# Design and analysis of solar parabolic trough collector

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## ABSTRACT

*Solar energy is radiant light and heat from the Sun that is harnessed using a range of ever-evolving technologies such as solar heating, photovoltaics, solar thermal energy, solar architecture, molten salt power plants and artificial photosynthesis. A parabolic trough is a type of solar thermal collector that is straight in one dimension and curved as a parabola in the other two, lined with a polished metal mirror. In this report, the study of parabolic shaped collector, receiver tube and loading that model in Ansys was being done and studying about various concepts used in the same. HTF (Heat Transfer Fluid) used in this project is water, which will pass through a solar absorber tube at certain velocity. After passing the fluid, Temperature and Flowrate of fluid was checked. The Numerical Solution was done for water as HTF and simulated for 9 AM to 4 PM. The maximum temperature obtained was 306.75 K at 1:00 PM. Therefore, the output Temperature contour was done by taking 1 PM as time.*

*Keywords***: -** *PTC, HTFs, HCE, SPTC, CFD, DNI.*

## 1.    INTRODUCTION

A Parabolic Trough Collector (PTC) is a linear concentrating system made of long, parabolic-shaped mirrors and a receiver tube placed along the focal axis of the parabola. DNI (Direct Normal Irradiance) is concentrated onto the receiver tube, where solar energy is absorbed by the HTF. A glass envelope is often placed around the HCE to limit convection losses and further improve the collector efficiency; the annulus space between the glass envelope and the receiver tube can be under vacuum. Parabolic troughs are highly modular and can be arranged in solar fields of various sizes and architecture, however, to minimize losses, the collector axis must be oriented either in an east-west or in a north south direction, both of which require single-axis tracking. In the case of a smaller solar field, dual-axis tracking can be used to reduce optical losses, however, this is relatively uncommon for linear concentrators. [1]

A parabolic trough collector system consists of a reflecting surface which resembles a parabolic shape. This reflecting surface is mostly made of reflecting mirrors or anodized aluminum sheets. The solar radiations falling on the reflecting surface is concentrated on the focal line of the parabola where a receiver tube carrying the heat transfer fluid is placed. Absorber tube either painted black or electroplated with nickel or chromium in order to increase the absorptivity of the tube. The heat transfer fluid picks up the heat figure 1. Parabolic Trough Collector system from the absorber tube which is utilized later in the desired way. The temperature in this type system can reach as high as 400oC, depending upon the type of reflecting surface, absorber tube materials and heat transfer fluid. A parabolic trough collector system must be positioned in agreement with the sun's position so that it can reflect the incoming beam radiations to the absorber tube. [2]
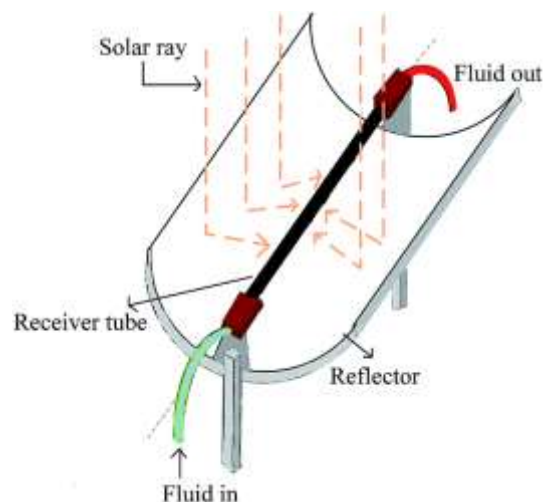


**Figure 1: Parabolic Trough Collector** *[2]*

Concentrating ratio is an important term when talking about concentrating collectors. It is defined as the ratio of the area aperture area of collector and absorber tube's area. Its value ranges from 12 to 70. Increase in concentration ratio corresponds to higher working temperatures. Various components of the system are shown in the figure 1. There are various types by which the concentration of solar ray can be done. They may be of the reflecting type utilizing mirrors or of the refracting types using lenses (Fresnel lens).

The reflecting surfaces may have reflected surface in different shapes such as parabolic, spherical or flat. Sometimes they may be classified on the basis of image formation, the concentrator which could be imaging or non-imaging. The imaging concentrator may focus on a line or at a point. [2]
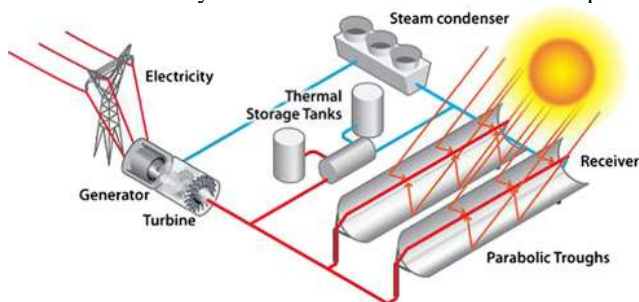


**Figure 2: Working of Parabolic Trough Collector** [3]

### 1.1 Working of Parabolic Trough Collector
Since parabolic trough have highly reflective material such as aluminum or mirrors, all the sun rays get reflected and concentrated at the focus of parabolic trough collector. The solar absorber tube isplaced at the focus of parabolic trough collector to absorb all the radiation reflected by parabolic trough collector. Heat transfer fluid (HTF) is made to pass through the tube due to which it gets heated. The heated HTF is then passed through heat exchanger where the water is converted intosteam by exchanging heat from HTF. This steam is then passed through steam turbine to produce electricity. After exchanging heat with water HTF is again passed through solar absorber tube. The steam after passing through steam turbine is passed to condenser where steam condense to water and then passed through steam generator. [3]

### 1.2 Heat Transfer Fluids (HTFs) used in PTC
The most widely used HTFs are water, water-glycol mixture, phase changing materials and refrigerants for low and medium temperature applications. Some most widely used HTFs are described below.

a.     Molten salts: - Molten salt was used as a heat transfer fluid in the American Solar-Two power tower project. Due to its simple storage concept, it is also suggested for use in parabolic trough plants. Different potential molten salts have been investigated in. In this study a nitrate salt mixture is used (40% NaNo 3, 60% KNO 3) which has a maximum operation temperature of 600°C. Molten salts are more user friendly and environmentally benign than oils. Molten salts are easily available in nature and are therefore they are less expensive. [4]

b.     Ionic liquids: - Ionic liquids are proposed as HTF with a maximum operation temperature of 459°C. Ionic liquids are a specific class of molten salts with a low melting point of less than 100°C. [5]

c.     Marton: - Marton proposes to use sulphur as HTF. In his approach sulphur is evaporated and superheated in a parabolic trough. The heat is transferred in a heat exchanger to a conventional Rankine cycle. [6]

d.     Rubbia: - Rubbia recommends to use CO 2 as HTF in the collector field. The heat from the collector field is transferred to an intermediate molten salt loop via heat exchangers. The molten salt loop is used for the transport of heat from the distributed collector field to the power block and for heat storage. [7]

e.     Nano-fluids: - Nano-fluids are made up of colloidal mixture of base fluid with nano-sized particles such as oxide ceramics, nitride ceramics, carbide ceramics, metals, semiconductors, carbon nanotubes and composite materials such as alloyed nanoparticles etc. They have predominant characteristics because of nanoparticles as nanoparticles are small in size and have high surface area which increases the heat transfer coefficient. [8]

## 2. OBJECTIVE
a.     To study the velocity distribution characteristics of water inside absorber tube.
b.     To study the temperature distribution of surface of Reflector.
c.     To determine the performance characteristics of Parabolic trough collector.
d.     To analyze the effect of solar heat flux on temperature profile of water in solar absorber tube with time of day.

## 3. SCOPE
India is located in the equatorial sun belt of the earth, thereby receiving abundant radiant energy from the sun. Solar thermal power generation can play a significant important role in meeting the demand supply gap for electricity. In a Solar parabolic trough collector (SPTC), the reflective profile focuses sunlight on a linear receiver tube or Heat Collecting Element (HCE) through which heat transfer fluid is pumped. This fluid collects the solar energy in the form of heat that can then be used in various applications. [9]

## 4. METHODOLOGY
ANSYS FLUENT 2020 R2 is used for simulating the solar absorber tube of SPTC, where water is made to flow through absorber tube. The water is simulated using one-phase modelling techniques, while solar load cell and solar ray tracing are used for simulation. [10]

In this chapter we will study about step-by-step procedure for conducting CFD simulation in detail.

### 4.1 Assumptions
The following assumptions were made during investigation of solar absorber tube:
a. The flow rate of HTF is assumed to be laminar flow.
b. The flow is assumed to be fully developed in the inlet and incompressible.
c. Steady state heat transfer is considered so that the heat flux at the wall does not change.
d. The thermophysical properties of HTF were assumed to be constant.

### 4.2 Parabola Calculator
To obtain Parabolic curve in our Geometry, it is necessary to get perfect shape of Parabola. In the Geometry section, we need to import the 3D curve of parabola for which we would need a text file containing co-ordinates of 3D curve. For calculating the co-ordinates, you need to download Parabola Calculator 2.0 software or else any website that includes calculation. Interface of the software is shown in Fig. 3.
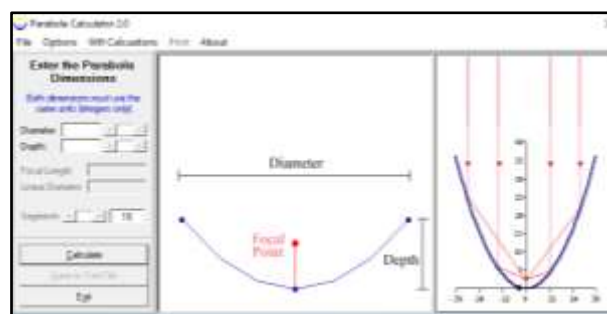


**Figure 3: Parabola Calculator 2.0 interface** [11]

To obtain co-ordinates, you need to mention either of the 2 input dimensions, i.e., Diameter and Depth OR Diameter and

f/d. In our calculations we used first option i.e., Diameter and Depth. We selected 894 mm as diameter and 200 mm as Depth, since our primary aim was to get 250 mm as Focal Length. Here we used trial and error method to obtain the required Focal Length. Instance selected are default i.e., 16. Due to less precision of the software, we were able to get the co-ordinates and focal length as 249.76 mm, but it can approximately be considered as 250 mm.

As you can see in Fig. 4, we have obtained focal length and liner diameter as 249.76 mm and 1001.63 mm respectively, which can be round off to 250 mm and 1000 mm respectively. Linear diameter is the length of curve or circumference of curve, which is useful for actual manufacturing of Parabolic reflector/ Parabolic collector.
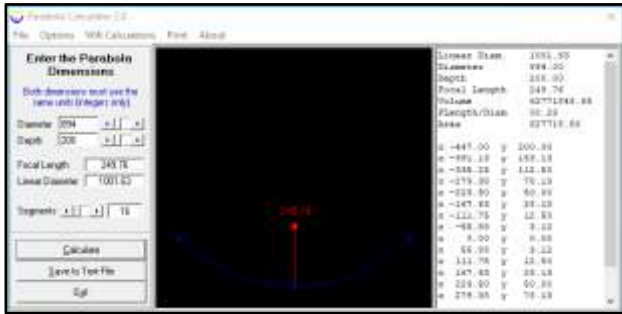


**Figure 4: Co-ordinates obtained from the software**

Since, this software only calculates the parabolic shape in 2D, the co-ordinates obtained are only 2 dimensional. As discussed earlier in this chapter, our aim is to import 3D curve in Geometry section, we will need to create another text document which includes 3-dimensional curve co-ordinates. Another software, i.e., Microsoft Excel is needed for this operation. Now we have x and y axis co-ordinates obtained from Parabola calculator software. While working on Excel we will need to create one more column which includes z axis co-ordinates. Since we calculated using 16 instances, in z-axis column, we will write the numbers 1 to 17. Fig. 5 shows x, y and z axis co-ordinates of our 3D parabolic curve.



**Figure 5: 3D curve Co-ordinates made using Excel sheet**

After writing the co-ordinates in a particular format shown in Fig. 5, we need to export that particular excel sheet as tab (delimited) i.e., text document, which will be imported in Geometry section of Ansys workbench. Fig. 6 shows 3D co-ordinates in text document.
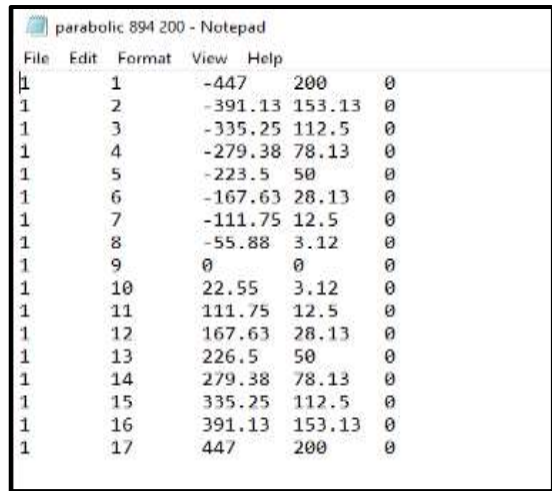


**Figure 6: Text document of 3D curve co-ordinates**

### 4.3  3D Geometric Model

3D model was made using CATIA V5 R20software and was exported in Solid works 2016 for Renderings and simulation [11]. The geometrical model of the project is as shown in Fig. 7. The design was carried out gradually, initially the parts were made individually as part files, then the assembly was made. In 3D model, we used same dimensions as of the Ansys model



**Figure 7: Isometric view**

Different views of 3D model are shown in Fig. 8 and Fig. 9 Simulation of this model was done in Solidworks 2016 showing single axis tracking system of Parabolic trough collector. Some screenshots are added in next chapter i.e., Results section.
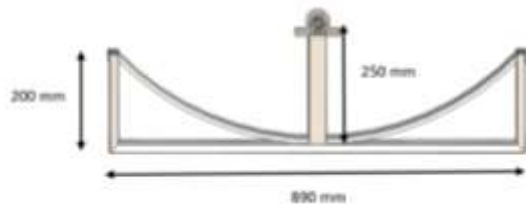


**Figure 8: Side view with dimensions**



**Figure 9: Rear view**

## 4.4 Ansys Workbench

Before starting the project, there are some things that should be taken into consideration. Make sure that Metric (kg, m, s, ºC) units is selected. Since the project is CFD based, Fluid flow (fluent) under Analysis system under Toolbox of Ansys workbench Interface was selected.

Once the FFF (Fluid flow fluent) is opened, there is one dialogue box which includes various steps for complete Simulation. It includes Geometry, Mesh, Setup, Solution and Results as shown in Fig. 10. The Question mark which is being displayed in front of every section, it indicates that the cell requires data (for example, a geometry). Once the geometry is defined, the state of the cell will change accordingly. Likewise, the state of some of the remaining cells in the system will change.
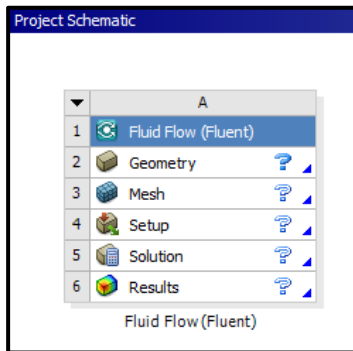


**Figure 10: Fluid Flow Fluent under Ansys workbench [10]**

## 4.5 Geometry

For the geometry of fluid flow analysis, you can either create a geometry in ANSYS DesignModeler, ANSYS SpaceClaim Direct Modeler, or import the appropriate geometry file. We selected Design Modeler for creation of Geometry. In Design Modeler, it is important to select appropriate units, i.e., millimeter.

Our aim was to create Parabolic shaped collector and absorber tube. Parabolic shaped 3D curve co-ordinates are already done earlier. So, our first step was to import that text file into current Geometry. Before selecting the file, make sure your co-ordinate unit is set to millimeter. Under Co-ordinates file, select the text file shown in Fig. 6.
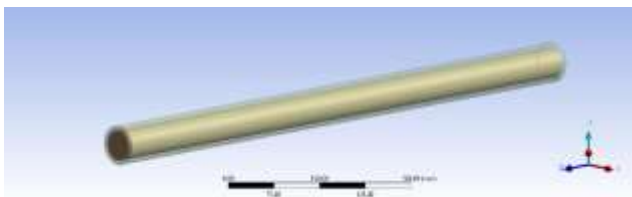


**Figure 11: Geometric model of Solar Absorber tube**

The exact next step is to create Extrude for Collector, whose sketch will be the 3D curve. Under that Extrude, specify Depth and Thickness (either Inward or Outward). Once all this is finished, we will need to Generate that particular Extrude and our Parabolic shaped Collector is ready. Similarly, the absorber tube was made using sketch command and extrude command. The absorber tube Geometry is shown in Fig. 11. The Transparent section is the copper pipe and the material inside it is assumed to be fluid domain (through which the fluid will pass). The complete Geometry i.e. Both Absorber tube and Collector is shown in Fig. 12. The arrow which is being shown on one of the edges is the direction of extrude (extent type 'fixed').
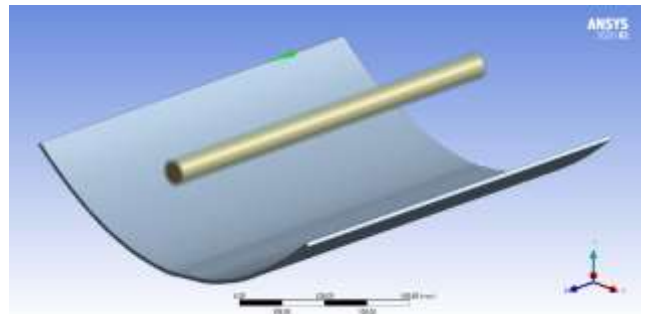


**Figure 12: Complete Geometry**

The geometry file is ready and is saved with an extension (FFF.agdb) where FFF indicates a Fluent based fluid flow system. If the geometry had been imported from another 3D modelling software instead of creating one, the file will be saved as (.stp). Some specifications of the geometry we made are shown in Table. 1.

**Table 1: Specifications of Parabolic Trough Collector**

| Parameters | Value |
|---|---|
| Parabolic Collector Width | 1000 mm |
| Rim angle | 90 ºC |
| Focal Length | 250 mm |
| Collector Depth | 200 mm |
| Linear diameter of Collector | 1000 mm |
| Solar Absorber tube Length | 1000 mm |
| Interior diameter of tube | 65 mm |
| Exterior diameter of tube | 70 mm |
| Absorptivity of receiver | 0.95 |
| Specular Reflectivity | 0.95 |

## 4.6 Meshing

After Geometrical modelling, that particular Geometry was meshed by using ANSYS Fluent 2020 R2 meshing modeler. 3D tetrahedral element was the type of meshing selected for computational domain. Meshing modeler automatically detects the contact regions in the geometry we created [12]. In some cases, it needs to be recreated. Recreation of contact regions allows the user to work effectively on meshing, i.e., renaming the contact regions for further work. The details of meshing of Absorber tube in shown in Fig. 13.
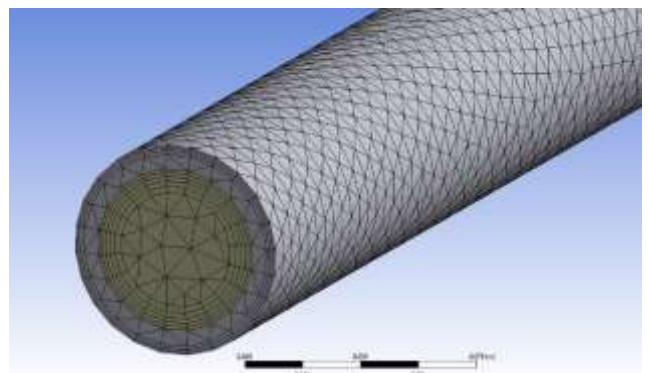


**Figure 13: Meshed model of Solar Absorber tube**

**4.6.1 About Inflation:** The inflation layer control is designed

to create thin elements that can capture the normal gradient with minimal elements; Use of inflation layers is important to correctly capture the velocity and temperature gradients near no-slip walls. Number of layers is necessary to specify. The purpose of using inflation layer meshing to accurately capture the boundary layer region for any wall bounded turbulent flows. [13]

This will provide more accurate resolution of the boundary layer. For certain simulations such as flows with strong wall-bounded effects, this resolution is absolutely necessary. Inflation layers for fluid domain was selected as 5 and that for tube was selected 3.

**4.6.2 Creating Named Selections:** Named Selection feature allows you to create named selections that can be transferred to the ANSYS Mechanical application, or used in the creation of some features. You can select any combination of 3D entities, including point feature points (PF points). As discussed earlier, in some cases it is necessary to recreate contact regions by creating named selections. Named selections option is also used to name a specific face (i.e., inlet and outlet), body (i.e., tube, fluid domain). With the help of named selections, it becomes very easy for further operation.

**4.6.3 Mesh Report**

**Table 2: Mesh Report (Sizing)**

| Sizing | |
|---|---|
| Use Adaptive sizing function | On: Curvature |
| Relevance Centre | Fine |
| Mesh Defeaturing | Yes |
| Defeature size | Default (3.4431e-4 m) |
| Smoothing | High |
| Transition | Slow |
| Span Angle Centre | Fine |
| Capture curvature | Yes |
| Curvature Min size | Default (6.882e-4 m) |
| Curvature Normal Angle | Default (18.0º) |
| Bonding box Diagonal | 1.3815 m |
| Average surface Area | 0.19867 m$^2$ |
| Minimum Edge Length | 1.e02 m |

**Table 3: Mesh Statistics**

| Statistics | |
|---|---|
| Nodes | 36803 |
| Elements | 90586 |

**4.7 Setup**

The next most important section after Meshing is Setup, i.e., Fluent solver. Input for solution accuracy, Selecting Energy Equation, Selection of Radiation Model, Applying Materials, Applying Cell zone Condition, Boundary Conditions, Meshing Interfaces, etc. In a nutshell, here we depict the real situation we want to simulate. Before starting fluent, unmarking double precision option makes the solver single precision. Processing options are to speed up your simulations, and using full power of a cluster computer.

Two types of solvers are available- Pressure based & Density based. If density is not changing then the Pressure based method is used. Pressure based solver is Default and handles Mach number in the range 0~2-3. For solving higher Mach number problems, Density based solver are used or they are used for special cases, for example, to capture interacting shock waves.

**Table 4: General Setting for simulation**

| Solver type | Pressure-based |
|---|---|
| Velocity formulation | Absolute |
| Time | Steady |
| Gravity | 9.81 m/s2 (in –ve Y direction) |

**4.7.1 Solar Load Cell Model:** ANSYS FLUENT 2020 R2 provides a solar load model that can be used to calculate radiation effects from the sun's rays that enter a computational domain. There are two options available for the model: solar ray tracing and discrete ordinates (DO) irradiation. The ray tracing approach is a highly efficient and practical means of applying solar loads as heat sources in the energy equations. In cases where we want to use the discrete ordinates (DO) model to calculate radiation effects within the domain, an option is available to supply outside beam direction and intensity parameters directly to the DO model. The solar load model includes a solar calculator utility that can be used to construct the sun's location in the sky for a given time-of-day, date, and position. In this project work as, solar radiation is required for the heating of HTFs, solar load cell model is used for this project work. [14]

Solar load model is applied for numerical simulation, where typical inputs day and time of the experiment and longitude and latitude of location are fed in the solar load cell. The day selected for the experiment is 15 May and time is from 9 AM to 4 PM.

The longitude and latitude for location of Mumbai is 19.0760° N, 72.8777° E. By substituting the input values, CFD solar load cell calculated the direct and solar radiation. S2S (surface-to-surface) radiation model is applied for modelling the radiation mode of heat transfer between diffuse surfaces involved in the system.

**Table 5: Model used for Simulation**

| Energy | On |
|---|---|
| Viscous model | Laminar (Viscous heating) |
| Radiation-S2S, Solar Loading | Solar ray tracing |
| Discrete Phase | Off |

**4.7.2 Material Model:** NSYS provides list of materials for its database. You can use the edit/create button to copy any material from Fluent database. Editing the properties is also possible, or creation of a new material is also possible by changing Density, Specific heat, Thermal Conductivity, viscosity and by changing chemical formula.

### Table 6: Thermophysical Properties of Materials

| Thermophysical Properties | Air | Copper | Aluminum |
|---|---|---|---|
| Density (kg/m3) | 1.225 | 8978 | 2719 |
| Specific heat (J/kg.K) | 1006.43 | 381 | 871 |
| Thermal Conductivity (W/m.K) | 0.0242 | 387.6 | 202.4 |
| Viscosity (m2 /s) | 1.789e-5 | -- | -- |

**4.7.3 Mesh Interfaces:** Mesh interface allows you to manually create mesh interfaces for use with sliding mesh. It is necessary to describe which interface zones make up both sides of each interface. In interface options, coupled wall was selected. Also, Dynamic mesh is used for simulating moving objects, such as for simulation of a moving turbine blade.

**4.7.4 Boundary Conditions:** Assigning of a boundary type of each zone and make required input for each boundary is expected in Boundary conditions. Various boundary types include, Pressure-inlet, Pressure-outlet, velocity-inlet, outflow, wall, etc. Under incompressible flow, velocity-inlet- it applies uniform velocity profile at the boundary:

Velocity specification method includes: -
a.     Magnitude normal to boundary.
b.     Components.
c.     Magnitude and direction.
d.     Turbulent quantities.
e.     Thermal conditions.

### Table 7: Boundary Conditions

| Inlet | Inlet-Velocity (300K) |
|---|---|
| Outlet | Pressure outlet |
| Wall-tube | Heat flux (concentrated by parabolic trough collector) |

**4.7.5 Cell Zone Conditions**

### Table 8: Cell Zone Conditions

| Parabolic Reflector | Aluminum |
|---|---|
| Absorber tube | Copper |
| Water | Water-liquid |

Note- *The materials selected in this section, were already imported earlier from Material model.*

## 5. RESULT AND DISCUSSIONS

After setting up all boundary conditions, selecting various models and materials, the Solar absorber tube is simulated. The simulation has been done for time of 9 AM to 3 PM for a constant velocity i.e., 0.5 m/s, using water as HTF. The temperature distribution on Reflector surface was obtained. Velocity of water inside tube at different sections were obtained. Pressure Distribution of Absorber tube was obtained.

**5.1  Run calculation- Graph**
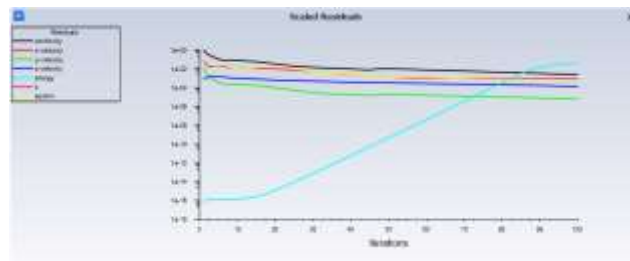


**Figure 14: Graph (Run Calculation)**

After selecting proper situation in Setup section, first step is to initialize the calculation. Before starting the calculations, it is necessary to initialize the flow fluid in the entire domain. The solution initialization allows to set initial values for the flow variables and initialize the solution using these values. Initialization method was selected as 'Hybrid Initialization'. Under that the number of iterations was selected as 15 to avoid convergence error. Reference frame was selected as Relative to cell zone.

Number of iterations for running calculation was set to 100. Reporting interval and Profile update interval was set to 1 respectively. As shown in the graph, Fig.14, The energy line must intersect the other lines. It means the calculations are proper. The graph includes continuity line, x velocity, y velocity and z velocity lines.

**5.2  Outlet Temperature v/s Time- Graph**

The solar absorber tube was simulated for the flowrate of 0.5 m/s using water as HTF for timing of 9 AM to 3 PM. The temperature was calculated manually for every timing by changing the time in setup section. All temperatures were plotted into graph as shown in Fig. 15. Approximate position of the Parabolic trough collector system was calculated at different timings by considering co-ordinates of Mumbai (15th May was selected as date). Sun's angle of elevation was calculated using online website and accordingly the Parabolic trough collector was made inclined. Simulation of the model is useful to understand Single axis tracking system. The model is assumed to kept at East-West orientation.
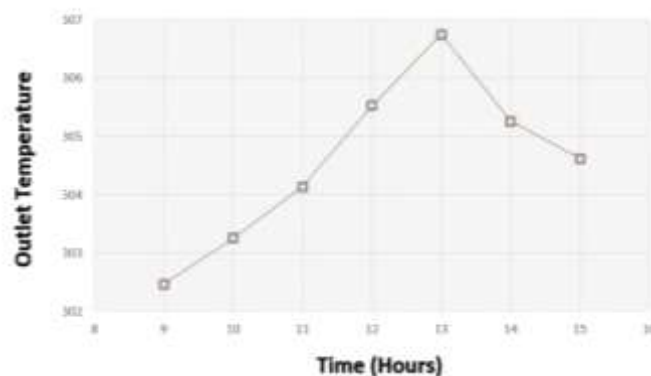


**Figure 15: Outlet Temperature at different times**

**5.3  Effect of Solar Fluxes on Solar Absorber tube**

To know the importance of PTC, 2 cases were done to investigate the effect of solar fluxes on solar absorber tube. One without PTC and one with PTC. The temperature distribution on solar absorber tube was investigated with PTC as shown in Fig.16.

After comparing both the cases, we found that there was just about 1 to 2 ℃ rise in temperature of water, which gives us idea importance of PTC. So, it can be said that, without collector, the Solar concentrated Parabolic trough collector system is ineffective. As the average outlet temperature of water was just increasing by 1 to 2 ℃ for the time 1 PM at 0.5 m/s, therefore by

above results it can be assured that by increasing the inlet velocity, there would have been very less rise in temperature. Therefore, other cases were not performed.
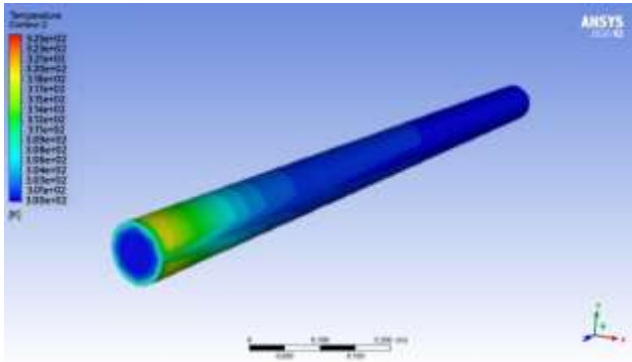


**Figure 16: Temperature Contour of water for timing 1 PM**

Temperature contours of Collector surface at different timings are as shown in Fig.16 Collector is exposed to sunrays. Material selected for collector is aluminum. The areas where the temperature is high, it is because of the Anisotropic Material and Absorptive property of material. Fig.17. shows Temperature distribution of collector surface at 1 PM and Fig.18. shows Temperature distribution of collector surface at 3 PM.
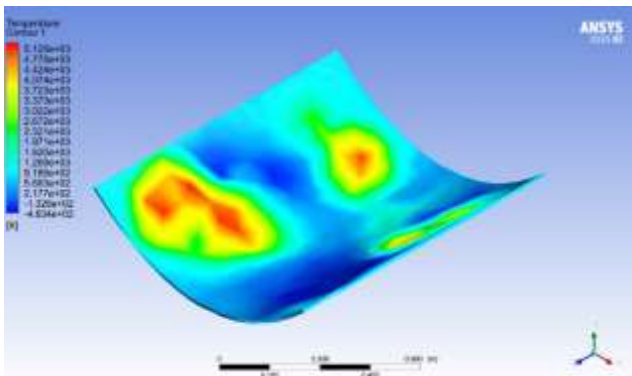


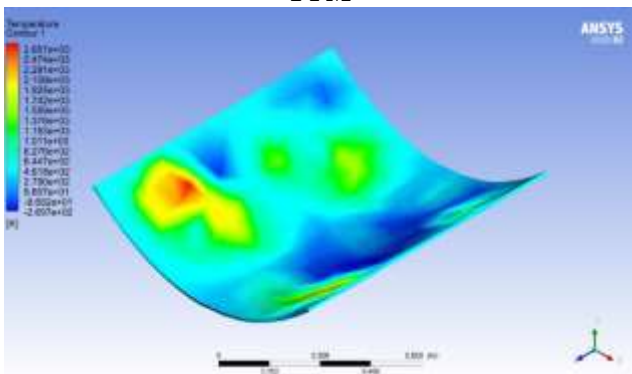**Figure 17: Temperature Distribution of Collector surface at 1 PM**



**Figure 18: Temperature Distribution of Collector surface at** 3 PM

**5.5 Velocity Distribution in Absorber tube**
Fig. 19. and Fig. 20. shows the velocity distribution at inlet and outlet. Outer region is observed blue in color, it indicates that the flow rate is minimum due to 'Boundary layer' formation. It shows the resistance is higher at outer side and resistance is low in core and giving out high velocity at core.
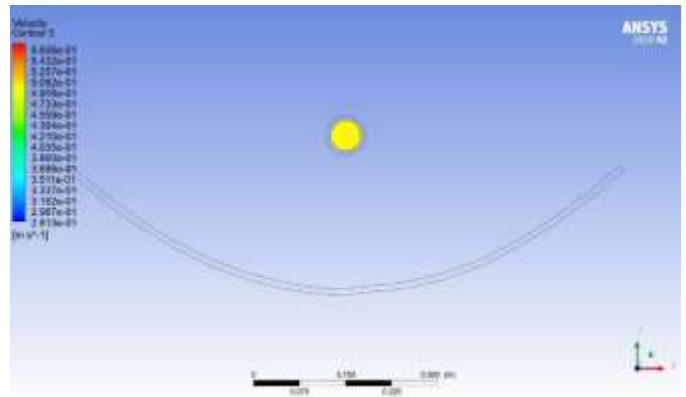


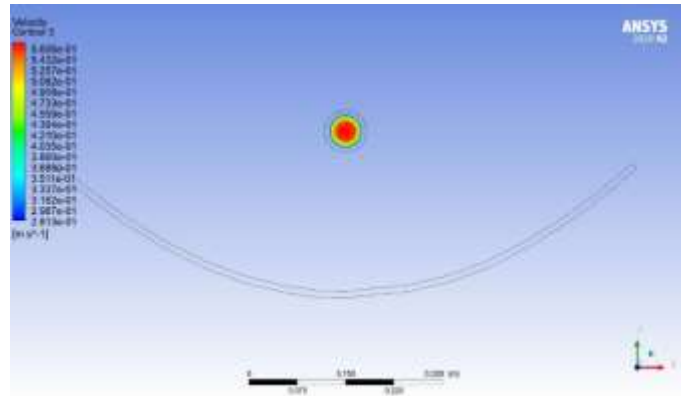**Figure 19: Inlet -water velocity**
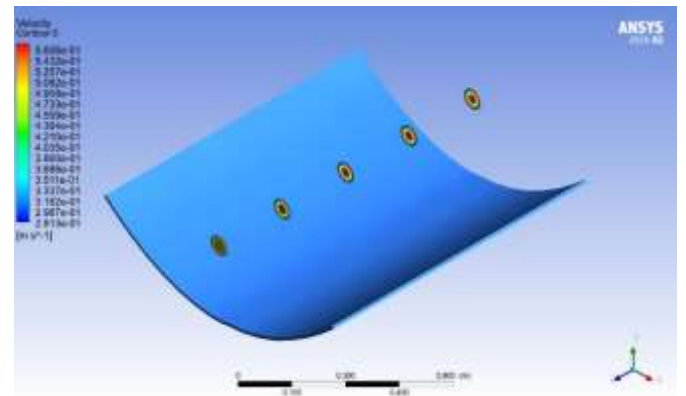


**Figure 20: Outlet-water velocity**



**Figure 21: Velocity Distribution inside tube at different sections**

Fig. 21. shows velocity distribution inside tube at different locations. It was obtained by creating different planes at 250 mm, 500 mm and 750 mm. Minimum velocity is 2.817e-01 m/s and maximum velocity is 5.606e-01 m/s. Animation of Velocity flow was done as shown in Fig. 22 and Fig. 23.
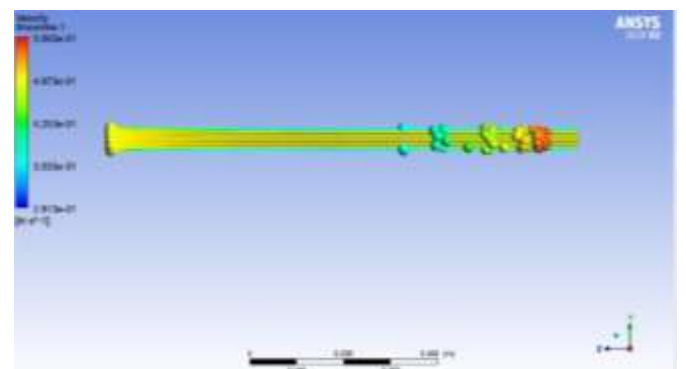


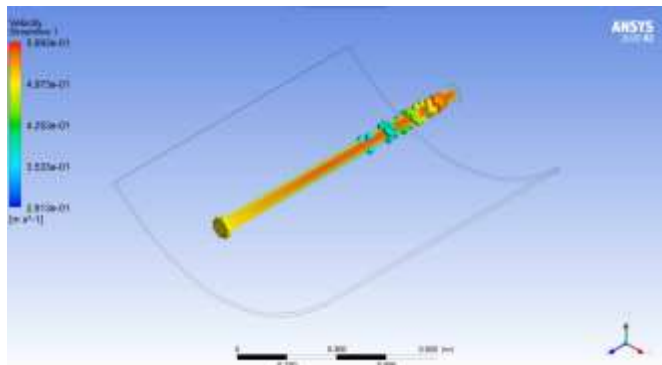**Figure 22: Velocity flow Animation screenshot 1**

**Figure 23: Velocity flow Animation screenshot 2**

## 6. CONCLUSION

Concentrating solar thermal is considered as one of the main options for renewable bulk electricity production. It is expected for the next years a concentrating solar thermal development similar in potential and magnitude to the wind power take-off Scope and Application of Solar Thermal Energy in India-A Review recently experienced. Recent economic support measures that have been considered in countries like Spain are going to make possible the first steps for this concentrating solar thermal emerging business.

The comparative study is done by using same flow rate for different time of the day for water as a HTF. The effect of mass flow rate on instantaneous efficiency of concentrated solar parabolic trough collector is analyzed. The temperature distributions on heat transfer fluid were also analyzed to get the idea of heating of the HTFs inside the solar absorber tube. It has also been seen that the outlet temperature increases with time till 1 PM and after that it starts decreasing for both heat transfer fluids. The reason for can be attributed to the increase in thermal losses to 52 [15]. Surroundings as the temperature difference between cover and surrounding increases. In present investigation it is also seen that higher outlet temperature can be attained with lowest flow rate i.e., at 0.5 m/s. This PTC system can be used as a water heater.

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