# Effect of HTF flow direction on thermal performance in upward facing cavity receiver

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## Abstract

An analysis is carried out to examine the influence of heat transfer fluid (HTF) flow direction on thermal performance in an upward-facing cone-cylindrical receiver. The receiver is modeled as a cone-cylindrical helical coil receiver which is subjected to concentrated solar flux from a 60 sq.m. Scheffler parabolic dish. The receiver is inclined at an angle equal to 25˚. Therminol-55 is taken as the HTF flowing through the coil receiver. A numerical approach is adopted to evaluate the convective and radiative heat loss parameters from the coil receiver. These parameters are used to evaluate the thermal efficiency of the coil receiver for two-fluid flow configurations: a) Up-flow (bottom-to-mouth), and b) down-flow (mouth-to-bottom). It is observed that for the down-flow configuration, the mean coil temperature is lower than the upward flow configuration, resulting in reduced thermal losses and higher thermal efficiency up to 5-10% under different operating conditions. The results will help in designing optimal helical coil solar cavity receivers for medium and high-temperature decentralized power generation applications, and, industrial process heat

*Keywords: Solar, Cavity, Receiver, Helical Coil, Scheffler dish, Thermal performance, Industrial process heat*

## 1. Introduction

Solar dish concentrator systems have been seen as a promising technology for decentralized power generation, and industrial process heat for a long time. These systems are point focus systems and use a cavity receiver, placed at the focus, to absorb the reflected solar radiation. The most used dish concentrator systems are parabolic dish concentrators, where, a downward-facing receiver is attached to the dish where the incoming high-density solar flux is absorbed (Hafez et al., 2016). A HTF circulates across the walls of the receiver and absorbs heat from the receiver wall. The temperature range achieved in a parabolic dish system is ideal for applications like generating hot compressed air for air Brayton cycles and supercritical carbon dioxide (s-CO2) for closed Brayton cycles. However, it is difficult to connect high-pressure pipelines to a moving receiver mounted on a dish, as shown in Fig 1. One solution to overcoming this issue is to use another category of the parabolic dish which provides a static focus at the ground level, called the Scheffler Dish (Munir et al., 2010). This aids in the installation of high-pressure lines and can also be used in the form of multiple clusters for scaled-up CSP applications (India-One, 2010). To overcome these issues, Scheffler dish technology could be used as it has a static focus, as shown in Fig 2 (Munir et al., 2010). The Scheffler dish rotates about the polar axis to perform daily tracking while keeping the receiver fixed, as shown in Fig 3. The receiver has an upward-facing orientation and is kept inclined at an angle equal to the local latitude.

Various parameters for an upward-facing cavity receiver like cavity shape, aperture ratio, wind effect, etc. are previously analyzed (Leibfried and Ortjohann, 1995). However, one parameter that is still not looked at is the effect of the flow direction in the cavity receiver with thermic oil as the HTF. In this paper, a cone-cylindrical-shaped helical coil cavity receiver is subjected to concentrated solar flux from 60 $m^2$. Scheffler dish, and is analyzed to evaluate the thermal efficiency of the coil receiver for two-fluid flow configurations: a) Up-flow (bottom-to-mouth), and b) down-flow (mouth-to-bottom). During this analysis, the thermal performance for two flow configurations for a range of mass flow rates will be analyzed. This study will be very useful in designing helical coil solar cavity receiver for medium and high-temperature decentralized power generation applications, that uses an upward-facing dish concentrator technology.


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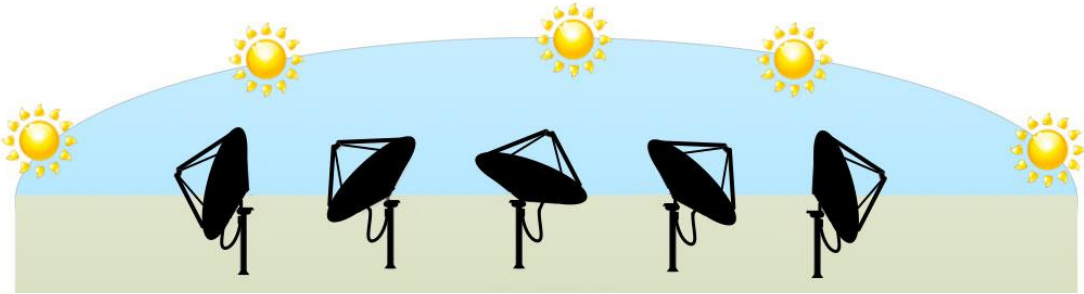


**Figure 1: Movement of the receiver with dish during day tracking**

**Figure 2: Scheffler Dish with static focus receiver**

## 2. System Description

An upward-facing cavity receiver is assumed under concentrated solar flux after reflection from a 60 $m^2$ Scheffler paraboloid reflector. The dimension of the Scheffler reflector in the current analysis is based on the dish used at the India One Solar Thermal Power Plant, Abu Road, India, as shown in Fig 4, and its dimensional details are shown in Table 1. Assuming no optical errors in the dish, ray tracing is performed for flux analysis of the cavity receiver, for which the reflector surface is discretized into $10^4$ points, and each point impinges with a solar ray. The position of the sun for this analysis is assumed to be at solar noon on equinox with a DNI value of 800 W/$m^2$. Each solar ray follows the trajectory wherein it first falls onto the dish surface, gets reflected and it then passes through the focus of the dish and finally hits the receiver, as shown in Fig 3.

The cavity receiver in the current analysis is assumed to have a cone-cylindrical shape, which is the most optimal shape in terms of thermal efficiency among the six shapes analyzed by Kumar et al (Kumar et al, 2018). The receiver is made of a helical coil, as shown in Fig 5, and its coil and tube dimensional details are shown in Table 2. The receiver is assumed to have an inclination of 25˚ (local latitude of Abu Road, India), which makes the normal vector from the receiver aperture parallel to the polar axis of the earth (the axis about which the Scheffler dish performs its day tracking operation). The receiver is positioned 375 mm behind the focus of the dish to ensure that all the solar flux is intercepted with no spillage. The schematic of the Scheffler Dish-cavity receiver system, shown in Fig 3, shows the effective aperture area of the Scheffler dish. The mathematical value of effective aperture area on equinox for a 60 $m^2$ Scheffler dish is evaluated using eq 1 and is found to be 43.72 $m^2$. For equinox, the declination angle is equal to zero and the shape of the aperture area is a circle.

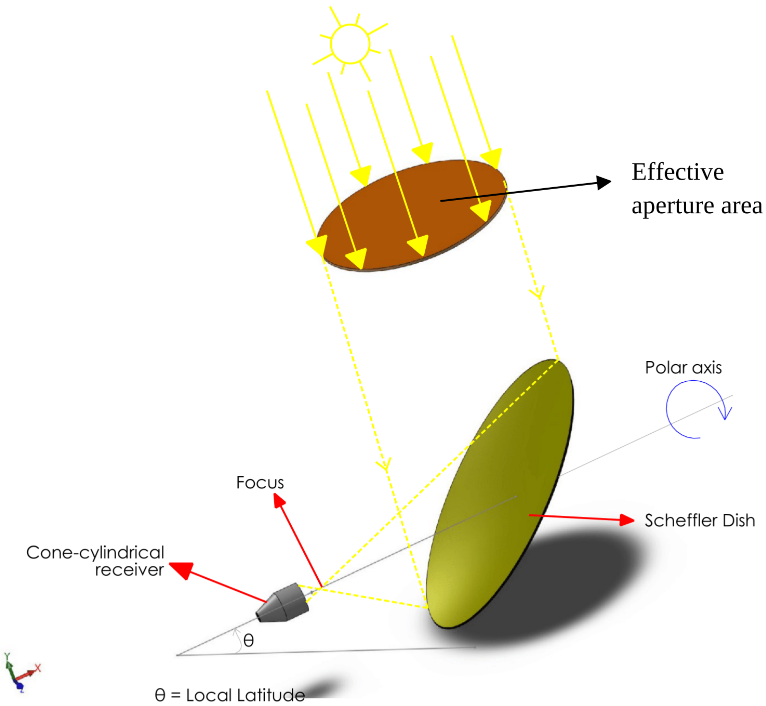
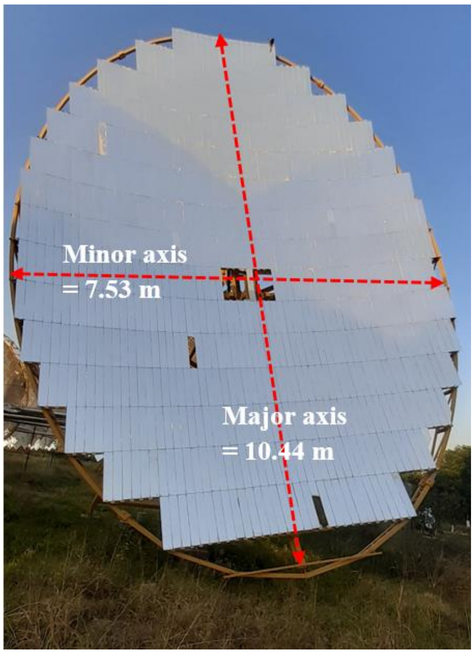
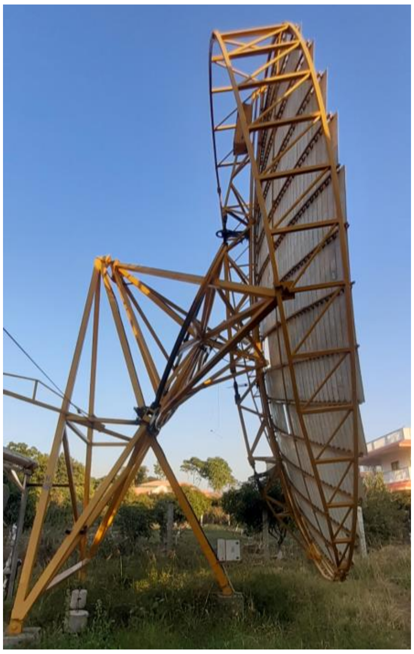



**Figure 3: Schematic of Scheffler dish-cavity receiver system**



**(a) Front View of Scheffler Dish** **(b) Lateral View of Scheffler Dish**
**Figure 4: Details of 60 m2 Scheffler Dish System**

**Table 1: Dimensional details of Scheffler Paraboloid Reflector at India-One**

| | |
|---|---|
| Focal Length | 3.79 m |
| Number of rectangular mirrors | 770 |
| Dimension of a rectangular mirror | 650 x 120 mm |
| Major axis of the elliptical outline of the dish | 10.44 m |
| Minor axis of the elliptical outline of the dish | 7.53 m |

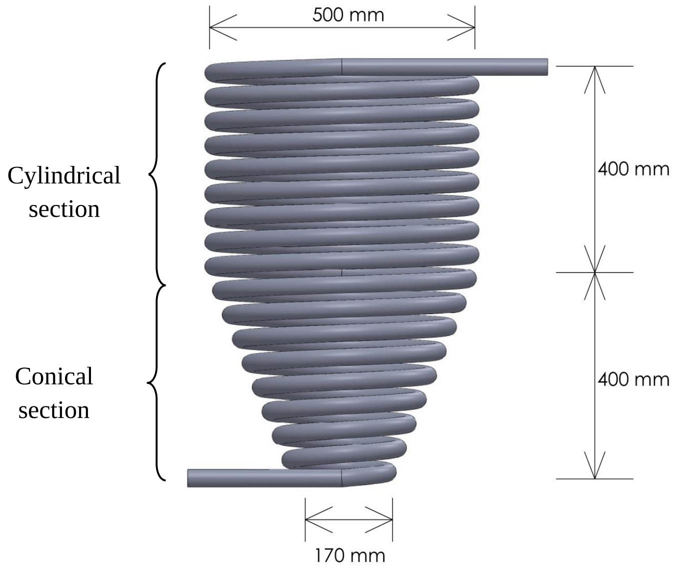



**Figure 5: Helical coil Cone-Cylindrical Receiver**

**Table 2: Dimensional detail of Cone-cylindrical receiver**

| | |
|---|---|
| Tube Outer Diameter | 33.4 mm |
| Tube Inner Diameter | 26.4 mm |
| Number of turns in coils | 17 |
| Pitch of coil | 47 mm |
| Ratio of Cone to Cylindrical section | 1:1 |
| Coil Diameter at bottom | 170 mm |
| Coil Diameter at Top | 500 mm |
| Coil Material | ASTM A 53-68 Welded & Seamless Steel Pipes |

$$Aperture\ Area = Reflector\ Area\ \cdot \{\cos\left(43.23^{\circ} - \frac{\delta}{2}\right)\} \quad \text{eq. (1)}$$

Where $\delta$ is the solar declination angle

In the current analysis, the aim is to analyze the effect of HTF flow direction on the thermal performance of the receiver. The two flow configurations are a) Up-flow, and b) Down-flow. In the Up-flow configuration, the cold HTF flows from the bottom of the receiver and exits the mouth of the receiver as hot HTF, whereas in the Down-flow configuration, the cold HTF flows from the mouth of the receiver, and exits as hot HTF from the bottom of the receiver. Both flow configurations are shown in Fig 6. The HTF chosen under analysis is Therminol-55, a synthetic fluid that is an efficient and reliable HTF for medium temperature-range operations up to 593 K.

## 3. Methodology

The thermal performance of the cone-cylindrical receiver under different flow configurations is compared by evaluating their respective thermal efficiencies, which is the ratio of net energy absorbed to the net incident flux. The value of total incident heat flux at the receiver aperture can be calculated by the eq (2):

$$Incident\ Solar\ Flux = (DNI) \cdot (Dish\ Apperture\ area) \quad \text{eq (2)}$$

However, for estimating the incident heat flux on each coil can be estimated by using ray tracing. To perform ray tracing, the entire cone-cylindrical receiver is divided equally into 10 sections along the axis 1-1', as shown in Fig 7, and the flux map is plotted for each section using discretized ray tracing operation. The resulting flux map is shown in Fig 8. The numerical values of flux map intensities are mentioned in Table 3 for each coil section.

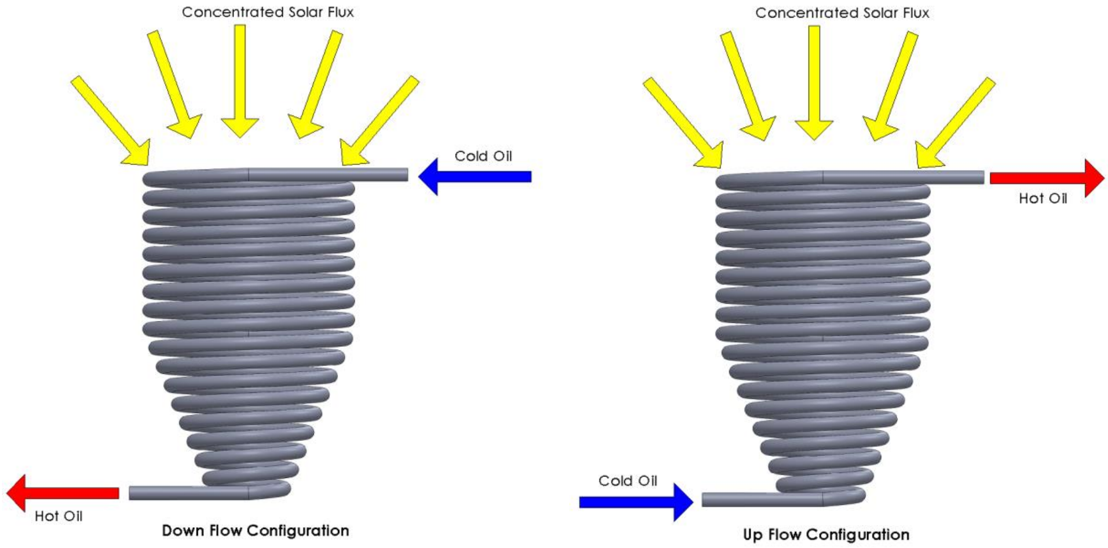



**Figure 6: Flow configuration for Heat Transfer Fluid**

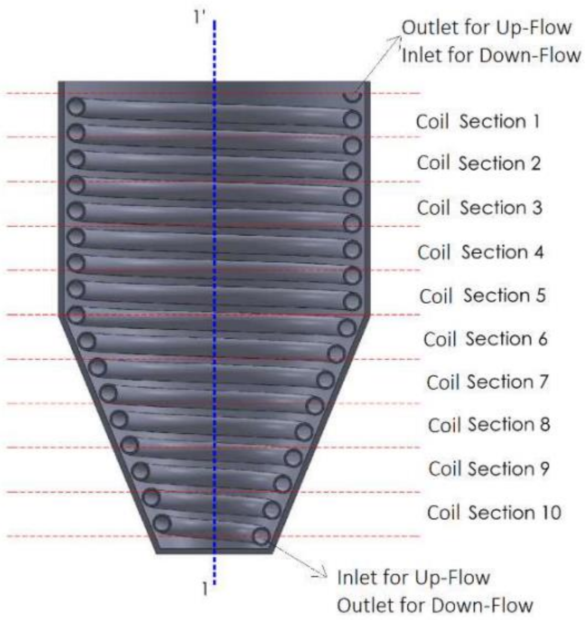



**Figure 7: Cone-cylindrical coil receiver divided equally along the axis into 10 sections**

The incident flux intensities value at each coil section can be used in the steady state energy balance equation, which equates it to the summation of their respective useful heat gains and thermal heat loss, as shown in eq (3):

$$Incident\ heat\ flux = Energy\ Absorbed\ by\ Coils + Thermal\ losses \quad \text{eq (3)}$$

$$Thermal\ heat\ loss = Q_{cond} + Q_{conv} + Q_{rad} \quad \text{eq (4)}$$

$$Heat\ gain\ by\ HTF = \dot{m} \cdot C_p \cdot \Delta T \quad \text{eq (5)}$$

As both terms on the right-hand side of eq (3), i.e., energy absorbed and thermal losses are unknown, an iterative method is proposed to evaluate these values. The flowchart for the iterative method is shown in Fig 9.

**Table 3: Section-wise flux distribution details on Cone-cylindrical receiver**

| Coil Section No. | Coil Length (m) | Flux intensity (W/m$^2$) |
|---|---|---|
| 10 | 1.087 | 6496 |
| 9 | 1.439 | 7920 |
| 8 | 1.791 | 9776 |
| 7 | 2.143 | 12320 |
| 6 | 2.495 | 15816 |
| 5 | 2.671 | 8304 |
| 4 | 2.671 | 11144 |
| 3 | 2.671 | 15552 |
| 2 | 2.671 | 22672 |
| 1 | 2.671 | 35392 |

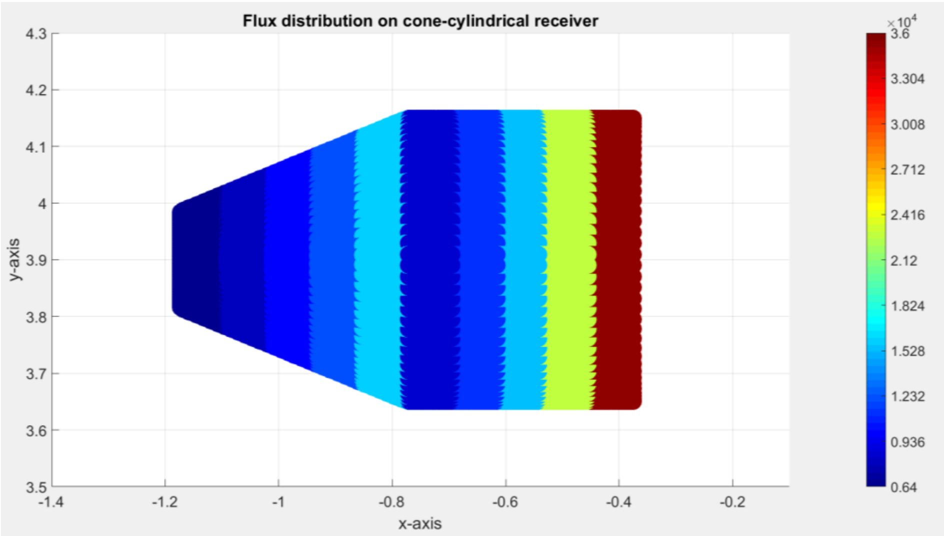



**Figure 8: Flux map distribution section-wise on the cone-cylindrical receiver**

## 3.1 An iterative method for estimating heat absorbed and heat losses at the coil section

*Step 1:* Choose the flow configuration between Up-flow & Down-flow with a mass flow rate, $\dot{m}$, and assume the inlet temperature $T_{\_f\_IN\_1}$ at the 1st coil section.

*Steps 2 & 3:* The entire coil length is divided into 10 equal sections of axial length about axis 1-1', as explained earlier. Using discretized ray tracing, average flux intensities are estimated at each coil section, with their respective values mentioned in Table 3, and these values are assigned as $Q_{incident}$.

*Step 4*: A fraction of $Q_{incident\_1}$ at coil section 1 is assumed to be $Q_{abs\_1}$, and it is equal to the useful heat gain for the HTF flowing through this coil section. For this assumed value of $Q_{abs\_1}$, and $T_{\_f\_IN\_1}$ from Step 1, calculate the outlet temperature $T_{\_f\_OUT\_1}$, using eq (6). Using the temperatures at the inlet and outlet, the surface temperature of the coil section is evaluated.

$$Q_{abs\_1} = \dot{m} \cdot C_p \cdot (T_{\_f\_OUT\_1} - T_{\_f\_IN\_1}) \qquad \text{eq (6)}$$

*Step 5:* The calculated value of outlet temperature at coil 1 is assigned as the inlet temperature at coil 2, i.e., $T_{\_f\_OUT\_1} = T_{\_f\_IN\_2}$

*Step 6:* The process of Steps 4 & 5 are repeated for all the coil sections, and the surface temperature at all coil sections is estimated.

*Step 7*: For the respective coil surface temperatures, the $Q_{conv}$ and $Q_{rad}$ are evaluated using eq (7) and eq (8) respectively. The h.t.c. value in eq (7) and view factor value in eq (8) are estimated using ANSYS Fluent.

*Step 8*: After estimating the $Q_{conv}$ and $Q_{rad}$ from the previous step, the energy balance equation is checked. If the energy conservation holds good, then the initial guess of $T_{\_f\_IN\_1}$ and $Q_{abs}$ are correct. If not, then the process is repeated with a new guess of $T_{\_f\_IN\_1}$.

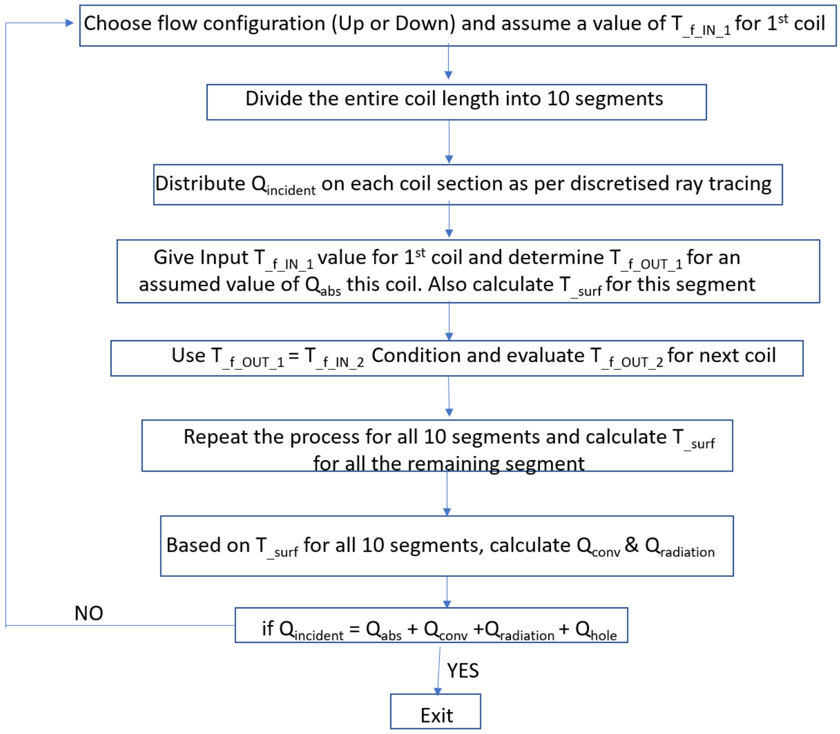



**Figure 9: Iterative method to estimate useful heat gain and thermal losses**

## 3.2 Heat transfer coefficient and View factor value for cone-cylindrical coil receiver to estimate $Q_{conv}$ & $Q_{rad}$

For estimating the convection and radiation heat losses, eq (7) and eq (8) respectively can be used:

$$Q_{conv\_i} = h \cdot A_i \cdot (T_{surf\_i} - T_{amb}) \quad \text{eq (7)}$$

$$Q_{rad\_i} = \sigma \cdot \epsilon \cdot F_{i\_aper} \cdot A_i \cdot \left(T_{surf_i}{}^4 - T_{amb}{}^4\right) + \sigma \cdot \epsilon \cdot F_{i\_insulation} \cdot A_i \cdot (T_{surf\_i}{}^4 - T_{insulation}{}^4) \quad \text{eq (8)}$$

However, the values of h.t.c. in eq (7) and view factor ($F_{ij}$) in eq (8) are very complex to determine and there is no straightforward empirical relation in the literature for determining these values. Therefore, these values for each coil section are estimated using ANSYS Fluent.

For h.t.c. estimation, CFD analysis is conducted by building the geometry and simulating it inside a large enough air enclosure, as shown in Fig 10. The enclosure is filled with air at ambient conditions (300 K and 1 atm) uniform throughout. Next, the model is meshed suing fine meshing near the coil section, and the mesh coarsens as the mesh goes far away from the coil area. The number of elements in the mesh is counted to be 7402418. For boundary conditions, an isothermal temperature condition is put at the coil surface, and this temperature for each coil section is estimated by the iterative methodology of section 3.1. The resulting h.t.c. values from CFD analysis are shown in Table 4.

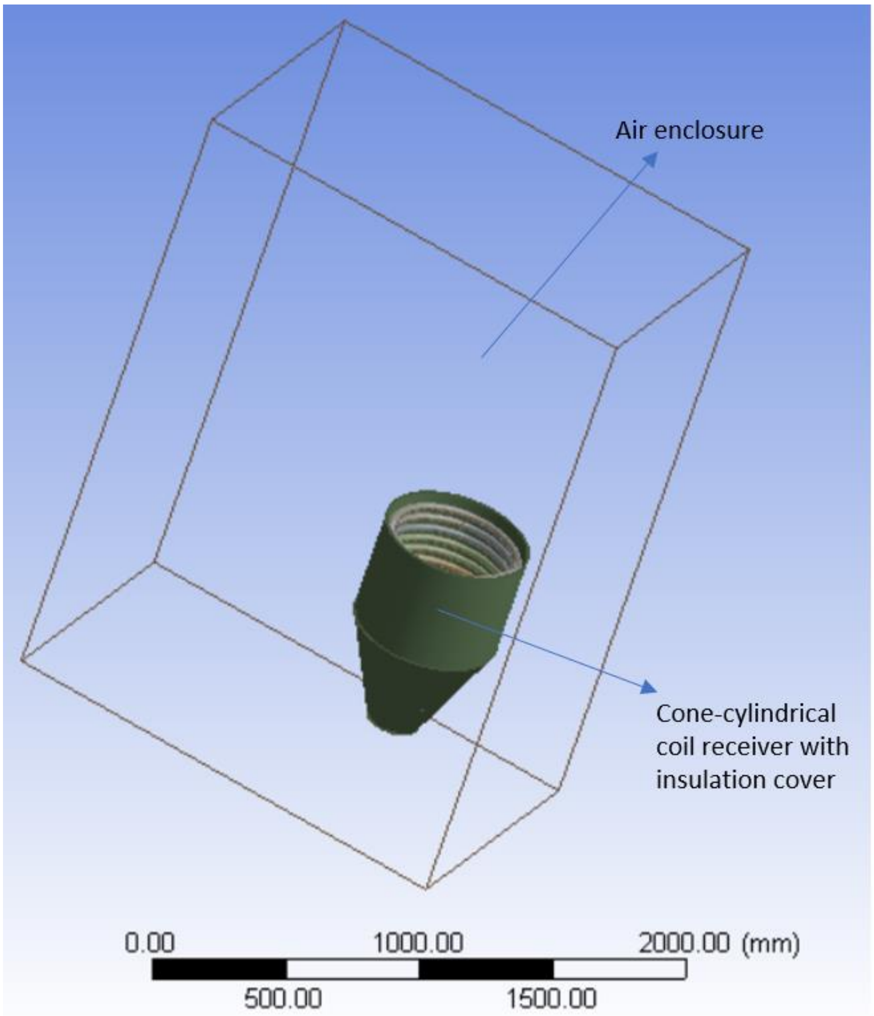



**Figure 10: Coil receiver in air enclosure**

**Table 4: h.t.c and view factor values for Up-flow configuration with inlet temp of 573 K and mass flow rate of 0.312 kg/s**

| Coil No. | Surface Temp (K) | h.t.c. ($W/m^2$-K) | View factor from coil to aperture, $F_{i\_aper}$ | View Factor from coil to insulation: $F_{i\_insulation}$ |
|---|---|---|---|---|
| 1 | 577 | 8.64 | 0.02 | 0.45 |
| 2 | 579 | 8.24 | 0.03 | 0.42 |
| 3 | 581 | 7.77 | 0.04 | 0.45 |
| 4 | 583 | 7.38 | 0.05 | 0.41 |
| 5 | 587 | 7.56 | 0.06 | 0.45 |
| 6 | 585 | 8.39 | 0.05 | 0.44 |
| 7 | 588 | 6.57 | 0.07 | 0.42 |
| 8 | 592 | 6.93 | 0.09 | 0.41 |
| 9 | 599 | 7.9 | 0.12 | 0.4 |
| 10 | 609 | 7.87 | 0.25 | 0.38 |

The radiation heat loss will comprise two radiative heat loss terms: radiation from the coil to receiver opening, and radiation from the coil to insulation cover. The view factors for both cases are shown in Table 4 and were calculated using ANSYS Fluent by applying a surface-to-surface radiation module. The temperature of the insulation cover is assumed to be 300 K in the present analysis.

## 4. Results & Discussion

The system is analyzed for Up-flow and Down-flow configurations using the iterative methodology explained in section 3.1. The corresponding temperature profiles are shown in Fig 11 and Fig 12. The corresponding mass flow rate, average Reynolds number, and thermal efficiencies are also mentioned in the plots of the temperature profile.

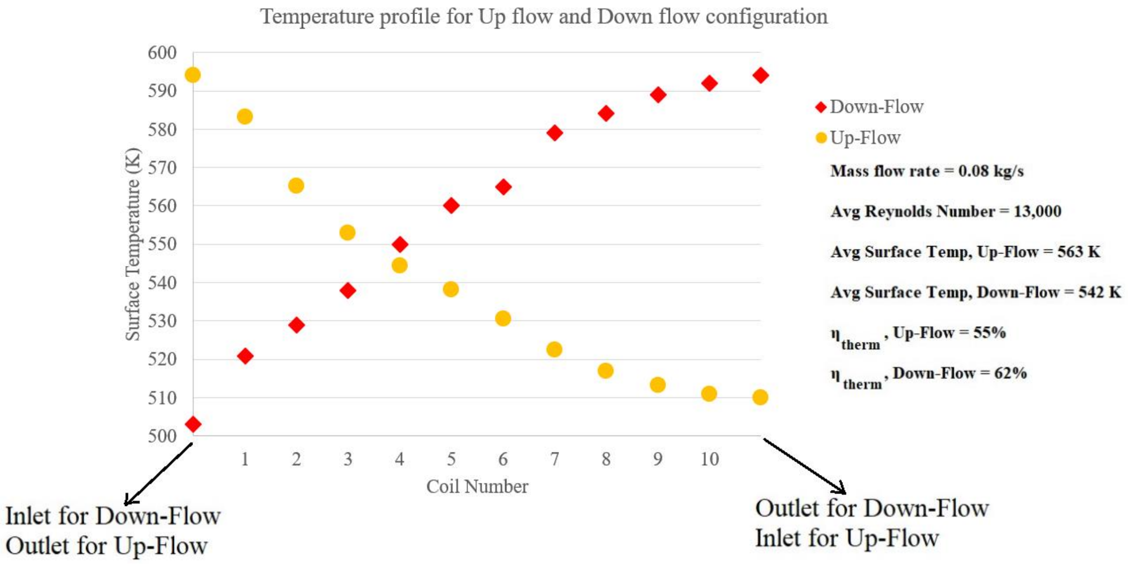



**Figure 11: Temperature profile for Up-flow and Down-flow configuration at 0.08 kg/s mass flow rate**

From the temperature profiles in Fig 11 and Fig 12, it is observed that the average surface temperature is lower when the flow configuration is Down-flow. This can be attributed to the fact that cold HTF enters from the top of the receiver and absorbs the most concentrated solar flux. As the temperature is low in the Down-flow configuration at the top, the heat losses are substantially less, resulting in higher thermal efficiency. However, it is also observed that as the Reynolds number is increased from 13000 to 50000, the difference in thermal efficiency between up-flow and down-flow reduces. This is because as the Reynolds number increases, the flow rate increases which results in a smaller temperature difference between coil surface temperature and HTF mean temperature.

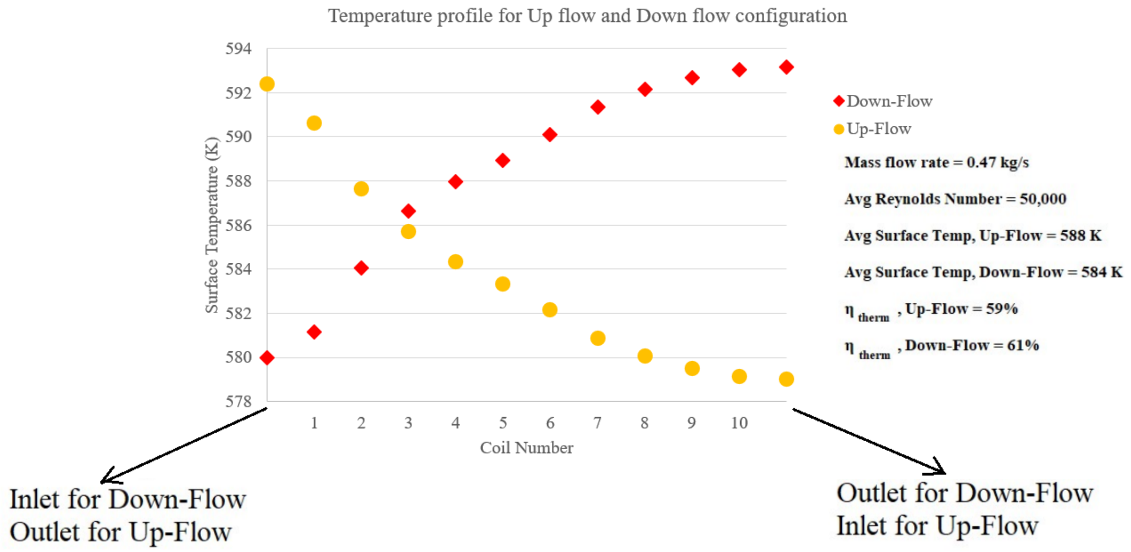



**Figure 12: Temperature profile for Up-flow and Down-flow configuration at 0.47 kg/s mass flow rate**

## 5. Conclusion

A cone-cylindrical cavity receiver was analyzed for two flow configurations: Up-flow & Down-flow. The cone-cylindrical receiver is assumed to be under concentrated solar flux incoming from a 60 $m^2$ Scheffler dish reflector. The HTF assumed for the analysis is Therminol-55, a synthetic fluid for moderate temperature operation. The analysis was conducted for two flow rates of 0.08 kg/s and 0.47 kg/s. It was observed that irrespective of the flow rates, the down-flow configuration had better thermal efficiency. This was attributed to the fact that in the down-flow configuration, the average surface temperature was lower than in the up-flow configuration, leading to lower thermal losses. However, as the flow rates increased, the temperature difference between fluid flow and coil surface reduced, which reduced the gap between thermal efficiencies of up-flow and down-flow.

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## References

Hafez, A.Z., Soliman, A., El-Metwally, K.A., Ismail, I.M., 2016, Solar parabolic dish Stirling engine system design, simulation, and thermal analysis, Energy Conversion and Management. 126, 60-75

"India One" Solar Thermal Power Plant," World Renewal Spiritual Trust, [Online]. Available: https://india-one.net/. [Accessed 9 September 2022].

Munir, A., Hensel, O., Scheffler, W., 2010, Design principle and calculations of a Scheffler fixed focus concentrator for medium temperature applications, Solar Energy. 84(8), 1490-1502

Leibfried, U., Ortjohann, J., 1995, Convective Heat Loss from Upward and Downward-Facing Cavity Solar Receivers: Measurements and Calculations, Journal of Solar Energy Engineering. 117, 75-84

Kumar, S.; Shendage, D. J.; Doke, P.; Kedare, S. B., Bapat, S. L.; Numerical Investigation of Convective Heat Loss from Upward Facing Cavity Receivers of Different Shapes at Different Inclinations and Temperatures, International Journal of Environment and Sustainable Development. 8, 7-11. DOI: 10.47469/JEES.2019.v08.100082