Performance Of P1 Model In The Prediction Of Static Temperature And Velocity Magnitude Of Therminol D-12 In An Evacuated Tube Solar Collector

P.Selvakumar, P.Somasundaram, A.Tamilvanan, R.Karthikeyan, T.Rajagopal

Abstract: Instant hot water requirement is more in tropical countries during the winter season. The conventional flat plate collector and evacuated tube collector based solar water heaters are unable to delivesr instant hot water in the presence of low solar radiation. Passive heating of water in an evacuated tube with heat transfer fluids having low specific heat can deliver a better solution to the above problem. Therminol D-12 was identified as one such fluid and its performance was studied under varying flow rates and radiation heat fluxes. The analysis was carried out with the CFD solver FLUENT 6.2. P1 radiation model was used to predict the static temperature and velocity magnitude of therminol D-12 at the exit of the evacuated tube. The result obtained from the CFD analysis was validated with the experimental result. The deviation of experimental result from the predicted result was found to be less than 5%. The error percentage increases with increasing radiative heat fluxes due to convection boundary conditions. The performance of P1 model was found to be good for solar radiation experiments less than 600 W/m^2.

***Keywords* : About four key words or phrases in alphabetical order, separated by commas.**

I. INTRODUCTION

Evacuated tube is an integral part of modern day solar water heating systems [1]. The performance of evacuated tube solar collectors is found to be better when compared to flat plate collector in medium and high temperature applications. Extracting heat from the evacuated tube is a major difficulty in evacuated tube solar collector applications [2]. The fluid-in-glass and fluid-in-metal are the two types of evacuated tube designs used in thermal applications. Due to low manufacturing cost and high thermal efficiency, fluid-in-glass collector is widely used by the manufacturers. The fluid in the tubes is heated by solar irradiance. Many researchers have made study on evacuated tube with water is used as heat transfer fluid. Morrison et al. [2] studied the natural circulation of heat transfer fluid in fluid-in-glass evacuated tubes experimentally and numerically. Budihardjo and Morrison [3] studied the long-term performance of fluid-in-glass evacuated tube solar collectors with transient modeling. Flow structure interaction between the tube and tank is studied using computational fluid dynamics solver FLUENT. Sawhney et al. [4] developed the thermal performance model of evacuated tube solar collector with U-shaped fluid channel embedded in a flat absorber. New technologies [5-7] have been developed to enhance the heat transfer from absorber tube to the working fluid. Few researchers have studied the influence of working fluids on collector performance that too in industrial applications [8-10]. Ouagued et al. [11] studied the properties of different thermal oils and determined the thermal performance of the heat transfer fluids under Algerian climate. Yan et al. [12] analyzed the flow structure in a water-in-glass evacuated tube solar water heater. The study was carried out to improve the system design and performance using computational fluid dynamics. FLUENT solver was used as CFD tool. Water was considered as heat transfer fluid and the required boundary conditions such as density and viscosity were provided for analysis. Solar radiation intensity was taken as 750 W/m2. Reddy and Satyanarayana [13] studied the performance of solar parabolic trough concentrator with porous finned receiver. Re-Normalized Group k-ε model was used to predict the turbulence in receiver tube. It was found that 13 x 105 cells are sufficient for the analysis of tubular receiver. First order upwind differencing scheme was used for solving momentum and energy equations. Pressure correction was obtained through SIMPLEC algorithm. In the present work numerical analysis was performed on evacuated tube using computational fluid dynamics solver FLUENT 6.2 to find the suitability of therminol D-12 as heat transfer fluid in instant hot water generation. Therminol D-12 was selected as the heat transfer fluid because of its resemblance to water in physical and thermal properties.

A. Therminol and its properties

Fluids with low specific heat can have high heat gain from incident solar energy. Few researchers [8-10] studied the enhancement of performance of solar water heater by alternate heat transfer fluids. Selvakumar et al. [14] studied the heat transfer and fluid flow characteristics of various heat transfer fluids like helium, therminol, calfo, duratherm, exceltherm, molten salt, dynalene and vegetable oil.

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sTherminol was suggested as the best heat transfer fluid for short flow length applications. Therminol is available in different grades and its selection depends on the safe operating temperature limits. Different grades of therminol and their working temperatures are shown in Fig.1. Therminol D-12 which has flash point of 62°C (Pensky-Martens) and fire point of 79°C (ASTM D-92) is an inexpensive and easily available heat transfer fluid. The other fluid properties like density and viscosity are close resemble that of water. The comparison of fluid properties of Therminol D-12 with that of water is shown in Table I.

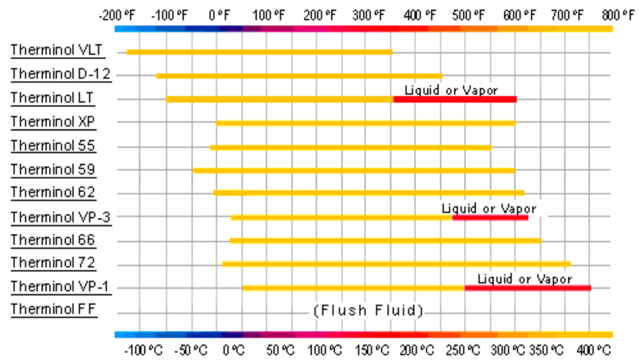

Fig. 1. Therminol grades and operating temperature limits (Source:www.therminol.com

Table- I: Comparison of properties between Therminol D-12 and Water

Properties	Therminol D-12	Water
Density at 20°C	755 kg/m^3	1000 kg/m^3
Specific heat	2.5 kJ/kg K	4.186 kJ/kg K
Kinematic Viscosity	1.42centi Stoke @ 20°C 0.66 centi Stoke @ 100°C	0.801 centi Stoke @ 30°C 0.294 centi Stoke @ 100°C

II. NUMERICAL MODEL

A 2-D model of evacuated tube was created and meshed using Gambit version 2.2.30 software. The meshed model is shown in Fig. 2.

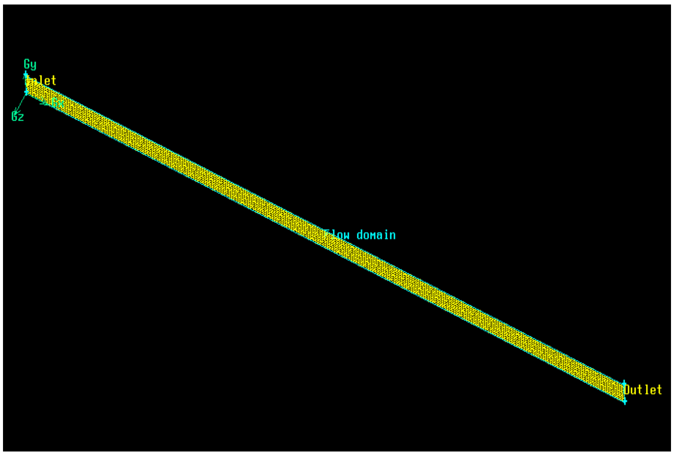

Fig. 2. Meshed model.

Mass flow inlet was set as the boundary condition for inlet and outflow was assigned for outlet. The wall was considered to be a smooth one and the properties of glass tube were assigned. The skewness value of a good mesh should be less than 0.8. In the present study, the value was 0.4 which ensures good quality. Continuity, momentum, energy and radiation equations were to be solved during the analysis. A standard k-ε model will give correct results on kinetic energy and turbulence equations. Energy equation will help to predict the static temperature and total energy. Different radiation models available in FLUENT 6.2 software for are shown in Fig.3.

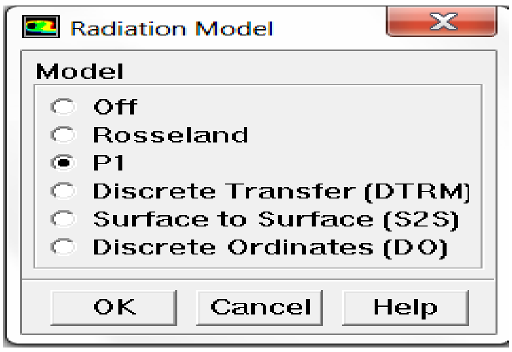

Fig. 3. Radiation models available in FLUENT 6.2

Among these models P1 model was selected in the present study based on the trial runs. Selection of the P1 model was justified by simulating the work of Massidda and Varone [15]. The results of the trial run are given in Table -II.

Table- II: Results of Trail Run (Hydrogen as HTF)

Parameters	Massida & Varone (2009)	Present work	Deviation
Mass flow rate	0.087 kg/s	0.087 kg/s	--
Inlet temperature	425 K	425 K	--
Outlet temperature	740 K	737 K	0.4%

The percentage of error in using P1 model was too small and it was acceptable.

A. Boundary and Operating Conditions

k-ε model was used for predicting the kinetic energy with the following co-efficient values: $C_\mu = 0.09$, $C_{1\varepsilon} = 1.44$, $C_{2\varepsilon} = 1.92$. The wall boundary conditions were as follows: Absorptivity (α) = 0.92, Emissivity (ε) = 0.7, Thermal conductivity (k) =1.2 W/m K. SIMPLE algorithm was used for solving the governing equations and the under relaxation factors for pressure, density, body forces and momentum were assigned as 0.3, 1, 1 and 7 respectively. Outlet temperature of the fluid, specific heat of the fluid and skin friction co-efficient were considered as deciding factors for selecting the heat transfer fluid for the system. At 0.08 kg/s of mass flow rate, flow analysis was carried out for three radiative heat flux values viz.,200, 400 and 600 W/m^2. Static temperature and velocity magnitude graphs at outlet of the tube were obtained for the above trials. Pressure co-efficient at inlet and outlet were also obtained to study the pressure drop during flow through the tube. Additionally, total energy at the outlet of the tube was also obtained to have final conclusions. For the same radiation conditions, the mass flow rate was kept at 0.008 kg/s and the analysis was performed. All the above parameters were obtained for the flow rate of 0.008 kg/s.

B. P1 Model

The treatment of boundary conditions in the P1 model at walls is discussed briefly in this section. The incident radiation equation for the given boundary conditions is given by the dot product of the outward normal vector and the heat flux. This is shown in Equation 1 and simplified as Eq. 2.

$$q_r \ . \ \vec{n} = -\Gamma \nabla G \ . \ \vec{n} \qquad \text{-------- Eq. 1.}$$

$$q_{r,w} = -\Gamma \frac{\partial G}{\partial n} \qquad \text{-------- Eq. 2.}$$

where G is the incident radiation and $q_{r,w}$ is the heat flux.

The radiative heat flux for the wall is computed using the following boundary condition.

$$I_w(\vec{r},\vec{s}) = f_w(\vec{r},\vec{s}) \qquad \text{-------- Eq. 3.}$$

$$f_w(\vec{r},\vec{s}) = \varepsilon_w \frac{\sigma T_w^4}{\pi} + \rho_w I_w(\vec{r},-\vec{s}) \qquad \text{-------- Eq. 4.}$$

In Eq. 4, ρ_w is the wall reflectivity.

Using Marshak boundary condition [16], final heat flux equation is obtained as Eq. 6.

$$\int_0^{2\pi} I_w(\vec{r},\vec{s}) \ \vec{n} \ . \vec{s} \ d\Omega = \int_0^{2\pi} f_w(\vec{r},\vec{s}) \ \vec{n} \ . \vec{s} \ d\Omega \qquad \text{--- Eq. 5.}$$

$$q_{r,w} = \frac{-4\pi \ \varepsilon_w \frac{\sigma}{\pi} T_w^4 - (1-\rho_w) G_w}{2\ (1+\rho_w)} \qquad \text{--------- Eq. 6.}$$

III. RESULT AND DISCUSSION

A. Results with Mass Flow Rate of Therminol D-12 as 0.08 kg/s

Initially, the mass flow rate of therminol D-12 is set as 0.08 kg/s and analyzed. The static temperature at the inlet of the tube is set as 303K. The direct solar radiation in the morning from 0600 hours to 0900 hours will vary between 200 W/m^2 and 600 W/m^2. So, the static temperature and velocity at outlet of the tube are obtained for solar radiation values 200 W/m^2, 400 W/m^2 and 600 W/m^2. Static temperatures at the outlet for radiative heat fluxes 200 W/m^2, 400 W/m^2 and 600 W/m^2 are depicted in Figures 4, 5 and 6 respectively.

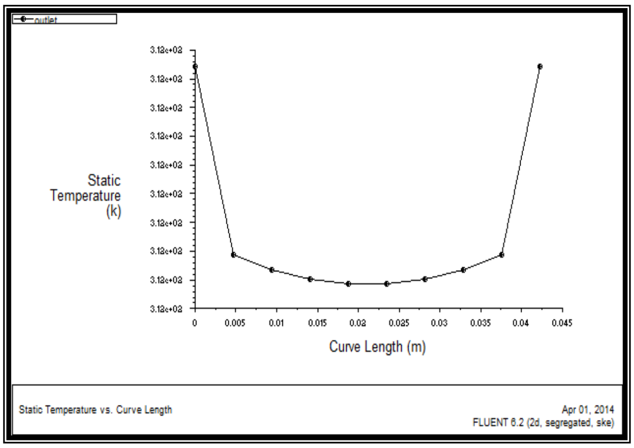

Fig. 4. Static temperature at outlet under 200 W/m^2 (at 0.08 kg/s)

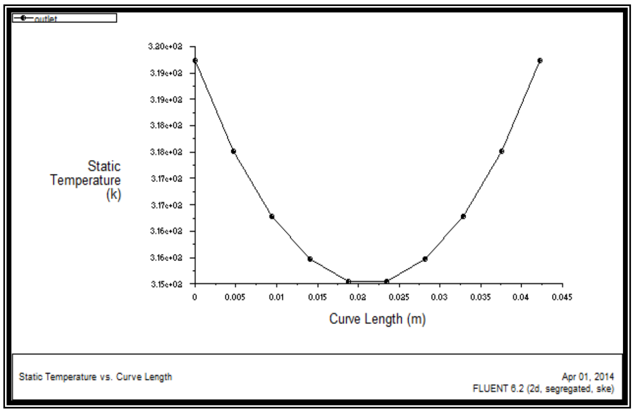

Fig. 5. Static temperature at outlet under 400 W/m2 (at 0.08 kg/s)

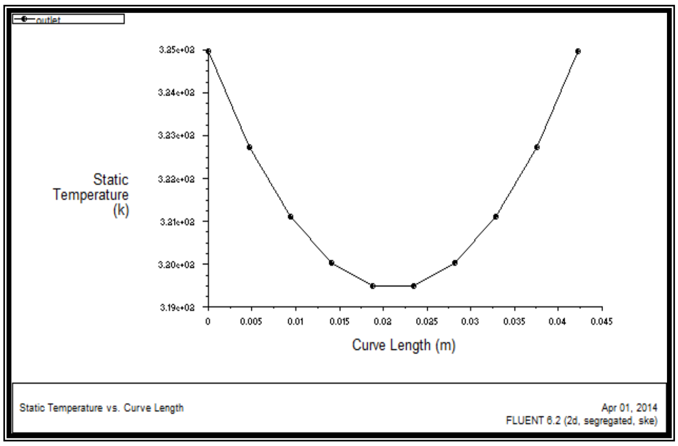

Fig. 6. Static temperature at outlet under 600 W/m^2 (at 0.08 kg/s)

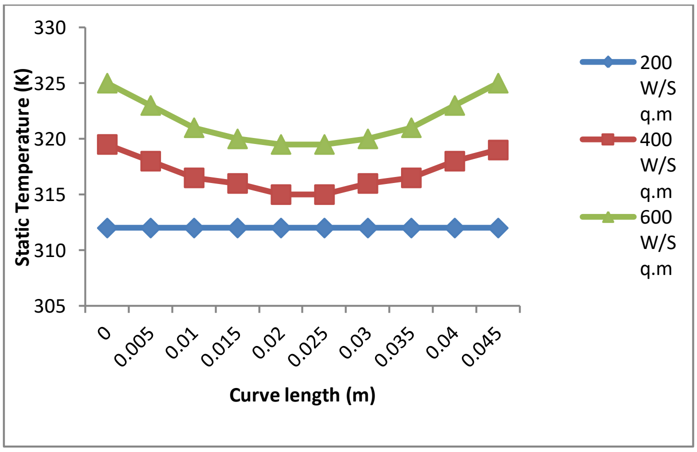

Fig. 7. Comparison of static temperatures at outlet for therminol D-12 (at 0.08 kg/s)

The static temperature was found to be 312 K during 200 W/m^2 and increases with increase in radiation. The comparison of static temperatures for varying solar radiation at a mass flow rate of 0.08 kg/s is shown in Fig. 7. The mass flow rate was assumed as 0.08 kg/s in the numerical analysis in order to predict the temperature in forced circulation mode. Velocity magnitude was also obtained at the outlet of the tube for ensuring negligible pressure drop. It is depicted in Figures 8, 9 and 10.

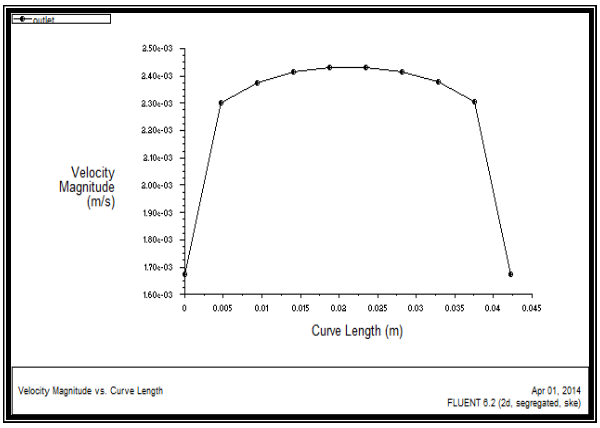

Fig. 8. Velocity at outlet under 200 W/m^2 (at 0.08 kg/s)

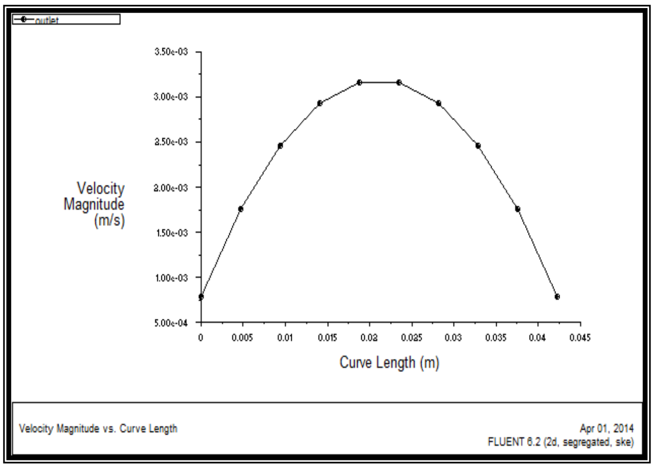

Fig. 9. Velocity at outlet under 400 W/m^2 (at 0.08 kg/s)

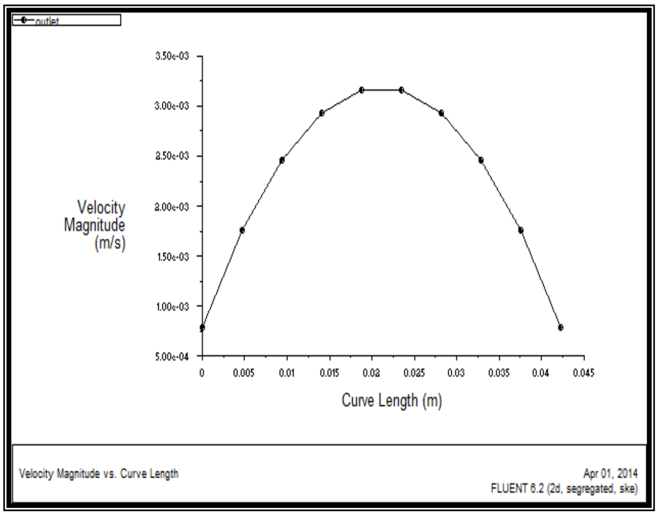

Fig. 10. Velocity at outlet under 600 W/m^2 (at 0.08 kg/s)

At 200 W/m^2, the velocity magnitude was around 0.0023 m/s which was very close to inlet velocity. Velocity magnitudes at outlet for three levels of radiations were compared in Figure 11. At 400 and 600 W/m^2, the velocity magnitudes were equal and the value was around 0.0028 m/s. With increase in solar radiation, the static temperature and the velocity magnitude of therminol D-12 increased gradually. The increase in velocity was too mild which ensured minimum pressure drop.

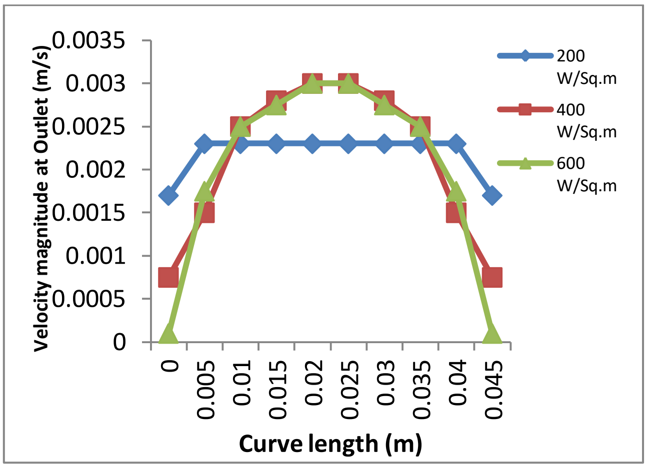

Fig. 11. Comparison of velocity magnitude at outlet for therminol D-12 (at 0.08 kg/s)

A. Results with mass flow rate of therminol D-12 as 0.008 kg/s

Mass flow rate of therminol D-12 was set as 0.008 kg/s (natural circulation mode) and analyzed. The static temperature at inlet was taken as 303 K and the velocity magnitude at inlet was taken as 0.00226 m/s. The static temperature and velocity at outlet of the tube were obtained for solar radiation values 200, 400 and 600 W/m^2. Static temperatures at outlet at 200 and 400 W/m^2 were found to be 312 and 324 K, respectively. Figures 12 and 13 confirm the afore-mentioned values. At 600W/m^2, the static temperature at the outlet was around 333K and it is shown in Figure 14. The comparison of static temperatures in all three cases is shown in Fig. 15.

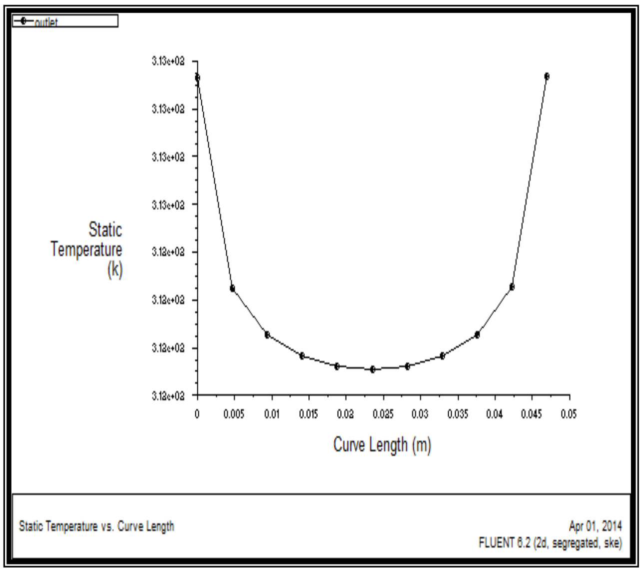

Fig. 12. Static temperature at outlet under 200 W/m^2 (at 0.008 kg/s)

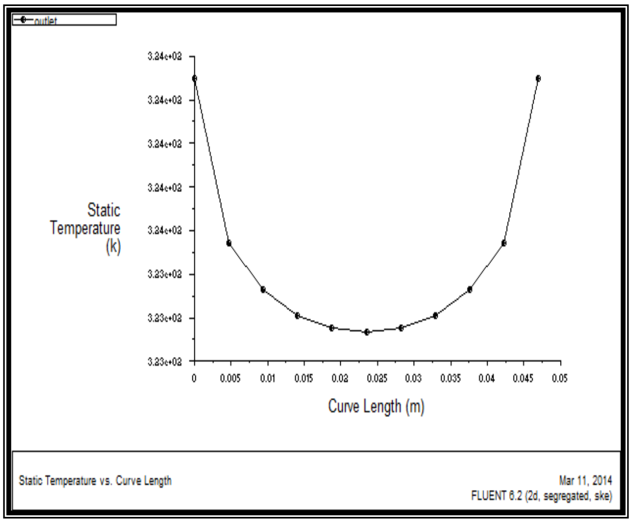

Fig. 13. Static temperature at outlet under 400 W/m^2 (at 0.008 kg/s)

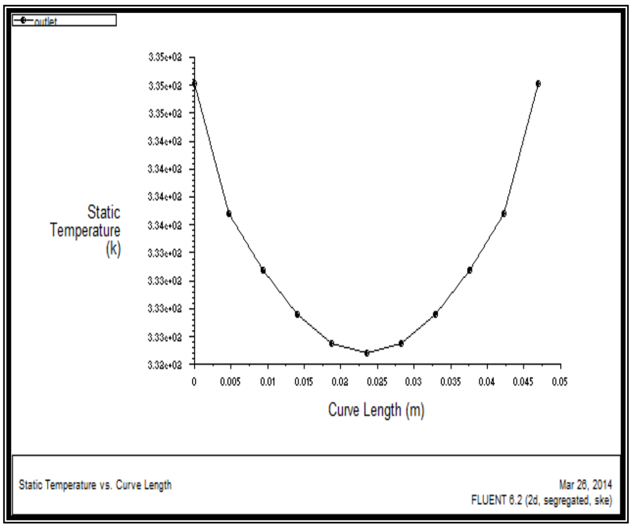

Fig. 14. Static temperature at outlet under 600 W/m^2 (at 0.008 kg/s)

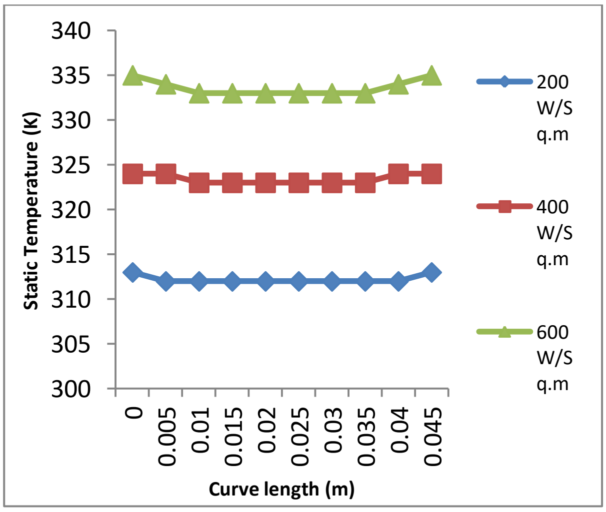

Fig. 15. Comparison of static temperature at outlet for therminol D-12 (at 0.008 kg/s)

The velocity magnitude at outlet is depicted in Figures 16, 17 and 18 for the respective radiations viz. 200, 400 and 600 W/m^2. The comparison of velocity magnitude in three cases is shown in Fig. 19.

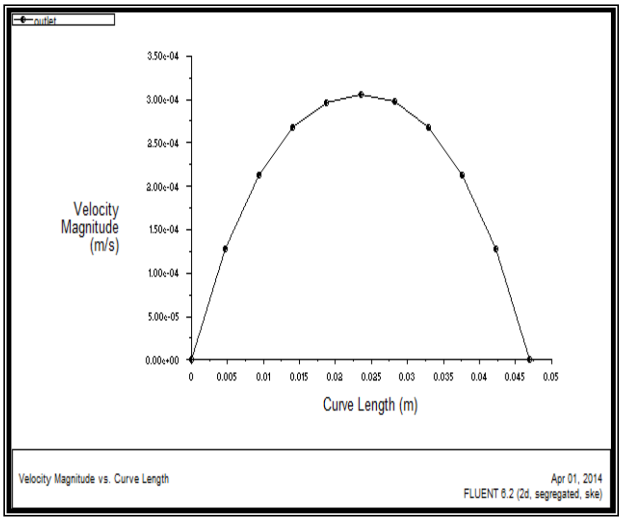

Fig. 16. Velocity at outlet under 200 W/m^2 (at 0.008 kg/s)

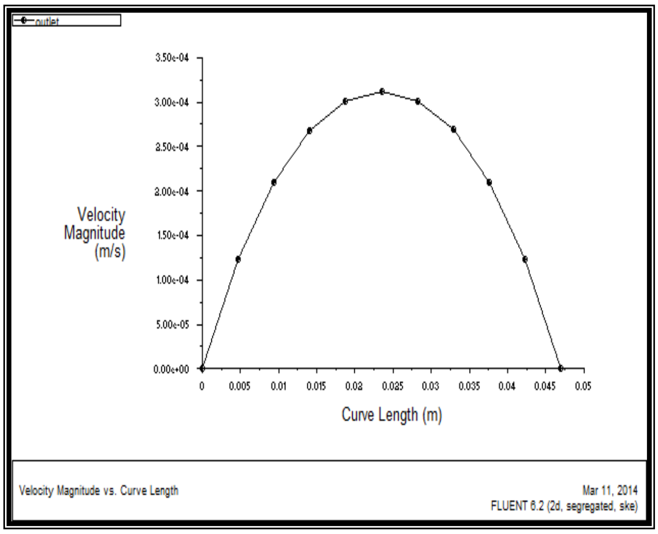

Fig. 17. Velocity at outlet under 400 W/m^2 (at 0.008 kg/s)

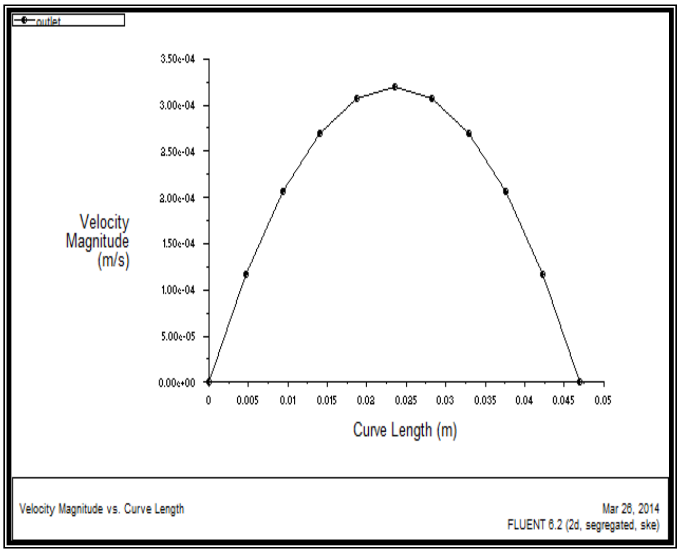

Fig. 18. Velocity at outlet under 600 W/m^2 (at 0.008 kg/s)

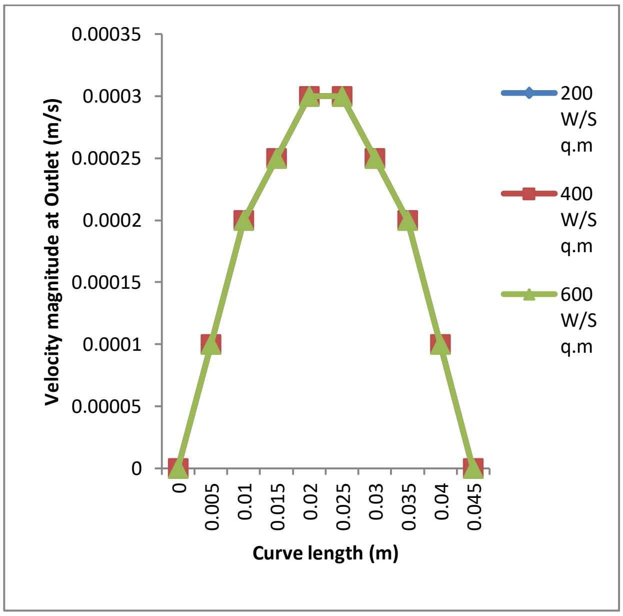

Fig. 19. Comparison of velocity magnitude at outlet for therminol D-12 (at 0.008 kg/s)

Therminol D-12 was identified as a better heat transfer fluid for low and medium temperature applications. Under a maximum solar radiation of 600 W/m^2, therminol D-12 reached 333 K at 0.008 kg/s while at 0.08 kg/s it reached 322 K. Velocity magnitude was found to be uniform at 0.008 kg/s.

B. Validation with experimental results

The static temperature results of numerical analysis on evacuated tube with therminol D-12 at flow rate of 0.008 kg/s during varying solar radiation was compared with that of experimental results[17]. The percentage deviation in static temperature in the three cases of solar radiation was from 1 to 4%. The comparison of static temperature values from numerical and experimental values is shown in Table-III.

Table-III. Comparison of Experimental and Numerical Results

Solar radiation range W/m^2	Outlet temperature of therminol D-12 in Kelvin		
	Numerical analysis value	Experimental analysis value	Deviation in %
0-200	312	307	1.6
0-400	324	313	3.5
0-600	333	323	3.1

The error percentage is less than 5% and the numerical results are acceptable.

IV. CONCLUSION

With the help of P1 radiation model, the static temperature and velocity magnitude at the outlet of evacuated tube were predicted. The static temperature varied by 1.6% from the experimental results under solar radiation range of 0 to 200 W/m^2. Under the solar radiation of 600 W/m^2, the static temperature varied by 3.1%. On an average, the predicted static temperature value will deviate by 3 to 4% from experimental results. The pressure drop obtained from the experimental results is negligible as glass tube is used in the experiment. This was confirmed in the predictions during numerical analysis. Hence, it is concluded that P1 radiation model holds good for the prediction of static temperature and velocity magnitude under solar radiation range of 0 to 600 W/m^2. However, for radiation above 600 W/m^2, the error percentage increases above 10%.

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