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# Numerical Simulation of Elliptical Absorber Tube in Parabolic Trough Collector for Better Heat Transfer

**V. K. Jebasingh*** **and G. M. Joselin Herbert**

Mechanical Department, Noorul Islam Centre for Higher Education, Nagercoil - 629180, Tamil Nadu, India; jebasingh.vk@gmail.com

## Abstract

Development on technology for harnessing solar energy has increased recently which makes a platform for generating thermal energy or electrical energy. Solar energy makes a pavement for use in many industries, residential and commercial sectors. The absorber tube of Parabolic Trough Collector (PTC) performance improvement is one of the major research topics in the field of solar energy engineering. Many earlier studies on absorber tube have showed much enhancement in heat transfer. In this study the traditional absorber tube has been experimentally tested and compared with a newly fabricated absorber tube with elliptical cross section for handling better heat transfer. Generally the mass flow rate is the main parameter which aids the PTC in absorbing more solar flux. In the present study the cylindrical absorber tube with circular cross section has been modified with an elliptical cross section. The designed elliptical absorber tube is fabricated and its performances have been calculated experimentally and numerically using MSC NASTRAN. The heat transfer and pressure drop are calculated for both type of absorber by varying three different mass flow rate such as 0.014, 0.021, 0.028 kg/s. The numerical 3-dimensional analysis shows a uniform heat transfer, which reduces thermal fatigue in elliptical absorber and consecutively found high pressure drop compared to circular absorber tube. Result also shows a slight improvement in outlet temperature on elliptical absorber which ultimately impacts the collector efficiency.

**Keywords:** Elliptical Absorber Tube, Numerical Analysis, Pressure Drop, Temperature Distribution

## 1. Introduction

Thermal energy which is one of the key for running many appliances in the world such as heat utilizing industries, desalination plants, refrigeration sectors, power plants etc. The only natural energy which is available abundantly in earth and can be directly utilized is solar energy. Even though many advancement created by many researchers in the field of solar energy for extraction of useful heat, few technologies have been successfully used for handling high temperature energy absorption. One of the technologies is Solar Parabolic Trough Collector (SPTC) which can handle a temperature of about 500$^{o}$C. Currently many countries have started utilizing PTC for power generation because of its matured technology and high thermodynamic efficiency. Since the absorption of complete solar radiation on earth look to be a dream yet maximum utilization of solar energy improves the plant efficiency and reduces the power demand by the whole world. Researches have done many modifications for refining the absorbers characteristics such as better useful heat transfer rate, fluid conduit aspect ratio and eventually optimizing the design. Javier Munoz and Alberto Abanades have replaced the absorber tube with an internal helically finned tube and done a Computational Fluid Dynamics (CFD) analysis by considering parameters such as pressure losses, thermal losses, thermo-mechanical stress and thermal fatigue[1]. Ricardo Vasquez Padilla et al. suggested the heat transfer and optical analysis are very essential for optimized study

* *Author for correspondence*

of PTC performance under various operating condition[2]. Hachicha et al. has studied about heat transfer analysis numerically and validated with experimental readings from Sandia National Laboratories. They created a numerical model based on energy balance equation for optimizing optical and thermal analysis[3]. O. Garcia-Valladares and N. Velazquez have done a numerical simulation to determine the thermal and fluid dynamic behaviour by considering single and double pass concept on PTC and concluded that double pass shows better performance[4]. M. I. Roldan et al. have done a CFD analysis to determine the absorber wall temperature with superheated steam as Heat Transfer Fluid (HTF) and evaluated with the experimental results[5]. Changfu You et al. have created a flow and heat transfer model and solved using Finite Element Method (FEM), they also suggested that fluctuation in radiation affects the Direct Steam Generation (DSG) drastically[6]. K. Ravi Kumar and K. S. Reddy have made a 3D numerical analysis of a porous disc line absorber in PTC and concluded that the heat transfer rate increased by 64.3% with better pressure drop which significantly enriches the system performance[7]. Z. D. Cheng et al. have made a 3D numerical simulation in fluent software using Syltherm 800 liquid oil as HTF; they considered Reynolds number and emissivity of inner wall of absorber as a variable for heat transfer rate analysis[8]. M. Natarajan et al. has done a numerical simulation for studying heat transfer characteristic in absorber tube by creating an insertion in internal flow such as triangle, inverted triangle and semi-circular inserts and commented that triangle insert absorber tube have increased life span from thermal stress effect[9]. Thus the researcher's investigation shows that the improvement of PTC plant can be done by enhancing the thermal or heat transfer rate and also by refining the pressure losses in the absorber tube.

## 2. Experimental Setup

The setup consists of solar PTC with a storage tank of 70 litre capacity, non-return valve for upholding the flow path and control valve for regulating the mass (water) flow rate. To obtain the readings the following gauging instruments are used namely, pyranometer, anemometer, flow meter and thermocouple with digital display. Pyranometer is used for measuring the solar radiation in the apparatus, digital anemometer for measuring the wind velocity similarly flow meter for measuring the mass flow rate of water and finally the thermocouple for temperature measurement. The Figure 1 shows the experimental set up of PTC. The basic parameters of parabolic trough collector and the designed elliptical absorber dimensions are shown in Table 1.

**Figure 1.** Experimental set-up showing parabolic trough collector.

Table 1. Design specifications of elliptical absorber tube of parabolic trough collector

| HTF | Water |
|---|---|
| Major axis of elliptical absorber (a) | 26 mm |
| Minor axis of elliptical absorber (b) | 16.7 mm |
| Thickness of absorber tube (t) | 2 mm |
| Outer diameter of glass tube (Do) | 58 mm |
| Aperture of the concentrator (W) | 1200 mm |
| Length of Parabolic trough | 1500 mm |
| Inner diameter of glass tube | 50 mm |
| Glass cover transitivity for solar radiation (τ) | 85% |
| Emissivity of glass (ε) | 0.82 |
| Collector aperture area | 1.8 $m^2$ |
| Absorber tube emissivity | 0.15 |

Table 2. Properties of absorber tube and working fluid (water)

| Absorber tube properties | | Properties of HTF (Water) at 20°C | |
|---|---|---|---|
| Density | 8978 $kg/m^3$ | Density of fluid (ρ) | 998.2 $kg/m^3$ |
| Thermal Conductivity (k) | 387.6 W/m K | Thermal Conductivity (k) | 0.600 W/m K |
| Specific heat capacity ($C_p$) | 381 j/kg K | Dynamic Viscosity (μ) | 0.001003 kg/m-s |
| | | Specific heat capacity ($C_p$) | 4.182 kj/kg K |

## 3. Methodology of Simulation

The numerical analysis is carried out using MSC NASTRAN for circular and elliptical cross sectioned absorber tube of PTC. The heat transfer (Thermal Load) and fluid flow (Dynamic fluid mode) analysis has been considered. The input parameters are taken from the experimental data's. The governing equations such as continuity equation, momentum equation, energy equations, K equation and ε equations are used during pre-processing stage. Two boundary conditions are applied namely one is the upper part of absorber tube were direct solar radiations are applied and another is the lower part were constant concentrated radiations are applied as stated by Cheng et al[8].

The general assumptions made during simulation are;

- Steady state heat transfer has been considered hence heat flux and wall does not change.
- Thermal conductivity of the absorber tube is taken as unchanging and constant.
- The absorber tube heat transfer through radiation is neglected.
- The flux distribution is assumed to be uniform along the surface of absorber tube.

The entire absorber tube is discretized using hexahedral meshing element and the inner surface is chosen with hybrid mesh which influences the consideration of fluid flow. The YND concept has been utilized for loading thermal analysis which accompanies the hybrid mesh using MSC Nastran. Similarly the boundary constrain are applied in wall surface by assuming like experimental stage fixed conditions. The governing equations are shown below,

- Continuity equation:

$$\partial \frac{\partial}{\partial x_i}(\rho u_i) = 0 \qquad (1)$$

- Momentum equation:

$$\partial \frac{\partial}{\partial x_i}(\tilde{n} u_i) = -\frac{\partial p}{\partial x_i} + \frac{\partial p}{\partial x_i}(\mu_i + \mu)\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)$$

$$-\left\{\left(\frac{2}{3}\right)(\mu_i + \mu)\left(\frac{\partial u_i}{\partial x_j}\delta_{ij}\right) + \rho g_i\right\} \qquad (2)$$

- Energy equation:

$$\frac{\partial}{\partial x_i}(\rho u_i, T) = \left\{\frac{\partial}{\partial x_i}\left(\frac{\mu}{pr} + \frac{\mu_i}{\sigma T}\right)\left(\frac{\partial T}{\partial x_i}\right)\right\} + Sr \qquad (3)$$

- K equation:

$$\frac{\partial}{\partial x_i}(\rho u_i, k) = \left\{\frac{\partial}{\partial x_i}\left(\mu + \frac{\mu_i}{\sigma k}\right)\left(\frac{\partial k}{\partial x_i}\right)\right\} + Pk - \rho\varepsilon \qquad (4)$$

- ε equation:

$$\frac{\partial}{\partial x_i}(\rho u_i, \varepsilon) = \left\{\frac{\partial}{\partial x_i}\left(\mu + \frac{\mu T}{\sigma \varepsilon}\right)\left(\frac{\partial \varepsilon}{\partial x_i}\right)\right\} + [\frac{\varepsilon}{k(C_1 Gk - C_2 \rho\varepsilon)}] \qquad (5)$$

Where the turbulent viscosity ($\mu_t$) and the production rate (Pk) are given by,

$$\mu_t = \frac{C_\mu(\rho(k^2)}{\varepsilon} \qquad (6)$$

$$\mathrm{Pk} = \left|\frac{\partial u_i}{\partial x_j\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)}\right| \qquad (7)$$

These governing equations are used for analysis, and in-addition YND (Y axis Nodal Deviation) formulation is applied in software tool for loading the boundary conditions and radiating thermal load.

## 4. Experimental Observations

The experiment work was done for a period of one year (from April 2012 to August 2013) and on every month the test was conducted for three sunny days using water as HTF in the traditional circular absorber tube and another three days with the elliptical newly fabricated absorber tube. The test was logged on hourly base. In this investigate the cold water from the storage tank is passed through the absorber tube in solar parabolic trough collector via gravity technique, because the storage tank is kept above the level of collector, and the heated water again enters the storage tank through the non-return valve. The flow of hot water takes place by thermo siphon (natural circulation) and hence the hot water is replaced by the cold water from the bottom of the storage tank. The measurement data's such as the total solar radiation on the collector, wind velocity, water mass flow rate and the temperatures at inlet, outlet and the ambient temperatures are noted. The temperature on the outer cover of the glass tube was also noted. Similarly the experiment is conducted using elliptical absorber tube and all the readings were recorded as stated earlier. In this system the solar tracking mechanism has been attached hence the collector tilts from east to west automatically. The mass flow rate of water kept for the three days test was 0.014, 0.021 and 0.028 kg/s.

Table 3. Average experimental data's during April 2012 to August 2013 for circular absorber with mass flow rate of 0.014 kg/s

| Sl. No | Time | Temperature °C | | | Total solar Radiation on collector (W/m²) | Wind Speed (m/s) |
|---|---|---|---|---|---|---|
| | | Ambient | Inlet | Outlet | | |
| 1 | 10.00 | 30 | 26 | 30 | 821 | 3.2 |
| 2 | 11.00 | 32 | 28 | 35 | 882 | 3.6 |
| 3 | 12.00 | 36 | 30 | 44 | 937 | 4.1 |
| 4 | 13.00 | 38 | 32 | 50 | 968 | 3.4 |
| 5 | 14.00 | 40 | 32 | 58 | 912 | 3.6 |
| 6 | 15.00 | 37 | 32 | 55 | 892 | 3.5 |
| 7 | 16.00 | 34 | 33 | 53 | 867 | 3.8 |

Table 4. Average experimental data's during April 2012 to August 2013 for elliptical absorber with mass flow rate of 0.014 kg/s

| Sl. No | Time | Temperature °C | | | Total solar Radiation on collector (W/m²) | Wind Speed (m/s) |
|---|---|---|---|---|---|---|
| | | Ambient | Inlet | Outlet | | |
| 1 | 10.00 | 29 | 28 | 34 | 883 | 4.0 |
| 2 | 11.00 | 32 | 31 | 48 | 912 | 3.8 |
| 3 | 12.00 | 37 | 35 | 55 | 983 | 3.9 |
| 4 | 13.00 | 38 | 37 | 61 | 1002 | 3.3 |
| 5 | 14.00 | 41 | 40 | 59 | 996 | 3.5 |
| 6 | 15.00 | 38 | 38 | 56 | 926 | 3.8 |
| 7 | 16.00 | 35 | 33 | 54 | 890 | 4.2 |

The Table 3 and 4 illustrates the average variation of temperature and solar radiations for the mass flow rate of 0.014 kg/s on both the circular and elliptical absorber tube, which are noted directly using thermocouples and pyranometer. The elliptical absorber tube shows a consecutive improvement in final temperature which leads to a better absorption of solar radiation. Similarly the test was conducted using a different mass flow rate of about 0.021, and 0.028 kg/s. It is found that beyond the mass flow rate of 0.028 kg/s the temperature absorption rate has been reduced.

## 5. Results and Discussion

The results obtained using MSC Nastran on circular and elliptical absorber tube is compared with the experimental readings and found to be good which shows a less than 4.6% deviation, thus validating the present numerical study. The results obtained using MSC Nastran for static thermal analysis, thermic fluid flow analysis and pressure drop are as discussed below:

The temperature analysis has been done on absorber tube in two stages, initially considering a static thermal analysis for checking the life of elliptical absorber tube over the circular absorber tube. Then a thermic fluid motion analysis has been done with the use of CFD module in NASTRAN software.

### 5.1 Static Analysis

The static thermal analysis has been conducted on absorber tube with circular cross sectioned tube and with the newly designed elliptical absorber tube. The real time maximum temperature load of 100°C (373 K) has been applied while considering water as HTF. In this case the thermal load is applied along the inner surface wall of the absorber tube. Result shows the thermal stress is reduced to 5.4% relatively while considering water as HTF in elliptical absorber tube. The linear distribution of temperature is noted on all nodes of elliptical absorber tube which shows a better life compared to the circular absorber tube. The Table 5 also shows the thermal expansion along the length in circular absorber tube is more compared to the elliptical absorber tube. Hence the elliptical absorber tube fabricated and used in the experimental testing was found to be successful.

Table 5. Static thermal analysis result on absorber tube

| Sl. No. | Thermal Load (K) | Circular absorber tube | | Elliptical absorber tube | |
|---|---|---|---|---|---|
| | | Expansion (mm) | Stress (N/m²) | Expansion (mm) | Stress (N/m²) |
| 1 | 373 | 1.0949 | 148.6 | 0.0869 | 140.6 |

### 5.2 Dynamic Analysis

The well developed and well supported CFD software tool is required for analysing the engineering problems. The MSC NASTRAN software has a many stable inbuilt modules hence this specific tool is used in thermic flow analysis. The CFD analysis has been done on the absorber tube with two different HTF for three mass flow rates for validation. The simulation result shows less than 5% deviation in the output fluid temperature when compared to the experimental result. The average experimental outlet temperature readings are calculated for 12 months and each month with three average readings. The temperature distribution predicted from the simulated result shows a deviation from experimental result mostly due to the neglect of solar radiation reflected from the absorber tube.

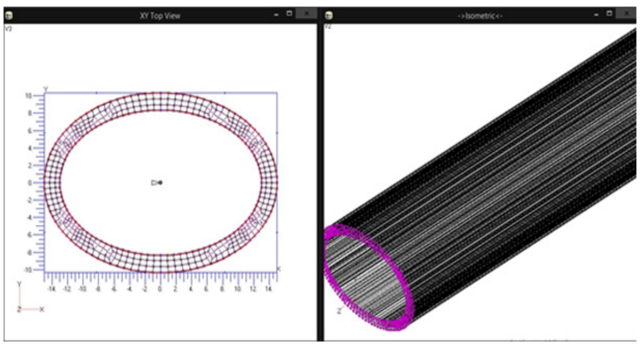

Figure 2. Hybrid meshing condition for influncing dynamic fluid flow.

The Figure 2 Shows the boundary conditions applied and the advanced hybrid mesh for better reslut while considering fluid motion analysis. And the fluid condition is applied along z axis direction.

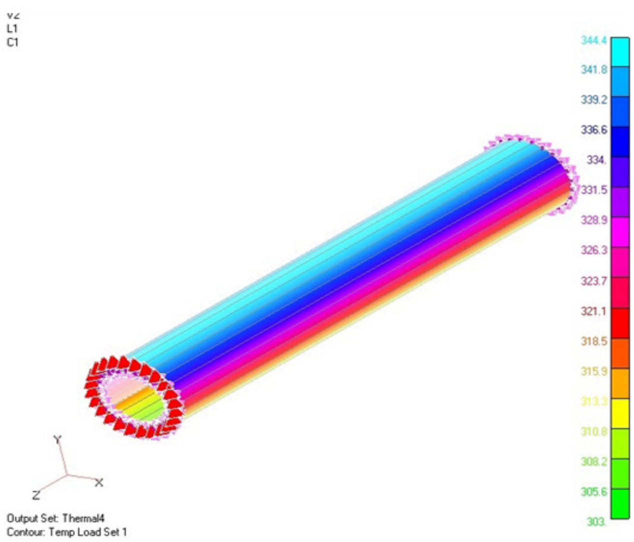


Figure 3. Temperature distribution in the elliptical cross-sectioned absorber tube.

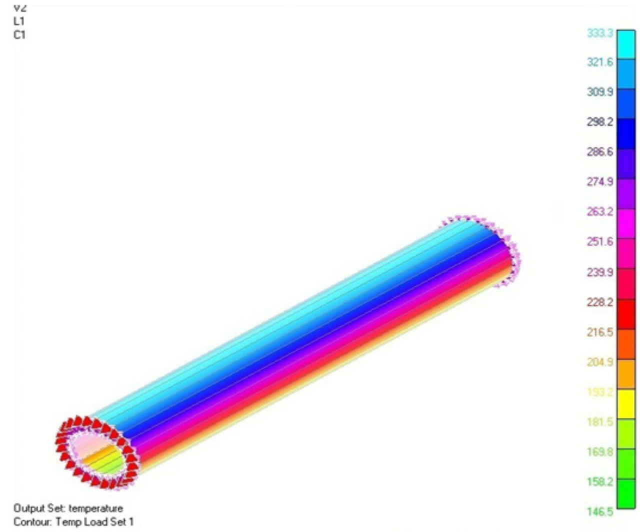


Figure 4. Temperature distribution in the circular cross-sectioned absorber tube.

From Figure 3 and Figure 4, the temperature transfer along the absorber tube can be studied which shows a systemic transfer of heat into the water takes place. The maximum temperature in the circular absorber is around 333.3K, whereas the maximium temperature in the elliptical absorber tube is 344.4K. Though the newly designed elliptical model shows less temperature improvement, the temperature distribution on all nodes are found to be uniform. Hence the thermal stress variation of low and high absorbtion is reduced which increases the life of absorber tube.

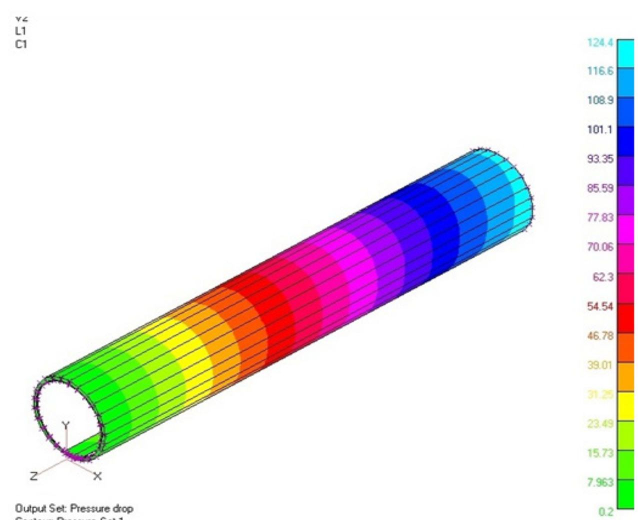


Figure 5. Pressure drop in the circular cross-sectioned absorber tube.

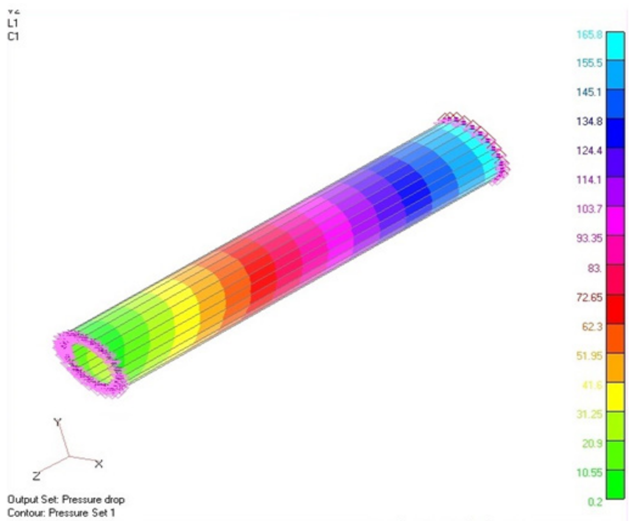


**Figure 6.** Pressure drop in the elliptical cross-sectioned absorber tube.

Figure 5 and Figure 6 shows the output display of MSC Nastran solver for the pressure drop throughout the circular and elliptical absorber tube. It shows in elliptical absorber during a mass flow rate of 0.028 kg/s, a maximum pressure drop variation of 165.8 N/m$^2$ has been predicted whereas in circular it shows only 124.4 N/m$^2$ for the same flow rate.

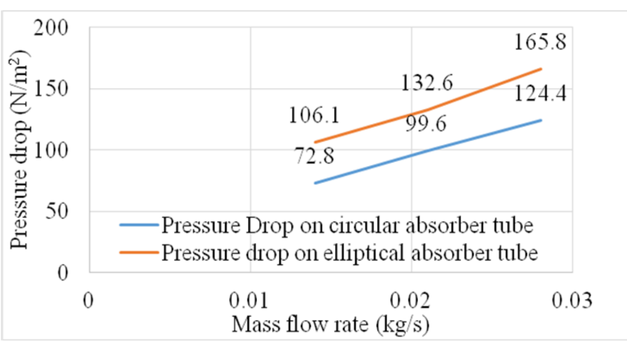


**Figure 7.** Pressure drop for different mass flow rate in both absorber tube.

Figure 7 describes the results of pressure drop for different mass flow rate of 0.014, 0.021 and 0.028 kg/s, finally the elliptical cross sectioned model reveals that the pressure drop has increased to 24.88% while compared to circular absorber tube which reduces the efficiency if used in power plant also it can be reduced with certain modification in pipe height etc.

## 6. Conclusion

In this present 3D numerical analysis study the fluid flow and heat distribution characteristics through the absorber tube of both circular and elliptical cross section has been predicted. Many results have also been studied from the simulation study.

- While using water as HTF, the average instantaneous efficiency of PTC with circular absorber tube is 48.89%, whereas the efficiency during the use of elliptical absorber tube is 54.13%. Thus with the use of elliptical absorber tube the increase in efficiency of about 9.7% for the period of August 2012 to July 2013 has been reported compared to circular absorber tube.
- The maximum outlet temperature of the water is increased to 69°C in elliptical absorber tube along with the high temperature gradient.
- The thermal stress on the circular absorber is found to be high due to rapid variation in temperature whereas the temperature variation is linear in elliptical absorber from initial stage to final outlet; hence the life of elliptical absorber tube will be more compared to the circular cross sectioned absorber tube.
- The thermal expansion is high in circular absorber tube compared to elliptical absorber tube, thus the case of buckling failure is avoided.
- The pressure drop which also plays a key role in collector's performance is found to be little higher while using elliptical absorber tube and shows a rise of 24.88 % more than circular absorber tube with the mass flow rate of 0.021 kg/s. The rate of flow also reduces the performance beyond the mass flow rate of 0.028 kg/s.
- The numerical analysis results are validated with the experimental results and found an error of less than 4%.

Thus the transient 3D analysis shows the variations in heat transfer and pressure drop are better on the newly fabricated elliptical cross sectioned absorber tube. Even though the temperature rise is low while comparing to circular absorber tube it is efficient, because a small improvement also can impact the increase in instantaneous collector efficiency. The future scope for this research states, the change in specific HTF with optimize design will ultimately improves the thermal absorption property of PTC.

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