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Numerical investigation of heat transfer enhancement inside a parabolic trough solar collector using dimpled absorber

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Abstract – *Three dimensional numerical investigation of heat transfer enhancement in a non-uniformly heated parabolic trough solar collector using dimpled absorber under turbulent flow was incorporated in the current paper. The governing equations were solved using the finite volume methods (CFD) with certain assumptions and appropriate boundary conditions. The Monte Carlo ray trace technique was applied to obtain the heat flux distribution around the absorber tube. The numerical results were validating with the empirical correlations existing in the literature and good agreement was obtained. The present results demonstrate that the inclusion of inserts provide a good performance in heat transfer, also the receiver temperature gradient are shown to reduce with the use of geometrical modification, the absorber geometry have a remarkable effect on the HTF velocity distribution.*

Keywords: *numerical investigation, parabolic trough solar collector, heat transfer enhancement, turbulent flow, dimpled tube.*

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I. Introduction

Heat transfer enhancement is an active and important field of engineering research. Many studies are carried out to improve the heat transfer following both numerical and experimental methods. Heat transfer achievement techniques are typically classified into three categories: active techniques (using external inputs, electrical power or RF signals, vibration, and synthetic jet….etc). Passive techniques (using surface or geometrical modification to the flow by incorporating inserts as: twisted tape, wire coils, fins, baffles, or by additives like gas bubbles, solid particles, liquid droplets…etc.) And compound techniques in which two or more passive or/and active techniques are employed together.

At present, different methods of convective heat transfer enhancement have been proposed and studied. Yakut et al. [1] experimentally investigated the effect of conical ring turbulators on the turbulent heat transfer, pressure drop. They indicated that Nusselt number increases with the smallest pitch arrangement. Ayhan et al. [2] examined numerically and experimentally the heat transfer improvement in a tube with truncated hollow cone inserts; they reported that tube with inserts gives higher heat transfer enhancement. Eiamsa-ard et al. [3] studied the effect of V-nozzle turbulators and conical nozzle on heat transfer and friction factor inside a uniformly heat flux tube, they found that heat transfer rate increases for using the both techniques. Saha et al. [4] investigated pressure drop and heat transfer characteristics in a circular tube equipped by regularly spaced twisted tape elements; they declared that pinching of place rather is a better property from thermo-hydraulic performance. Amina et al. [5] investigated numerically the effect of triangular and rectangular longitudinal fins on heat transfer enhancement inside PTC receiver; they concluded that PTC thermal performance increase with inserting fins. Amina et al. [6] studied again the effect of baffles on heat transfer enhancement, they reported that high Nusselt number and friction factor are obtained for tube fitted with baffles and the inserts have a remarkable effect on fluid flow characteristics.

The aim of this numerical investigation is to estimate the convective heat transfer enhancement in the fully developed turbulent flow under a non-uniform heat flux using dimpled absorber; the results of these studies are presented in the form of Nusselt number and Darcy friction factor.

II. Geometrical configuration model

In this work; we have considered a simplified model of a 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 Figure 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 principal objective of this paper is to improve heat transfer inside PTC receiver using simple geometrical mechanisms easily realizable in the industry, by means of modifying the absorber geometry by longitudinal dimples which acts as a passive vortex generators.

The configuration proposed is shown in Figure 2. And the physical parameters are given in table. 1.

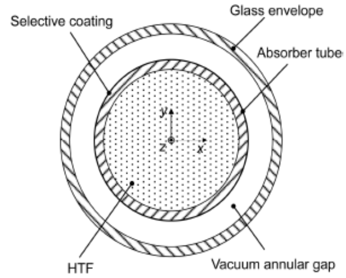


Figure 1. Schematic of cross-section of the receiver

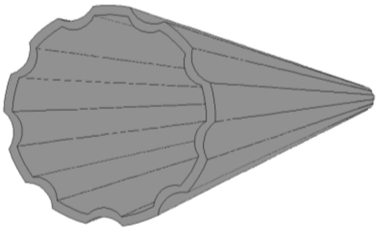


Figure 2. Schematic of dimpled absorber

Table 1. Receiver's physical parameters.

Focal length	1.71 m
Aperture width	5.77 m
Receiver length	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
Material of the absorber	steel
Material of the glass cover	Borosilicate
Transmittance of the glass envelope	>95%
Glass cover emissivity	0.837

III. Boundary conditions

In this study, the outer absorber's wall receives a non-uniform heat flux obtained by using MCRT technique [7] and taking the DNI of 1000 W/m^2, the local concentration ratio distribution results are illustrated in Figure 3. 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 [8], [9]:

$$T_{sky} = 0.0552 T_{amb}^{1.5} \quad (1)$$

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

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

Additionally, the convection heat transfer coefficient used for the boundary condition is defined by the experimental correlation [10]:

$$h_w = 4 v_w^{0.58} d_{go}^{-0.42} \quad (3)$$

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

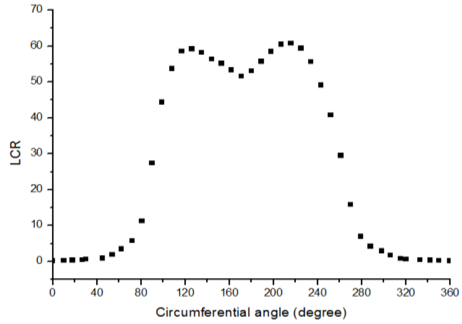


Figure 3. Local concentration ratio on a cross-section of absorber outer surface.

IV. Validation of the numerical results

The present numerical results for smooth absorber were validating using empirical correlations.

For Nusselt number, we used Gnielinski [11] and Notter-Rouse [12] correlations; and for friction factor results, the numerical data was compared with Petukhov [13] and Blasius [14] correlations.

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

$$Nu = 5 + 0.015\, Re^{0.856}\, Pr^{0.347} \quad (5)$$

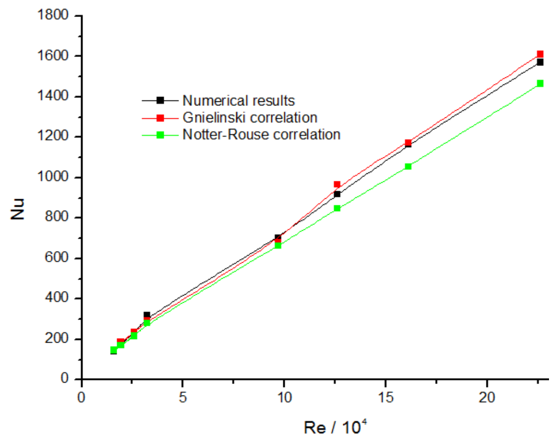
$$f = (0.79 \ln Re - 1.64)^{-2} \quad (6)$$

Where Re varies from 10^4 to 5×10^6

$$f = 0.316\, Re^{-0.25}; Re \le 2\cdot10^4 \quad (7)$$

$$f = 0.184\, Re^{-0.2}; Re > 2\cdot10^4 \quad (8)$$

As clearly seen in Figure 4, the numerical model was been successfully validated with the empirical results, where the maximum deviation was less than 8%.



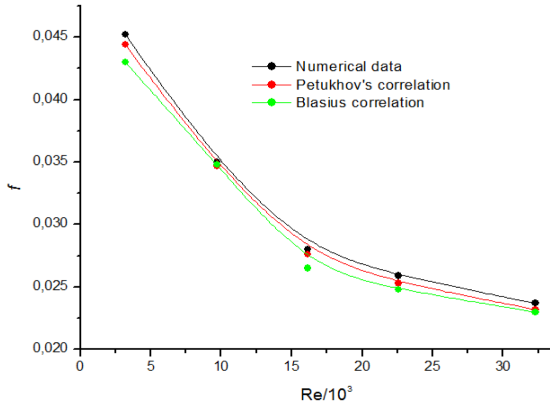


Figure 4. Validation of numerical results.

V. Results and interpretations

V.1. Effect of absorber geometry on heat transfer

The numerical results on heat and fluid flow characteristics in a non-uniformly heated PTC receiver with inserts are presented in the form of Nusselt number and friction factor. The numerical data carried out under forced turbulent flow conditions are reported in Fig. 5 and Figure 6.

Figure 5 illustrates the enhancement of the average Nusselt number with Reynolds number due to the presence of inserts, the Nu increases with increasing Re for smooth absorber and enhanced absorber. As can be noticed, the solution of the dimpled absorber retrieves a higher Nusselt number compared to the smooth tube model, where the Nusselt number increases of about (1.4 to 2 times which means that the absorber geometry plays an important role in the heat transfer so, these results have indicated the beneficial effects due to the inserts in the tube side of PTC receiver.

On the other hand, Figure 6 represents the variation of Darcy friction factor for tube with and without inserts. As expected in literatures the friction factor decreases with increasing Reynolds number. It can be seen that the friction factor augments about 1.14 times, these higher values are the results of the swirling flow induced by the longitudinal dimples that act like an obstacle.

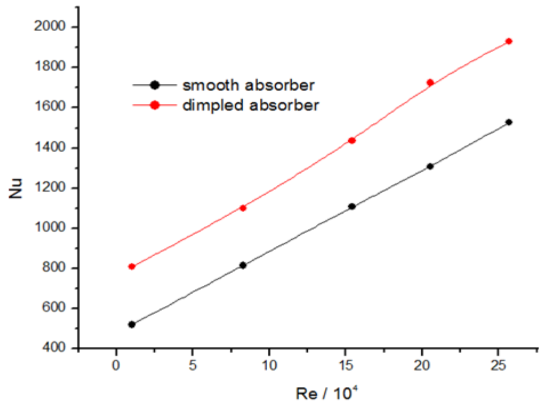


Figure 5. Variation of Nusselt number with Reynolds number for absorber with and without heat transfer enhancement.

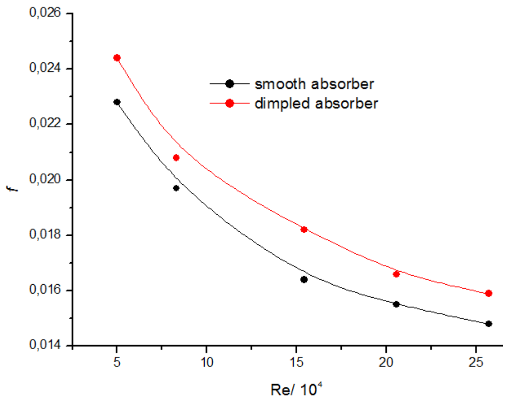


Figure 6. Variation of friction factor with Reynolds number for absorber with and without inserts.

VI.2. Temperature distribution analysis

Figure 7 presents the temperature distributions of the HTF along the radial direction on the middle cross section of the absorber, the higher temperature on the bottom part dues to the non-uniform heat flux, however the heat flux distribution is symmetrical approximately, that's why half of the circumferential angles are presented, the temperature increases where the inserts are placed but decreases in clear fluid region, The maximum temperature region close to the receiver tube rises up along the inner wall, Increased heat transfer performance is expected to reduce the temperature gradients in the receiver's absorber tube.

On the other hand, the variations of temperature distributions of the absorber tube which play a crucial role in the heat collecting is studied. It can be seen from Fig. 8 that the absorber equipped with inserts give a slight reductions in the absorber tube temperature gradients which leads to the higher heat transfer enhancement.

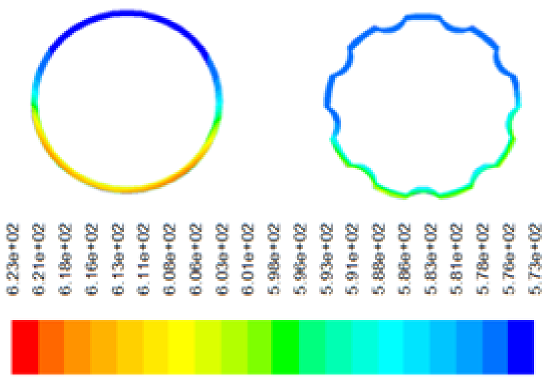


Figure 7. HTF Temperature distributions on the absorber's middle cross-section for plain tube and dimpled tube

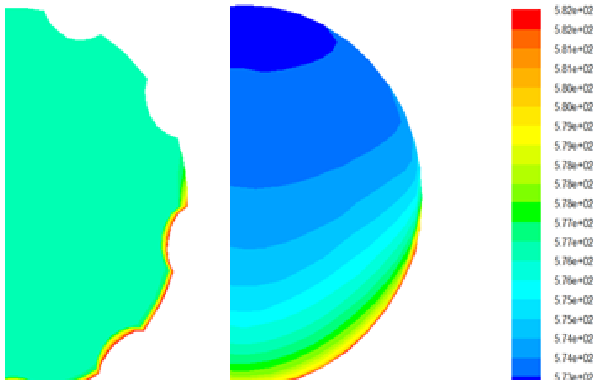


Figure 8. Absorber temperature distribution for smooth tube and enhanced tube.

VI.3. Velocity field analysis

Figure 9 presents the HTF velocity distribution at the cross-section in fully developed region for the tube with and without inserts at the same conditions.

It is noticed that the HTF velocity inside a tube is maximum at the center and tends to zero at the walls, which is clearly shown in Figure 9 in the case of smooth absorber, while the inclusion of inserts change the velocity distributions where the velocity is almost uniform in a large area of the absorber and minimal at the walls.

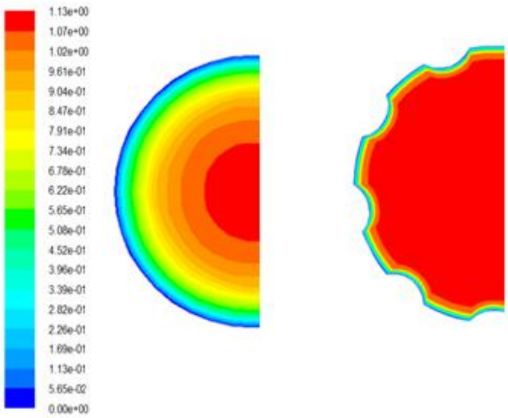


Figure 9. HTF Velocity distributions on the middle cross-section.

VI. Conclusion

Three-dimensional numerical simulation on enhancing heat transfer in a non-uniformly heated parabolic trough solar collector under turbulent flow by using a passive technique is performed in this paper. The following conclusion can be drawn:

The Nusselt number for absorber fitted with inserts increases by around 104 to 120%. The skin friction coefficient of dimpled tube augments 1.14 to 1.45 times compared to the smooth tube. The absorber geometry has remarkable effects on HTF temperature, on the inner wall absorber temperature distribution and on HTF velocity.

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