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Design, Optimization and Development of Solar Thermal Heat Receiver System with Parabolic Concentric Collector

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Abstract

Against a backdrop of our world's changing climate solar thermal power generation shows great potential to move global energy production away from fossil fuels to non-polluting sources. A parameter study was conducted based on the previous analysis to improve specific aspects of the initial design using a value of benefit analysis to evaluate the different design. This project focused on the design, analysis and verification of a high temperature solar receiver. Computational Fluid Dynamic (CFD) analysis of Radiation model is carried out with new geometry design of receiver. Discrete Transfer Radiation Model (DTRM) model is used for numerical simulation.
Keywords: CFD, Radiation model, Receiver

I. Nomenclature

h	***Heat transfer coefficient, w/m$^{2\cdot}$k***
k	***Thermal conductivity of the material, w/m.k***
$\dot{m}$	***Mass flow rate of fluid, kg/s***
$\dot{m}_c$	***Mass flow rate of cold fluid***
$\dot{m}_h$	***Mass flow rate of hot fluid***
Nu	***Nusselt number***
Q	***Amount of heat flux, w***
q	***Heat flux, w/m^2***
T	***Temperature, °C***
ΔT	***Temperature differences between the hot and cold fluid, k***
U	***Overall heat transfer coefficient,***

Greek Symbols

ρ	***density ,kg/m3***
v	***Kinematic Viscosity, m2/s***
µ	***Dynamic viscosity, pa/s***
$\propto$	***Rim angle***
η	***Overall enhancement ratio***

II. Introduction

Solar concentration is device which concentrates the solar energy incident over a large surface on to a smaller surface. The concentration is achieved by the use of suitable reflecting elements, which result in an increase flux density of absorber surface as compare to that existing on the concentrator aperture. In order to get maximum concentration, an arrangement for tracking the sun's virtual motion is required. An accurate focusing device is also required. Thus solar concentrating device consists of a focusing device a receiver system and tracking arrangement. Temperature as high as 3000^{o} C can be achieved using solar concentrator. Solar concentrating devices have been used since long. ln Florence, as early as 1695, a diamond could be melted by solar energy. Lavoisier carried out a number of experiments with his double lens concentrator. The knowledge of concentrator dates back even to the time of Archimedes, whose book "On Burning Mirror" is an evidence of this fact. Many uses of concentrators were reported in the eighteenth and nineteenth centuries, particularly in the heat engine and steam production.

However, concentrator is an optical system and hence optical loss terms become significant. Further, it operates only on the beam component of the solar radiation, resulting in the loss of diffused component. Although the basic component of flat plate collectors are applicable to concentrating system, a number of non-uniform flux on absorbers, wide variation in shape, temperature and heat loss behavior of absorbers and finally the optical consideration in the energy balance condition. It may be noted that the higher the concentration of the collector, higher is the precision of optics and more is the cost of the units and complexity of the system the maintenance requirements are also increased.

III. LITERATURE REVIEW

Billy anak sup et al [P1] studied effect of rim angle to the flux distribution diameter in solar parabolic dish collector. They have used the ray tracing simulation and 2D computer aided drawing. The imaging diameters were in the ranges of 17mm to 286mm while the non-imaging diameter value was in the range of 23mm to 345mm. Rim angle affect the incoming radiation of sun radiation and manufacturing of parabolic dish. The value of rim angles decrease with increase of focus point. They have concluded that the rim angle determines the focal length of parabolic dish and the value of rim angle to optimize the amount of solar flux. The efficiency of the parabolic dish was relying on flux intensity of the focus point. The focal region area affects both optical efficiency and the concentration ratio of the solar parabolic dish.

Lifang Li et al [P2] studied a new design approach for solar concentrating parabolic dish based on optimized flexible petals. The dish mirror was formed from several optimal shaped thin flat metal petals with a highly reflective surface. Attached to the rear surface of the mirror petals were several thin layer whose shape were optimized to have reflective petal from into a parabola when their ends are pulled towards each other by cables or rods. An analytical model to optimize the shape and thickness of the petals was presented. If the focal error was equal to or smaller than focal area radius, reflected ray would be absorbed by the receiver. Otherwise, the rays would miss the receiver. They conclude that attached to the backside of the petal were thin metal layers that were optimized to have the reflective petal form into the parabola when their ends were pulled towards each other by cable or rods. The validity of the concept was demonstrating using Finite Element Analysis and laboratory experiments. In the design of all dish collector such disturbance as gravity and wind loading need to be considered

A.R. El Ouederni et al [P3] worked on parabolic dish solar concentrator. Experiment device consist of a dish of 2.2 m opening diameter. Its interior surface was covered with a reflecting layer and equipped with disc receiver in its focal position. Experimental measurement of solar flux and temperature distribution on the receiver had been carried out. In this work, solar concentration system had been constructed and tested by using two discs as receiver. The first experience consists to place a thick disc in the focal position in order to carry out the solar temperature distribution on the lighted face of the thick disc. In a second step a thin disc was placed in the focal region in order to determinate solar flux concentrated and efficiency of their system.

Le roux et al [P4] worked on computational fluid dynamics analysis of parabolic dish tubular cavity receiver. They have used surface to surface radiation model. This CFD simulation is a conjugate heat transfer model that evaluates the heat transfer to the heat transfer fluid as well as the losses from the cavity insulation and due to thermal re-radiation. The method is evaluated for an ambient lower pressure experimental test at the University of Pretoria as well as a theoretical implementation at Brayton cycle conditions. They conclude that the two-stage CFD approach solving first for the RTE and then performing a conjugate heat transfer simulation was found to be an effective method. Computational cost was lowered by considering an axi-symmetric model alongside a coarser 3-D model of the optical solution. Two conditions were evaluated and future work will consider reasons for deviations from experimental and theoretical results.

IV. METHODOLOGY AND SIMULATION

Computational fluid dynamics is one of the most important tools, which is normally used to solve fluid flow problems. CFD is a tool used almost exclusively in research. The major advantages of using these CFD are reducing time scale, improve processes, reducing cost and analyzing the problem with variation on the simulation. The set of equations that describes the fluid flow equation and energy equation are called Navier-Stokes equation, which is contains the momentum, heat and mass transfer.

A. Radiation Model:

The main assumption of the DTRM is that the radiation leaving the surface element in a certain range of solid angles can be approximated by a single ray. This section provides details about the equations used in the DTRM. The primary advantages of the DTRM are threefold: it is a relatively simple model, increase the accuracy by increasing the number of rays, and it applies to a wide range of optical thicknesses.

1) Radiative Transfer Equation

The radiative transfer equation (RTE) for an absorbing, emitting, and scattering medium at position $\vec{r}$ in the direction is $\vec{s}$ is

$$\frac{dI(\vec{r},\vec{s})}{ds} + (a+\sigma_s)I(\vec{r},\vec{s}) = an^2\frac{\sigma T^4}{\pi} + \frac{\sigma_S}{4\pi}\int_0^{\pi} I(\vec{r},\vec{s}')\Phi(\vec{s}.\vec{s}')d\Omega' \qquad (3.1)$$

$(a+\sigma_s)$s is the optical thickness or opacity of the medium. The refractive index n is important when considering radiation in semi-transparent media. Figure illustrates the process of radiative heat transfer.

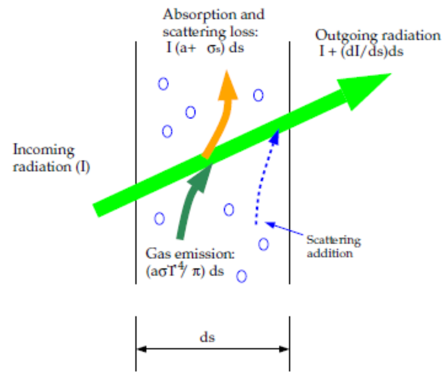


Fig. 3.1: Radiative Heat Transfer

2) The Discreate Transfer Radiation Model (DTRM) Theory:

The equation for the change of radiant intensity, dI, along a path, ds, can be written as

$$\frac{dI}{ds} + aI = \frac{a\sigma T^4}{\pi} \tag{3.2}$$

Where ‘a’ is absorption coefficient, ‘I’ is intensity and T is local temperature.

Here, the refractive index is assumed to be unity. The DTRM integrates Equation (3.2) along a series of rays emanating from boundary faces. If a is constant along the ray, then I(s) can be estimated as

$$I(s) = \frac{\sigma T^4}{\pi}(1 - e^{-as}) + I_0 e^{-as} \tag{3.3}$$

Where I_0 is the radiant intensity at the start of the incremental path, which is determined by the appropriate boundary condition (see the description of boundary conditions, below). The energy source in the fluid due to radiation is then computed by summing the change in intensity along the path of each ray that is traced through the fluid control volume.

The “ray tracing” technique used in the DTRM can provide a prediction of radiative heat transfer between surfaces without explicit view factor calculations. The accuracy of the model is limited mainly by the number of rays traced and the computational mesh.

B. CFD Analysis of the Problem:

1) Numerical Methodology:

The commercial code ANSYS 15.0 is adapted to simulation of flow and heat transfer in a receiver. The numerical simulation is performing with a three dimensional steady state turbulent flow system. To solve the problem, governing equations for the flow and heat transfer are modified according to the conditions of the simulation set up. Because the problem is assumed to be steady state, the time dependent properties are dropped out from the governing equations. Receiver has design in Creo Parametric 2.0 Software and this geometry import in ANSYS 15.0 software. Discrete Transfer Radiation Model (DTRM) model have chosen for analysis of radiation model. To solve the problem, governing equations for the flow and heat transfer are modified according to the conditions of the simulation set up.

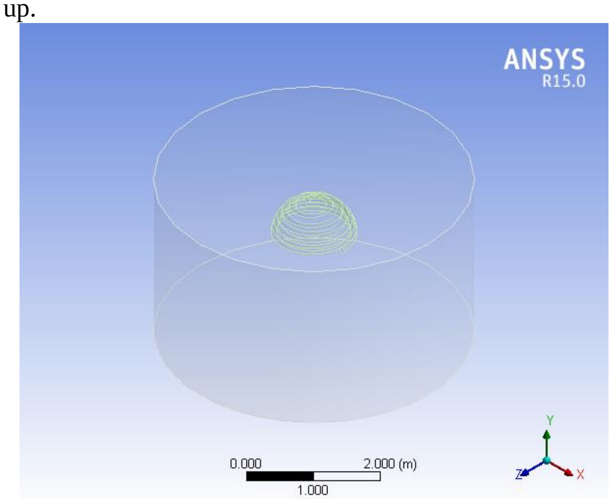


Fig. 3.2: Design of radiation model

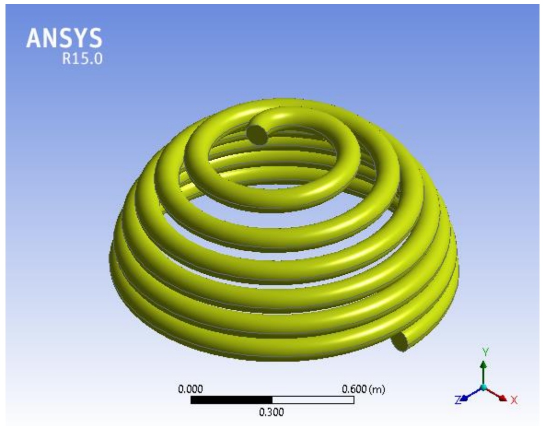


Fig. 3.3: design of receiver

The resulting equations are:
Continuity equation can be expressed as:

$$\frac{\partial}{\partial x_i}(\rho u_i) = 0 \tag{3.4}$$

Momentum equations can be expressed as:

$$\frac{\partial}{\partial x_i}(\rho u_i u_k) = \frac{\partial}{\partial x_i}\left(\mu \frac{\partial u_k}{\partial x_i}\right) - \frac{\partial p}{\partial x_k} \tag{3.5}$$

Energy equation can be expressed as:

$$\frac{\partial}{\partial x_i}(\rho u_i t) = \frac{\partial}{\partial x_i}\left(\frac{k}{C_p}\frac{\partial t}{\partial x_i}\right) \tag{3.6}$$

Here to solve the problem renormalization-group (RNG) model is adopted because it is better results for near- wall flows and flows with high streamline curvature.
Transport equations for RNG k$\boldsymbol{\varepsilon}$ model in general form are:
Turbulent kinetic energy:

$$\frac{\partial}{\partial x}(\rho k) - \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left(\alpha_k \mu_{eff} \frac{\partial k}{\partial x_j}\right) + G_k + \rho\varepsilon \tag{3.7}$$

And turbulent energy dissipation:

$$\frac{\partial}{\partial t}(\rho\varepsilon) + \frac{\partial}{\partial x_i}(\rho\varepsilon u_i) = \frac{\partial}{\partial x_j}\left(\alpha_k \mu_{eff} \frac{\partial \varepsilon}{\partial x_j}\right) + C_{1\varepsilon}\frac{\varepsilon}{k}G_k - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \tag{3.8}$$

Where G_k represents the generation of turbulence kinetic energy due to the mean velocity gradients and,

$$\mu_{eff} = \mu + \mu_t\,,\ \ \mu_t = \rho c_\mu \frac{k^2}{\varepsilon}\,,\ C_{1\varepsilon} = C_{1\varepsilon} - \frac{\dot{\eta}\left(1-\frac{\dot{\eta}}{\dot{\eta}_0}\right)}{1+\beta\dot{\eta}^3}\,,\ \dot{\eta} = \left(2E_{ij}E_{ij}\right)^{1/2}\frac{k}{\varepsilon} \ \text{ and}$$

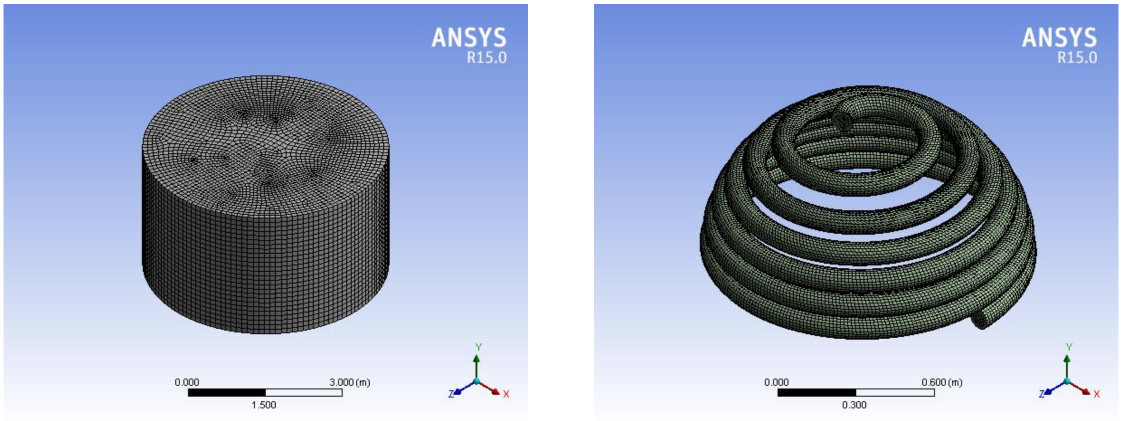
$$E_{ij} = \frac{1}{2}\left[\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right] \tag{3.9}$$

The empirical constants for the RNG k-e model are expressed as:

$$C_\mu = 0.0845\,,$$
$$C_{1\varepsilon} = 1.42\,,$$
$$C_{2\varepsilon} = 1.68\,,$$
$$\beta = 0.012\,,\ \dot{\eta}_0 = 4.38\,,$$
$$\alpha_k = \alpha_\varepsilon = 1.39.$$

C. CFD Analysis of Radiation Model:

In the modeling, reflector size is 4.8 m and focal length is 2.897 m so the rim angle is set 45° [P4] and DTRM radiation model is used for analysis in ANSYS 15.0. In this model air is used as working fluid. The diameter of receiver is 90mm and height is 635mm, material is used as steel and mass flow rates is 0.08 kg/s. Reflectivity of reflector is selected as 90% and material of reflector is aluminum. Upper portion that means top portion and housing are selected as semi-transparent respectively.



ig. 3.4: meshing of radiation model

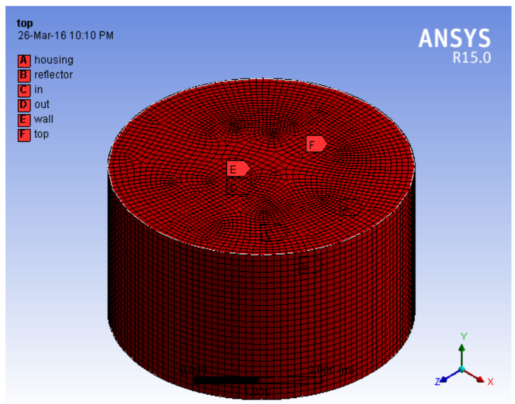


Fig. 3.5: Boundary condition of radiation model theory

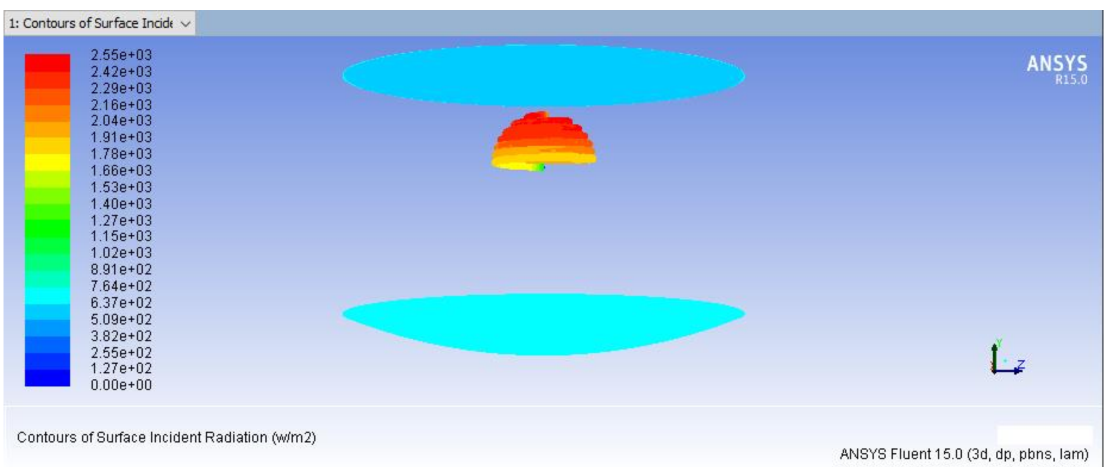


Fig. 3.6: Contour of surface incident radiation on receiver

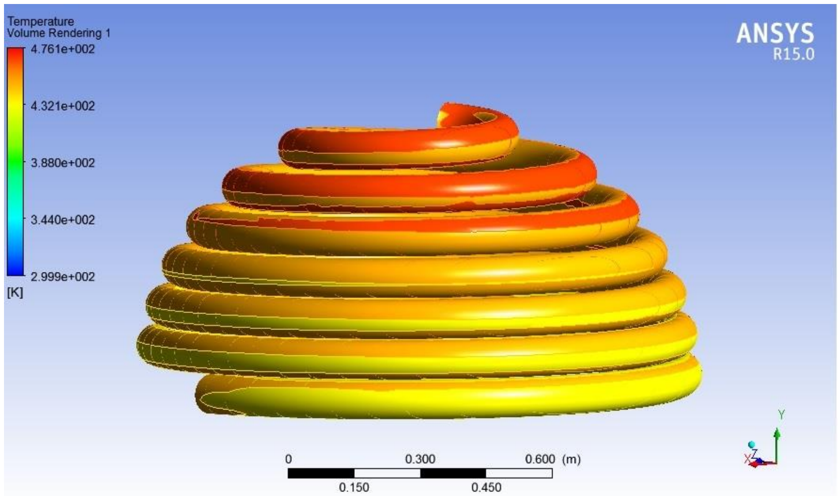


Fig. 3.7: contour of temperature on receiver

As shown in fig average temperature achieve on receiver wall is 453 K. At 0.08 kg/s mass flow rate of air, average temperature achieved at outlet is 392 K. Average incident radiation 2550 w/m^2 reflected from the reflector whose reflectivity is 90%.

V. RESULTS AND DISCUSSION

In the present work, after modeling radiation model in ANSYS 15.0 software outlet temperature of HTF (air) is archived about 392 K for mass flow rate of 0.08 kg/s. In this radiation model Direct Solar Irradiation is 1000 W/ m^2 and also assumes that reflectivity of reflector is 90% that means emissivity of reflector is 0.1 and aluminum material is selected for reflector. Boundary condition for radiation model as follow

Table - 3.1
Boundary condition for DTRM model

Surface	***BC type***	***Boundary value***
Inlet	***Mass-flow inlet***	***0.08 kg/s; 300K***
Outlet	***Pressure outlet***	***0Pa gauge***
Sides and top	***Mixed thermal condition***	***300K (T_{conv}); h_c =0 w/m^2; 300 ($T_{rad} = T_{Sky}$)***

Results with DTRM model is given as

Table - 3.2
Results with DTRM model

Sr no	***Outlet Temperature (CFD)[4] [K]***	***Outlet Temperature (CFD) [K]***
1	***347.8***	***392.089***

VI. CONCLUSION

In this study, by using this type of receiver higher temperature is achieved compare to the cylindrical type receiver. From Computational Fluid Dynamic (CFD) software, it is cleared that if reflectivity of reflector is higher and by selecting best HTF (Heat Transfer Fluid), higher temperature of fluid is achieved.

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