HEAT TRANSFER BEHAVIORS IN A PARABOLIC TROUGH SOLAR COLLECTOR TUBE WITH COMPOUND TECHNIQUE

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ABSTRACT

A three dimensional numerical investigation using computational fluid dynamics (CFD) has been carried out to examine the effect of the presence of baffles and nanofluid inside a non-uniformly heated parabolic through solar collector under turbulent flow. The results show that the inclusion of baffles improves the heat transfer characteristics with a pressure drop as penalty; the baffles dimensions have an important effect on heat transfer enhancement. The inserts have also a non-negligible effect on the temperature distribution and heat transfer fluid velocity. The remarkable improvement was observed in the utilization of nanofluid as heat transfer fluid, however the combination of the two methods offer a better heat transfer performance.

Keywords *– Baffles, nanofluid, heat transfer enhancement, Monte Carlo ray trace technique, numerical study.*

I. INTRODUCTION

Solar energy technologies have a great potential such as diversification of energy supply, reduction of dependence on natural gas and energy fossils, offset greenhouse gas emissions…etc. Parabolic through solar collector is currently the most proven solar concentration techniques. To enhance the heat transfer rate from solar radiation to heat transfer fluid (HTF), one of the effective techniques is to improve the convective heat transfer inside the inner tube; for this reason many researches are focused for enhancing heat transfer inside PTC receiver using many passives techniques like twisted-tapes, wire coils, swirl generators, ribs, fins, baffles and others. Munoz et al. (2011) [1] used the computational fluid dynamics (CFD) tools to analyze the pressure losses, thermal losses, thermal mechanical stress and thermal fatigue of the internal finned PTC. They estimated that the performance of a 20MW solar plant cooled by oil can improve about 2% if helically fined receivers can be used. Seyed Ebrahim Ghasemi et al. (2013) [2] studied numerically the performance of parabolic solar collector with three segmental rings; they declared that the use of three segmental rings in tubular solar receiver enhances the Nusselt number and system performance. By decreasing the inner diameter of three segmental rings, the Nusselt number increases, but with considering the pressure loss, thermal performance decreases. Ghadirijafarbeiglo et al. (2014) [3] numerically investigated the thermal performance of PTCs equipped with a new perforated louvered twisted-tape. The results showed that the new twisted-tape can provide better thermal performance compared with traditional twisted-tape especially for low Reynolds number. Huang et al. (2015)[4] investigated numerically heat transfer enhancement inside a PTC receiver using helical fins, protrusions and dimples; their results demonstrate that the receiver tube with dimples has superior performance of heat transfer augmentation compared with that with protrusions or helical fins.

Recently, a new class of fluids called nanofluid has been developed and tested, this term was proposed by Choi in (1995) [5] at Argonne National Laboratory; as a liquid mixture with a small concentration of nanometer-sized solid particles in suspension. The literature survey shows that nanofluids significantly improve the heat transfer capability of conventional heat transfer fluids such as oil or water by suspending nanoparticles in these base liquids. Many researchers have investigated the heat transfer performance and flow characteristics of various nanofluids with different nanoparticles and base fluid materials. Pack et al. (1998) [6], Xuan et al. (2000) [7], Qiang et al. (2002) [8], Yang et al. (2005) [9], Heris et al. [10] (2007), Nguyena et al. (2007)[11], Velgapudi et al. (2008) [12], Duangthongsuk et al. (2010) [13], Nasiri et al. (2011) [14], Murgesan et al. (2012) [15], Darzi et al. (2013) [16], Nield et al. (2014) [17], have investigated the convective heat transfer of nanofluids, they reported that the heat transfer enhancement depends on several parameters such as: the size and shape of nanoparticles, the volume fraction of particles suspended and the thermo-physical properties of particles material.

The aim of this study is to improve heat transfer inside parabolic through solar collector under turbulent flow using two different passive techniques, the first affects the absorber geometry by inserting baffles inside it, and the second one is the utilization of 1%.vol of the fullerenes nanoparticles suspended in Therminol VP-1; the results of these studies are presented in the form of Nusselt number and Darcy friction factor.

II. MODEL CONFIGURATION

In this work; we have considered a simplified model of the parabolic trough receiver in which the effect of the central rod and other supports is considered negligible. A detailed schematic diagram of the receiver is presented in Fig. 1, where the materiel used for the glass cover and the absorber tube are borosilicate glass and steel respectively, the annular space between both tubes is considered as vacuum at very low pressure and ambient temperature. The aim of this study is improving heat transfer by inserting baffles in the tube-side of the PTC. Fig.2 shows the model configuration used in this work. The dimensions and the physical parameters of the receiver are given in Table.1.

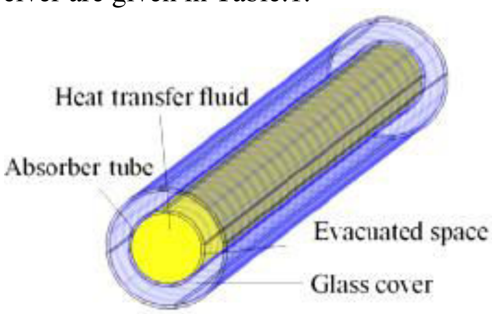

Fig. 1: schematic of PTC receiver

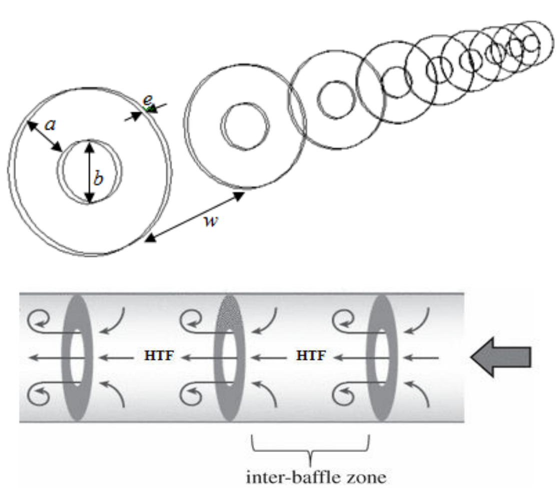

Fig. 2: Model configuration with geometrical parameters.

Table 1. Receiver dimensions.

Receiver length "L"	200 cm
Absorber inner radius	3.2 cm
Absorber outer radius	3.5 cm
Glass cover inner radius	5.96 cm
Glass cover outer radius	6.25 cm
Coating absorbance	95%
Glass emissivity	0.837

III. METHODOLOGY DESCRIPTION

1. CFD modeling

A commercially available CFD code has been used to investigate the numerical calculations. The K-Ɛ [18] turbulent model was used; the simple algorithm pressure-velocity coupling was employed. Second order scheme was used for energy and DO radiation model; the first order scheme is adapted for the other equations.

2. Heat transfer fluid properties

For the numerical simulation, the flow is considered as hydrodynamically developed and thermally developing flow. The heat transfer fluid used is a nanofluid contains nanoparticules of fullerene C60 which are a non-metallic particles composed entirely of carbon atoms interconnected in pentagonal and hexagonal rings in the shape of hollow sphere, ellipsoid or tube; the spherical fullerenes are also called buckyballs and cylindrical ones are called carbon nanotubes (CNT). This nanoparticules are dispersed in a synthetic heat transfer fluid "the Therminol VP-1" which is a eutectic mixture of 73.5% diphenyl oxide and 26.5% diphenyl, it is suitable for the most process heating because of its operating temperature range varies from -85 to 400°C.
The thermo-physical properties formulae of therminol VP-1 [19] are given as function of temperature in Table2 (Temperature is expressed in °C).
The correlations [20, 21, 22, 23] used for calculate the nanofluid properties are shown in Table. 3.

Table 2. Physical properties formulae of Therminol VP-1

$\rho = -0.90797T + 0.00078116T^2 - 2.367\cdot10^{-6}T^3 + 1083.25$
$C_P = 0.002414T + 5.9591\cdot10^{-6}T^2 - 2.9879\cdot10^{-8}T^3 + 4.4172\cdot10^{-11}T^4 + 1.498$
$\lambda = -8.19477\cdot10^{-5}T - 1.92257\cdot10^{-7}T^2 + 2.5034\cdot10^{-11}T^3 - 7.2974\cdot10^{-15}T^4 + 0.137743$
$\nu = exp\left(\frac{544.149}{T+114.43} - 2.59578\right)$

Table 3. Thermo-physical properties of nanofluid

Density (kg/m^3)	$\rho_{nf} = (1-\phi)\rho_f + \phi\rho_p$
Heat capacity (KJ/kg.K)	$(\rho C_p)_{nf} = (1-\phi)(\rho C_p)_f + \phi(\rho C_p)_p$
Thermal conductivity (W/m.K)	$\lambda_{nf} = \lambda_f \dfrac{\lambda_p + 2\lambda_f - 2\phi(\lambda_f - \lambda_p)}{\lambda_p + 2\lambda_f + \phi(\lambda_f - \lambda_p)}$
Dynamic viscosity (Pa.s)	$\mu_{nf} = \dfrac{\mu_f}{(1-\phi)^{2.5}}$

3. Boundary conditions:

In this study, the outer absorber's wall receives a non-uniform heat flux obtained by using MCRT technique [24], and taking the DNI of 1000 W/m2, the local concentration ratio distribution results are illustrated in Fig. 3.

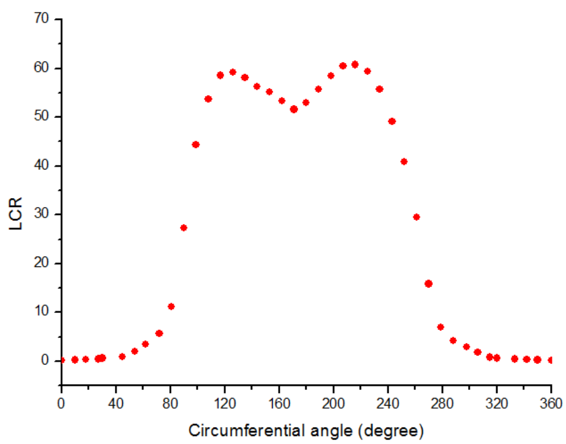

Fig. 3: The local concentration ratio on a cross-section of the absorber outer surface

For the outer glass envelope, a thermal boundary condition that includes the convection and radiation heat transfer is used. Sky temperature and sky emissivity can be calculated using the following correlations [25], [26]:

$$T_{sky} = 0.0552 T_{amb}^{1.5} \tag{1}$$

$$\varepsilon_{sky} = 0.711 + 0.56\frac{T_{dp} - 273.15}{100} + 0.73\left(\frac{T_{dp} - 273.15}{100}\right)^2 \tag{2}$$

where the ambient temperature used in this simulation is 300K and T_{dp} is dew point temperature (K).

The convection heat transfer coefficient used for the boundary condition is defined by the experimental correlation [27]:

$$h_w = 4 v_w^{0.58} d_{go}^{-0.42} \tag{3}$$

where: v_w is the wind speed (2m/s in this study) and d_{go} is the glass cover outer diameter.

IV. RESULTS AND INTERPRETATIONS

1. Validation of numerical data

For validate purposes, the numerical results of Nusselt number and friction factor for smooth tube was compared with those calculated by the empirical correlations available in the literature.

Gnielinski [28] introduced a following correlation for predicting Nusselt number inside tubes under turbulent flow as function of Reynolds number, Prandtl number and friction factor calculated by the Petukhov's [29] correlation.

$$Nu = \frac{\frac{f}{8}(Re - 1000)Pr}{1 + 12.7\left(\frac{f}{8}\right)^{0.5}\left(Pr^{2/3} - 1\right)} \tag{4}$$

$$f = (0.79 \ln Re - 1.64)^{-2} \tag{5}$$

Ditus-Boelter [30] proposed a simple correlation for calculating Nusselt number depending only on Reynolds number and Prandtl number.

$$Nu = 0.023 Re^{0.8} Pr^n \tag{6}$$

n=0.4 if the wall temperature is higher than the bulk temperature ($T_w > T_b$), and n=0.3 in the opposite case.

Blasius [31] recommended a correlation for the calculation of friction factor inside smooth pipes under turbulent flow as follow:

$$f = 0.316 Re^{-0.25}; Re \le 2 \cdot 10^4 \tag{7}$$

$$f = 0.184 Re^{-0.2}; Re > 2 \cdot 10^4 \tag{8}$$

Fig.4 shows compatible results of the average Nusselt number and friction factor, where the maximum deviation is less than 8.5% and the minimum deviation is approximately 0.2%.

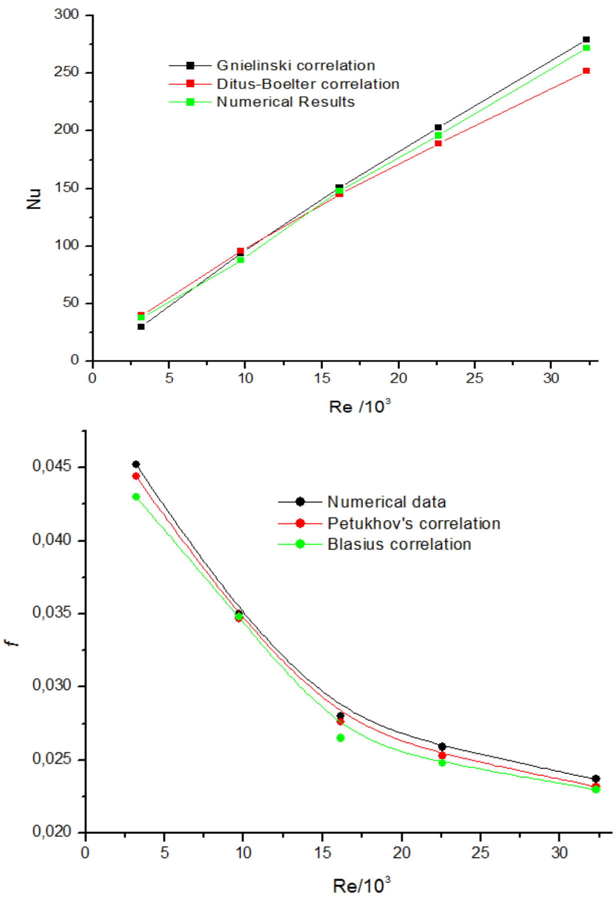

Fig. 4: Validation of numerical results for a smooth absorber.

2. Effect of baffles on heat transfer and fluid flow characteristics

Fig. 5 shows the average Nusselt number evolution as function of Reynolds number for the smooth and enhanced tubes, the results demonstrate that the baffles improves heat transfer greatly compared to the plain tube, the increase on Nusselt number can reach 2 to 3 times when Reynolds number varies from 3229 to 32294. Fig.6 illustrates that the increase of Nusselt number is also accompanied with increasing Darcy friction factor; this is due to the presence of baffles which play the role of obstacles that create a swirling flow.

Fig.7 shows that with the inclusion of baffles, the HTF temperature reduces and become almost uniform in the large part of the cross-section, and on the other hand fig.8 shows that the wall temperature decreases evenly by inserting baffles. This reduction of temperature gradient plays an important role in enhancing heat transfer. The temperature contours for the baffles is shown in fig.9, the highest temperature in the baffles bottom is due to the non-uniform heat flux distribution.

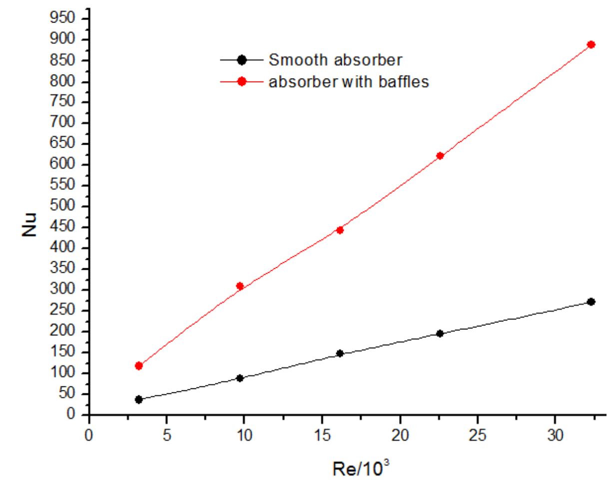

Fig.5: Variation of Nusselt number for tube with and without baffles.

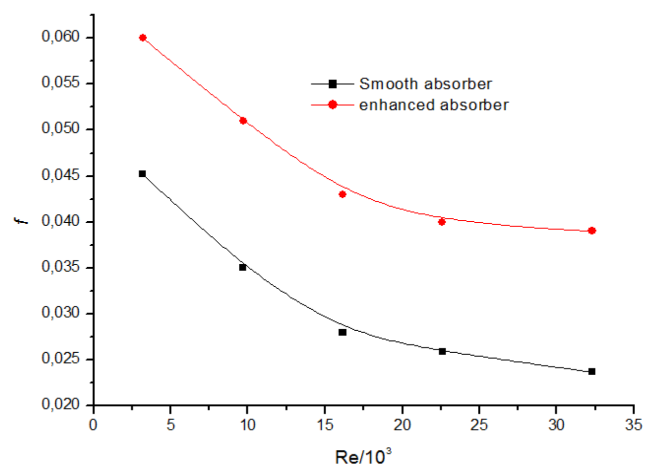

Fig.6: Evolution of friction factor for tube with and without baffles.

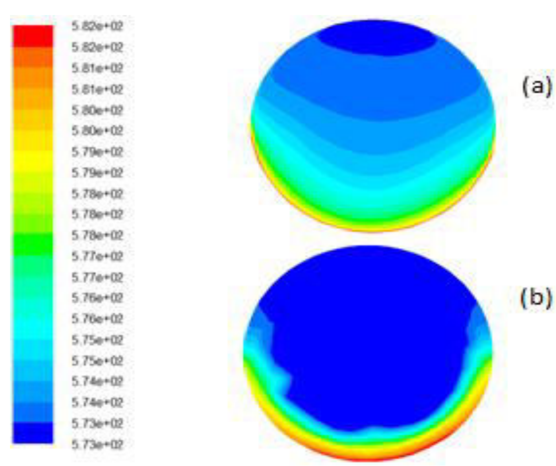

Fig.7: HTF Temperature distribution for smooth tube (a) and baffled tube (b).

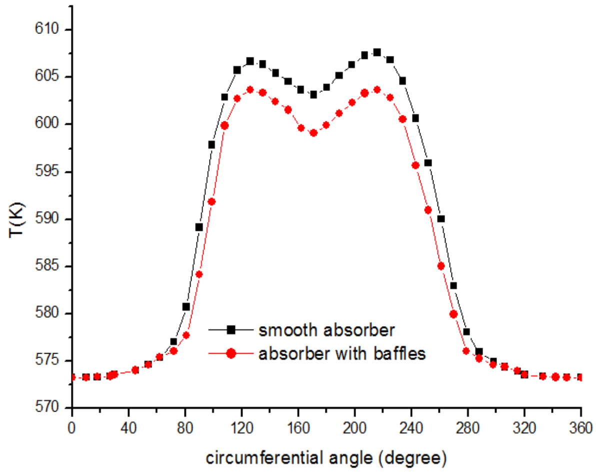

Fig.8: absorber temperature distribution on the middle cross-section.

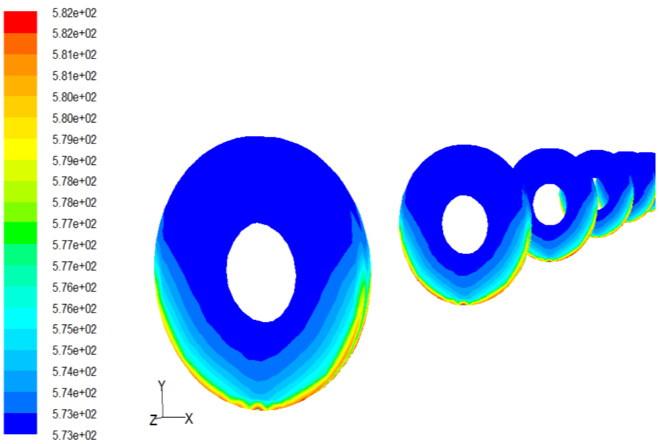

Fig.9: Temperature contours of baffles

3. Velocity field analysis

As it is recommended, the HTF velocity distribution inside a tube is maximal in the center and tends to zero near the walls which is clearly obtained in the case of our simulation and it's illustrated in fig.10, simply in the case of tube fitted with baffles the HTF velocity augments and becomes almost uniform in the large area, this velocity improvement is due to the reduction of flow surface. Augmenting velocity leads to higher convective heat transfer coefficient.

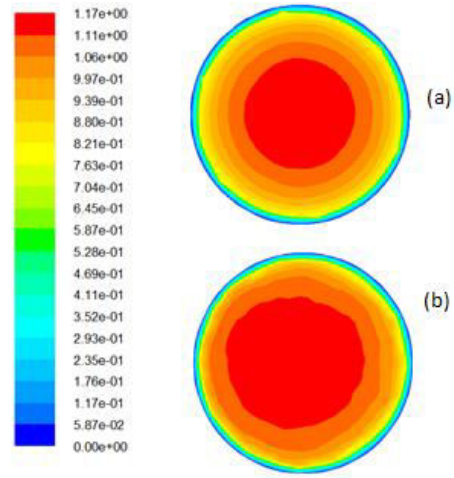

Fig. 10: HTF Velocity distributions on the middle cross-section.

4. Effect of baffles dimensions

Numerical analysis was carried out for baffles dimensions effects, fig.11 shows that the heat transfer coefficient augments as baffles thickness "e" increases because of more heat diffusion to the working fluid; we studied also effect of distance between two consecutives baffles "w", Fig.12 illustrates that the heat transfer coefficient increases with decreasing the distance between baffles because of large heat transfer area.

5. Simultaneous effects of nanofluid and baffle on heat transfer enhancement

Fig.13 describes that the heat transfer augments with the presence of 1% fullerenes nanoparticules in base fluid, hence using nanofluid as HTF in the tube equipped with baffles offer a better heat transfer where the Nusselt number augments about 3.5 times compared to the plain tube with base fluid.

Fig.14 predicts the effect of combining the two mechanisms on pressure drop, the results demonstrates that the Darcy friction factor increases by inserting baffles which is due to the formation of vortices that disturbed the boundary layer, and, thus, enhanced mixing by extension heat transfer rate between the fluid at the core and the heated surface can be achieved.

To evaluate the effect of baffles and nanofluid on heat transfer enhancement, we used the thermal performance criteria defined as the ratio of the dimensionless Nusselt number and the dimensionless friction factor, given by the following relation [32]:

$$PEC = \frac{\frac{Nu}{Nu_0}}{\left(\frac{f}{f_0}\right)^{1/3}} \tag{9}$$

where the subscript 0 refers to the solution of the smooth tube.

Fig.15 exhibits the variation of PEC for enhanced tubes, the PEC values vary from 2.8 to 3.4 for absorber fitted with baffles and using naofluid as HTF, which indicates that the augmentation of heat transfer can cover the penalty of increased flow resistance so this is a sign of good performance in heat transfer enhancement.

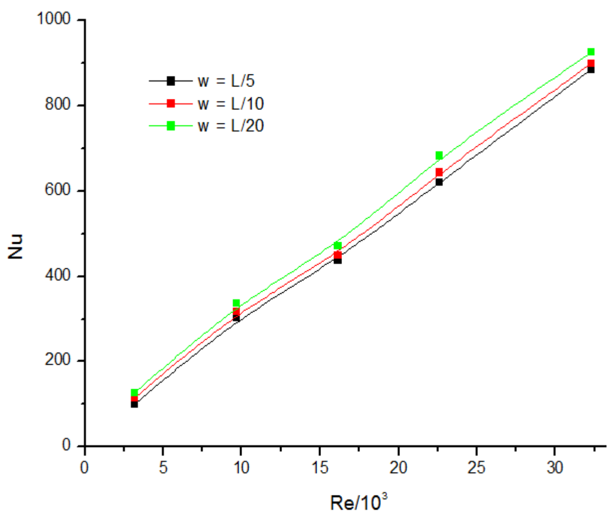

Fig.11: Effect of distance between two consecutives baffles on heat transfer.

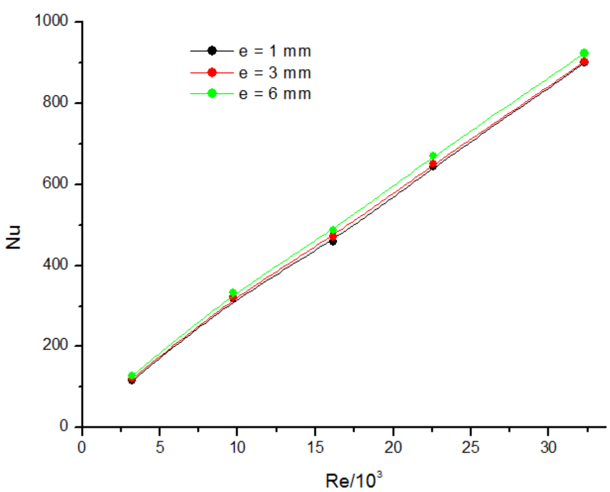

Fig.12: Effect of baffles thickness on Nusselt number.

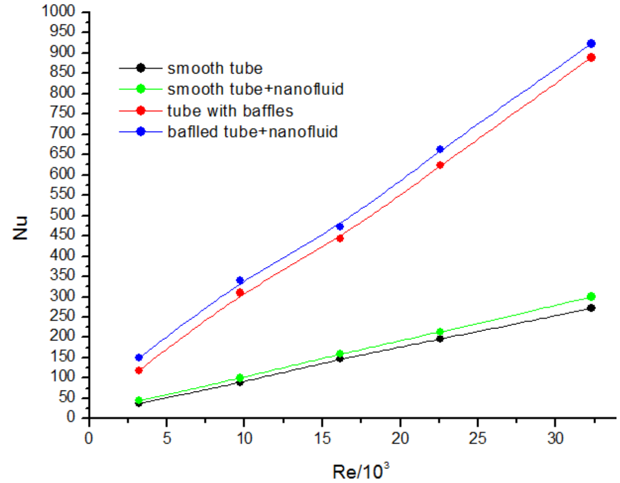

Fig.13 Effect of using baffles and nanofluid on heat transfer characteristics

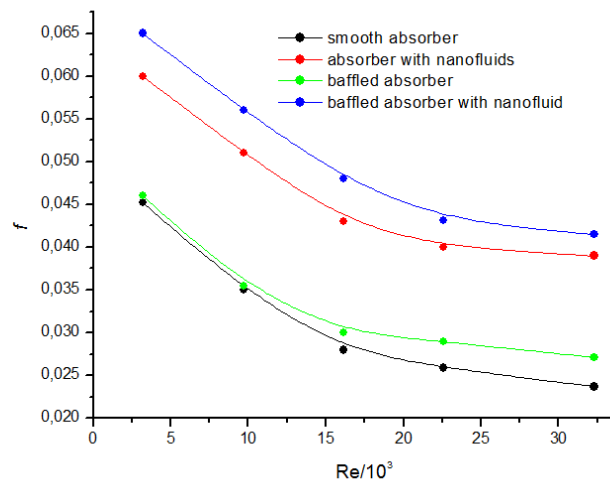

Fig.14: effect of baffles and nanofluid on pressure drop

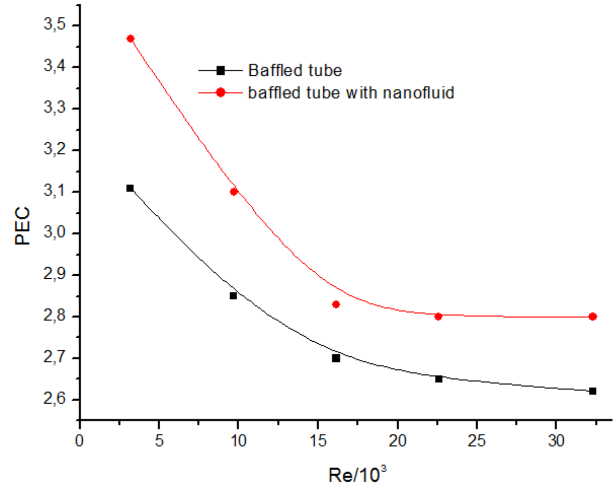

Fig.15: Thermal performance of enhanced absorber

V. CONCLUSION

Numerical investigation of heat transfer and fluid flow characteristics inside a parabolic through solar collector receiver under turbulent regime is carried out by using compound technique; the following conclusions can be made:

- High Nusselt number and friction factor are obtained for tube fitted with baffles compared to plain tube.
- Insertion of baffles has non-negligible effects on fluid flow characteristics.
- Nusselt number increases with increasing baffles thickness and decreasing the distance between baffles.
- The inclusion of fullerenes nanoparticles produced an interesting increase of the heat transfer with respect to that of the base liquid.
- Utilization of nanofluid as HTF inside absorber with baffles resulted higher thermal performance.

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