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Increasing the Energy Efficiency and Exergy of a Solar Collector Using Turbulators and Nanofluids Inside the Absorber Tube

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ABSTRACT

The limited availability of fossil fuel resources and the environmental issues caused by greenhouse gas emissions have underscored the need to adopt renewable energy sources, particularly solar energy. Improving the efficiency of solar energy systems increases productivity, reduces fuel and electricity consumption, and improves air quality. In this study, the governing equations were numerically solved in ANSYS Fluent using the finite volume method (FVM) with the k-ω-SST turbulence model. The thermal–hydraulic performance of a parabolic trough solar collector was investigated using a water-based CuO-SWCNT hybrid nanofluid at nanoparticle volume fractions of 1%, 2%, and 4%, and Reynolds numbers ranging from 4000 to 10000. Two modified twisted tape turbulators with different V-cut numbers and angles were examined. The results showed that the twisted tape with three V-cuts achieved the highest performance evaluation coefficient (PEC) and improved collector efficiency compared to the two-cut design, particularly at higher Reynolds numbers.

Keywords: Parabolic solar collector, twisted tape, hybrid nanofluid, performance evaluation coefficient.

NONMENCLATURE

Abbreviations	
P-TT	Plain twisted- tape
PEC	Performance Evaluation Coefficient
Symbols	
C_p	specific heat, kJ/kg-K
D	Diameter of the tube, mm
Nu	Nusselt Number
Re	Reynolds number
Tu	Turbulent Intensity
ω	specific rate of turbulence dissipation, s^{-1}
μ	Dynamic viscosity (kg/m·s)
ϕ	Nanoparticle volume fraction (%)

1. INTRODUCTION

Increasing energy demand drives the need for improved efficiency in heat transfer systems [1, 2], with solar energy becoming a leading renewable source. Parabolic trough collectors (PTCs) concentrate solar radiation to generate heat around absorber tubes, widely used for thermal energy conversion. Heat transfer enhancement methods are categorized as active (requiring external power), passive (using geometric modifications), or combined [3]. This study focuses on passive techniques, specifically using modified twisted tape inserts that create turbulent swirling flow to improve heat transfer[4-7].

Twisted tape inserts enhance heat transfer by inducing swirling flow and increasing axial velocity with a relatively moderate pressure drop compared to other inserts. Various modifications—such as toothed, multiple, slotted, and serrated twisted tapes—have been developed to optimize performance, often combined with nanofluids to further boost thermal efficiency. Hybrid nanofluids, particularly ternary nanoparticle composites, are promising due to superior thermophysical properties but require careful optimization of nanoparticle volume fraction to balance heat transfer gains against increased pressure drop[8, 9].

Despite extensive studies on twisted tape designs and nanofluids, limited research exists on the effects of cut angle and the number of cuts on twisted tape performance, especially using hybrid CuO-SWCNT-water nanofluids. This study investigates the influence of V-cut twisted strip inserts on heat transfer, efficiency, and the Performance Evaluation Coefficient (PEC) in parabolic trough collectors, through turbulent flow simulations at Reynolds numbers between 4000 and 10,000 under a constant heat flux of 1200 W/m². The novelty lies in analyzing the two-cut twisted strip geometry combined with hybrid nanofluids to optimize solar collector performance. Furthermore, an extended version of this study, in which the findings will be elaborated in greater detail, is being considered for submission to a peer-reviewed journal.

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2. . NUMERICAL MODEL AND SIMULATION SETUP

2.1 *Geometrical Model and Operating Conditions*

Figure 1 presents the schematic of the simulated design. Case 1 represents a plain tube, while Cases 2 and 3 incorporate twisted strip inserts. The tube has a diameter of 22 mm and a length of 600 mm. The twisted strip has a thickness of 0.7 mm, height of 20 mm, cut edge length of 4 mm, and a twist cut angle of 60°, with Case 3 featuring a cut angle of 120°. Additional characteristics include a turbulator rotation of 0.5 relative to the horizontal axis, a peak distance of 20 mm between strips, and a tape length of 200 mm. The hybrid CuO–SWCNT–water nanofluid, with volume fractions of 1%, 2%, and 4%, enters the tube at 300 K under varying Reynolds numbers. A uniform heat flux of 1200 W/m² is applied, and all simulations are performed in ANSYS Fluent 19.2.

$$\rho\left(u_i\frac{\partial u_j}{\partial x_j}\right) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_i}\left((\mu + \mu_{turb})\frac{\partial u_i}{\partial x_i}\right) .j = 1.2.3$$

- Energy conservation:

$$\frac{\partial(\rho u_i k)}{\partial x_j} = \gamma.P_k - \beta_1\rho k\omega + \frac{\partial}{\partial x_i}\left(\left(\mu + \frac{\mu_{turb}}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right)$$

Additional equations for turbulent kinetic energy k specific dissipation rate ω, turbulence viscosity μ_{turb}, periodicity γ, and other turbulence parameters are solved simultaneously (see [11] for details). The variable γ indicates the flow regime, ranging from 0 (laminar) to 1 (turbulent), and is used to compute correction functions in the model.

2.3 *Hybrid Nanofluid Properties*

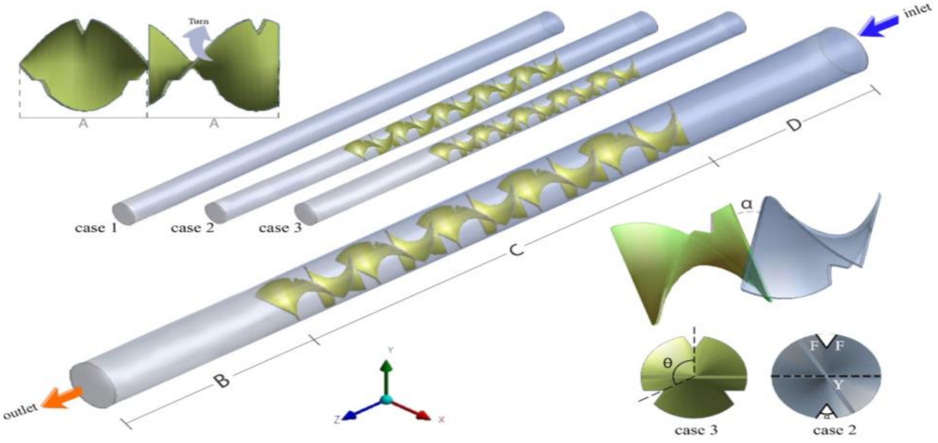

Fig.1 : General diagram of the simulated design

2.2 *Boundary Conditions and Governing Equations*

The computational domain is a 3D channel with twisted strip inserts, with a constant wall temperature of 300 K and a uniform heat flux of 1200 W/m² applied. Zero relative pressure is set at the outlet.

The Performance Evaluation Coefficient (PEC) is defined as: $\mathrm{PEC} = \frac{\mathrm{Nu}/\mathrm{Nu}_\rho}{(\Delta P/\Delta P_\rho)^{1/3}}$

The steady-state flow of CuO-SWCNT-water nanofluid is modeled as a single-phase homogeneous fluid. The mass, momentum, and energy conservation equations are solved using the Shear Stress Transport (SST) turbulence model [10].

- Mass conservation:

$$\frac{\partial u_i}{\partial x_i} = 0$$

- Momentum conservation:

The hybrid nanofluid consists of water (base fluid) mixed with CuO and SWCNT nanoparticles. Its thermophysical properties—density (ρ), heat capacity (ρc_p), viscosity (μ), and thermal conductivity (K)—are calculated using following equations. Three different nanoparticle volume concentrations are considered in this study.

$$\rho_{hnf} = (1 - \varphi_1 - \varphi_2)\rho_{bf} + \varphi_1\rho_{np1} + \varphi_2\rho_{np2}$$

$$(\rho c_p)_{hnf} = (1 - \varphi_1 - \varphi_2)(\rho c_p)_{bf} + \varphi_1(\rho c_p)_{np1} + \varphi_2(\rho c_p)_{np1}$$

$$\mu_{hnf} = \frac{\mu_{bf}}{(1 - \varphi_1 - \varphi_2)^{2.5}}$$

$$K_{hnf} = K_{bf}\left(\frac{(K_{np1} + K_{np2}) + 2K_{bf} - 2\varphi_{np1}(K_{bf} - K_{np1})}{(K_{np1} + K_{np2}) + 2K_{bf} + \varphi_{np1}(K_{bf} - K_{np1})}\right.$$

2.4 . Numerical Methods and Solution Procedure

ANSYS Fluent 2019 is used to solve the governing equations via the finite volume method, employing the k-ω Shear Stress Transport (SST) turbulence model as described by Menter et al. [11]. A pressure-based, steady-state solver is applied, with pressure–velocity coupling handled through the coupled algorithm, which simultaneously solves the continuity and momentum equations to improve convergence speed.

3. MESHING AND NUMERICAL VALIDATION

Figure 3 shows the mesh for Case 3. An inflation layer is applied to capture rapid velocity and temperature changes in the boundary layer, with quadrilateral elements used for both the tube wall and twisted strip. To ensure accuracy, simulation results are validated against the experimental data of Bhattacharyya et al. [10] for turbulent flow in a heat exchanger with a simple twisted strip. The predicted average Nusselt numbers show excellent agreement with the experimental values, exhibiting minimal error (Figure 2).

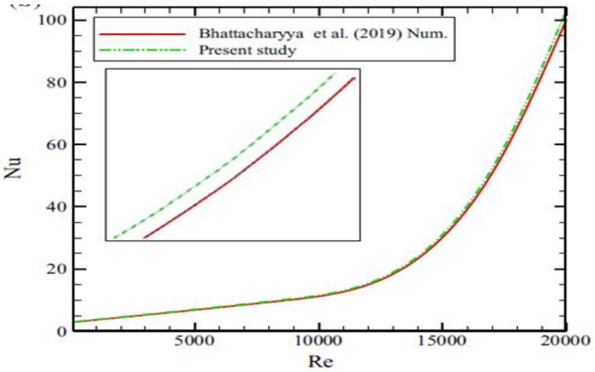

Fig. 2 : Validation of Nusselt values vs Reynolds number in the present study and Bhattacharyya et al.

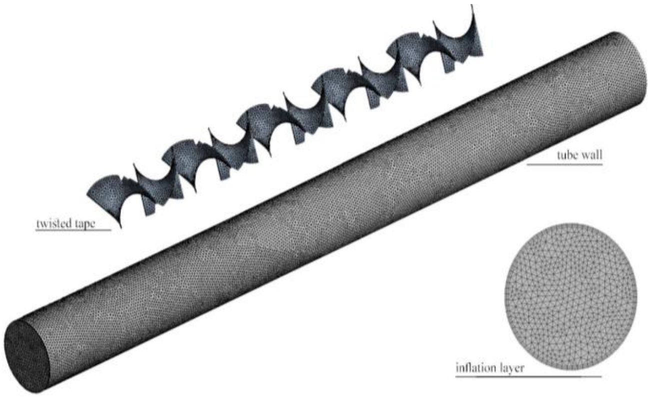

Fig. 3 : Mesh of the simulated model (Case 3)

4. RESULTS

Figures 4 illustrate the variation of the Nusselt number with Reynolds number for Case 3. While twisted strips enhance heat transfer compared to a plain tube, Case 3 (with three cuts at 120°) exhibits a slight reduction in both Nusselt number and Performance Evaluation Coefficient (PEC) compared to Case 2 (two cuts). Nonetheless, Case 3 achieves higher solar collector efficiency, likely due to a more favorable balance between heat transfer enhancement and pressure drop, which reduces pumping power requirements. Figures 6 further shows that PEC increases with higher nanoparticle volume fractions, highlighting the trade-off between improved heat transfer and increased frictional losses. Efficiency decreases with rising Reynolds number, as pressure drop effects increasingly offset thermal benefits. Overall, the results demonstrate effective solar collector performance improvement through optimized twisted strip designs and hybrid nanofluid application. These improvements have significant practical implications. The enhanced efficiency makes the proposed turbulator–nanofluid configuration suitable for large-scale solar thermal power plants, industrial process heating, and residential solar water heating. By lowering operational costs and boosting energy yield, the findings support broader adoption of renewable energy in real-world applications.

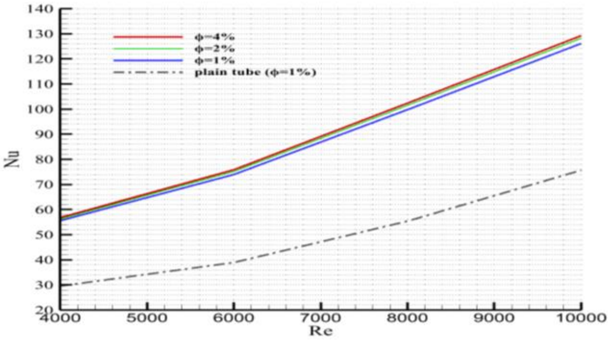

Fig. 4 : Variation of average Nusselt numbers with Reynolds number for Case 3

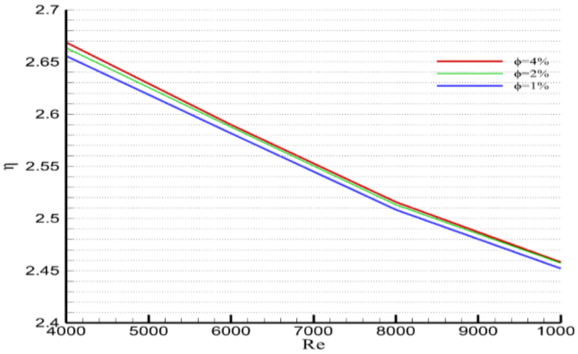

Fig. 5 : Variation of solar collector efficiency with Reynolds number for Case 3

As the Reynolds number increases, the fluid velocity along the tube increases, which intensifies the rotational disturbance caused by the twisted strip, further increasing the heat transfer rate.

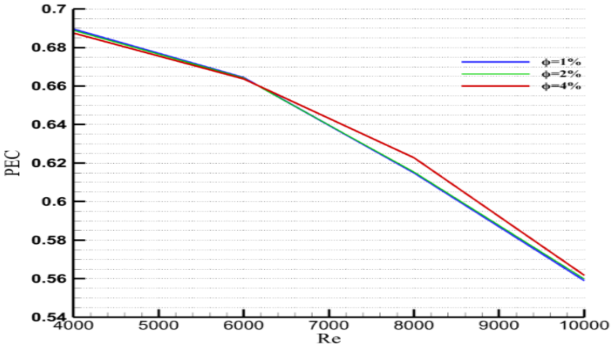

Fig. 6 : Variations of the PEC coefficient with Reynolds number in Case 2

Furthermore, the stronger flow mixing between the central and near-wall regions at higher speeds results in increased wall heating and a more uniform temperature distribution along the heated wall, compared to lower Reynolds numbers. These changes, especially regarding the localized points in the middle of the tube, are clearly visible in Figure 8.

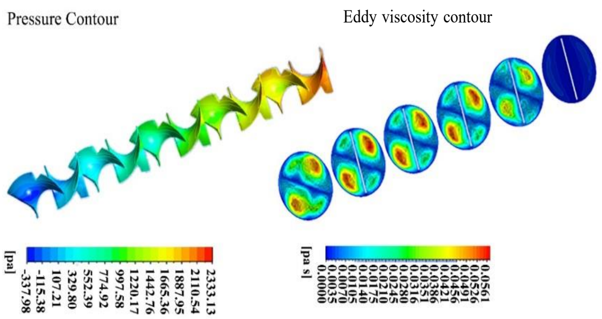

Fig. 7 : Contours of the turbulator for Case 2 at Re=10,000 and φ=1%

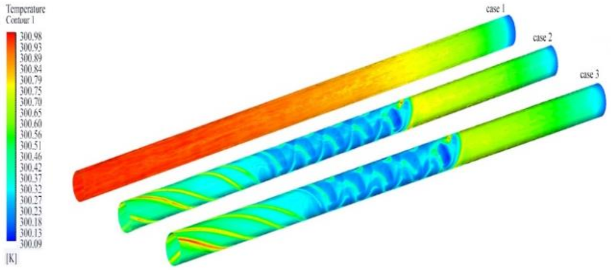

Fig. 8 : : Vector velocity contour for Re=10000 and φ=4%

5. CONCLUSIONS

A three-dimensional circular tube with twisted strips was numerically studied for nanoparticle volume fractions of 1–4% and Reynolds numbers of 4000–10000. Results show that increasing nanoparticle concentration enhances heat transfer but also raises friction. At Re = 10000, raising the concentration from 1% to 4% increases the average Nusselt number and friction coefficient by 4% and 2%, respectively. Increasing the number of cuts on the twisted strip (Case 3) improves solar collector efficiency while reducing pressure drop; for example, at Re = 10000 and ϕ = 1%, efficiency rises by 2.22% and pressure drop falls by 4%. The highest PEC (0.67) occurs at Re = 6000 for Case 3 with ϕ = 4%.

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