eta}{dT}(T_{opt}) = 0 \quad \text{...(7)} \]

Solving this equation numerically, optimum temperatures of receiver, for its corresponding maximum temperatures are obtained according to concentration ratio as shown in Fig. 3 and some available values of optimum and maximum temperature are shown in Table No.1 [7].

Table No.1 Available maximum and optimum temperatures

| Sr. No. | Tmax | Topt |
|---------|------|------|
| 1       | 1720 | 970  |
| 2       | 2050 | 1100 |
| 3       | 3060 | 1500 |
| 4       | 3640 | 1720 |
| 5       | 5300 | 2310 |
Multiple regression analysis using MS Excel is applied to these available values of TRmax and TRopt. An equation is obtained in order to get optimum temperature values of the receiver for corresponding maximum temperature. Following equation is obtained giving the relation between optimum temperature and maximum temperature of the receiver.

\[ T_{opt} = 0.375 \times T_{max} + 337.35 \]  

...(8)

Receiver temperature TR is taken as the optimum temperature of the receiver.

### 3.3. Thermal power loss by convection from the receiver

Thermal power lost by convection \( P_{CVL} \) is calculated by

\[ P_{CVL} = hA(T_R - T_a) \quad \text{...(9)} \]

where \( A \) is the area of cavity in m\(^2\)

\( T_R \) = Receiver temperature in Kelvin

\( T_a \) = Ambient temperature in Kelvin

\( h \) = Mixed convection heat transfer coefficient in W/m\(^2\)K

Siebers [3] recommended an equation for correlating and estimating mixed convection heat transfer data by following expression :

\[ h = h_{forced} + h_{free} \quad \text{...(10)} \]

Heat transfer coefficient for forced convection i.e. \( h_{forced} \) is obtained by estimating the convective heat transfer coefficient for the receiver as if only pure forced convection occurs. The term \( h_{free} \) is obtained by estimating the convective heat transfer coefficient for the receiver as if only pure natural convection occurs. The value of exponent \( n \) in equation is based on results of experimental study of mixed convection from a vertical, flat high temperature surface parallel to a horizontal flow of air by Siebers [3].

For obtaining the heat transfer coefficient \( h \), the dimensionless numbers - Reynolds Number (forced convection), Grashof Number (free convection) and Nusselt Number (forced convection and free convection) are calculated as follows [3]

Mean temperature of the receiver (\( T_m \)) in K = \((T_R + T_a)/2\)  

...(11)

Properties of air are taken at different temperatures from property table of air given in [11]. Multiple regression analysis is done using MS Excel and is applied to property table of air. The following relations for thermal conductivity and kinematic viscosity of air at different temperatures are obtained.

Thermal conductivity \( k \) in W/mK = 0.0000583812\( T_m \)  

...(12)

Kinematic viscosity \( \nu_m \) in m\(^2\)/s = 0.000000166567\( T_m \) - 0.0000363676  

...(13)

The coefficient of thermal expansion, \( \beta = 1/T_m \), where \( T_m \) is in Kelvin  

...(14)

Reynolds Number = \( Re = \frac{vel \cdot D}{\nu_m} \)  

...(15)

Where, \( D \) = Diameter of receiver in m.

\( vel = \) Mean velocity of wind in m/s

\( \nu_m = \) kinematic viscosity of fluid in m\(^2\)/s

Nusselt Number for forced convection (\( Nu_{forced} \)) = 0.00239 \( Re \)\( 0.98 + 0.000945 \) \( Re \)\( 0.89 \).  

...(16)

This correlation is valid for Reynolds number between \( 3.7 \times 10^4 \) and \( 10^7 \)

Heat transfer coefficient for forced convection (\( h_{forced} \)) = \( (\pi/2) \times \frac{Nu_{forced} \cdot k}{D} \)  

...(17)

Grashof Number (\( Gr \)) = \( \left( \frac{g\beta(T_R - T_a)H^3}{\nu_m^2} \right) \)  

...(18)

Where \( g = \) acceleration due to gravity = 9.81 m/s\(^2\)

\( H = \) Height of the receiver in m.
Nusselt Number for free convection = \( N_{ufree} = 0.098 Gr^{0.333} \left( \frac{T_a}{T_R} \right)^{0.14} \) ...(19)

Heat transfer coefficient for free convection \( (h_{free}) \) for rough surface = \( (\pi/2) \frac{N_{ufree} k}{H} \) ...(20)

4. Simulation

Modelling and simulation of cavity receiver is done by using the computer code developed in Visual Basic. The software uses the formulae mentioned in article 2 for calculations. The results obtained from software are verified using the results obtained from International Energy Agency Small Solar Power Systems (IEA SSPS), Almeria, Spain for cavity receiver having heat transport fluid as sodium with output power of 2.5 MWth. The receiver in IEA SSPS was north facing cavity type, having a vertical octagonally shaped aperture. The aperture area is 9.7 m\(^2\) and total cavity area is 62 m\(^2\). The absorber panel is a 120\(^\circ\) segment of a circular cylinder of 4.5 m diameter and height of 3.6 m giving an active surface area of 17 m\(^2\). Sodium enters the inlet at 270\(^\circ\)C and exists through outlet at 530\(^\circ\)C. The location of the absorber panel inside cavity is such that the peak heat flux density is about 0.63 MW/m\(^2\), with 0.16 MW/m\(^2\) as average value. The results showed that, input power to the receiver was 2.8 MW\(_{in}\) and output was 2.4MW\(_{out}\), the total heat loss due to radiation and convection being 0.4 MW\(_{th}\). Results with variation of 13% were obtained for the above mentioned input values, using the developed software, thus verifying the same.

Hourly weather data obtained from the National Renewable Energy Laboratory (NREL) website for one of the cities of Rajasthan (state receiving highest solar radiation), namely Jaipur, is taken for simulation of cavity receiver. Here day of 27\(^{th}\) Feb receiving the highest solar radiation is taken for study. Weather data shows that incident solar radiation is maximum at 13.00 Hr and wind velocity is maximum at 15.00 Hr on 27\(^{th}\) Feb. Calculations of thermal losses is done for entire day. The thermal losses obtained are shown in Fig.4. It can be observed from Fig.No.4, that radiation loss is maximum at 13.00 Hr. Convection loss is maximum at 15.00 Hr as convection loss mainly depends upon wind velocity. It also shows that total thermal loss is maximum at 15.00 Hr. From Fig.No.5, it is observed that the thermal power absorbed is maximum at 13.00 Hr, thermal loss is maximum at 15.00 Hr and net thermal power obtained is maximum at 12.00 noon.

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Fig. 4 Variation of thermal power loss due to radiation and convection

Fig. 5 Variation of thermal power absorbed and net power obtained
5. Conclusion

Mathematical modelling is done and a computer code is developed for the simulation of central receiver solar thermal power plant using Visual Basic 6. In terms of receiver area, in cavity receiver, radiation losses depend on the size of aperture of cavity, whereas convection losses depend upon the cavity area. Convection losses are a combination of natural convection and forced convection. The simulation made for whole day shows that maximum amount of power is obtained during afternoon as the incident flux is highest in the afternoon. As the flux intensity increases, the net power absorbed by the receiver increases but as there is increase in losses, net power generated and the overall efficiency of the receiver is almost constant. The solar radiation received is less in the months of June, July and August due to rainy season. Hence, it is observed from Fig.No.6 & 7 that thermal power absorbed is also less in these months. Net thermal power produced is approximately 70% of the thermal power absorbed by the plant.

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