



The Performance of Compact Heat Exchangers in Different Configurations Utilising MWCNT/H₂O Nanofluid: A Numerical Study

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ABSTRACT

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Recently, nanofluids have been extensively investigated for enhance heat transfer in heat exchangers. Many enhancements have been incorporated into heat exchangers to improve hydraulic and thermal performance, including nanofluids and rib profiles. However, none of them have adopted rib configurations with multi-walled carbon nanotube (MWCNT) nanofluids due to the design complexity. Therefore, the aim of this study is to assess the thermal and hydraulic influences of a smooth pipe shell and helical coil heat exchanger (SHCHE) with various concentrations (1%, 3%, and 6%) of MWCNT nanoparticles at Dean number (De) ranging from 4000 to 9000 using a single-phase model. Also, the study includes analysing the impact of the highest ratio, 6% MWCNT-based water nanofluid, on the behaviour of three- and four-head ribs SCHCE and compares the results with circular geometry under similar conditions. The findings revealed that increasing volume concentrations results in enhancing the Nusselt number (Nu) and the performance evaluation criterion (PEC). The average Nusselt number (Nu_{av}) enhancements were 7.1%, 14.6%, and 28.5% at (1%, 3%, and 6%) MWCNT/H₂O nanofluid in the smooth coil heat exchanger, respectively. However, the highest attainable heat transfer was recorded as 41.4% and 34.9% at 6% MWCNT-based water for three and four head ribs of SCHCE, respectively. Notably, the highest attainable PEC of the employed nanofluid is 1.380, which belongs to the 6% volume concentration, $De = 4342$, and flowing through the three head ribs of SCHCE. It was revealed that the heat transfer rate enhances when the number of ribbed heads is reduced; therefore, the nanoadditive fraction of 6% with three ribs tends to be the best option for the designers in giving the optimal heat transfer enhancement.

1. INTRODUCTION

A heat exchanger is a specialized thermal device designed to enable efficient heat transfer across various industrial applications. The most important part is the configuration of the tubes, which are carefully coiled into a smooth, tight structure. This helical structure makes heat transfer more efficient by causing fluid turbulence, which helps with mixing, and by maximizing the surface area accessible for heat exchange. Using helical coil configurations in heat exchangers is exceptionally helpful since they boost heat transfer and take up less space than straight tube configurations [1]. The Dean number (De) quantifies the intensity of the secondary flow in curved tubes [2, 3].

For more than a decade, research on the applications of nanomaterials has been gaining traction among scientists. In 1995, a novel category of classic heat transfer fluids was presented, containing suspended nanoparticles ranging from 1 to 100 nm in size inside the base fluids [4]. Using nanofluids in coil heat exchangers could save energy, reduce operating

costs, and improve the performance of the system. Nevertheless, difficulties including nanoparticle stability, erosion of heat exchanger surfaces, and cost-effectiveness need to be fixed in order to secure widespread adoption. Shirejini et al. [5] observed a 10.3% increase in the heat transfer rate following the incorporation of Al₂O₃ nanoparticles into the base fluid. Wu et al. [6] found that the Nusselt number (Nu) increases with a corresponding rise in alumina nanoparticle concentration. Under turbulent flow, Fotukian and Esfahany [7] documented an improvement in the hydrodynamic and thermal properties of nanofluids by around 20% and 25%, respectively.

Numerous investigations have shown that nanofluids can greatly improve heat transfer in heat exchangers. Initiatives are being implemented to reduce the costs related to the production of highly efficient heat exchangers. Bouselsal et al. [8] investigated innovations in tube and shell heat exchangers by modifications in tube designs and the incorporation of nanoparticles. The research shows that employing of 2% Al₂O₃-multi-walled carbon nanotube (MWCNT) nanofluid

with high flow rates improves heat transfer efficiency by 103.07%. Suresh et al. [9] examined the heat transfer and friction factor (f) for both smooth and helical surfaces using CuO/water nanofluid. The heat transfer rate increases at high volume concentration. Wang et al. [10] studied the thermal properties of CNT/water nanofluids in a horizontal smooth tube. They found that the improvement in average Nusselt number ($Nu_{av.}$) rises with the augmentation of nanoparticle concentrations. Similarly, Kumar et al. [11] reported that rising heat transfer coefficients and pressure drop (ΔP) were augmented by an increase in Al_2O_3 particle concentration through a helical tube.

Kahani et al. [12] studied the influence of MWCNT/ H_2O nanofluid inside a helical tube. The highest Nu can be reached by changing the curvature ratio only a little and making the pitch spacing bigger. Jassim et al. [13] examined the impact of a swirl generator on the hydro-thermal efficiency of a double helical tube. Results demonstrated that better thermal performance is achieved with a smaller swirl generator.

Geometrical change represents a highly effective method for improving thermal performance. Hasan et al. [14] conducted a computational analysis on the efficiency of a helical heat exchanger utilizing (Al_2O_3 , CuO, SiO_2 , and ZnO)/ H_2O nanofluids, examining several head rib designs with distinct coil revolutions. The helical tube with two head ribs and thirty coil revolutions was found effective for all tested nanofluids. Using two rib head geometries enhanced the performance by 20%–80%, and by 17%–66% utilizing thirty coil revolutions. Xu et al. [15] found that the 4-head rib tube improved the performance by 5%–35% compared to the plain tube. Likewise, Pourhedayat et al. [16] studied the hydrothermal properties of a helical tube made of spring wire. It was discovered that an increase in wire diameter corresponds to an increase in friction. Also, the exergy destruction decreased as the wire diameter increased. Luo et al. [17] concluded that employing the helical corrugation increased the performance by 19%.

Vahidifar and Kahrom [18] conducted an experimental investigation on the augmentation of heat transfer in a twin tube heat exchanger utilizing an insert composed of wire and rings. Employing wire coils and rings to augment the heat transfer ratio resulted in an increase of 2.30 to 2.40 for rings, compared to the absence of inserts, yielding an overall performance of 128.0% in the ring insert. Prabhanjan et al. [19] examined the performance rate of helical and smooth tubes, finding a superior performance in the helical tube relative to the smooth tube. Wu et al. [6] noted a 0.37% to 3.43% enhancement in the performance for Al_2O_3/H_2O nanofluid relative to the conventional fluid in the helical heat exchanger. Chen et al. [20] evaluated the heat transfer performance of a corrugated helical tube. They found that the f increases substantially with the corrugation geometry. Moradi et al. [21] conducted an experimental evaluation of the heat and entropy in a vertical helical tube. The outcomes indicate that the flow system enhances the performance by 35% and boosts entropy generation by 26%. Gao et al. [22] examined the thermal performance of a heat recovery system featuring a spring blade while altering the Reynolds number (Re). Results indicated that employing the mixed spring-blade resulted in increased performance by 35% to 45% compared to the insets standalone. The ΔP also increased markedly as the performance evaluation criterion (PEC) increased.

Based on the aforementioned literature survey, it is observed that many studies have attempted to enhance the

hydrothermal performance by incorporating nanofluids, rib profiles, etc. Therefore, the present study concentrated on a detailed analysis of heat transfer and ΔP in shell and helical coil heat exchangers (SHCHE), taking into account various head rib geometries (three and four ribs), and using MWCNT/water nanofluids as the target fluid. The rib design geometry and nanoparticle concentrations enhance heat transfer by promoting fluid mixing. This research will also provide benefits to heat transfer, nanofluids, process industries, and other related fields. The effective heat exchanger can be used in industries to save power consumption because it works better than traditional heat exchangers.

2. PHYSICAL MODEL

A nanofluid with spherical nanoparticles and 6% water-based MWCNT flows through the SHCHE. Figure 1 represents a diagram of the SHCHE. The coil has a hydraulic diameter (d_c) of 8 mm, 28 turns, and a pitch of 12 mm. The present study was performed by selecting three distinct cross-sectional geometries: circular, three-rib, and four-rib profiles, as depicted in Figure 2, with their appropriate dimensions. Table 1 shows the characteristics of MWCNT and water. The helical coil tube's wall experiences a constant flow rate, characterized by a De of 4704 along the shell, with fully developed flow. The nanoparticles are anticipated to achieve a uniform dispersion (single phase) in water. The inlet temperature on the coil tube side is set at 80 °C, while the shell side maintains an inlet temperature of 27 °C. The flow on the coil side is modified with De ranging from 4000 to 9000, whereas the shell side flow remains at a steady velocity of 0.5 m/s. The tube wall is kept at a consistent temperature throughout. A counterflow configuration is established between the shell and coil sides.

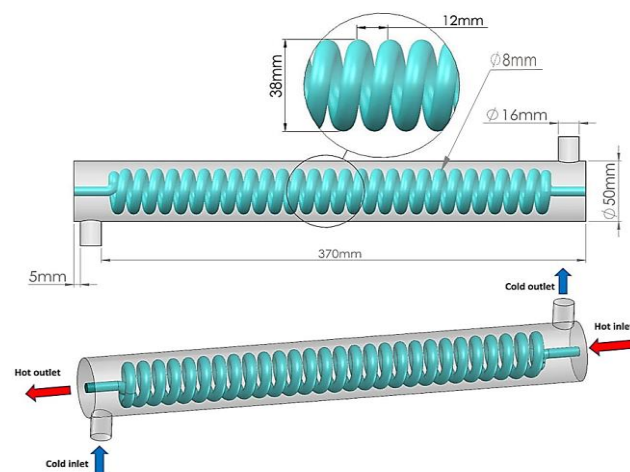


Figure 1. Schematic diagram of the physical model for shell and helical coil heat exchanger (SHCHE)

Table 1. Thermophysical properties of H_2O and multi-walled carbon nanotube (MWCNT) [23-26]

Properties	H_2O	MWCNT
Density ($kg \cdot m^{-3}$)	997	2100
Specific heat ($J \cdot kg^{-1} \cdot K^{-1}$)	4180	711
Thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)	0.607	3000
Dynamic viscosity ($kg \cdot m^{-1} \cdot s^{-1}$)	0.000891	---

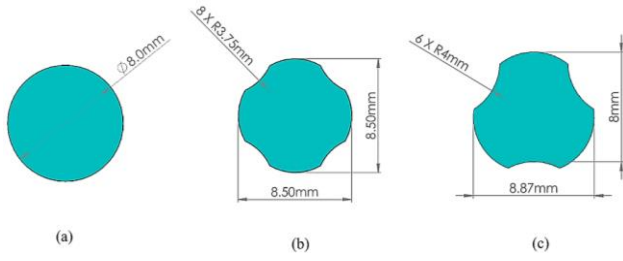


Figure 2. The cross-section, (a) circular, (b) four ribs, and (c) three ribs

3. MATHEMATICAL EQUATIONS

The precision of the single-phase model is predominantly contingent upon the exact evaluation of the thermo-physical properties of nanofluids. The mixture is thought to be homogeneous, with very little slip movement between the pure fluid and the particles. The liquid and nanoparticles are in a state of hydrodynamic and thermal equilibrium, which means that there is very little exchange of momentum and interactions between the two phases. It has been suggested to use a single-phase model since it is accurate enough and costs less to compute for moderate concentrations of nanoparticles [27]. The governing equations are presented below:

Continuity equation:

$$\nabla \cdot (\rho_{nf} u_{nf}) = 0 \quad (1)$$

Momentum equation:

$$\nabla \cdot (\rho_{nf} u_{nf} u_{nf}) = -\nabla p + \nabla \cdot (\mu_{nf} \nabla u_{nf}) + \rho_{nf} g \quad (2)$$

Energy equation:

$$\nabla \cdot (\rho_{nf} c_{p,nf} u_{nf} T_{nf}) = \nabla \cdot (k_{nf} \nabla T_{nf}) \quad (3)$$

Other characteristics of nanofluids are expressed as:

Density:

$$\rho_{nf} = (1 - \sum \varphi_{np}) \rho_f + \sum \varphi_{np} \rho_{np} \quad (4)$$

Specific heat:

$$c_{p,nf} = \frac{(1 - \sum \varphi_{np})(\rho c_p)_f + \sum \varphi_{np}(\rho c_p)_{np}}{\rho_{nf}} \quad (5)$$

Viscosity:

$$\frac{\mu_{nf}}{\mu_f} = (1 - \sum \varphi_{np})^{-2.5} \quad (6)$$

Thermal conductivity:

$$\frac{k_{nf}}{k_f} = \frac{k_{np} + 2k_f - 2 \sum \varphi_{np} (k_f - k_{np})}{k_{np} + 2k_f + \sum \varphi_{np} (k_f - k_{np})} \quad (7)$$

The expression for the critical Re in the helical coil is as follows [28]:

$$Re_{cr} = 2100 \left[1 + 12 \sqrt{\frac{d}{D}} \right] \quad (8)$$

Furthermore, De is stated as follows [29]:

$$De = Re \sqrt{\frac{d}{D}} \quad (9)$$

where, $Re = \frac{\rho v d}{\mu}$.

The $(k-\varepsilon)$ model was utilised and presented in Eqs. (10) and (11). A number of comparative studies have indicated the stability and computational efficiency of this model; therefore, it was selected for the numerical calculations [30-33].

$$\nabla \cdot (\rho_m \nabla k) = \nabla \cdot \left(\frac{\mu_{t,m}}{\sigma_k} \nabla k \right) + G_m - \rho_m \varepsilon \quad (10)$$

$$\nabla \cdot (\rho_m \nabla \varepsilon) = \nabla \cdot \left(\frac{\mu_{t,m}}{\sigma_\varepsilon} \nabla \varepsilon \right) + \frac{\varepsilon}{k} (C_1 G_m - C_2 \rho_m \varepsilon) \quad (11)$$

where, $\mu_{t,m} = \rho_m C_\mu \frac{k^2}{\varepsilon}$, and the constants are $C_1 = 1.44$, $C_2 = 1.92$, $\sigma_\varepsilon = 1.3$ and $\sigma_k = 1.0$.

4. NUMERICAL DESCRIPTION AND GRID INDEPENDENCE

To determine the optimal mesh size, it is essential to understand that making the mesh finer produces a more accurate solution, but it also produces high computing costs and processing time. Thus, finding the best mesh means finding a compromise between accuracy and cost-effectiveness. The mesh in the present study is modeled through a 3D computational domain utilising the ANSYS Fluent program, as illustrated in Figure 3.

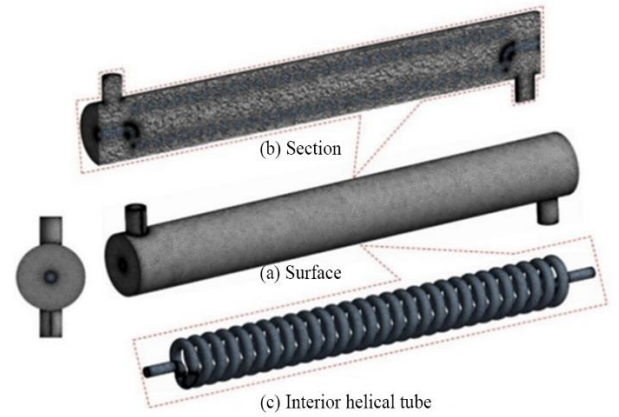


Figure 3. Mesh topology, (a) surface, (b) section, and (c) interior tube

A comprehensive tetrahedral grid is implemented across the entire model, as illustrated in Figure 3. Various grid sizes with different distinct resolutions are examined for the base fluid at ($De = 4342$) to ensure a grid-independent solution. The mesh sizes that were tested can be found in Table 2 for Nu_{av} and ΔP . The findings indicate that the estimated Nu_{av} and ΔP values remained largely unchanged when using fine and very fine meshes. The maximum variance for Nu_{av} and ΔP was less than 0.74% and 0.11%, respectively. The mesh independence study was meticulously assessed by examining the fluctuations in both Nu and ΔP across various grid levels, as illustrated in Figure 4. The choice of G-4 as the most suitable mesh is determined by the inflection point, indicating stability, beyond

which additional mesh refinement yields no substantial alterations in the results. Hence, Grid G-4 is used for all computations to maintain accuracy while minimizing computational cost and time.

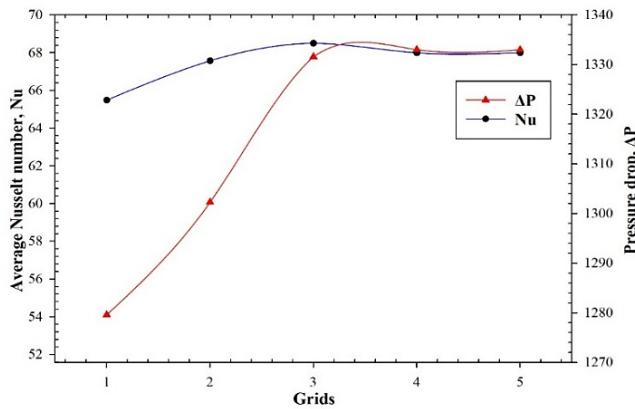


Figure 4. Grid test of pressure drop (ΔP) and Nusselt number (Nu)

Table 2. The impact of grid sizes on the average Nusselt number ($Nu_{av.}$) and pressure drop (ΔP)

Type	Number of Elements	$Nu_{av.}$	ΔP (Pa)
Coarse (G-1)	576087	65.50	1279.71
Medium (G-2)	1922180	67.58	1302.37
Fine (G-3)	4042546	68.51	1331.60
Very Fine (G-4)	4402028	68.00	1333.03
Extremely Fine (G-5)	6450135	68.00	1333.01

5. RESULTS AND DISCUSSION

In the following section, the effects of geometrical variations were assessed and compared with the findings of previous researchers. The present study was performed on a 6% MWCNT/H₂O nanofluid in a SHCHE for various cross sections (circular, 3 ribs, and 4 ribs), with De varying from 4000 to 9000.

5.1 Validation

The numerical findings from this study were validated through comparisons with the numerical simulations and experimental data of previously published research. Thereby, Nu values with various De were validated against the experimental study conducted by Chen et al. [20] and Tuncer et al. [34] and with the numerical correlations of Shchukin [35] for the turbulent flow, as illustrated in Figure 5. It can be noticed that the computed values of the Nusselt number (Nu) for water align with the predictions of the above-mentioned studies, indicating a maximum relative variance of less than $\pm 7.0\%$. Meanwhile, the f across various De is validated against the correlations of Ito [36], Srinivasan et al. [37], and Mishra and Gupta [38] as presented in Figure 6. The findings indicate robust alignment with previous correlations, with a maximum deviation of about $\pm 2.87\%$. This agreement validates the computational methodology utilized in the current work and supports its applicability for further investigation of heat transfer and flow characteristics.

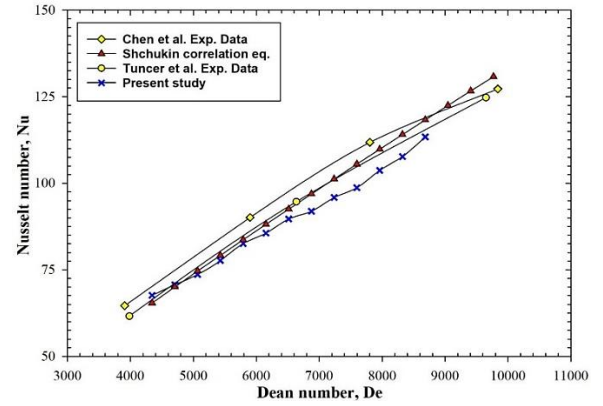


Figure 5. Validation of the Nusselt number (Nu) with experimental studies

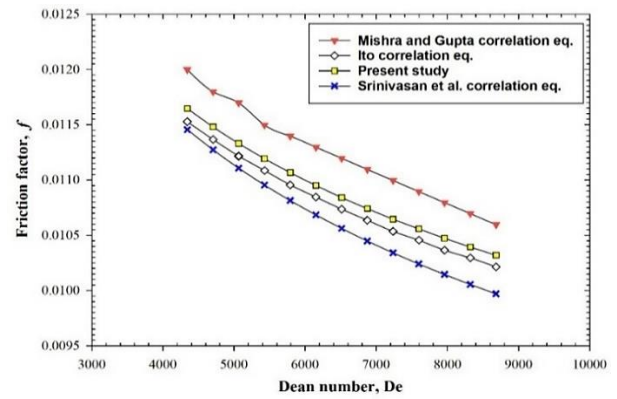


Figure 6. Validation of the friction factor (f) with experimental correlation studies

•Shchukin [35] correlation:

$$Nu = 0.0316 Re^{0.8} Pr^{0.4} \left(\frac{d}{D}\right)^{0.05} \quad \text{for } 0.63 < Re \left(\frac{d}{D}\right)^2 < 20 \quad (12)$$

$$Nu = 0.0266 Re^{0.85} Pr^{0.4} \left(\frac{d}{D}\right)^{0.15} \quad \text{for } 20 < Re \left(\frac{d}{D}\right)^2 < 700$$

•Ito correlation [36]:

$$f = 0.076 Re^{-0.25} + 0.00725 \left(\frac{d}{D}\right)^{0.5} \quad (13)$$

•Srinivasan et al. [37] correlation:

$$f = \frac{0.084 \left(\frac{d}{D}\right)^{0.2}}{De^{0.2}} \quad (14)$$

•Mishra and Gupta [38] correlation:

$$f = 0.0791 Re^{-1/4} + 0.0075 \sqrt{\frac{d}{D}} \quad (15)$$

5.2 Thermal and hydrodynamic characteristics

The impact of adding the nanoparticles was studied and

depicted in Figure 7, which shows the findings of the Nu of (1%, 3%, and 6%) MWCNT/H₂O nanofluid employing a single-phase model through the coil heat exchanger at De ranging from 4000-9000. The average enhancement in Nu was observed as (7.1%, 14.6%, and 28.5%) at volume fractions (1%, 3%, and 6%), respectively, along the considered circular pipe of SHCHE. It can be seen that Nu is overestimated at $\phi = 6\%$. The main reasons for enhancing Nu could be attributed to the improved efficiency of heat transfer and the thermal conductivity of MWCNT-H₂O nanofluids. Furthermore, the chaotic motion of MWCNT nanoparticles is predicted to enhance heat transfer and increase turbulence intensity due to the adoption of effective properties and the flow field, thereby improving overall heat transfer [4, 30, 34].

Figure 8 represents the outcomes of the Nu of 6% MWCNT/H₂O nanofluid employing various geometries of SHCHE. The average improvement in Nu was observed as (28.5%, 41.4%, and 34.9%) along the circular, three-head ribs, and four-head ribbed pipes of SHCHE, respectively. Implementing a ribbed geometry is highly significant for increasing the heat transfer rate of helical pipes [15], which is in agreement with the results of the current study. Curvatures in the ribbed profile boost mixing in the SHCHE. Curvature increases mixing, which augments heat dissipation. Three-head ribs have the largest Nu compared to circular and four-head ribs. Smaller rib head numbers mean greater Nu for helical heat exchangers.

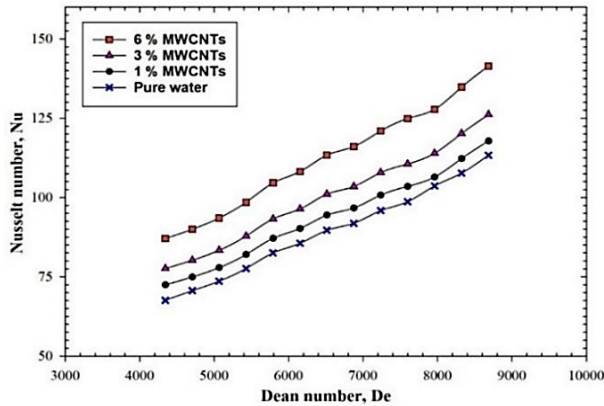


Figure 7. Average Nusselt number (Nu_{av}) of water and multi-walled carbon nanotube (MWCNT)/H₂O nanofluid at ϕ (1%, 3%, and 6%) versus Dean number (De)

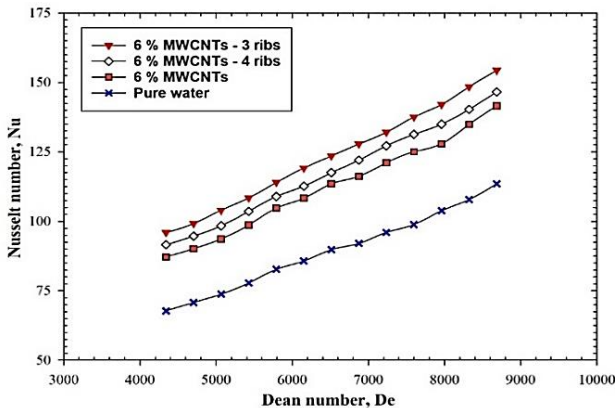


Figure 8. Average Nusselt number (Nu_{av}) of water and multi-walled carbon nanotube (MWCNT)/H₂O nanofluid at ϕ (6%) with circular, three, and four ribs versus Dean number (De)

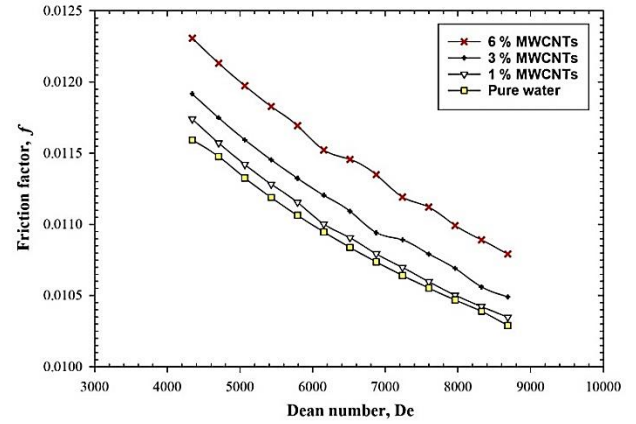


Figure 9. Friction factor (f) of water and multi-walled carbon nanotubes (MWCNT)/H₂O nanofluid at ϕ (1%, 3%, and 6%) versus Dean number (De)

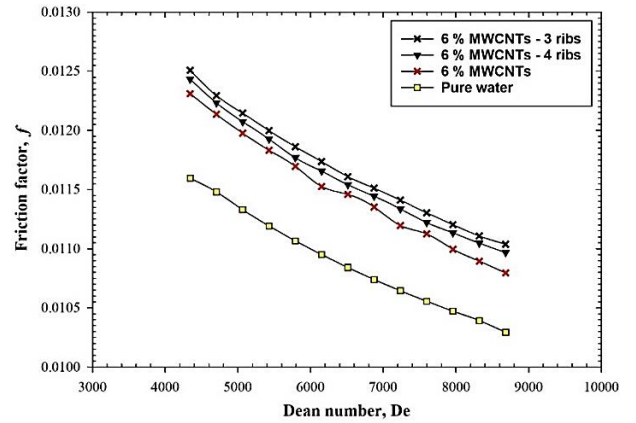


Figure 10. Friction factor (f) of water and multi-walled carbon nanotube (MWCNT)/H₂O nanofluid at ϕ (6%) with circular, four, and three ribs versus Dean number (De)

Greater energy consumption is required for pumping when there is increased pressure loss. Hence, to improve heat transfer, it is vital to consider pressure loss because it significantly influences the efficiency of SHCHE [13]. Figure 9 displays the predicted f values along the coil heat exchanger at De (4000-9000). Also, Figure 10 illustrates the variation of f for a 6% concentration with three configurations: three head ribs, four head ribs, and a smooth tube. The outcomes indicate that f rises with increasing volume fractions and decreases as De rises throughout the employed SHCHE. This trend arises from a slight rise in the viscosity ratio and the thinness of the small velocity boundary layer [39]. Moreover, the maximum penalty of f values for MWCNT nanofluid in circular geometry was 0.82%, 2.4%, and 5.7% at concentrations of 1%, 3%, and 6%, respectively. From Figure 10, it was observed that the highest values of f at 6% MWCNT-based water nanofluid were (5.7%, 7.5%, and 6.7%) for smooth, three- and four-head ribs of SHCHE, respectively. The observation reveals that f is significantly increased because of the influence of turn areas, resulting in a ΔP that subsequently raises the consumption of pumping power [2, 40, 41].

Figure 11 depicts the velocity vectors at 6% and De (4704) velocity vector of turbulence strength, indicating that the velocity vector of turbulence strength is increased in the turn regions due to eddy formation. This phenomenon boosts the thermal performance, as centrifugal forces lead to a great velocity gradient near the curvature of the coil wall. The eddy

formation in the recirculation areas is considered a crucial merit of the coil structure in comparison to the traditional one

in improving heat transfer.

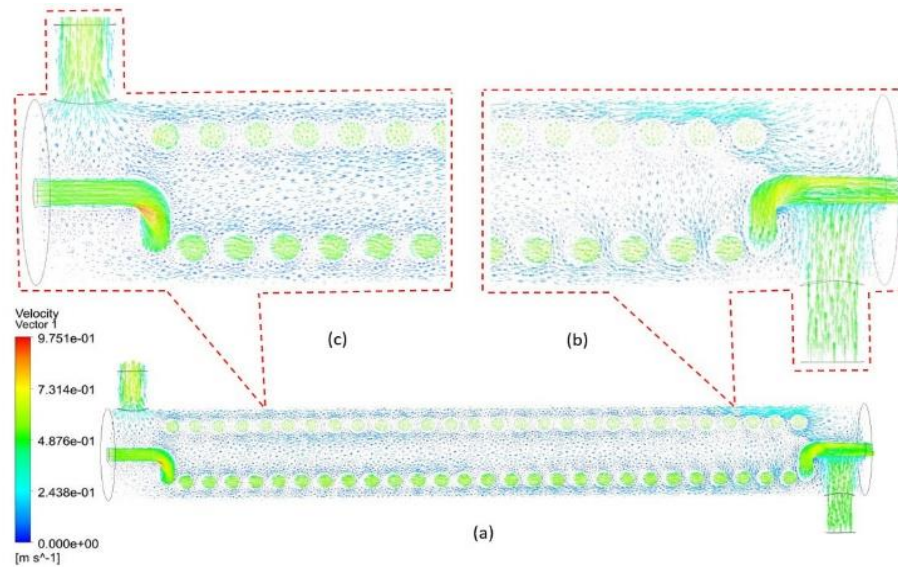


Figure 11. Velocity vector for multi-walled carbon nanotube (MWCNT)/H₂O nanofluid at ϕ (6%) and Dean number (De) (4704), (a) longitudinal section, (b) inlet shell cold side, (c) outlet shell cold side

5.3 Temperature contour

The longitudinal sections of temperature contours are illustrated in Figure 12, which presents the thermal behavior of SHCHE using 6% MWCNT nanofluid and $De = 8684$. At the inlet Figure 12(a), a highly non-uniform temperature distribution, with more intense temperatures at the top than at the bottom. This reveals that thermal boundary layers are starting to emerge and that coil curvature is causing flow effects that are not symmetrical. In the middle section of Figure 12(b), the temperature contour becomes more homogenized at the top and bottom regions. This indicates strong secondary flow due to the enhanced mixing. At the outlet part in Figure 12(c), the distribution of temperature becomes almost uniform, reflecting the effective dissipation of

heat along the coil length [42-45].

The temperature contours of four head ribs for MWCNT volume fraction at $\phi = 6\%$ and $De = 8684$ are illustrated in Figure 13. At the inlet Figure 13(a), the temperature distribution is not uniform, with higher temperatures concentrated near the top. This reveals the impact of secondary flow in curvature zones on the production of thermal boundary layers. In the middle area Figure 13(b), the ribs significantly elevate fluid mixing, resulting in higher temperatures through the top and bottom zones of the pipe than in the circular layout. This is because the ribs disturb the boundary layer and make Dean vortices stronger. The temperature distribution becomes almost uniform by the outlet section Figure 13(c), revealing effective heat dissipation and enhanced energy transfer.

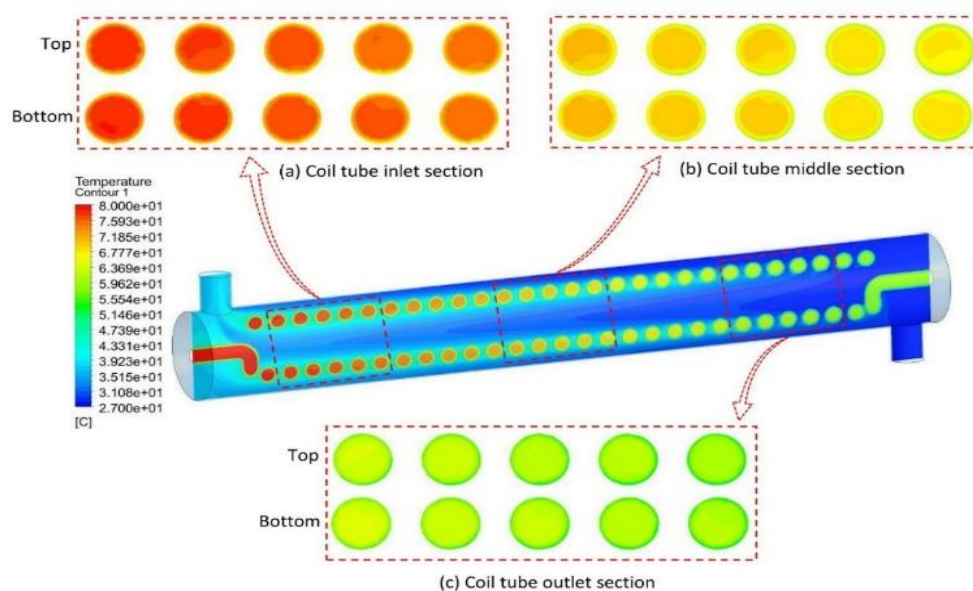


Figure 12. Temperature contours of the longitudinal section for shell and helical coil heat exchanger (SHCHE) of multi-walled carbon nanotube (MWCNT) volume fraction at $\phi = 6\%$ and Dean number (De) = 8684

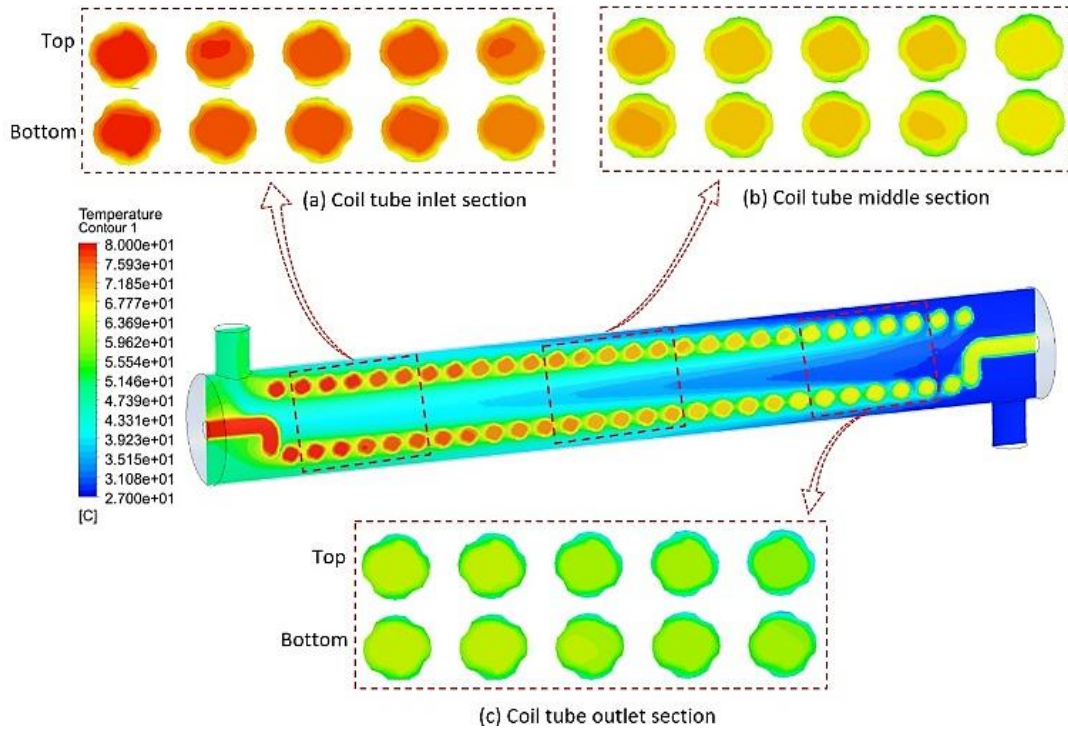


Figure 13. Temperature contours of four head ribs for multi-walled carbon nanotube (MWCNT) volume fraction at $\phi = 6\%$ and Dean number (De) = 8684

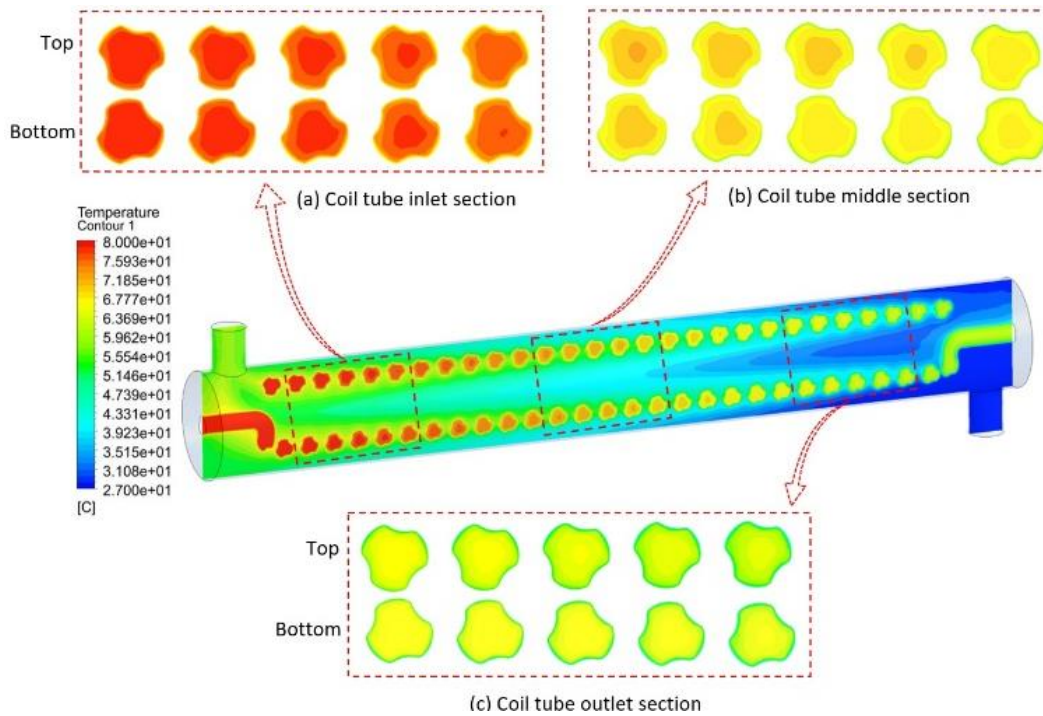


Figure 14. Temperature contours of three head ribs for multi-walled carbon nanotube (MWCNT) volume fraction at $\phi = 6\%$ and Dean number (De) = 8684

In Figure 14, the temperature contours of the three-head ribs in the SHCHE utilizing MWCNT nanofluid at a volume fraction of $\phi = 6\%$ and $De = 8684$ demonstrate a considerable improvement in thermal performance along the tube length. The temperature distribution at the outlet section in Figure 14(a) is clearly non-uniform, with high temperatures observed at the top. This indicates that secondary flow is generated due to the curvature configuration, resulting in the formation of thermal boundary layers. Moving to the middle Figure 14(b), the temperature distribution and mixing become higher than at

the inlet due to the three-head ribs' geometry. The outlet in Figure 14(c) shows a more uniform and less extreme temperature, indicating effective heat distribution.

When comparing the three configurations (smooth tube, three-head, and four-head ribs) at $\phi = 6\%$ and $De = 8684$, the three-rib layout reveals the best thermal performance. This is because the temperature is most evenly distributed along the length of the tube, especially in the middle and outlet areas, where thermal gradients are minimized more efficiently than in the other cases. The enhanced uniformity means that the

mixing is effective and the secondary flow is heightened because of rib-induced disturbances, which greatly disrupt the thermal boundary layer.

5.4 Performance evaluation criteria

PEC is an effective engineering method to assess the overall thermal efficiency of engineering systems, including heat exchangers, while incorporating enhancements like nanofluids or extended surfaces, and can be given by the following expression [46]:

$$PEC = \left(\frac{Nu_{nf}}{Nu_f} \right) \cdot \left(\frac{f_{nf}}{f_f} \right)^{-1/3} \quad (16)$$

Figure 15 demonstrates the influence of a 6% MWCNT-based water nanofluid on the PEC across various geometries of a coil heat exchanger (circular, three head ribs, and four head ribs) at De ranging from 4000 to 9000. PEC values decreased slightly with increasing De throughout the whole range. Overall, all three configurations exhibit higher PEC values, achieving the highest PEC at lower De . These were reported as (1.262, 1.380, and 1.320) for the circular, three ribs, and four ribs, respectively. The values of PEC then fluctuated slightly with increasing De . In contrast, the lowest values of PEC were reported at the highest De as (1.224, 1.329, and 1.264) for all tested configurations, respectively.

Hence, the findings reveal that the highest obtainable PEC of 6% MWCNT-based water nanofluid is 1.380 circulating within three ribs helical coil heat exchanger. Consequently, the incorporation of three head ribs in SHCHE appears to be the most favorable option for designers seeking to enhance heat transfer.

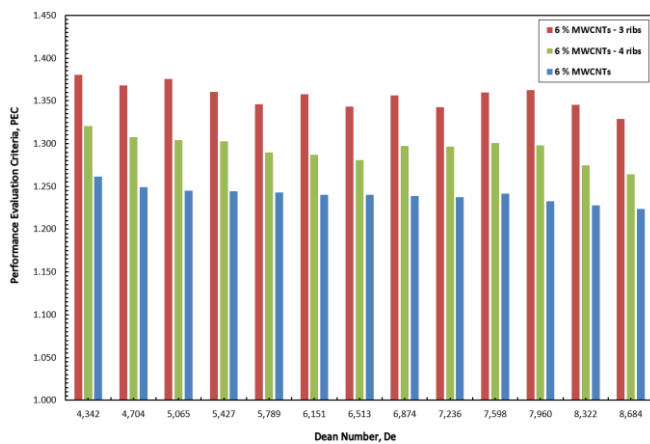


Figure 15. Performance evaluation criteria (PEC) of multi-walled carbon nanotube (MWCNT)-based water nanofluid at various volume fractions and Dean numbers (De)

6. CONCLUSION

This study numerically analyzes the geometrical effects on the thermal and hydrodynamic characteristics of turbulent flow conditions in a water nanofluid containing MWCNT flowing through a helical coil heat exchanger. The investigation was performed on circular, three- and four-head ribs of SHCHE utilising a single approach at a volume concentration range of ($1\% \leq \phi \leq 6\%$). The following outcomes were achieved:

- Augmenting the De improves Nu and reduces f throughout the tested SHCHE. The enhancement of Nu is notably more significant at $\phi = 6\%$, leading to an improvement in thermal efficiency.

- It was noticed that three head ribs enhance heat transfer better than other configurations, since the increment in heat transfer was recorded as 28.5%, 41.4%, and 34.9% for circular, three, and four head ribs, respectively.

- The three-head rib configuration shows the best thermal performance at $\phi = 6\%$ and $De = 8684$, revealing the lowest thermal gradients and the most uniform temperature distribution along the tube. This is because of the strong Dean vortices and the enhanced mixing, as well as the efficient disturbance of the thermal boundary compared with circular and four-head ribs SHCHE.

- The highest attainable PEC was recorded as 1.380, belonging to the 6% volume concentration, $De = 4342$, and flowing through three-head ribs SHCHE.

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NOMENCLATURE

<i>De</i>	Dean number
<i>D</i>	coil diameter (mm)
<i>d</i>	tube diameter (mm)
<i>g</i>	gravitational acceleration ($m \cdot s^{-2}$)
<i>m</i>	mass (kg)
<i>Pr</i>	Prandtl number
<i>P</i>	pressure ($Kg \cdot m^{-1} \cdot s^{-2}$)
<i>T</i>	temperature (K)
<i>u</i>	velocity ($m \cdot s^{-1}$)

Greek letters

ρ	density ($kg \cdot m^{-3}$)
φ	volume fraction (%)
μ	dynamic viscosity ($Kg \cdot m^{-1} \cdot s^{-1}$)

Subscripts

av.	average
<i>f</i>	base-fluid
<i>nf</i>	nanofluid
<i>np</i>	nanoparticle
<i>cr</i>	critical