International Journal of Recent Technology and Engineering (IJRTE)
ISSN: 2277-3878, Volume-8 Issue-5, January 2020

Effect of Greenhouse Gases on the Behaviour of Parabolic Trough Collector Based on CFD Simulation

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Abstract: ***Energy extraction by solar energy harnessing method is one of the most futuristic approach to accelerate towards green technologies. The parabolic trough solar collectors are most widely used entities in entire world for solar water heaters. The existing problem of low rate of water heating is disadvantageous for its commercial use. Hence the study focuses on observing the effect of greenhouse when the evacuated tubes are equipped with most common greenhouse gas CO_2 (Carbon dioxide). The simulations were carried out on Ansys (FLUENT) at steady state conditions. The parameters observed to compare the rate of boiling are Cell Reynolds number, Surface skin friction and the average steady state temperature. The greenhouse gas seems effective in increasing the rate of boiling due to which the Cell Reynolds number has increased in both minima and maxima.***

Keywords: PTC, Greenhouse Gasses, Solar Collector, CFD, Evacuated Tube

I. INTRODUCTION

The parabolic trough collectors (PTC) are mostly used solar collector devices in the world. Most of the industries uses PTC based on three numerical factors i.e. thermal efficiency, improvement by research and development and mass production improvement. The parabolic trough collector concentrates the sun rays to a focus at which an evacuated tube is assembled. The evacuated tube is made of Borosil glass. Hence the factors taken in this study is accordingly due to the Borosil glass. The concentration factor of sun rays also plays an important role in defining the thermal efficiency of the PTC. In Greenhouse gases, CO_2 (Carbon dioxide) shows the heat trapping nature causing the phenomenon of global warming. In a wide aspect, the average temperature of earth has increased to five degrees. Hence, studying the effect of replacing the vacuum with greenhouse gases is primal objective of this study. The factors are estimated both numerically and mathematically using ANSYS 15.0. Modelling of the evacuated tube was done by taking reference from the prototypes available in markets. The boundary conditions and calculations are discussed further in the report.

Manuscript published on January 30, 2020.
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II. LITERATURE SURVEY AND OBJECTIVE

Parabolic trough collectors were first simulated by Lippke [1]. He calculated the data under different conditions and the correlation obtained from the experiment was used directly from solar field. Forristall [2] carried out heat transfer analysis which was used to calculate the thermal performance of the parabolic trough collector. Stuetzle [3, 4] stimulated the dynamic model of parabolic trough collector.Harrigan[5] modelled the parabolic trough solar technology capable of working with a Rankine cycle with or without fossil-fuel backup. NREL (National Renewable Energy Laboratory) [11] developed a complex model for a parabolic trough, with comprehensive economic analysis.

Montes et al. [6] carried out. Economic optimization of Thermal performance for different solar power plants, he analysed it at nominal load conditions Rolim et al. [7] developed an analytic model with PTC and solar thermal electric generating system new power block was proposed by using Kalina cycle by Mittelman and Epstein [8] which produced low solar insolation (300-400$\frac{W}{m^2}$). A simplified conceptual and numerical methodology for designing of parabolic trough solar energy systems was by Stine and Harrigan [9] proposed a numerical method of designing a parabolic trough collector. They proposed a storage sizing graph, which was used to optimize the collector area for certain location. Mohamed, Eltahir Ahmed [10] proposed the methodology to compute design and efficiency of PTC by comparing LMTD of heat transfer fluid. Sato, A.I., Scalon, V.L. and Padilha, A. [11] developed the application of computational fluid dynamics (CFD) software. It implemented model for simulating the behaviour of fluid numerically and improved the thermal performance of the PTC Basavanna, S., and K. S. Shashishekar [12] simulated the flat plate solar collector using evacuated tube by using ANSYS Fluent software and found similarity between numerically simulated and calculated results.

III. METHODOLOGY

The study focuses on the effect of greenhouse gases on the behaviour of Parabolic trough collector.

The Heat flux is at first calculated for the geographic location from which the solar insolation is taken. The minimum solar insolation for the earth is taken to be 1316$\frac{W}{m^2}$. Hence for the location of Dehradun the insolation is to be calculated by PTC designing methods.

The heat flux in Dehradun on 1st January was found to be 3027.67 $\frac{W}{m^2}$. Now, an in-depth study of greenhouse gases at an atmospheric pressure was done. Of which CO_2 (Carbon dioxide) was found asmost suitable, available and affordable. The evacuated tube was then simulated by CFD (Computational Fluid Dynamics) method on Ansys Fluent. The comparison was made between the steady state temperature of Evacuated tube and the CO_2 (Carbon dioxide) tube. Hence the comparison of temperature and nusselt numbers was done with descriptive discussion on velocity profile developed in the the Solar water heater tube. The Heat Transfer Fluid taken in the analysis is water. The Fig.1 shows the methodology used in determining the results.

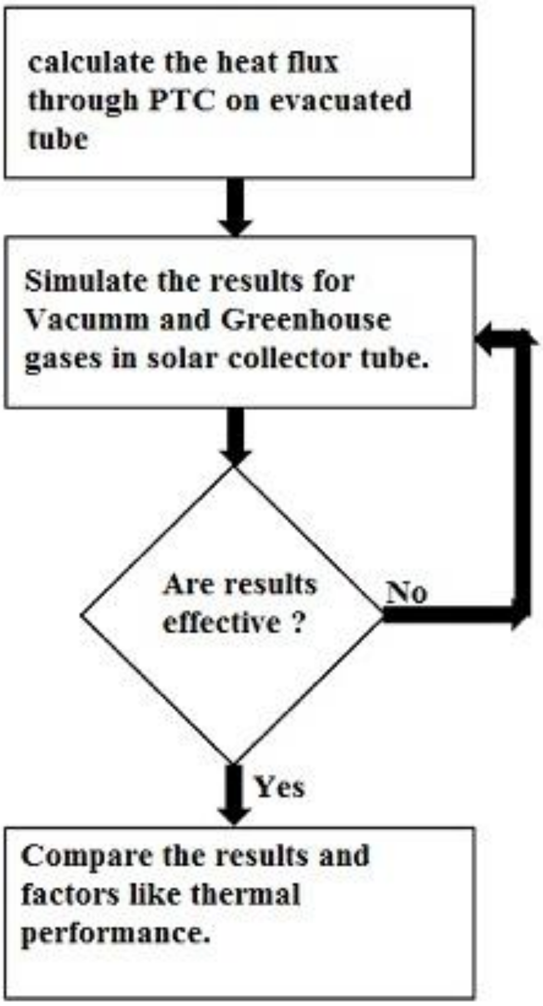

Fig 1 Methodology of the study

IV. DESIGN AND CONSTRAINT

The design of evacuated tube taken in reference is of length and diameter available in the markets. Hence the design of the tube is of 47 mm internal diameter, 58mm outer diameter and 1800mm length. The designing is done in geometry module of Ansys as shown in the Fig.2.

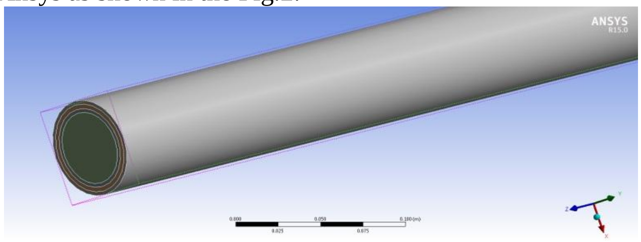

Fig 2 geometry of evacuated tube.

Meshing of the solar collector tube is done by using Ansys Fluent module. At overall 2111850 elements. The figure 3 shows the mesh quality and shape of mesh formed during the pre-processing phase.

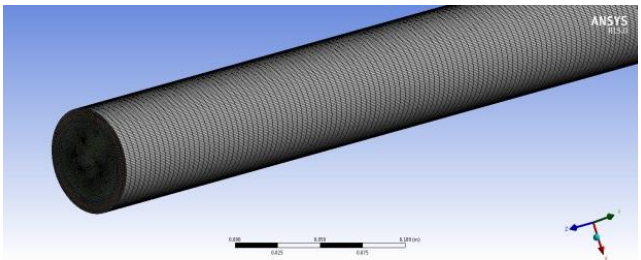

Fig 3 Meshing of evacuated tube

The orthogonal ratio of average 0.97 manifests the quality of mesh formed during the simulation. Consideration related to the boundary conditions are first solved both numerically and mathematically. As, the solar insolation depends upon the geographic coordinated of the location. So, application of designing the parabolic trough collector is used in calculating the heat flux, velocity, mass flow rate. The results like nusselt number and Reynolds number are also taken into the consideration in both vacuum and carbon dioxide. In reference of solar insolation calculations, 1st January 2017 in Dehradun with geographic coordinates of 30.31°N and 78.03°E. The declination angle (δs), is determined by the expression:-

$$\delta s = 23.45 \sin \frac{360\,[284+n]}{365} \quad (1)$$

The variable (n) denotes the number of days to 365 days on 31st December. The observer latitude (Ø) is taken as 66.55° as derived by the relation.

$$\sin\alpha = \sin\delta \sin\emptyset + \cos\delta \cos\omega \cos\emptyset \quad (2)$$

Where ω is Hour angle derived by following expression

$$\sin\omega = \frac{-\cos\alpha \sin A_z}{\cos\delta} \quad (3)$$

Estimated A_z (Azimuth angle) for Dehradun is 137.25°. Hence for further calculation of PTC, as per reference, collectors taken into the consideration were of following technical specification given in table.1.

Table. 1 technical specification

Parameters	Values
Aperture	1 m
Rim Angle	90°
Focal Length	0.25 m
Receiver Diameter	3.8 cm
Geometrical concentration ratio	26.3
Concentrator Height	0.25 m

The average mass flow rate when water in an evacuated tube reaches a certain gained temperature is 0.0048 Kg/ Sec. hence the velocity of heat transfer fluid is taken as 2.7 cm/sec by relation (4).

$$v_f = \frac{m_f}{\rho_f A_{ia}} \qquad (4)$$

Hence by the reference heat transfer method, the heat flux calculated has the value of minimum insolation of 1316 W/m^2 and maximum insolation on January, 1 2017. The relation used to estimate the initial solar insolation is given in equation (5).

$$Q_{a-f(conv)} = \dot{\pi}\, Nu\, K_f (T_a - T_f) \qquad (5)$$

The emissivity varies in case of both vacuum and greenhouse gases but for reducing the complexity of the research and study, the emissivity (ε) of the solar collector tube is taken as 0.90. The properties of evacuated tube is taken t a pressure of 10^-3 Pascal. The comparison is done on the basis of adiabatic process and Greenhouse effect on solar collector tube.

V. RESULTS AND DISCUSSION

The properties of Borosil glass taken in the study is discussed in the table 2.

Table 2. Properties of Borosil glass

Parameters	**Value**
Coefficient of Linear Expansion	32.5 x10 / C°
Strain Point	515 C°
Annealing Point	565 C°
Thermal Conductivity	(Cal / cm / C / sec) 0.0027

Boundary conditions applied to the solar collector tubes are governed by equations of laminar conditions as described in energy balance equation.

Continuity equation.

$$\nabla(\rho V) + \frac{\partial \rho}{\partial t} = 0 \qquad (6)$$

Momentum equation.

$$\frac{\partial}{\partial x_j}(\rho U_i U_j) = \frac{\partial \rho}{\partial x_i} + \frac{\partial}{\partial x_j}[\mu \frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_j} - \rho \bar{U}_i \bar{U}_j] \quad (7)$$

Energy equation.

$$\frac{\partial}{\partial x_i}(\rho U_i T) = \frac{\partial}{\partial x_j}[\frac{\mu}{P_r}\frac{\partial}{\partial x_j} - \rho \bar{U}_i T] \qquad (8)$$

The mesh generated in analysing the results had average skewness of 0.1236, which defines the excellent quality of meshing method used. The evacuated tube was analysed in CFD module of Ansys with boundary conditions of velocity of Heat transfer fluid at input is 2.7 cm/s and emssiveisty (ε) of 0.90. The heat flux at the top surface of the solar collector tube was given a value of 3027.6769 W/m^2. The lowest solar insolation obtained on 1st January 2017 was 1316 W/m^2 which was calcualted at 288 K of temperature. The friction factor between the glass and air is taken 0.04455 by the relation (9).

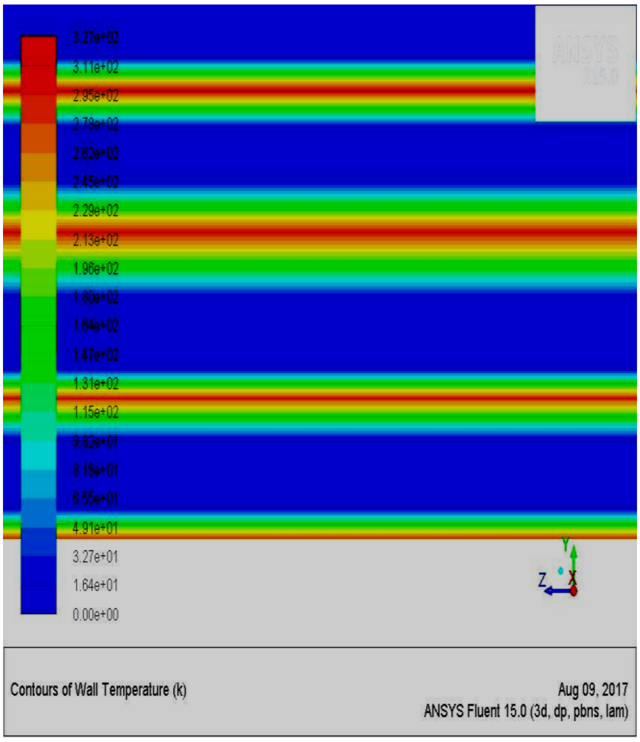

Fig 4 Wall temperature in greenhouse gas equipped solar collector tube.

$$C_f = 0.0054 + \frac{2.3 \times 10^{-8}}{R_e^{-3/2}} \qquad (9)$$

The results were compared both graphically for vacuum and greenhouse gasses. The table 3 and table 4 shows the result of vacuum and greenhouse gasses respectively.

Table 3. Result of vacuum and greenhouse gasses respectively

Model	**Maximum temperature (At steady state)**	**Difference in temperature (%)**
With vacuum	326 K	0.30 %
With greenhouse gases	327 K	

The cell Reynolds number also varies according to the medium used in evacuated tube. The maximum cell Reynolds number varies from 130.185 in vacuum to 132.92 in Co_2 (Carbon dioxide). Hence this shows that the chaotic eddies and change in temperature is increasing at higher rate as compared to vacuum. The higher cell Reynolds number indicates that the turbulence system will soon developed while analysing the transient systems.

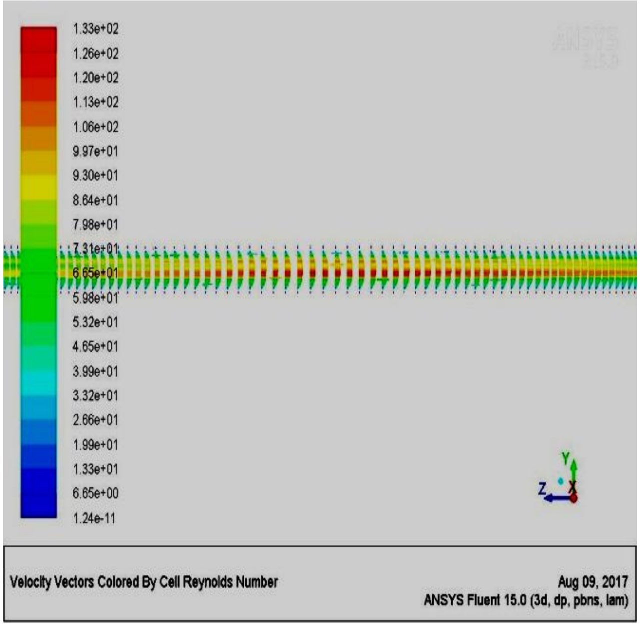

Fig 5 Cell Reynolds number of greenhouse gas equipped solar collector tube

The lower Reynolds number of vacuum is 8.7429 $\times 10^{-18}$ and 1.2441$\times 10^{-11}$ in greenhouse effect solar collector tubes. These results manifest the turbulent conversion model of evacuated tube equipped with greenhouse gasses as shown in the figure 6. With wall temperature remained almost same i.e., 327.31 K. There is a slight change in skin friction coefficient of about 5.4 % after equipping the solar collector tube with greenhouse gasses as shown in figure 7.

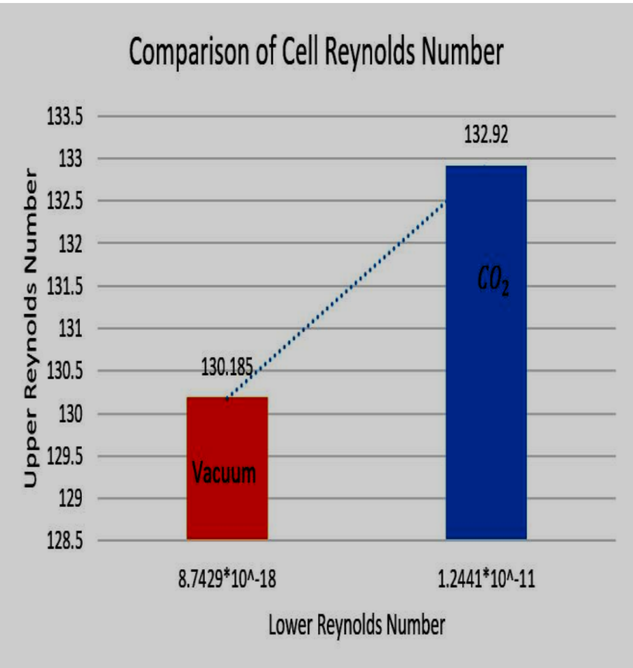

Fig 6 Comparison of cell Reynolds number of evacuated tube and greenhouse gas solar collector tube

Graphical representation of cell Reynolds number in both vacuum and greenhouse gas equipped solar collector tube is shown in the figure5. The difference in steady state temperature according to the steady state analysis in Ansys shows an improvement of 0.30% as shown in table 2.

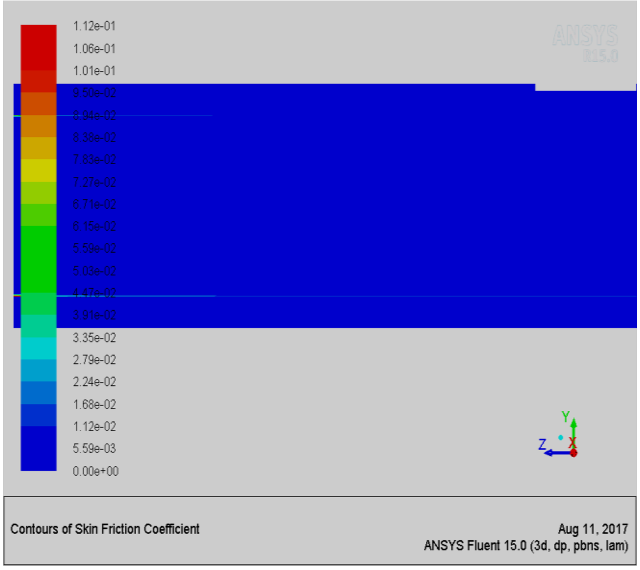

Fig 7 Skin friction coefficient of greenhouse gas equipped solar collector tube

The difference in skin friction coefficient is depicted in the figure 8. Hence, an increase in boiling rate is indicated by greenhouse gas equipped solar collector tube. The transition of laminar flow model to turbulent model is manifested by the change in rate of parameters.

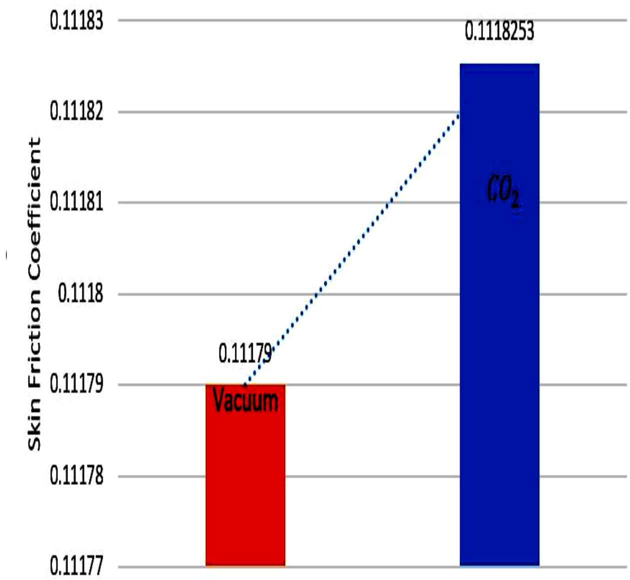

Fig 8 Comparison between skin friction coefficient of evacuated tube and tube equipped with greenhouse gases

VI. VALIDATION OF RESULTS

As per the other models available and analyzed for CFD behaviour of the PTC, the evacuated tube equipped with greenhouse gases shows an enhanced behaviour with approx. 26℃ more temperature [13]. The comparison of temperature is shown in the figure 9. Between temperature of existing and proposed greenhouse gas equipped solar collector tube.

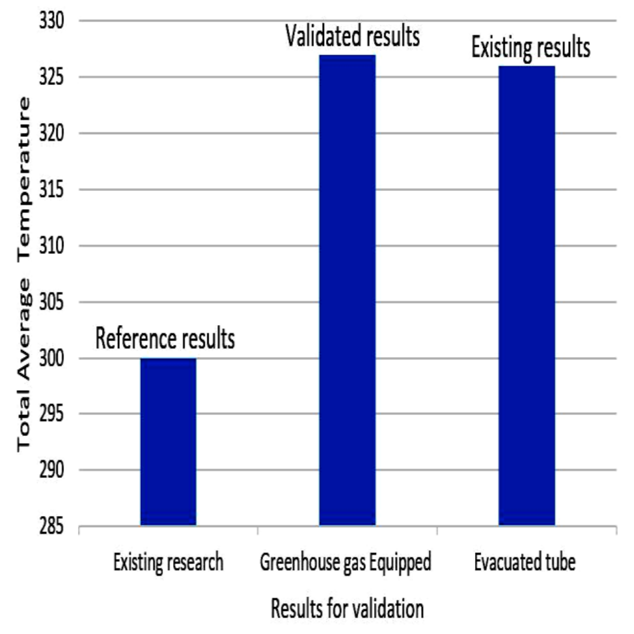

Fig 9 Validation graph representation between existing study and greenhouse gas equipped solar collector tube

VII. CONCLUSION

There has been a significant change in the rate of boiling as manifested by the graphical representation of cell Reynolds number and skin friction coefficient. This can be concluded that there may not be any improvement in heat transfer coefficient in steady state analysis while equipping the evacuated tube with greenhouse gasses. But, further study on the transition behaviour of the greenhouse effect on solar collector tube can clearly manifest the change in rate of heat transfer with respect to time.

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