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Research Article

Analysis of Cylindrical Cavity Receiver for Different Heat Losses

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ABSTRACT

The heat losses are mainly affects on the performance of cavity receiver of solar concentrator. In this paper, the experimental and numerical study is carried out for different heat losses from cylindrical cavity receiver of 0.35 m cavity diameter and 0.55 m opening diameter with wind skirt. The total and convection losses are studied experimentally to no wind conditions for the temperature range of 60 °C to 80 °C at 0°, 25°, 50°, 75° and 90° inclination angle of cavity receiver .The experimental set up mainly consists of cylindrical cavity receiver which is insulated with glass wool insulation to reduce the heat losses from outside surface.. The numerical analysis was carried out with Fluent Computational Fluid Dynamics (CFD) software, to study connective heat losses for no wind condition. The numerical results are compared with experimental results and found good agreement with maximum deviation of 13%. The effect of inclination angle of cavity receiver on total losses & convection losses shows that as the inclination angle increases from 0° to 90°, both losses decreased due to decreased in convective zone into the cavity receiver. The effect of operating temperature of cavity shows that as the temperature of cavity receiver increases, the total and convective losses goes on increasing. The present results are also compared to the convective losses obtained from M. Prakash. The convective loss from M. Prakash shows nearest prediction to both experimental and numerical results.

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1. Introduction

The performance of cavity receiver of solar concentrator depends on different heat losses of cavity. Therefore by minimizing the losses, the efficiency of cavity receiver can be improved. So many researchers have worked to investigate heat losses from different geometries of cavity receiver to reduce the heat losses. Harris & Lenz [1] analyzed cavity receiver for energy loss mechanism. They studied five different shaped cavity geometries for system efficiency and found that cavity geometry has very little effect on system efficiency. T. Taumoefolau et al. [2] investigated natural convection heat losses experimentally from electrically heated cylindrical cavity receiver with different orientation of cavity. They also carried out numerical analysis by using CFD software and found good agreement with experimental results. U. Leibfried & J. Ortjohann [3] conducted experimental study for convective heat losses from downward and upward facing cavity receiver of solar concentrator. They studied for spherical and hemispherical shaped cavity receiver geometries and also studied the effect of different opening ratio and operating temperature of cavity on convection heat losses. Stine & Mc Donald [4] studied experimentally convection heat losses for the effect of orientation of cavity, operating temperature of cavity and variation of aperture size. They also

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developed a correlation considering the effect of tilt angle, geometry and cavity temperature. M. Prakash et al. [5] analyzed three different cavity receivers for convective heat losses with the same heat transfer area. The analysis has done by using CFD software for the effect of different opening ratio at different operating temperature of cavity receiver and developed a generalized correlation for all cavity geometries to find convective losses. A.M. Clausing [6] studied the cavity receiver for convection loss by presenting analytical model. This model represents the importance of ability to heat air into cavity receiver and effect of wind on convective losses. This model validated by the same author [7] by conducting experimental study with square opening of cavity receiver. Koenig & Marvin [8] investigate the model for convection heat losses considering the high temperature of cavity receiver between 550 °C to 900 °C and developed an empirical correlation. P. Le Quere et al. [9] analyzed isothermal cubical cavity for natural convection to opening ratio 1 and at inclination from -90 to +90. They found large variation of nusselt number with experimental results. R.D. Jilte et al. [10] studied numerically combined natural convection & radiation heat losses for different shapes of cavity geometries.

S.Y. Wu et al. [11] conducted an experimental analysis for different heat losses to fully open cylindrical cavity considering different boundary conditions. M. Kim et al. [12] presented two-dimensional numerical simulation of natural convection into square enclosure. H.N. Kim et al. [13] conducted a test on three solar receivers for the thermal performance based on the concept of tubular receiver. A.M. Clausing et al. [14] carried out study of natural convection from cubical cavity with the combination of side facing opening. N. Sendhil kumar & Reddy [15] conducted numerical analysis for convection losses in a modified cavity receiver of solar concentrator. C.F. Hess & Henze [16] investigate the natural convection losses experimentally for horizontal rectangular open cavities at different inclination angles. He found that natural convection loss can be reduced up to 10% by using flow restriction at the aperture plane. Sajid Abbas et al. [17] studied the effect of the concentration ratio on the thermal performance of a conical cavity tube receiver for a solar parabolic dish concentrator system. Djelloul Azzouzi et al. [18] carried out an experimental and analytical thermal analysis of cylindrical cavity receiver for solar dish. Wang et al. [19] conducted optical efficiency analysis of cylindrical cavity receiver with bottom surface convex. Pawar et al. [20] carried out an experimental examination of a helically coiled conical cavity receiver with Scheffler dish concentrator in terms of energy and exergy performance. Martín-Alcántara et al. [21] carried out modelling the external flow of a novel HorseShoe receiver and the evaluation of thermal performance. K. S. Reddy and S. Kumar [22] used 2-D model to estimate convection loss from modified cavity receiver by assuming the uniform & peak solar flux distribution in to the receiver. They also studied combined natural convection and radiation numerically by using CFD software. R.Y. Ma [23] studied the effect of wind on convection heat loss from the cavity receiver of solar concentrator. He found that the convection losses are increased with increase in wind speed. M. Prakash et al. [24, 25] carried out investigation of heat losses from cylindrical cavity receiver with aperture diameter greater than cavity diameter. They also studied the effect of wind on total and convective losses for low temperature application. They carried out numerical analysis to determine the stagnation and convective zone by CFD software. V. C. Shewale et al. [26, 27] conducted experiments and computational evaluations of spherical cavity receivers for a different inclination angle of cavity receiver at different temperatures.

The study of heat losses from different cavity receivers of solar concentrator such as cylindrical, conical, spherical, cubical and elliptical has done by some researchers. The research and investigation of cylindrical cavity receiver is limited and no attempt has been made to study the heat losses from cylindrical cavity receiver for no wind conditions having aperture diameter is greater than the cavity diameter. Therefore there is need to investigate heat losses by considering the effect of different parameters on cavity receiver. Here copper tube material cylindrical cavity having cavity diameter 0.35 m and aperture diameter 0. 55 m with wind skirt is used to investigate different heat losses for no wind conditions which were not found in any previous study. In this paper, the heat losses are investigated from downward facing cylindrical cavity receiver for the temperature range of 60 °C to 80 °C at different inclination angle of cavity receiver.

2. Experimental set up and Analytical development

2.1. Details of Cavity Receiver

The front view of cylindrical cavity receiver used in the present investigation is shown in Fig. 1. The internal diameter of cavity receiver is 0.35 m and opening diameter is 0.55 m with wind skirt and has 46 numbers of turns of copper coil. The diameter of copper tube is 0.0012 m. A layer of glasswool insulation 150 mm thick are provided on the surface of cavity receiver and covered with aluminium cladding on outer surface to reduce the heat losses. The back side of cavity receiver is closed by small circular copper plate.

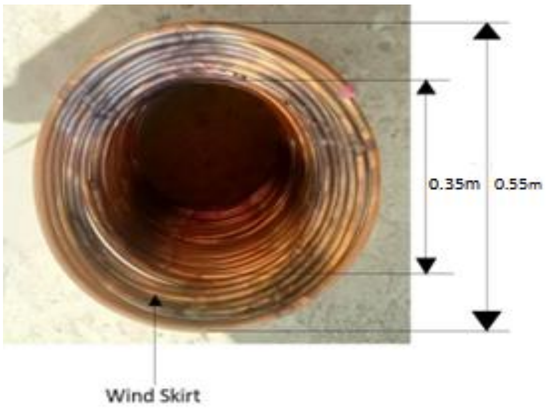

Figure 1. Front view of cylindrical cavity receiver

2.2. Experimental set up

The schematic diagram of experimental set-up is shown in Fig. 2, which is used for low temperature test from 60 °C to 80 °C. The set up mainly consists of a downward facing cylindrical cavity receiver supported by stand and angle adjustment mechanism is provided to incline the cavity at inclination angles 0°, 25°, 50°, 75°, & 90° with respect to horizontal. The hot water is used as a working fluid into the receiver tubes and a tank of capacity 140 liter having two numbers of heater (2 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 rotameter. The tube temperature of cavity receiver and air temperature into the cavity receiver are measured with 16 K-type thermocouples at different locations in to the cavity receiver. The fluid inlet & outlet temperatures are measured with two K-type thermocouples. The ambient temperature was measured from the location, where there is no effect of receiver temperature. Data acquisition system is used to record the data of temperature measurement. 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. All K-type thermocouples and rotameter used in the experimental set up for measurements are calibrated from laboratory. The error considered in the thermocouple reading is ±0.75 % for the temperature range of 60 °C to 80 °C, while the error considered in rotameter reading is ±3.5% for the measurement of mass flow rate 60 kg/hr.

In this experimental set-up the hot water is used as a working fluid and experiment is carried out at different inlet temperatures of hot water such as 60 °C, 70 °C & 80 °C. The inlet temperature of hot water and mass flow rate is kept constant for each test of experiment. 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. The direction of entry and exit of working fluid in to the cavity receiver is shown in Fig. 2. The tube temperature and air temperatures inside the cavity receiver and fluid temperatures are measured at an interval of 10 second by keeping the constant flow rate of hot water at 60 kg/hr. The readings are taken when steady state has reached and the heat losses are calculated at steady state condition.

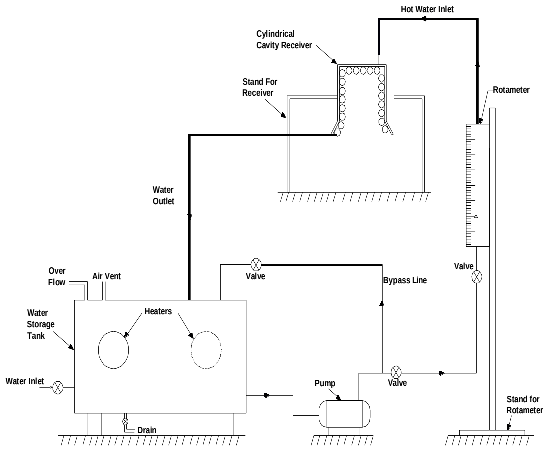

Figure 2. Experimental set-up

Figure 3. Actual photograph of set up

2.3. Analytical Development

The energy balance of cylindrical 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,

$$Q_{tot/\theta} = Q_{cond/\theta} + Q_{convec/\theta} + Q_{rad/\theta} \tag{1}$$

where $Q_{tot/\theta}$, $Q_{cond/\theta}$, $Q_{convec/\theta}$, $Q_{rad/\theta}$ 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

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

where, m is mass flow rate of water, C_p is specific heat of water, T_{fi} and 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 wooden plate which was insulated on all sides by mineral wool to prevent the convective & radiative heat losses from the opening of cavity receiver. Then the tests are conducted for fluid inlet temperature 60 °C, 70 °C & 80 °C at 90° inclination angle of cavity receiver. The loss obtained from these tests is conductive loss at these temperatures for cavity receiver.

$$Q_{cond/openingcloed} = mC_p(T_{fi} - T_{fo}) \tag{3}$$

The Radiation loss through the opening of cavity receiver is calculated theoretically by using the following equation at 90° inclination angle of cavity receiver.

$$Q_{rad/theoreticlly} = \in A_{op}\sigma\left(T_m^{\ 4} - T_a^{\ 4}\right) \tag{4}$$

where, $\in$ 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

$$Q_{convec/\theta} = Q_{tot/\theta} - Q_{cond/\theta} - Q_{rad/\theta} \tag{5}$$

The Nusselt number is calculated to the values of convective losses for no wind condition. The fluid inlet temperatures of 60 °C to 80 °C are used to calculate the Nusselt number for all inclination angle of cavity receiver.

$$Nu = \frac{h_{op}d}{k} \tag{6}$$

where, h_{op} is heat transfer coefficient based on opening area and d is opening diameter of cavity receiver. The heat transfer coefficient based on the opening area of cavity receiver is given by the following equation.

$$h_{op} = \frac{Q_{convec/\theta}}{(T_m - T_a)A_{op}} \tag{7}$$

where, $Q_{convec/\theta}$ is convective heat loss at cavity inclination θ and A_{op} is opening area of cavity receiver. It is noticed that the Nusselt number goes on increasing with decrease in inclination angle of cavity receiver. The highest Nusselt number is found at 0° inclination angle of cavity receiver while the lowest Nusselt number is found at 90° inclination angle of cavity receiver.

3. Numerical Analysis

All The numerical analysis is carried out for cylindrical cavity receiver and the simulations are completed to convective heat loss analysis for no wind condition only. The inputs for cavity receiver analysis are the fluid inlet temperature and mass flow rate of fluid. The geometry of cavity receiver and mesh were created using ANSYS ICEM-15.0. Fig.4 shows the cavity receiver model. The grid independence study has been carried out with fine grid for the cylindrical cavity receiver and coarse grid for cubical enclosure. The total number of cells has been fixed approximately 2.1 million tetrahedral cells in cylindrical cavity receiver and 0.5 million hexahedral cells in cubical enclosure. Boussinesq approximation is used for air properties as the tests are carried out for low temperature. In this analysis, for the cavity external wall the isothermal condition is assumed and walls of enclosure are maintained at atmospheric temperature.

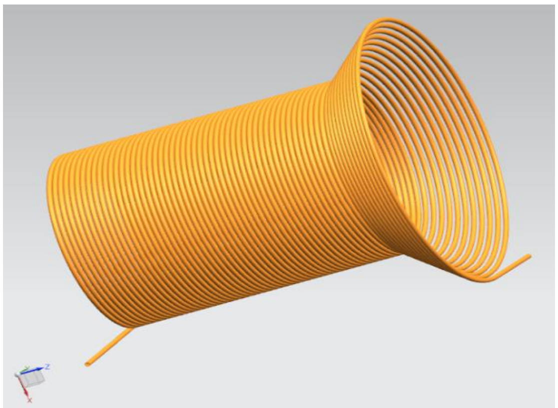

Figure 4. Model of cavity receiver

The solutions are getting by solving continuity, momentum and energy equations simultaneously. The steady state and 3-D governing equations are solved in ANSYS FLUENT 15 using an implicit solver. For pressure velocity coupling, semi-implicit pressure linked equation “SIMPLE” algorithm has been used. The discretization of momentum and energy was carried out using second order upwind scheme. The minimum convergence criteria were set at 10^{-3} for continuity and velocity equations and 10^{-6} for energy equation. To obtain the heat transfer and flow solutions, the solver undertakes the iteration until the convergence criteria is satisfied.

4. Results and Discussion

4.1. Experimental Results

4.1.1. Total Heat Loss for No Wind Condition

Total and convection heat losses are measured for 60 °C, 70 °C and 80 °C operating temperature of cavity receiver for no wind condition at 0°, 25°, 50°, 75° and 90° inclination angle of cavity. This variation of total heat loss and convection heat loss of cavity receiver with inclination angles are shown in following figures.

Fig. 5 shows the variation of heat losses with inclination angle of cavity receiver for conduction, convection, radiation and total heat loss obtained by experimentally at 80 °C operating temperature of cavity receiver. The convection losses and total losses goes on decreasing with increase in cavity inclination angle from 0° to 90°, while the conduction losses & radiation losses were constant as they are independent on inclination angle of the cavity receiver. Fig.6 shows the variation of total heat loss with inclination angle to no wind condition which shows that heat losses are decreases with increase in inclination angle for operating temperature 60 °C, 70 °C and 80 °C of cavity receiver.

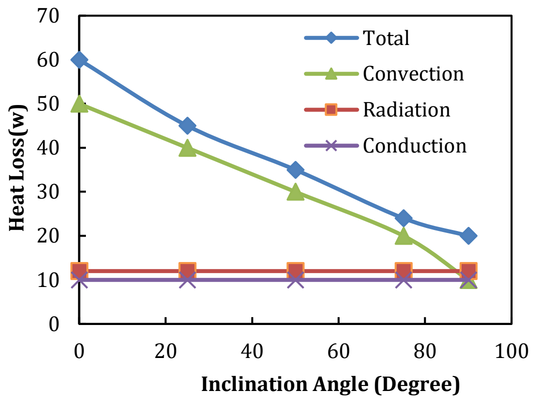

Figure 5. Variation of heat loss with inclination angle for no wind at 80 °C cavity temperature

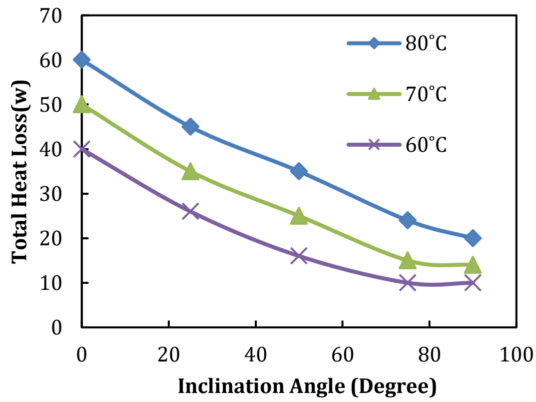

Figure 6. Variation of total heat loss with inclination angle for no wind condition

4.1.2. Convection Heat Loss for No Wind Condition

Fig. 7 shows the variation of convective loss with inclination angle to no wind condition for different operating temperature of cavity receiver. The maximum convective losses are found at 0° inclination and minimum convective losses are found at 90° inclination angle of cavity receiver. As maximum portion of cavity receiver volume being in stagnation zone and minimum portion of cavity receiver volume in convective zone, the convective losses decreases from 0° to 90° inclination angle. It was also observed that the convection losses are not completely zero as suggested by some models but found minimum at 90° inclination angle.

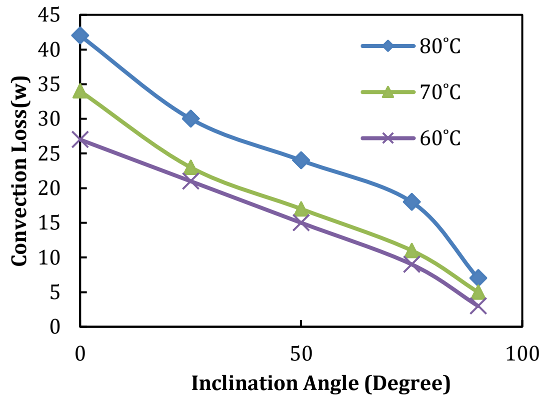

Figure 7. Variation of convection heat loss with inclination angle for no wind condition

4.2. Numerical Results

The convective losses obtained from numerical analysis for no wind condition are compared with experimental heat losses and found a good agreement with experimental results. In this analysis it is found that the maximum losses are obtained at 0° inclination angle of cavity receiver while the minimum losses are obtained at 90° inclination angle of cavity receiver. As cavity receiver is tilted from 0° to 90° inclination, the average air temperature in to the cavity receiver increases due to increases in stagnation zone. Therefore because of increase in average temperature of air in to the cavity, the temperature difference is reduced between the average temperature of air and inner surface of cavity. This causes less air current existence in to the cavity and reduces convective loss which is similar to the results observed by S. Paitoonsurikarn [29].

4.3. Comparison between Experimental Results, Numerical Results and Previous studies

The convective heat losses measured experimentally for no wind condition are compared with numerical results and the values obtained from correlation of previous study at 70 °C and 80 °C operating temperature of cavity receiver. Fig. 8 shows the comparison of convective losses at 70 °C cavity temperature and Fig. 9 shows the comparison of convective losses at 80 °C cavity temperature. Both figure shows the variation of convective loss with inclination angle of cavity for experimental results, numerical results & values from correlations of M. Prakash [5] in which the correlations of model shows the same dependence of convective heat loss on inclination angle with the present investigated results. The experimental result shows good agreement with numerical results for all temperatures with maximum deviation of 13% at all inclination angle of cavity receiver. M. Prakash model [5] shows higher side convective losses as compared to experimental and numerical results.

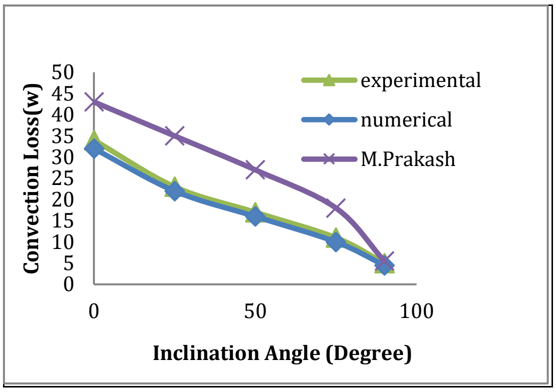

Figure 8. Comparison of convection heat loss at 70 °C cavity temperature

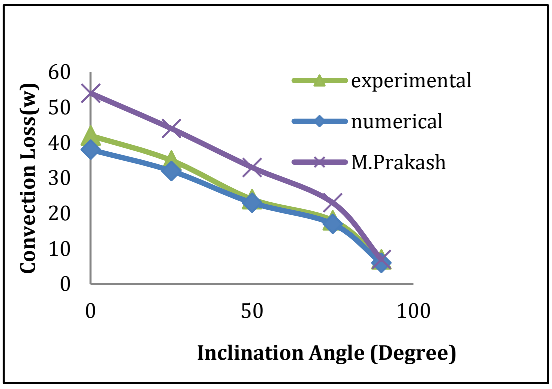

Figure 9. Comparison of convection heat loss at 80 °C cavity temperature

The deviations of convective loss for M. Prakash model [5] shows higher deviation for 0° to 25° inclination angle whereas lower deviation and close agreement for 25° to 90° inclination angle of cavity with the present results. The experimental results, numerical results and the values from correlation of M. Prakash model [5] are showing minimum convective losses at 90° inclination angle of cavity receiver.

Conclusions

In this paper, the experimental and numerical analysis is carried out to study the total and convective heat losses for no wind conditions. The temperature range used for the present investigation of heat losses is 60 °C to 80 °C. The effects of inclination angle of cavity receiver, inlet temperature of fluid on total and convective heat losses are studied for downward facing cylindrical cavity receiver. The cavity receiver is made up of copper tubing material having opening diameter greater than the cavity diameter. The experimental results are compared with numerical results for no wind condition at all inclination angle of cavity receiver and found good agreement. It is found that the highest heat losses are observed at 0° inclination angle and lowest heat losses are observed at 90° inclination angle of cavity receiver for no wind conditions. It is also found that as the mean temperature of cavity receiver increases, the heat losses of cavity receiver are also increases for no wind condition.

Nomenclature

A_{op}	Opening area of cavity receiver [m²]
C_p	Specific heat of working fluid [kJ/kg-K]
d	Opening diameter of cavity receiver [m]
D	Diameter of cavity receiver [m]
Gr	Grashoff number [-]
h_{op}	H.T.C on opening area of cavity [$Wm^{-2}k^{-1}$]
k	Thermal conductivity [$Wm^{-1}k^{-1}$]
Nu	Nusselt number [-]
$Q_{tot/\theta}$	Total heat loss at cavity angle θ [Watt]
$Q_{cond/\theta}$	Conduction heat loss at cavity angle θ [Watt]
$Q_{convec/\theta}$	Convection heat loss at cavity angle θ [Watt]
$Q_{rad/\theta}$	Radiation heat loss at cavity angle θ [Watt]
T_{fi}	Inlet temp. of fluid entering the receiver [°C]
T_{fo}	Outlet temp of fluid leaving the receiver [°C]
T_m	Mean temperature of working fluid [°C]
T_a	Atmospheric temperature [°C]

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Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this manuscript. In addition, the authors have entirely observed the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy.

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