CFD Analysis of Parabolic Collector To Observe Heat Transfer Rate

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Abstract- *Solar energy is one of the most promising energy sources for humanity's survival and sustainability. The main objective of this thesis is to maximize the calorific value of the absorption tube of a parabolic collector. Realization of the digital analysis of the flow rates on the basic drawing of the absorber tube of a collector with parabolic channel and performing digital flow analysis on a modified absorber tube design of a parabolic collector. The conclusion was summarized as the maximum temperature at the exit of the parabolic collector for all projects with solar radiation of 1000 W/m2 and its maximum value of 47.67 oC for design-3. Therefore, the absorber tube design-3 of vacuum parabolic collector receiver tube is recommended to provide highest temperature.*

Keywords- CFD, Solar energy, PTC, Absorbent tube

I. INTRODUCTION

Solar energy is one of the most promising energy sources for human survival and sustainability. We can solve problems like global warming with a clean energy source like solar energy. It offers an excellent opportunity to reduce pollution economically. Present commercial energy sources are harmful to the environment. To avoid pollution and create a sustainable environment, it is therefore necessary to improve the potential of renewable energies. The government has set a renewable energy target of 175 GW, of which 100 GW is for solar energy. The Ministry of Renewable Energy has started to implement and support various programs to achieve the goal. Solar energy is one of the most important renewable energy sources that will provide an alternative to fossil fuels in industry and households. [2] The sun emits energy at the rate of 3.8 * 10^{23}KW, of which only a small fraction, reaches the earth's surface, which is a thousand times higher than the current energy consumption. Solar concentrating device reflects solar energy from the reflector to the focal point or focal line through which the liquid passes. These devices for heat application and power generation are gaining attention. [4]

Solar energy technologies consist of photovoltaic solar cells, flat solar panels and concentric collectors, solar towers, etc. from which concentrated solar collectors such as parabolic collectors (PTC) can produce hot water or steam which can be used to generate electricity for industrial processes. It is a cost-effective solar energy technology that is used in both households and industry.

II. LITERATURE REVIEW

Wiesław Zima et al. [1] The paper presents a one-dimensional dispersed boundary model to reproduce the transient activity of an illustrative authority. The investigated sun based gatherer has a measured design and is furnished with a two-pivot sun oriented global positioning framework to build the sunlight based energy yield. The sensor is expected for homegrown and different applications with medium nuclear power needs. In fostering the mathematical model, the comparing differential energy balance conditions are defined for the individual segments of the authority. Conditions are tackled utilizing various plans. The outcome is a progression of temperatures as an element of time and position for every one of the sensor parts and the functioning liquid.

Tagle-Salazar et al. [2] The target of this examination is to introduce the cutting edge of allegorical sunlight based gatherer innovation with an accentuation on different strategies for warm execution investigation and the segments utilized in the assembling of the authorities, just as different structure materials and their properties. Furthermore, their modern applications, sun based energy transformation measures and innovative advances in these fields are talked about.

Mario A. Cucumo et al. [3] In this work a sunlight based warm generator is broke down according to an energy perspective. It is a clamshell authority that is essential for a concentrating sun based board framework. The framework being referred to is utilized to produce low enthalpy nuclear power as a combination into the boiling water framework for some understudy dorms of the University of Calabria.

lalkundan et al. [4] The current work assesses the presentation of sunlight based boards utilizing Al_2O_3-$C_2H_6O_2$-H_2O nanofluid as working liquid, both by test examination and CFD. An ethylene-glycol-water blend (40:60 v/v) is utilized as the base fluid, where α-Al_2O_3 nanoparticles with a normal size of 20 nm are scattered to create a nanofluid with four distinct volumetric focuses (Conc. vol.) From 0.05, 0.075, 0.1 and 0.125%.

III. OBJECTIVE

The following objectives can be expected from this work

- The main objective of this thesis is to maximize the calorific value of the absorbent tube of a parabolic collector.
- Execution of the numerical analysis of the flows on the basic paper drawing of the absorber tube of a collector with parabolic channel and validation.
- Performing digital flow analysis on a modified absorption tube design of a parabolic collector.
- Comparison of the results and the best suggested result of the absorber tube of the parabolic vacuum collector.

IV. METHODOLOGY

The parabolic solar collector receives heat from the sun's solar radiation. Parabolic channel solar collector systems use a parabolic channel, which consists of mirrors mounted on the support structure, to reflect solar radiation and focus it on the focus of the parabolic channel. This concentrated energy is then used for many applications such as air heating, solar pump, solar cooker, etc.

In the present work, a total of three models of parabolic vacuum collector's receivers were developed using the modular design of ANSYS fluent, then digital flow analyzes were performed to study the temperature distribution using the Navier model.

4.1 Mathematical analysis of parabolic trough collector:

Following are the assumptions for mathematical calculations;

- Total solar radiation intensity after reflection from the aperture of a parabolic trough concentrator is intercepted by receiver at the focus.
- No portion of aperture area of a parabolic trough concentrator is shaded by the receiver.
- Solar radiation intensity falls on the aperture of a parabolic trough concentrator is constant.

Mass Flow Rate:

$\dot{m} = \rho A_{cross}\, v$

Where,

ρ = Density of working fluid (kg/m^3)

A_{cross} = Cross-section area of absorber tube (m^2)

v = Mean velocity of fluid (m/s)

Mean velocity of fluid

$$v = \frac{\dot{m}}{\rho \times A_{cross}}\ m/sec$$

Reynolds number

$$R_e = \frac{\rho \times v \times D_h}{\mu}$$

prandtl number

$$P_r = \frac{\mu C_p}{k}$$

C_p= Specific heat capacity in W/kg.K

μ= Dynamic viscosity

k = Kinematic viscosity

Nusselt number

$$Nu = \frac{h_a D_h}{k} = 0.023 Re^{0.8} Pr^{0.4}$$

The convection heat transfer between the inner tube and the working fluid is

$$Q_{conv} = hA_a(T_a - T_{hot})$$

Where:

h= convective coefficient between working fluid and inner surface of absorber tube

A_a = inner surface area of absorber tube

T_a = inner surface area temperature

T_{hot} = Temperature of hot fluid

$$N_u = \frac{\left(\frac{f}{8}\right)(R_e - 1000)P_r}{1 + 12.7\left(\frac{f}{8}\right)^{1/2}\left(P_r^{\,1/2} - 1\right)}$$

f = friction factor

R_e = Reynolds Number

P_r = Prandtl number

$$f = (0.79 \ln R_e - 1.76)^{-2}$$

$$R_e = \frac{v.D}{\upsilon}$$

υ= kinematic viscosity

Thermal Efficiency:

$$\eta_{th} = \frac{mc\Delta T}{I \times A_s}$$

Where,

m = mass flow rate of fluid (kg/s)

c= specific heat capacity (J/kg℃)

ΔT= temperature difference

I= Intensity of solar radiation (W/m^2)

A_s= surface area of transparent glass (m^2)

4.2 Algorithm used for Computational fluid dynamics analysis:

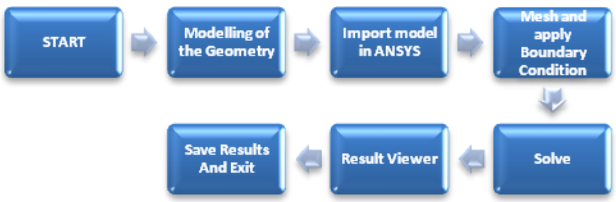

Figure 1: Algorithm used for Computational fluid dynamics analysis

The general assumptions are made for computational fluid dynamics analysis.

1. Steady state heat transfer has been considered hence heat flux and wall does not change with respect to time.
2. The flux distribution is assumed to be uniform along the surface of absorber tube.

4.3 Governing Equations:

4.3.1 Conservation of mass or continuity equation:

The equation for conservation of mass, or continuity equation, can be written as follows:

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho\,\vec{v}) = S_m$$

Where S_m= mass added to the continuous phase or any user defined sources.

For 2D axisymmetric geometries, the continuity equation is given by

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho v_x) + \frac{\partial}{\partial r}(\rho v_r) + \frac{\rho v_r}{r} = S_m$$

Where *x* is the axial coordinate, *r* is the radial coordinate, v_x is the axial velocity, and v_r is the radial velocity.

4.3.2 Momentum Conservation Equations:

Conservation of momentum in an inertial reference frame is described by

$$\frac{\partial}{\partial t}(\rho\vec{v}) + \nabla.(\rho\,\vec{v}\vec{v}) = -\nabla p + \nabla.(\bar{\bar{\tau}}) + \rho\vec{g} + \vec{F}$$

Where,

p= static pressure

$\bar{\bar{\tau}}$ = stress tensor

$\rho\vec{g}$ = gravitational body force

$\vec{F}$ = external body forces

The stress tensor $\bar{\bar{\tau}}$ is given by

$$\bar{\bar{\tau}} = \mu\left[(\nabla\vec{v} + \nabla\vec{v}^{T}) - \frac{2}{3}\nabla.\vec{v}I\right]$$

Where,

μ = molecular viscosity

I = unit tensor,

For 2D axisymmetric geometries, the axial and radial momentum conservation equations are given by

$$\frac{\partial}{\partial x}(\rho v_x) + \frac{1}{r}\frac{\partial}{\partial x}(r\rho v_x v_x) + \frac{1}{r}\frac{\partial}{\partial r}(r\rho v_r v_x) = -\frac{\partial p}{\partial x} + \frac{1}{r}\frac{\partial}{\partial x}\left[r\mu\left(2\frac{\partial v_x}{\partial x} - \frac{2}{3}(\nabla.\vec{v})\right)\right] + \frac{1}{r}\frac{\partial}{\partial r}\left[r\mu\left(\frac{\partial v_x}{\partial r} + \frac{\partial v_r}{\partial x}\right)\right] + F_x$$

And

$$\frac{\partial}{\partial t}(\rho v_r) + \frac{1}{r}\frac{\partial}{\partial x}(r\rho v_x v_r) + \frac{1}{r}\frac{\partial}{\partial r}(r\rho v_r v_r) = -\frac{\partial p}{\partial r} + \frac{1}{r}\frac{\partial}{\partial x}\left[r\mu\left(\frac{\partial v_r}{\partial x} + \frac{\partial v_x}{\partial r}\right)\right] + \frac{1}{r}\frac{\partial}{\partial r}\left[r\mu\left(2\frac{\partial v_r}{\partial r} - \frac{2}{3}(\nabla.\vec{v})\right)\right] - 2\mu\frac{v_r}{r^2} + \frac{2\mu}{3r}(\nabla.\vec{v}) + \rho\frac{v_z^2}{r} + F_r$$

Where,

$$\nabla.\vec{v} = \frac{\partial v_x}{\partial x} + \frac{\partial v_r}{\partial r} + \frac{v_r}{r}$$

Where,

v_x= Axial velocity

v_r= Radial velocity

1. v_z = swirl velocity

4.3.3 Energy Equation:

The energy equation for the mixture takes the following form:

$$\frac{\partial}{\partial t}\sum_{k=1}^{n}(\alpha_k\rho_k E_k) + \nabla.\sum_{k=1}^{n}\left(\alpha_k\vec{v}_k(\rho_k E_k + p)\right) = \nabla.(k_{eff}\nabla T) + S_E$$

where k_{eff} = effective conductivity

S_E= volumetric heat sources

$$E_k = h_k - \frac{p}{\rho k} + \frac{v_k^2}{2}$$

Where,

$E_k = h_k$ for an incompressible phase and h_k= sensible enthalpy for phase *k*

4.3.4 $k-\epsilon$ $model$:

The turbulence kinetic energy, *k*, and its rate of dissipation, ϵ, are obtained from the following transport equations:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k v_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k + G_b - \rho\epsilon - Y_M + S_k$$

and

$$\frac{\partial}{\partial t}(\rho\epsilon) + \frac{\partial}{\partial x_i}(\rho\epsilon v_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\epsilon}\right)\frac{\partial\epsilon}{\partial x_j}\right] + C_{1\epsilon}\frac{\epsilon}{k}(G_k + C_{3\epsilon}G_b) - C_{2\epsilon}\rho\frac{\epsilon^2}{k} + S_\epsilon$$

In these equations, G_k represents the generation of turbulence kinetic energy due to the mean velocity gradients.

G_b is the generation of turbulence kinetic energy due to buoyancy.

Y_M represents the contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate.

$C_{1\epsilon}$, $C_{2\epsilon}$, and $C_{3\epsilon}$ are constants.

σ_k and σ_ϵ are turbulent Prandtl numbers for k and ϵ, S_k And S_ϵ are user-defined source terms.

4.3.5 Model validation:

In order to validate the results of present work, a comparative analysis have been done with selected base paper *"Salma Marrakchi at el. Temperature distribution analysis of parabolic trough solar collector using CFD, 11th International Conference Interdisciplinary in Engineering, Tirgu-Mures, Romania, Procedia Manufacturing vol. 22, year 2018, page from 273-279"* using computational fluid dynamic analysis to evaluate temperature distribution for parabolic trough collector.

After performing computational fluid dynamics analysis of base model of parabolic trough collector the temperature increases from 298K (25 ºC) to 318K (35 ºC) due to the increase of heat solar radiation during the day for 1000 W/m^2. In the present work the maximum temperature of 317.90K at solar radiation during the day for 1000 W/m^2 as shown in figure 4.2

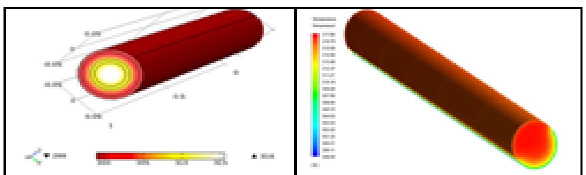

Figure 2: (a) Temperature distribution [Salma Marrakchi at el]	Figure 2: (b) Temperature distribution [present work]

Figure 2: Temperature distribution

From the above validation work it has been observed that the compared result of temperature distribution variation is less than 1% from base paper which shows very good agreement with negligible error. After the validation from base model some other designs of parabolic trough collector's receiver have been used for computational fluid dynamics analysis to enhance the thermal performance of the parabolic trough collector.

4.3.6 Computational fluid dynamics analysis for Receiver tube of parabolic trough collector:

CAD geometry:

In the present work a two dimensional CAD model of absorber tube of parabolic trough collector has been created using design modular of ANSYS workbench. The dimensional parameters are for design-1 is as follows, inner diameter of absorber tube is taken as 27.5 mm with length of 1000 mm A two dimensional view of absorber tube is shown in figure 3.

Figure 3: CAD geometry of absorber tube of parabolic trough collector for design-1

Meshing: For the discretization of the CAD geometry size of element is set as 1 mm. The total no of nodes generated in the present work is 71370 and total no. of elements is 69502. Types of elements used are rectangular which is a rectangular in shape with four nodes on each element.

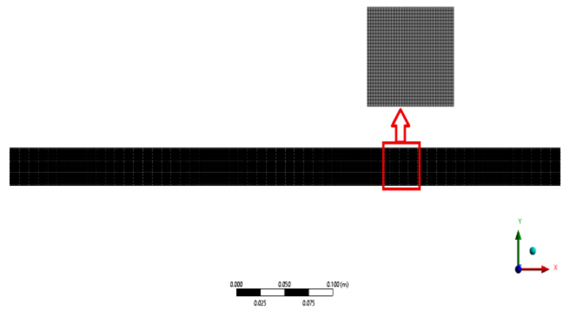

Figure 4: Meshing of absorber tube of parabolic trough collector for design-1

Quality of meshing: The quality of the mesh plays an important role in the accuracy and stability of the calculation. In the present work the Quadrilateral elements have been generated during discretization.

Orthogonal mesh quality: Orthogonal quality is computed for cells using the vector from the cell centroid to each of its faces corresponding face area vector and the vector from the cell centroid to centroids of each of the adjacent cells. The worst cells will have an orthogonal quality closer to 0, with the best cells closer to 1. In the present case the minimum value is 1 and maximum value is 1 and average value is 1, which means the mesh quality is acceptable and very good.

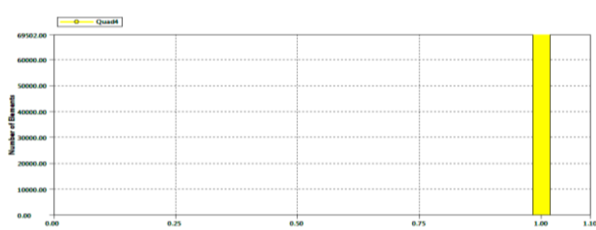

Figure 5: Orthogonal mesh quality of absorber tube of parabolic trough collector for design-1

Definition of material properties: For any type of analysis, the material properties are the most important elements to define before continuing with the analysis. The working medium used is water, which flows through the absorbent tube of the parabolic collector, and the material properties such as thermal conductivity, density, and heat capacity are also shown in the following table.

Model dimensions	Density $\rho\left(\frac{Kg}{m^3}\right)$	Specific Heat $C_p\left(\frac{J}{Kg.}\right)$	Thermal Conductivity $K\left(\frac{W}{m.k}\right)$	Dynamic Viscosity $\mu\left(\frac{Kg}{m.s}\right)$
Water liquid	998.20	4182	0.60	0.001003
Air	1.2250	1009	0.3095	0.0000218
Copper	8700	385	400	-
Glass	2210	730	1.40	-

Source: Salma Marrakchi at el.

Figure 6: different boundaries of parabolic trough collector for design-1

Boundary condition:

1. To check the thermal performance of the absorber tube of parabolic trough collector need the energy equation.
2. Defining of material property, set fluid as water liquid and solid as copper with thermal conductivity of 0.6 W/m-K & 16.27 W/m-K.
3. The mass flow rate of 0.014 kg/s used at the inlet of the absorber tube.
4. For the outlet boundary condition the gauge pressure needs to be set as zero because the flow of water inside the absorber tube of parabolic trough collector is atmospheric.
5. Solar radiations were used on bottom walls of absorber tube.
6. The fluent solver is used for steady analysis.

V. RESULT ANALYSIS

In the present work, digital flow analyzes were performed for three different models of channel parabolic collector's receivers in order to improve the thermal performance of the absorption tube of parabolic channel collectors and the results were compared. For this a Newtonian and incompressible fluid with constant thermo physical properties was used. For solid walls, the moment boundary condition is defined without sliding. The inlet is defined as a mass flow inlet while the outlets are defined as a pressure outlet. Flowing software is used to calculate fluid flow and heat transfer in computational fields. The governance equations are solved iteratively by formulating the finite volume with the SIMPLE algorithm. The second-order wind diagram is used for the turbulence of the momentum energy and its dissipation rate.

The maximum outlet temperature for all parabolic collectors at 200 W/m^2 of solar irradiation varies from 32.78 °C to 33.84 °C according to figure 7. and the maximum temperature of 33.84 ºC is observed in design-3.

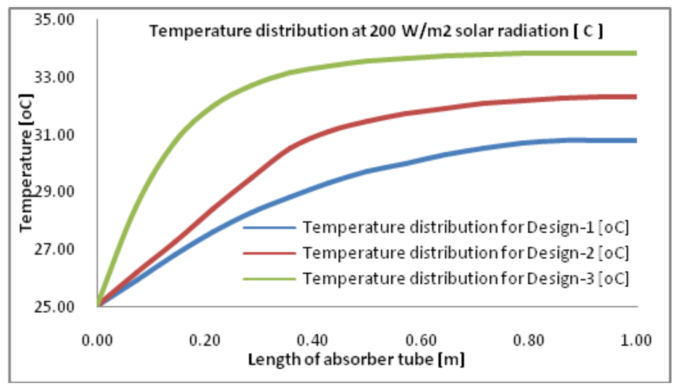

Figure 7: Temperature distribution at 200 W/m2 solar radiations

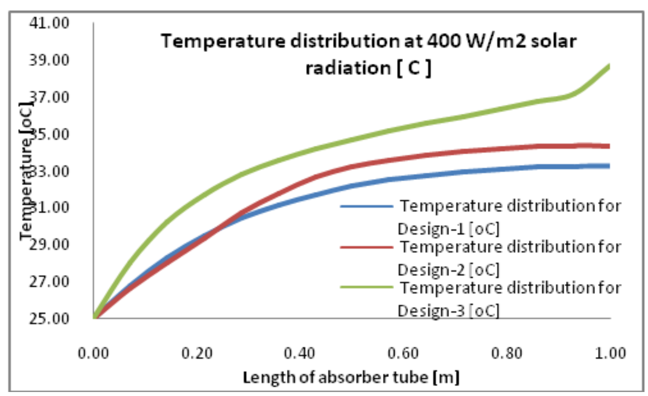

Figure 8: Temperature distribution at 400 W/m^2 solar radiations

It has been observed from the figure 8 the maximum temperature at outlet for all design of parabolic trough collector at 400 W/m^2 solar radiation vary from 33.761 ºC to 38.719 ºC and the maximum temperature of 38.719 ºC recorded for design-3.

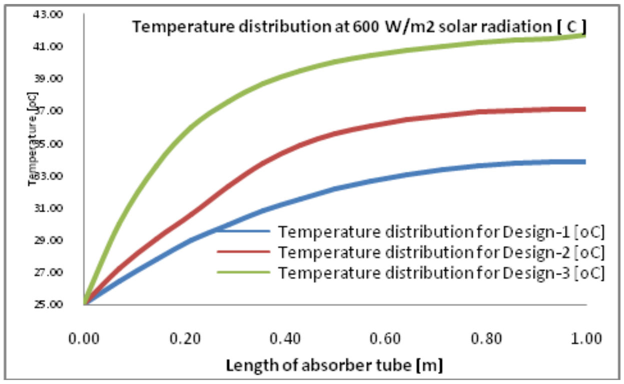

Figure 9: Temperature distribution at 600 W/m^2 solar radiations

It has been observed from the figure 9 the maximum temperature at outlet for all design of parabolic trough collector at 600 W/m^2 solar radiation vary from 36.731 ^{o}C to 42.671 ^{o}C and the maximum temperature of 42.671^{o}C recorded for design-3.

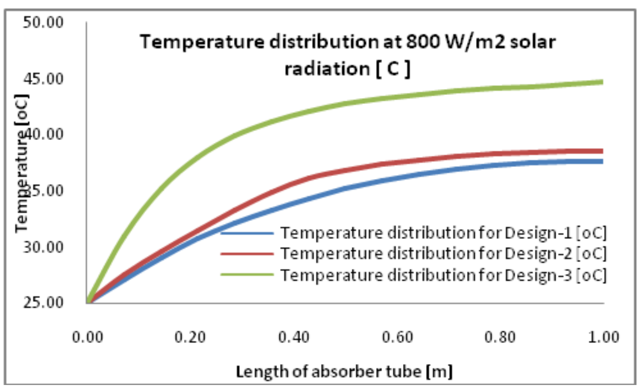

Figure 10: Temperature distribution at 800 W/m^2 solar radiations

It has been observed from the figure 10 the maximum temperature at outlet for all design of parabolic trough collector at 800 W/m^2 solar radiation vary from 41.681 ^{o}C to 45.732 ^{o}C and the maximum temperature of 45.732 ^{o}C recorded for design-3.

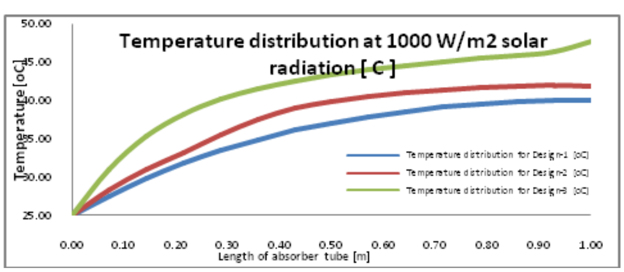

Figure 11: Temperature distribution at 1000 W/m^2 solar radiation

It has been observed from the figure 11 the maximum temperature at outlet for all design of parabolic trough collector at 1000 W/m^2 solar radiation vary from 44.651 ^{o}C to 47.669 ^{o}C and the maximum temperature of 47.669 ^{o}C recorded for design-3.

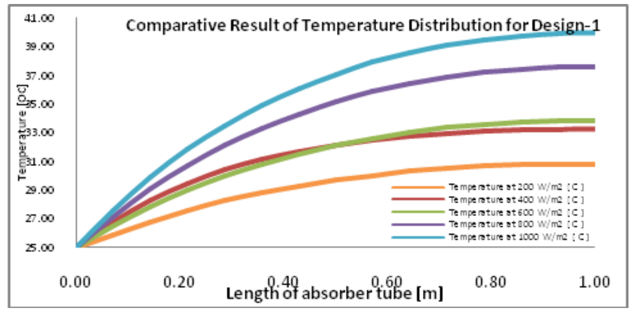

Figure 12 Comparative Result of Temperature Distribution for Design-1

It has been observed from comparative result of temperature distribution for design-1 at different solar radiation range from 200 W/m^2 to 1000 W/m^2 the maximum temperature at outlet of parabolic trough collector are 30.80 ^{o}C, 33.26 ^{o}C, 33.86 ^{o}C, 37.61 ^{o}C & 39.97 ^{o}C. and the maximum temperature at outlet of PTC is 39.97 ^{o}C recorded at 1000 W/m^2.

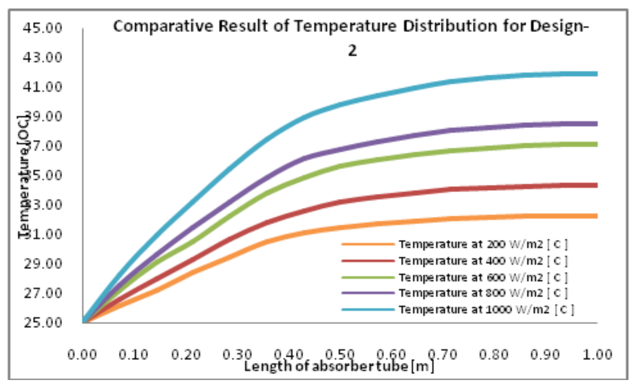

Figure 13 Comparative Result of Temperature Distribution for Design-2

It has been observed from comparative result of temperature distribution for design-2 at different solar radiation range from 200 W/m^2 to 1000 W/m^2 the maximum temperature at outlet of parabolic trough collector are 32.29 ^{o}C, 34.36 ^{o}C, 37.12 ^{o}C, 38.50 ^{o}C & 41.94 ^{o}C. and the maximum temperature at outlet of PTC is 41.94 ^{o}C recorded at 1000 W/m^2.

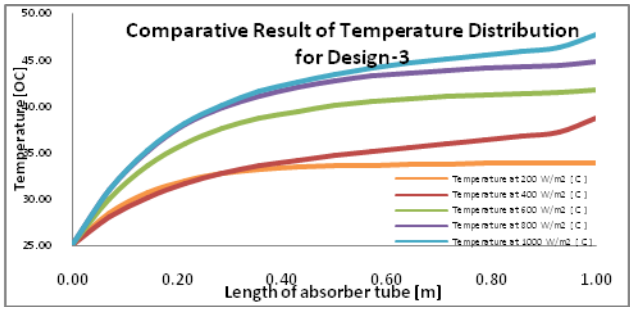

Figure 14 Comparative Result of Temperature Distribution for Design-3

It has been observed from comparative result of temperature distribution for design-3 at different solar radiation range from 200 W/m^2 to 1000 W/m^2 the maximum temperature at outlet of parabolic trough collector are 33.84 ºC, 38.72 ºC, 41.74 ºC, 44.73 ºC & 47.67 ºC. and the maximum temperature at outlet of PTC is 47.67 ºC recorded at 1000 W/m^2.

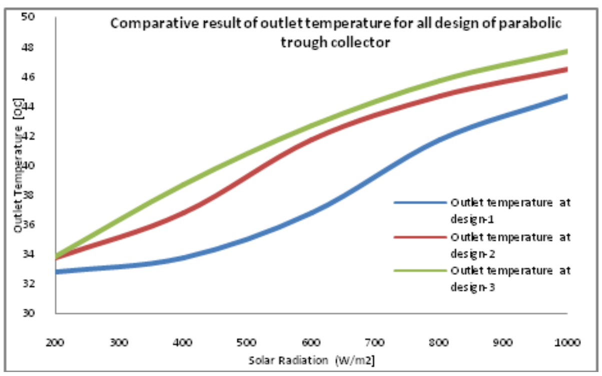

Figure 15 Comparative result of outlet temperature for all design of parabolic trough collector

It has been observed from comparative result of outlet temperature for all design of parabolic trough collector at different solar radiation range from 200 W/m^2 to 1000 W/m^2 the maximum temperature at outlet of parabolic trough collector at 1000 w/m^2 are 44.651 ºC, 46.483 ºC, & 47.669 ºC and the maximum temperature at outlet of PTC is 47.669 ºC recorded for design-3.

Mathematical calculation:

Mean velocity of fluid

$$v = \frac{\dot{m}}{\rho \times A_{cross}}\ m/sec$$

$$v = \frac{0.14}{998.2 \times 0.000593}\ m/sec$$

$$v = 0.236\ m/s$$

Reynolds number

$$R_e = \frac{\rho \times v \times D_h}{\mu}$$

$$R_e = \frac{998.2 \times 0.236 \times 0.0275}{0.001003}$$

$$R_e = 6457.6$$

prandtl number

$$P_r = \frac{\mu C_p}{k}$$

C_p= Specific heat capacity in W/Kg.K

μ= Kinematic viscosity

$$P_r = \frac{0.001003 \times 4182}{0.6}$$

$$P_r = 6.99 \cong 7$$

Nusselt number

$$Nu = \frac{h_a D_h}{k} = 0.023 Re^{0.8} Pr^{0.4}$$

$$Nu = 0.023 \times 177.895^{0.8} \times 7^{0.4}$$

$$Nu = 3.16$$

$$3.16 = \frac{h \times 0.0275}{0.6}$$

$$h = 68.95\ {}^{W}/_{m^2.K}$$

VI. CONCLUSION

In present work computational fluid dynamics analysis have been performed on three different designs of the absorber tube of parabolic trough collector to get better heating performance and temperature distribution over the length of absorber tube. The fluent software is used to calculate the fluid flow and heat transfer in the computational domains. The inlet is set as mass flow inlet where the outlets are set as pressure outlet. The governing equations are iteratively solved by the finite volume formulation with the SIMPLE algorithm. The second order upwind scheme is used for the momentum energy turbulence and its dissipation rate. There are following conclusions having been observed from this work.

- After performing computational fluid dynamics analysis for an absorber tube of parabolic trough collector of design-1 at different solar radiation range from 200 W/m^2 to 1000 W/m^2 the maximum temperature at outlet of parabolic trough collector are 30.80 ºC, 33.26 ºC, 33.86 ºC, 37.61 ºC & 39.97 ºC and the maximum temperature at outlet of PTC is 39.97 ºC recorded at 1000 W/m^2.
- After performing computational fluid dynamics analysis for an absorber tube of parabolic trough collector of design-2 at different solar radiation range from 200 W/m^2 to 1000 W/m^2 the maximum temperature at outlet of parabolic trough collector are 32.29 ºC, 34.36 ºC, 37.12 ºC, 38.50 ºC & 41.94 ºC and the maximum temperature at outlet of PTC is 41.94 ºC recorded at 1000 W/m^2.
- After performing computational fluid dynamics analysis for an absorber tube of parabolic trough collector of design-3 at different solar radiation range from 200 W/m^2 to 1000 W/m^2 the maximum temperature at outlet of parabolic trough collector are 33.84 ºC, 38.72 ºC, 41.74

ºC, 44.73 ºC & 47.67 ºC and the maximum temperature at outlet of PTC is 47.67 ºC recorded at 1000 W/m^2.

From the above conclusion it has been summarized that the maximum temperature at outlet of the parabolic trough collector form all design is at solar radiation of 1000 W/m^2 and its maximum value is 47.67 ºC for design-3. Hence it is recommended that the design-3 of the absorber tube of parabolic trough collector gives better heating performance with higher temperature.

VII. FUTURE SCOPE

The present work is concentrated to improve the heating capacity of absorber tube of parabolic trough collector by changing its design. Though the study is performed with an utmost care then also there is scope for further improvement. Some of the suggestions for future study might be possible are explained.

1. In the present work material of absorber tube is taken as copper but some other materials can also be used for future improvement.
2. In the present work water is taken as working fluid but some other nano-fluids may also be used.

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