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Numerical Analyses of The Thermal Performance of SiC Nanofluids in Flat Tube with Twisted Tapes

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ABSTRACT

This study numerically investigates the thermal performance of a flat tube with a SiC/water nanofluid as the working medium. The study investigates the effects on different twisted tape insert models, including double twisted tapes (varying twist ratios), triangle corrugated tapes, and double twisted circular corrugated tapes. The results are compared to those of a flat tube without twisted tape to make sure they are correct. The results indicate that tubes with twisted tapes have much better thermal performance than plain tubes. According to the findings, flat tubes with twisted tapes perform significantly better thermally than flat tubes. The greatest improvement in heat transfer by a double-twisted tape with a 25 mm twist pitch (Model 4), which increased the Nusselt number by 44%. A double twisted tape with a triangle corrugation (Model 5) also showed an impressive improvement of 38%. But Model 4's enhanced thermal performance means that it has a much higher friction factor than Model 5, for both water and nanofluid.

1. Introduction

Improving heat transfer performance in a tube is a recurring theme in thermal engineering, motivated by the desire to make industrial machinery more compact and efficient. Methods are generally divided into two categories among the different strategies that have been developed: active and passive. Because they don't need external power, passive techniques in particular have attracted a lot of attention from researchers and practitioners because they are easy to use and reasonably priced.

A prominent passive approach involves the substitution of conventional heat transfer fluids with nanofluids. These engineered colloids consist of a base liquid suspended with solid nanoparticles, usually metals or metal oxides with nanometer diameters. The incorporation of these nanoparticles markedly improves the effective thermal conductivity of the mixture, leading to heat

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transfer performance. This property, combined with a relatively small increase in pressure drop, has made nanofluids a very attractive and widely studied topic in thermal science. **[4-1]**. Heat transfer enhancement technologies provide an effective path to improving the thermal performance of power systems, leveraging methods such as turbulent, extended surfaces, and nanofluids to achieve higher efficiency without consuming external energy [5]. Dimpled twisted tapes improve thermal-hydraulic performance in EG-W heat exchangers, yielding a performance factor up to 1.42[6]. This numerical investigation revealed that employing two counter-directional twisted tapes in Al2O3-water nanofluid as working fluid flow within flat tubes yields the greatest heat transfer coefficient increase, but it incurs the maximum pressure drop[7]. The numerical study and optimization of a ribbed flat-tube spiral coil demonstrated that rib shape improves heat transfer and system efficiency, with an optimal design resulting in a 22.35% increase in heat transfer. The Reynolds number was identified as the primary determinant affecting efficiency [8]. Experimental study of oil and water in a micro fin tube revealed a heat transfer performance enhancement critical Reynolds number of 6000 for oil and a substantially increased friction factor of up to 50% for Reynolds numbers above 30000 [9]. This study experimentally demonstrates that a micro fin tube (OD: 15.9 mm) enhances the heat transfer coefficient and friction factor by 1.8 times over a smooth tube for Re=1000-3000, utilizing 0.3 mm high fins at an 18° helix angle [10]. Optimized dimple-protrusion twisted tape insert enhances heat transfer at D/H=3 and minimizes friction at D/H=4.5 in double-pipe heat exchangers [11]. This work builds on previous research on micro fin tubes by analyzing a 5 mm tube with an 18° helix angle. It highlights important fin-fluid interactions and reveals an ideal configuration that maximizes condensation heat transfer despite a large pressure drop penalty[12].

A numerical study validated with experiments analyzed TiO_2-water nanofluid forced convection in smooth and micro-fin tubes under constant wall temperature, presenting property assessments and distributions of pressure, temperature, and velocity[13]. Experimental results show water outperforms other fluids in heat transfer within smooth tubes, with microfin tubes providing further enhancement that increases with Reynolds number.[14]. Variations twisted tapes have become another common form of increasing flow turbulence intensity [15, 16]. Other duct designs have a lower heat transfer rate and pressure drop than the triangular duct. The importance of these ducts increases as their heat transfer improves. Two different forms of nanoparticles are successfully prepared and measured in distilled water[17].Modified twisted tapes with nanoparticles enhanced thermal performance in circular tubes by increasing heat transfer performance and reducing pressure loss compared to conventional systems [18]. While edge-cut twisted strips reduce thermal performance, center-free twisted strips dramatically improve heat transfer [19]. This analysis compares helical screw inserts using aluminum oxide (Al_2O_3)/water and carbon nano tube (CNT)/water nanofluids in a plain pipe, revealing heat transfer performance with CNT/water nanofluid[20]. This simulation study demonstrates that twisted flat tubes enhanced thermal performance up to 70% compared to Plain tubes, with alternating helical models further improving performance [21]. Based on the literature review, it is noted that there is a lack of simulation study and detailed flow simulations regarding twisted tapes insertions inside flat tubes using Silicon Carbide (SiC)/water nanofluids, especially across various twisted tapes geometries.

2. Flat Tube Geometry

The geometry created in Ansys workbench. Table 1 and shows in
Fig. **1** contains a list of the tubes' specs that are shown in this illustration. It should be noted that the circumference of the flat tubes is the same as that of the circular tubes. This study will assess sex distinct arrangements of twisted tapes, which include model 1flat tube only , model 2 double twisted

tape with 50 mm twist pitch, model 3 double twisted tape 75 mm twist pitch, model 4 double twisted tape 25 mm twist pitch, model 5 double twisted tape triangle corrugated tape and model 6 double twisted tape circular corrugated tape, all tape with same direction twist.

Table 1 Flat tube details

Length	**1000 mm**
Perimeter	**31.40 mm**
Pitch of twisted tapes	75-50-25 **mm**
Tapes thickness	**0.75 mm**

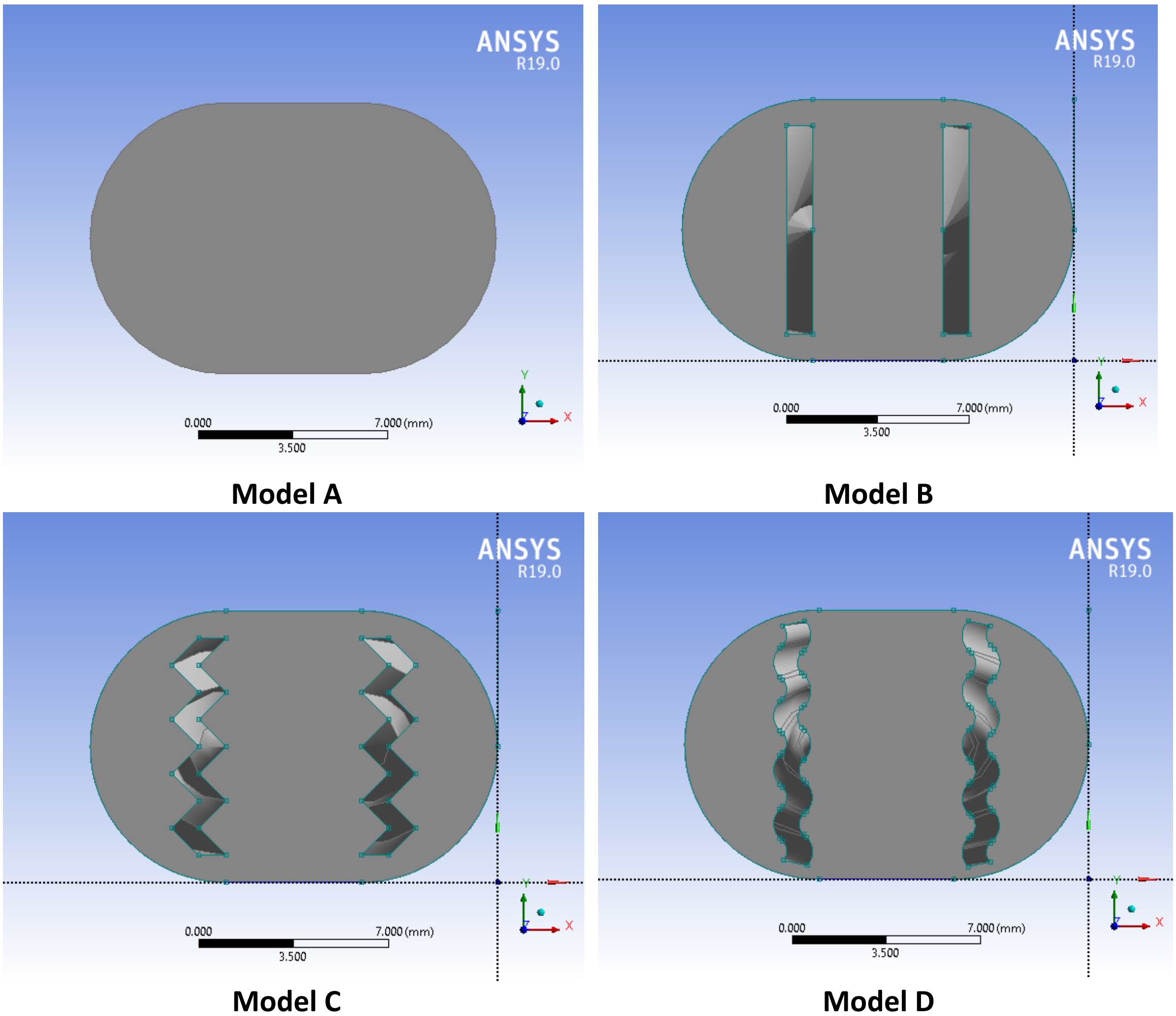


Fig. 1 The geometry tube details

3. Data Reduction

Table 2 summarises the fundamental equations employed to evaluate the heat transfer performance during the experimental investigation. The first parameter quantifies the heat transfer rate from the tube side based on the mass flow rate, specific heat capacity, and temperature difference of the working fluid. The second section defines the effective heat transfer area and coefficient, incorporating the mean bulk temperature and wall temperature to determine the overall heat exchange efficiency. The third and fourth parameters—Reynolds number and friction factor—are used to characterise the flow regime and fluid resistance within the system. Finally, the Nusselt number relates the convective to conductive heat transfer, serving as a dimensionless indicator of thermal performance. Together, these parameters form the analytical framework for assessing the heat transfer behaviour of the system under different experimental conditions.

Table 2
Experiments on heat transfer.

No.	Parameter	Equation
1	Heat transfers form the tube side	$Q = m_{water}\, C_p(T_{in} - T_{out})$
2	Heat transfer coefficient	$A_{eff} = \pi d_{eff} L$ $T_b = \frac{T_{in} + T_{out}}{2}$ $h_{eff} = \frac{Q}{(T_b - T_{w,avg})A_{eff}}$
3	Reynolds number	$Re_{eff} = \frac{\rho_{nf} u_{eff} d_{eff}}{\mu_{nf}}$
4	Fraction Factor	$f_{eff} = \frac{\Delta p\; d_{eff}}{2\rho_{nf} L\; u_{eff}}$
5	Nusselt Number	$Nu = \frac{h_{eff} D_{Hydo}}{k}$

.

4. Simulation Setup

The present study utilizes a mixture-model numerical nanofluid flow in flat tubes enhanced by twisted tape. This approach captures equilibrium across spatial scales by solving integrated continuity, momentum, and energy equations for the mixture, along with a volume fraction equation for nanoparticles, thus modelling separate phase velocities and local concentration variations within an integrated framework.

In the simulation, use ANSYS CFX 19.1 the initial inlet temperate condition 298.15 K and the constant wall temperature 325.15 K with the Reynold number (3000-10000) and the working fluid used by many types of Nanofluid with the deficiency volume fraction shown in the table. [22]. And used the K-Epsilon turbulence model and outlet static pressure 0 Pa , the will no slip. Convergence criteria 1.E 4.

Table 3
Properties of working fluid

Working fluid	Cp(J/kg · K°)	ρ (kg / m^3)	κ(W /m · K°)	μ(kg / m · s)
Water	4144. 00	997. 90	0. 609	0. 000943
Water / SiC (0.3 % Vol)	4141. 20	1006. 00	0. 615	0. 000950

5. Grid Independence Test (GIT)

The generation of grids plays a vital role in any analysis. A correct mesh gives us rough solutions for partial differential equations. Depending upon the operating condition, the mesh can be rough or fine. The grid independence test for geometry was done in this section to obtain the most suitable mesh faces. The mesh for micro fins tube Tight-fit twisted tape inserts (D_{Hydro}=13.18mm) and the velocity of flow 0.214 m/s are clearly shown in Figure. 2 the Wall heat transfer Coefficient in the same

XY plot was measured with all mesh Number of Elements. There was a structured and consistent discrete grid.

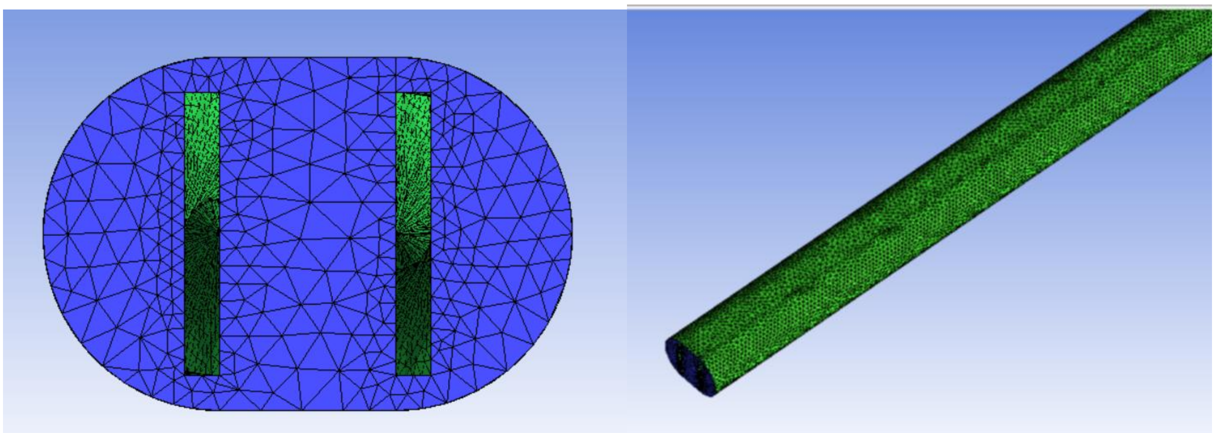


Fig. 2 Mesh of geometry.

As shown in Figure 3, a volume mesh type Tetra/Mixed and the method Robust (Octree) was used to create good-quality prism layers. The wall heat transfer coefficient results are similar for all nine mesh elements (1190380, 1328920, 1879413, 2693597, 3281870, 4763594, 6185654, 7447010 and 8668200). For geometry. The number of the element (4763594) is used as the best for the exactness and computational time, with the Wall Heat Transfer Coefficient (2826.03). Grid size with additional nodes would give better results accurately, but with the increase in cell density, the computational time would become much longer.

6. Validation of Numerical Models

The turbulent flow produced by a 13.10 mm diameter pant pipe at a Reynolds Number of 3000 was verified numerically in this section. The Renormalization Group (RNG) k–Epsilon, standard k–Epsilon, BSL Reynolds Stress, SSG Reynolds Stress, Reynolds Stress Omega, and Reynolds Averaged Navier-Stokes (RANS) turbulence models were among the suite of Shear Stress Transport (SST) models used in the analysis.

The computational predictions for the Nusselt number (Nu) and friction factor (F) were validated against experimental data, as shown in Figure 4. The results indicate that the RNG k–Epsilon model yielded Nusselt number predictions that were in closest consensus with the experimental measurements. Furthermore, flow calculations confirmed that both the SST and RNG k–Epsilon models provided a significantly more accurate prediction of the friction factor compared to the other models assessed.

The numerical accuracy was quantified, revealing that the SST model deviated from the experimental Nusselt number data by an average error of 8.23%, while the RNG κ–Epsilon model exhibited a marginally higher error of 8.71%.

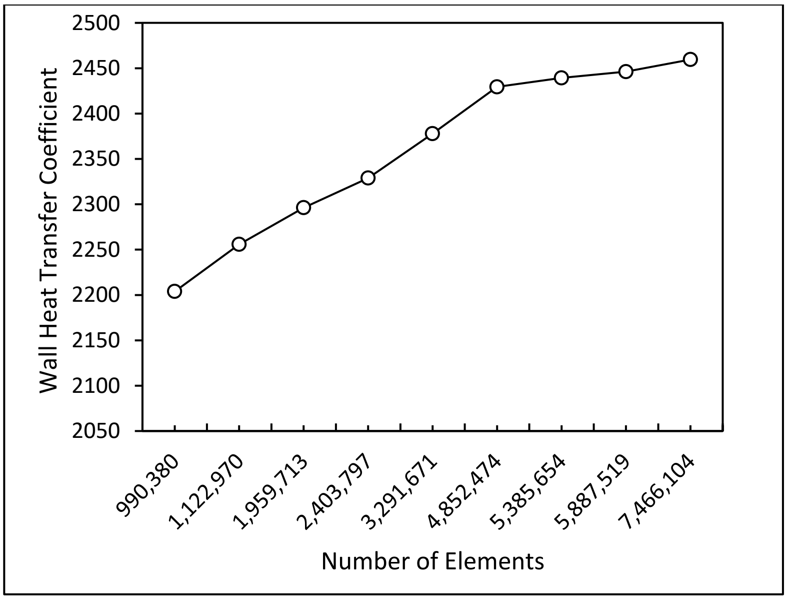


Fig. 3 The wall Heat transfer Coefficient with Number of Elements

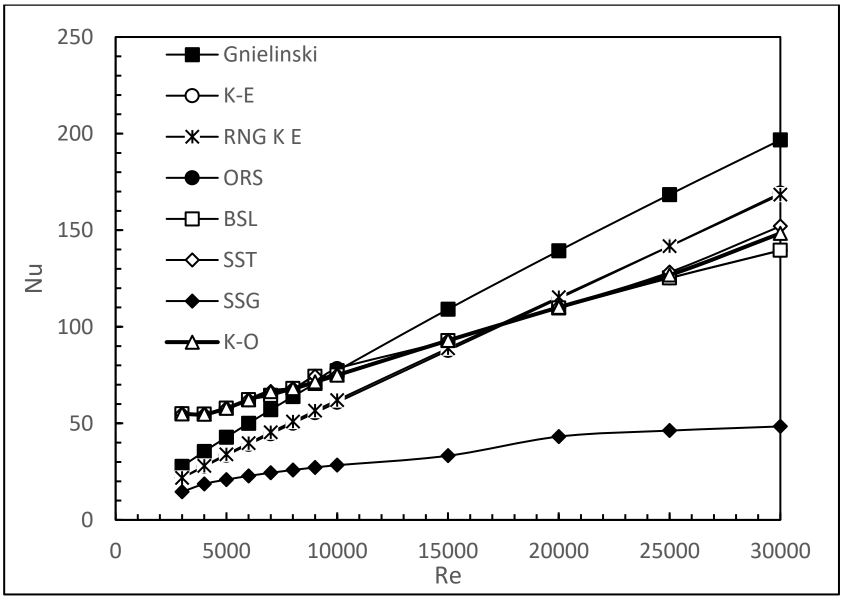


Fig. 4 Model test

7. Result and discussion.

To validate the experimental results, a comparative analysis was performed. The Nusselt numbers for the flat tube in the high Reynolds number regime were benchmarked against the established correlation of Gnielinsk [23, 24]. concurrently, the friction factor data for the plain tube were compared with the values predicted by the Filonenko correlation [25].

$$Nu = 0.0145 Re_{plain}^{0.851} Pr^{0.4} \qquad f = 0.9181 Re_{plain}^{-0.37}$$

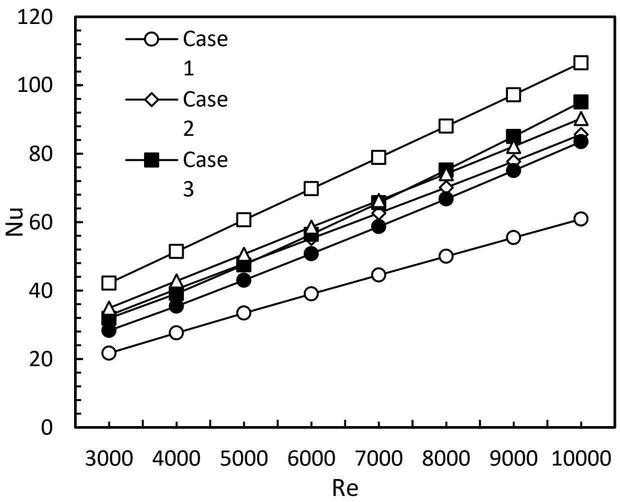


Figure 3 Nusselt Number for six models with working fluid water.

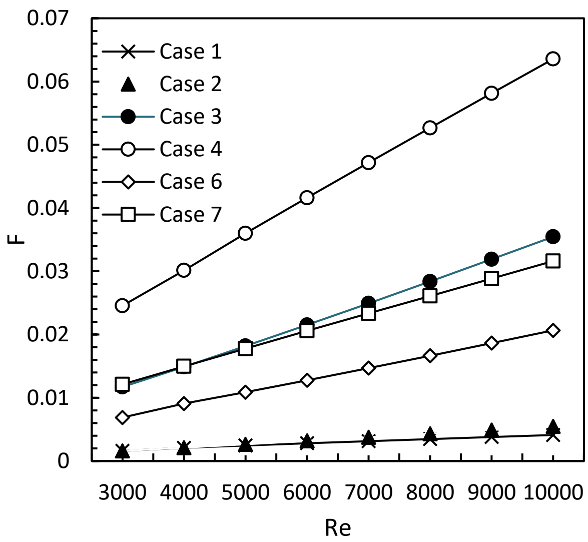


Figure 4 : The friction factor for six models with working fluid water.

All six models are simulated, and the effect of different twisted tape models on flat tubes using water will be studied and analyzed. Figure 3 and Fig. **5** shows the Nusselt number with Reynolds numbers range (3000-10000) in a turbulent flow for six cases: model 1flat tube only, model 2 double twisted tape with 50 mm twist pitch, model 3 double twisted tape 75 mm twist pitch, model 4 double twisted tape 25 mm twist pitch, model 5 double twisted tape triangle corrugated tape and model 6 double twisted tape circular corrugated tape and containing water. The use of model 4 increases the Nusselt number by 42 % and the use of model 5 increases the Nusselt number by 36% compared to the use of a flat tube with no tapes inside and containing water as the working fluid.

In this section, all six models are simulated, and the effect of different twisted tapes models on flat tubes using nanofluid will be studied and analyzed. **Error! Reference source not found.**and Fig. **6** show the Nusselt number at different Reynolds numbers in a turbulent flow for six different cases containing Nano fluid. In fact, the use of model 4 increases the Nusselt number by 44 % and the use of model 5 increases the Nusselt number by 38% compared to the use of a flat tube with no tapes inside and containing water as the working fluid.

Figure 4 and **Error! Reference source not found.** show the investigated double twisted tape i nserts on the friction factor. The results demonstrate a significant increase in the friction factor compared to the plain tube (baseline value of 0.004118). Specifically, Model 2 induces the highest hydraulic resistance, with a friction factor of 0.06001, which is 14.6 times higher than that of the flat tube. Model 1 increases the friction factor to a value of 0.032353, an increase of 7.9 % compared to the flat tube.

This notable rise in the friction factor is enhanced fluid mixing and the disruption of the boundary layer caused by the double twisted tape, the more aggressive design of Model 2 creates greater flow obstruction and swirl intensity, leading to higher shear stress at the tube wall and, consequently, the highest friction factor among the tested models.

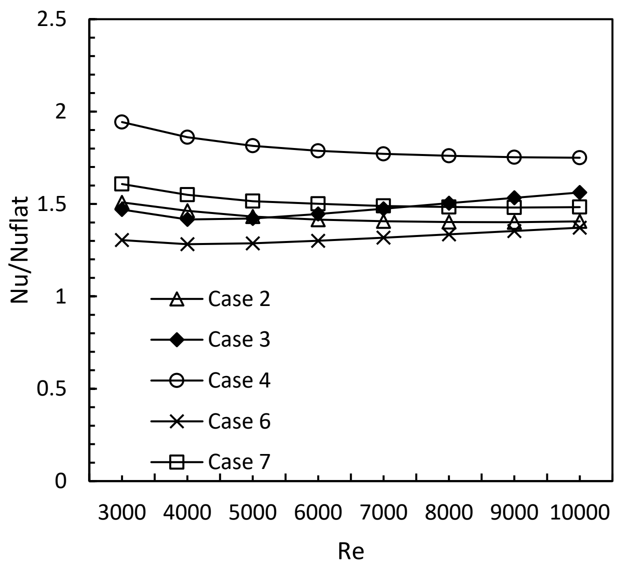


Fig. 5 Nusselt Number/Nu Flat tube for six models with working fluid water.

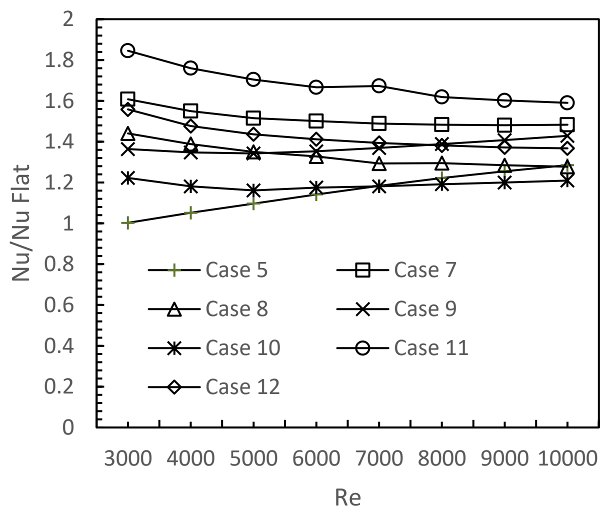


Fig. 6 Nusselt Number/Nu Flat tube for six models with working fluid Nano fluid

The Fig. **6** and Figure 7 show the heat transfer coefficient with Reynolds Number for water and Nano fluid as working fluids

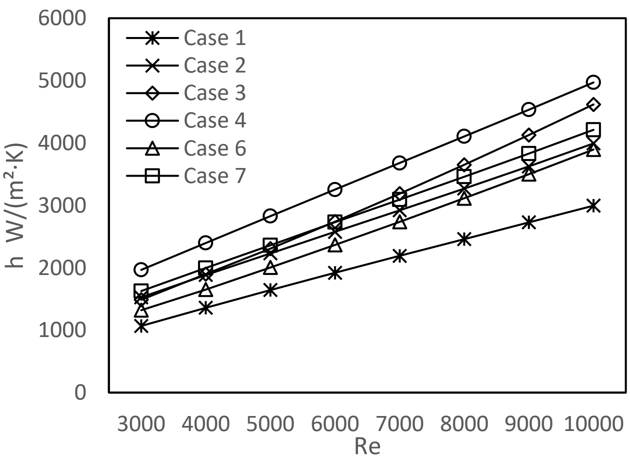


Figure 7 Heat transfer coefficient with Renold Number (water)

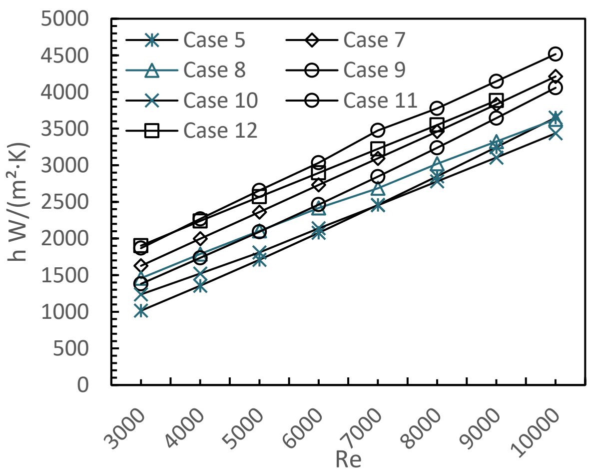
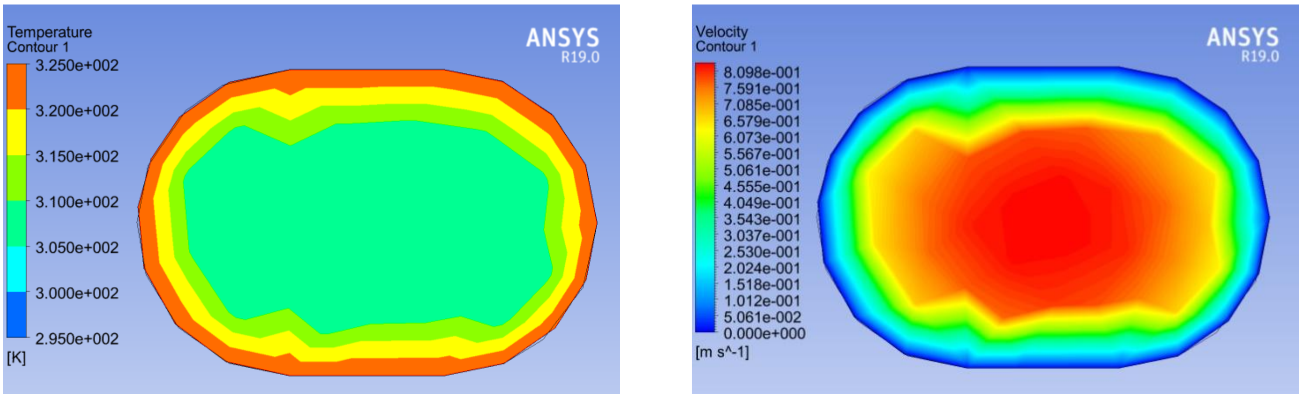


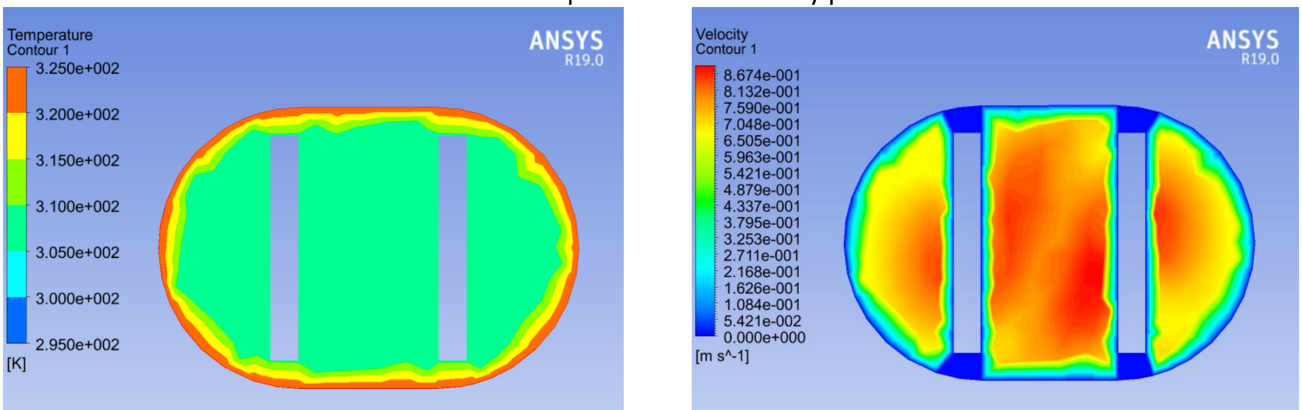
Figure 8 Heat transfer coefficient with Renold Number (Nano fluid)

Illustrates the temperature contours and velocity profiles at the output sections of tubes. The data presented in this figure is beneficial for the thermal design of tubes employed in many industrial applications.

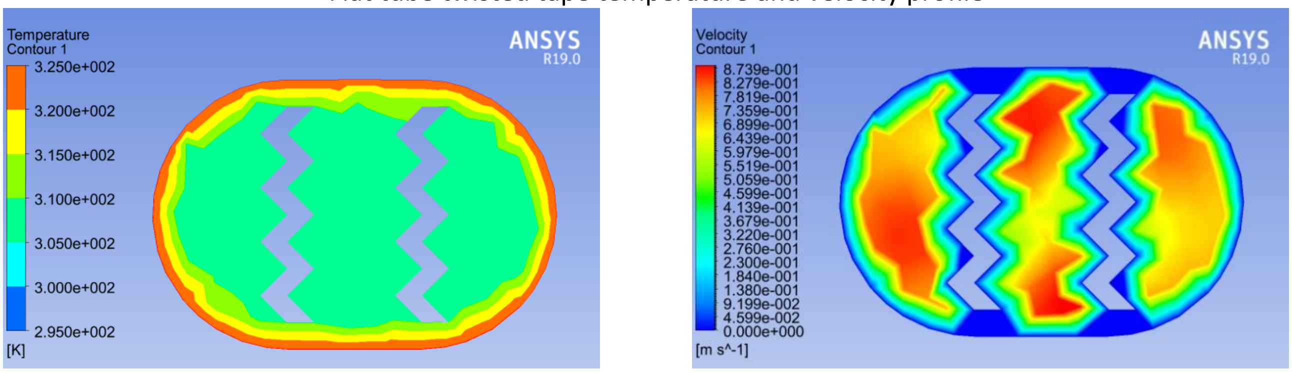
This study indicates that each method enhancing heat transfer performance and elevates the friction factor, hence resulting in increased pressure drop within the tubes. Consequently, by multi-objective optimization, the optimal operating positions that fulfill both heat transfer and friction factor criteria may be identified.



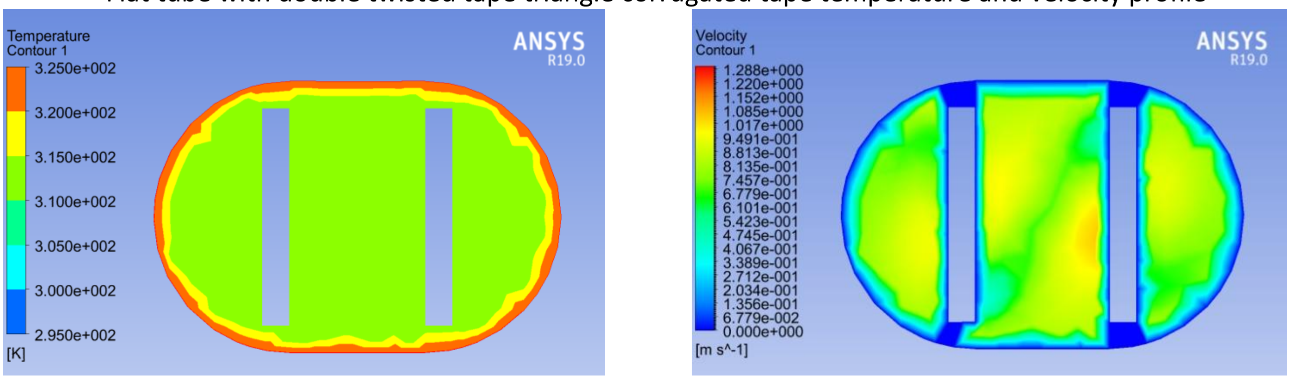
Flat tube temperature and velocity profile



Flat tube twisted tape temperature and velocity profile

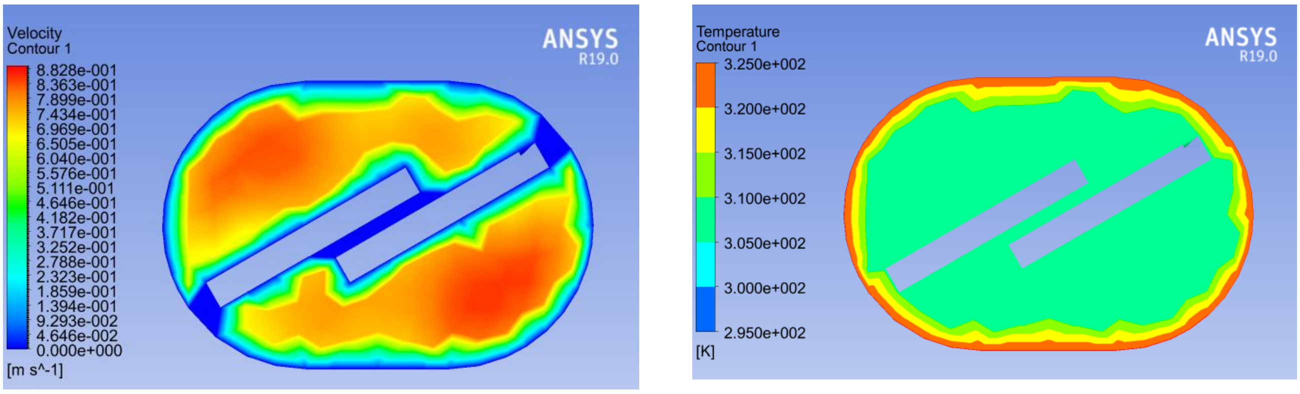


Flat tube with double twisted tape triangle corrugated tape temperature and velocity profile

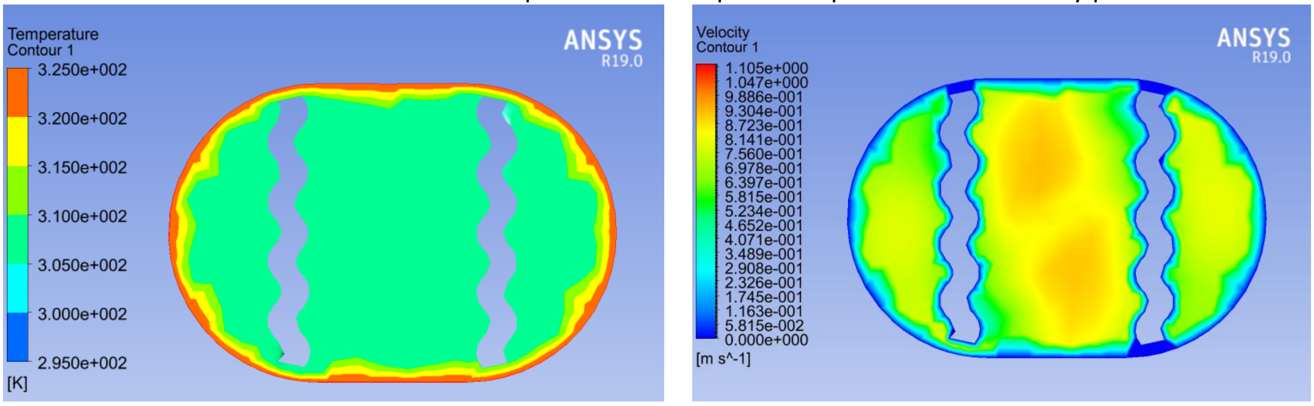


Flat tube with double twisted tape 25 mm twist pitch temperature and velocity profile

Fig. 9 Temperature and velocity profile for all models.



Flat tube with double twisted tape 75 mm twist pitch temperature and velocity profile



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Flat tube with twisted tape circular corrugated tape temperature and velocity profile

Fig. 10 Continue

8. Conclusion

This study was conducted to study the effect of the twisted plat in micro fin tube with working Nano fluid SiC/water. This study will assess sex distinct arrangements of twisted tapes, which include model 1flat tube only, model 2 double twisted tape with 50 mm twist pitch, model 3 double twisted tape 75 mm twist pitch, model 4 double twisted tape 25 mm twist pitch, model 5 double twisted tape triangle corrugated tape and model 6 double twisted tape circular corrugated tape, all tape with same direction twist. The number of the element (4763594) is used as the best for the exactness and computational time.

Models operate. Flow calculations also showed that both models were running. Show a significant improvement over other models in the capture process Behavior of friction factor. The turbulence models of the SST k–Epsilon are valid within 8.23 % error limit with Nusselt number measurements. In addition, 8.71% for the RNG K- Epsilon error with Nusselt number.

In fact, the use model 4 (double twisted tape 25 mm twist pitch) increases the Nusselt number by 44 % and the use model 5 (double twisted tape triangle corrugated tape) increases the Nusselt number by 38% compared to the use of flat tube with no tapes inside and containing a water working fluid, but the friction factor for model 4 very higher compere with model 5 with water and nano fluid working fluids .

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