

Computational Study of Heat Transfer Characteristics in Conical Spiral Tubes Under Turbulent Flow Conditions

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Abstract

The curved tubes have various engineering applications in various thermo-hydraulic systems. The detailed parametric thermo-hydraulic study of conical spiral tubes is a lesser explored domain. In the present study using the numerical simulation method, the heat transfer characteristics of conical spiral tube for the turbulent flow is studied. The influence of Reynolds number (in the range of 10^4 to 10^5) and of geometrical parameters such as cone taper angle and curvature of conical spiral tube on the local and total heat transfer is investigated. The CFD results show that the local circumferential and total coil heat transfer increased with the increase in cone taper angle and Reynolds number. The fully developed Nusselt number is found to be achieved by angular length of 210° from inlet plane in the coil.

Keywords: Conical spiral tube; Numerical simulation; Local Nusselt number; Circumferential heat transfer.

1 Introduction

The thermo-fluid characteristics of curved tubes is of relevance as it finds application in various thermo-hydraulic systems [1][2].

In a curved tube, due to the curvature of tube, a centrifugal force acts on the fluid particles thereby forming a secondary flow that is perpendicular to the main flow and has an impact on the flow and heat transfer characteristics of the curved tube [3]. The coil curvature significantly influences the heat transfer due to secondary flow. The curved tubes may be helical or conical spiral. In a conical spiral tube, the fluid flow and heat transfer should be influenced by the conical spiral tube's specific geometry of varying curvature from one end to the other. Rare literature on heat transfer characteristics of conical spiral tubes are reported in the literature.

Among the previous studies on curved tube, Mori and Nakayama [4][5] investigated the effect of curvature on heat transfer in curved tubes with a constant heat flux boundary condition, both theoretically and experimentally. Across a cross section, the velocity and temperature distributions were measured experimentally and a theoretical analysis of the temperature in the region of fully developed flow in a curved tube with uniform wall temperature boundary condition was undertaken. The study concluded that the secondary flow had a significant impact on heat transfer. Rogers and Mayhew [6] studied the heat transfer in helical coils and proposed correlations to predict the Nusselt number.

Xin and Ebadian [7] investigated the effects of Prandtl numbers and geometrical parameters on the local and average convective heat transfer characteristics in five helical tubes considering three different fluids- air, water, and ethylene glycol. The study concluded that in the turbulent flow regions, the peripheral wall temperature and relative Nusselt number variation increase as the Dean number (De) increases for low Prandtl number fluids (such as air), but decrease as the Dean number increases for higher Prandtl number fluids (such as water). The effects of torsion and coil orientation were not observed in the experimental range by the authors. The study proposed correlation for fully developed average Nusselt number in the turbulent regime covering the most practical application parameter ranges.

NOMENCLATURE

| | | |
|--------|---|----------------------|
| d | tube diameter ($2r$) | m |
| D | pitch circle diameter of tube curvature ($2R$) | m |
| De | Dean Number | |
| f | friction factor | |
| H | coil pitch | m |
| L | length of tube | m |
| N | number of coil turns | |
| Nu | Nusselt number | |
| P | pressure | Pa |
| Pr | Prandtl number | |
| Re | Reynolds number | |
| T | temperature | K |
| u | velocity in tube x -axis-direction | (ms^{-1}) |
| V | velocity of flow | (ms^{-1}) |
| v | velocity in y axis –direction | (ms^{-1}) |
| w | velocity in z -axis direction | (ms^{-1}) |
| χ | Dimensionless temperature Gradient $\left(\frac{T_w - T}{T_w - T_c}\right)$ | |

Greek letters

| | | |
|----------|---|--------------|
| δ | curvature ratio $[r/R]$ | |
| α | cone taper angle | $[^{\circ}]$ |
| θ | angular distance of a section from inlet | $[^{\circ}]$ |
| Φ | circumferential angle of a location in a tube section from inner most edge | $[^{\circ}]$ |

Subscripts

| | |
|------------|----------------------------------|
| <i>avg</i> | peripheral average |
| <i>B</i> | big end of conical spiral tube |
| <i>c</i> | centre of the tube cross-section |
| <i>C</i> | conical spiral tube |
| <i>H</i> | helical tube |
| <i>CS</i> | conical spiral tube |

Local

| | |
|----------|-----------|
| <i>m</i> | minimum |
| <i>w</i> | tube wall |

For a helical coil, Lin and Ebdian [8] used the FLUENT/UNS code as a solver to investigate the developing heat transfer for a definite pitch and constant wall temperature case. The study discovered that the peripheral variation of local Nusselt number was much steeper on the inner side than on the outer side at each cross section along the coil length. The magnitude difference in local Nusselt number between the outer and inner tube bend of the pipe grows as the flow proceeds downstream. Various parameters such as the pitch, curvature ratio, and Reynolds number all have an impact on the development of the turbulent thermal field.

Jayakumar et al. [9] presented the detailed characteristics of fluid flow and heat transfer inside a helical coil. The study revealed the variation of local Nusselt number along the length and the circumference at the wall of a helical tube. The CFD simulations were performed to study the influence of pitch circle diameter, tube pitch and tube diameter on heat transfer. Correlations to predict the Nusselt number were proposed for constant wall temperature as well as for constant heat flux boundary conditions. Also, correlations to predict the local values of Nusselt number as a function of angular location of the point were also presented for both the boundary conditions. Hardik et al. [10] experimentally investigated the local heat transfer coefficient in a helical coil with water as the working medium. The Nusselt number variation was observed to be sinusoidal along the circumferential direction and more uniform at outer circumference than that at inner circumference of the tube. Also an empirical correlation was proposed for total coil Nusselt number for fully developed flow with uniform wall heat flux conditions.

Among the studies related to conical spiral tubes include the work by Yan Ke et al. [11] which reported that there was a significant effect of cone taper angle and cross section on heat transfer while pitch had relatively little influence. The study also reported that for a given cross section area, the tube with circular cross-section performed with higher

heat transfer than elliptical cross section. Yan Ke. et al. [12] investigated the heat transfer and resistance characteristics of conical spiral tube bundle using regression analysis based on numerical simulation data. The study found that the effect of Reynolds number on heat transfer of conical spiral tube bundle was higher than conical degree in laminar flow; while the influence of the conical degree was larger in turbulence fluid flow. Saksena and Lakhera [13] [14] studied the pressure drop and heat transfer characteristics of conical spiral tube and found that heat transfer variation and pressure difference between inner and outer tube bend increased along with flow in conical spiral tube which was found to be influenced significantly by curvature and cone taper angle.

There have been relatively few studies related to the fluid flow and heat transfer in conical spiral tubes. The literature review concludes that further parametric studies are required to understand the thermo-hydraulic performance of conical spiral tubes. The present study aims to investigate the influence of Reynolds number and geometrical parameters such as cone taper angle, coil curvature on local and coil heat transfer for the turbulent flow of water in conical spiral tubes using the numerical simulation approach.

2 The numerical simulation approach

The temperature distribution in the tube section and the local Nusselt number across various cross sections along the coil length were numerically investigated in this study. In order to analyse the heat transfer characteristics in conical spiral tubes, the numerical modelling and simulation was undertaken using ANSYS Fluent.

2.1 Geometry of a conical spiral tube

The schematics of a conical spiral tube is shown in Fig. 1 wherein the tube diameter is $d (= 2r)$, the pitch circle radius at one end of the conical spiral tube is R_M which is the maximum value of curvature radius, while the pitch circle radius at the other end of the conical spiral tube is R_m , which is the lowest value of curvature radius [13] [14]. The axial distance between the two adjacent coil turns is defined as the coil pitch, H . In a conical spiral tube, the curvature ratio (δ) is defined as r/R , where R is the distance between the tube axis and the coil axis. The angle formed by a line passing through the centres of the cross-sections cut by a plane passing through the coil axis with the coil axis is considered as the cone taper angle (α). Thus, the cone angle of the conical spiral coil is 2α .

In order to investigate the effect of the cone taper angle and curvature ratio on heat transfer, seven different cases were numerically simulated. Table 1 provides the details related to parameters studied [13] [14].

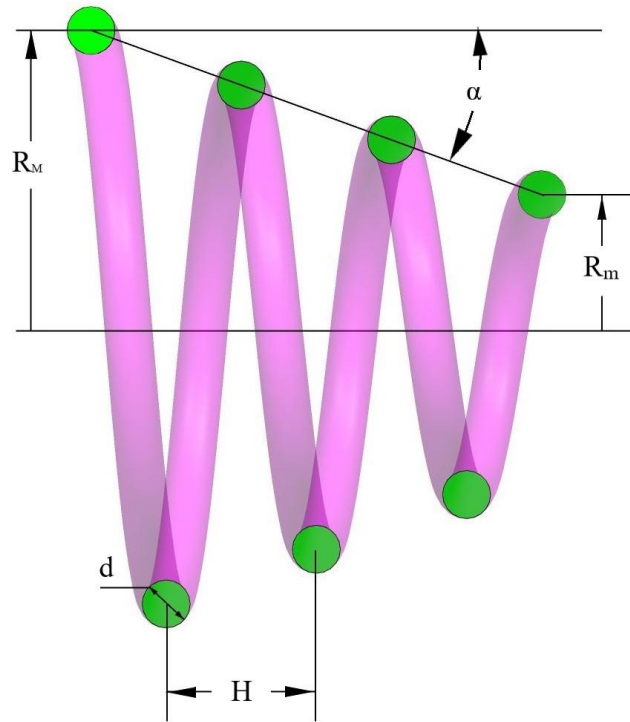


Figure 1. Various geometrical parameters related to a conical spiral coil tube.

Table 1: The various cases modelled for simulation study

| Case. No. | R_M (m) | r (m) | H (m) | α ($^\circ$) | N | δ_B |
|-----------|-----------|---------|---------|-----------------------|-----|------------|
| 1. | 0.20 | 0.01 | 0.03 | 30 | 2 | 0.05 |
| 2. | 0.15 | 0.01 | 0.03 | 10 | 2 | 0.067 |
| 3. | 0.15 | 0.01 | 0.03 | 20 | 2 | |
| 4. | 0.15 | 0.01 | 0.03 | 30 | 2 | |
| 5. | 0.15 | 0.01 | 0.03 | 40 | 2 | |
| 6. | 0.15 | 0.01 | 0.03 | 50 | 2 | |
| 7. | 0.15 | 0.01 | 0.03 | 60 | 2 | |

The location of cross-sections, considered for the present analysis, are identified by the angle (θ) which the plane of cross-section makes with the plane passing through the tube inlet at the big end of a conical spiral tube as shown in Fig. 2(a). A circumferential angle (Φ) around the periphery of a tube cross-section is designated and measured in an anticlockwise direction, as shown in Fig. 2(b). The closest point on the circumference of any cross-section of a conical spiral tube to the coil axis is designated as INNER ($\Phi = 0^\circ$), while the farthest point is designated as OUTER ($\Phi = 180^\circ$). RIGHT at $\Phi = 90^\circ$ and LEFT at $\Phi = 270^\circ$ are the other two significant locations on the circumference of the tube cross-section.

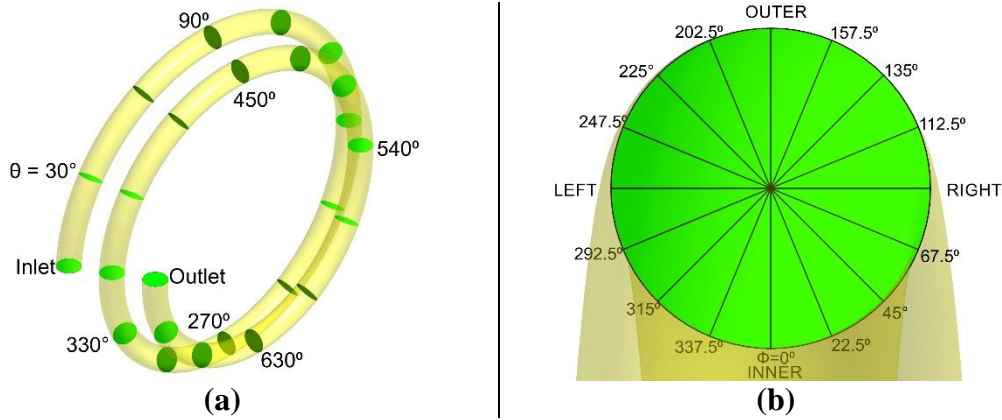


Figure 2: (a) Indication of the tube section's angle θ with respect to the inlet. (b) Designation of circumferential angle Φ in a tube cross-section.

2.2 The turbulence model and boundary conditions

The detail of governing equations can be seen in the earlier report [13] by the authors on pressure drop characteristics in conical spiral tubes. The geometries of the coils used for simulation study were modelled using the SolidWorks® modelling software. The (.IGS) files were imported to the ANSYS® FLUENT software and Cartesian system of coordinates was considered for the solution of numerical equations. The SIMPLEC scheme was used for the pressure and velocity coupling while QUICK scheme was considered for discretizing the momentum equation. The realizable k - ϵ turbulence model and the scalable wall functions were used in these computations [15]. The power-law scheme was used for discretizing the turbulent kinetic energy and dissipation rate. The convergence criterion used for continuity, velocities, k , and ϵ was $1.0e-5$. For the energy equation, third order QUICK discretization scheme was employed and the convergence criteria for energy balance was $1.0e-7$.

The fluid flowing through the conical spiral tube in the present numerical simulations was considered water and assumed to begin flowing at a temperature of 300K from the inlet and heats up as it passes through the coil with the constant tube wall temperature of 320K. Table 2 provides a summary of the boundary conditions considered for the study [13] [14].

Table 2: Boundary conditions for simulation.

| Field variable | Inlet | Wall | Outlet |
|----------------|---------------------------|---------------------------|---------------------------|
| U | 0.0 | 0.0 | $\partial u/\partial n=0$ |
| V | $0.5 - 5 \text{ ms}^{-1}$ | 0.0 | $\partial v/\partial n=0$ |
| W | 0.0 | 0.0 | $\partial w/\partial n=0$ |
| T | 300 K | 320 K | $\partial T/\partial n=0$ |
| P | $\partial P/\partial n=0$ | $\partial P/\partial n=0$ | $\partial P/\partial n=0$ |

2.3 The mesh and grid sensitivity analysis

The mesh was created using the meshing module of the ANSYS FLUENT package. In models of conical spiral tubes, the tube wall thickness was not considered and only the fluid control volume was modelled. A structured grid with seven layers of inflation and equal circumference divisions was taken into consideration in order to mesh the area close to the control volume's surface. Unstructured grid was taken into account at interior volume cells and along the length of the tube.

For a conical spiral tube with $\alpha = 30^\circ$, $R_M = 0.15$ m, and $r = 0.01$ m, various grid strategies were considered to check grid independence. Simulations runs with the boundary conditions listed in Table 2 for 1 m/s inlet velocity were undertaken. The percent deviation of $\Delta Nu = \frac{Nu_n - Nu_{n-1}}{Nu_{n-1}}$, between the successive grids, where n is the number of grid-strategy, was calculated and is presented in Fig. 3. For Grid no. 4 and 5, the percent deviation in the value of Nu between successive grids is less than one. Finally, Grid-5 was considered for the simulation study.

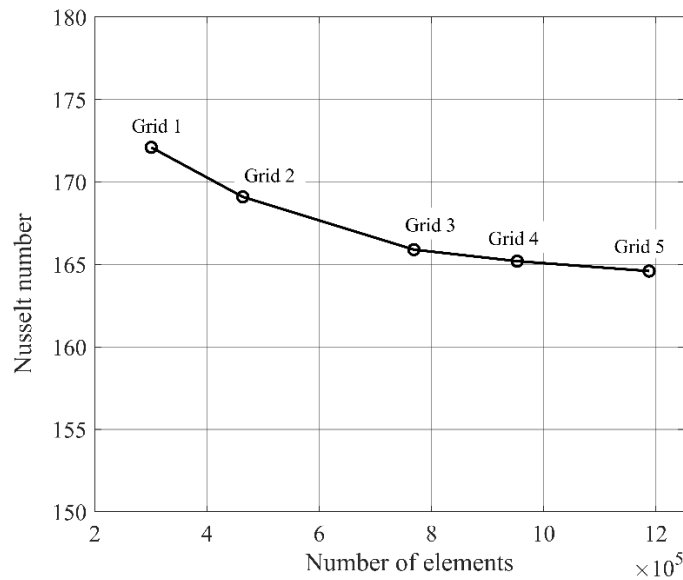


Figure 3. Grid independence check.

3 Results and discussion

The effect of cone taper angle (α) ranging from 10° to 60° , curvature radius R_M , and Reynolds number ranging from 10^4 to 10^5 on heat transfer are discussed. At the tube wall, the development of the local Nusselt number and the average Nusselt number were evaluated and analysed.

3.1 Heat transfer in conical spiral tubes

In conical spiral tubes with different α values ranging from 10° to 60° , Fig. 4(a) shows the Nusselt number (Nu_{CS}) values of conical spiral tubes at different Reynolds number

flows[14]. The excess over the values expected for a helical tube is one of the most prominent features of the coil average Nusselt numbers (Nu_{CS}) of conical spiral tubes, as shown in Fig. 4(a). With the same tube radius (r) and coil curvature radius (R_M), the Nusselt number value of a conical spiral tube with $\alpha \geq 20^\circ$ is found to be greater than that of a helical tube for the presented Reynolds number range. The values of Nusselt number is observed enhanced in the tubes with $\alpha > 20^\circ$. This is due to the increased value of δ along the tube length, which enhances the intensity of secondary flow due to increased centrifugal force. This phenomenon results in increased heat transfer in a conical spiral tube with a greater value of α . Fig. 4(b) presents the influence of coil curvature on Nusselt number in the two different conical spiral tubes with the same α . It can be observed from the figure that the coil with $R_M = 0.15$ m has greater value of Nusselt number than that for the coil with $R_M = 0.20$ m for the entire range of Reynolds number presented. Nusselt number is found to be enhanced with increase in curvature ($\delta = r/R$) by 6 – 8 % for $Re \geq 20000$. Hence, it is established that heat transfer is enhanced with an increase in the curvature ratio ($\delta = r/R$) of the conical spiral tube.

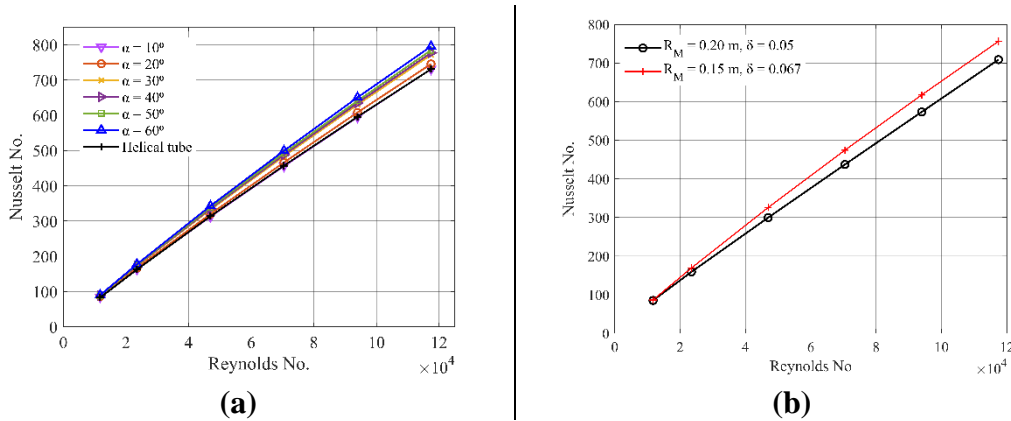


Figure 4: (a) Nusselt number in conical spiral tubes with different values of α . (b) Influence of curvature ratio on coil Nusselt number.

3.2 Heat transfer in a tube section

Fig. 5 presents the influence of α on Nu_θ/Nu_{CS} in a tube section at $\theta = 450^\circ$ of the conical spiral tubes with different α but same d and R_M . Fig. 5 shows that the value of Nu_θ/Nu_{CS} in the tube at identical θ ($= 450^\circ$) vary marginally with the α due to increases in δ . However, values of Nu_θ/Nu_{CS} can be observed quite similar at the section for various velocities conforming the preceding discussion. This is due to the fact that R decreases and hence, δ increases for the section at $\theta = 450^\circ$ in the tubes with greater value of α . However, it was observed that for the different value of δ of the corresponding tube section, the velocity at which Nu_θ/Nu_{CS} is maximum, is also different.

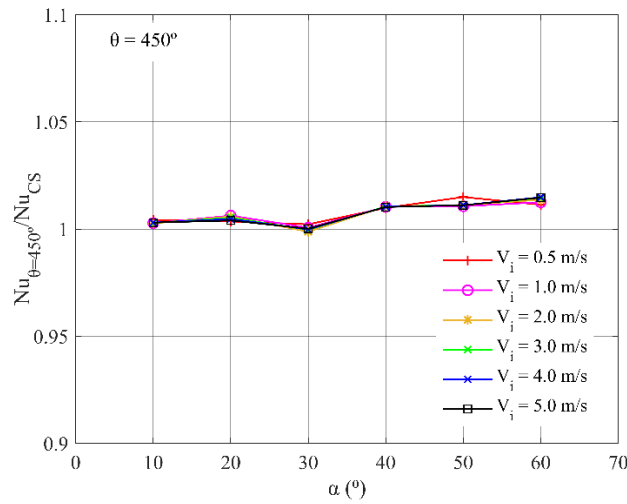


Figure 5. The influence of α on Nu_{θ}/Nu_{CS} in a tube cross-section (at $\theta = 450^\circ$).

Fig. 6 presents the influence of α on Nu_{θ}/Nu_{CS} in a cross-section at $\theta = 450^\circ$ of conical spiral tubes with same d and R_M . The results showed that for the given inlet velocity of the flow, variation of the value of Nu_{θ}/Nu_{CS} was observed to vary between 0.995 and 1.015 with the increase in α . A conical spiral tube with $\alpha = 30^\circ$ had the least value of Nu_{θ}/Nu_{CS} for the entire range of Reynolds number presented in Fig. 6. While coil with $\alpha = 60^\circ$ had the highest value of Nusselt number ratio for $Re > 20000$. This is due to the increased variation in the value of local curvature ratio in the tube axial direction of a conical spiral tube with the greater value of α .

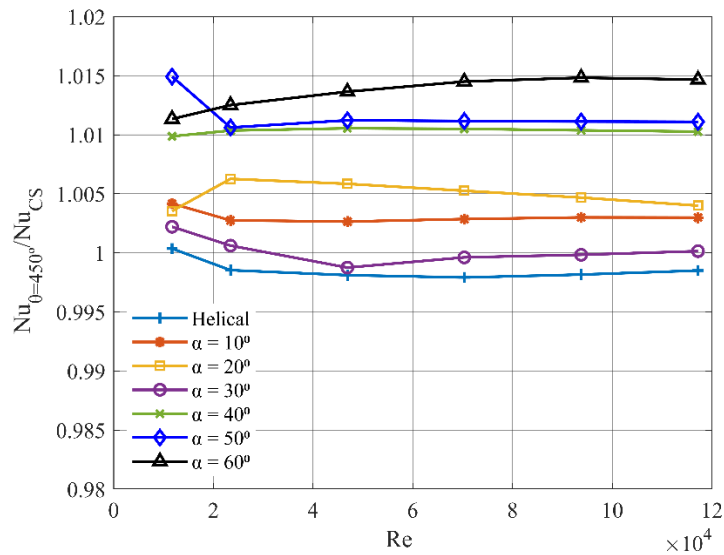


Figure 6. Influence of Re on $Nu_{\theta=450^\circ}/Nu_{CS}$ in a tube cross-section.

3.3 Development of local Nusselt number

The variation and development of the local Nusselt number at the circumference of the tube sections, as well as along with the flow, are shown in Fig. 7 (a and b). The Nusselt number was calculated using the local wall heat transfer coefficient values at different tube sections of a conical spiral tube with $R_M = 0.2$ m, $d = 0.02$ m, and $\alpha = 30^\circ$. The horizontal axis in each figure corresponds to circumferential angle (Φ) in degrees, while the vertical axis displays the ratio of local Nusselt number to total Nusselt number (Nu_ϕ/Nu_{CS}) values. The angular measurement (Φ) is as shown in Fig. 2(b). The growth of the Nu_ϕ around the circumference is depicted by selected sections at various angles (θ). The Nu_ϕ/Nu_{CS} profile has values less than unity up to the short length of the flow, up to the section at $\theta = 48^\circ$, in the tube. The highest value of Nu_ϕ/Nu_{CS} shifts from $\Phi = 225^\circ$ in the section at $\theta = 8^\circ$ to $\Phi = 180^\circ$ in the section at $\theta = 48^\circ$, i.e. OUTER, as the influence of centrifugal force becomes more dominant. In the downstream flow, the Nu_ϕ/Nu_{CS} curve develops to a fully developed curve with four shunts of enhanced Nu_ϕ/Nu_{CS} values by $\theta = 210^\circ$, as shown in Fig. 7(a). Because it has multiple minima and maxima values, the Nu_ϕ/Nu_{CS} curve for a conical spiral tube differs from that of a helical tube [7][8][9]. However, local Nusselt number profile in a tube section reported by Kalb and Seader [16] for higher Dean number in laminar flow in helical tube with $R/r = 20$ and $Pr = 5$ had profile with multiple local sinusoidal variation of values in the curve. The variation of Nu_ϕ/Nu_{CS} around the circumference is periodic from angle $\Phi = 50^\circ$ to angle $\Phi = 300^\circ$, with the highest peak at $\Phi = 180^\circ$. In the thermally fully developed region, i.e. flow beyond $\theta = 210^\circ$, the circumferential variation of Nu_ϕ/Nu_{CS} is much steeper on the inner than on the outer tube bend. Hardik et al. [10] observed local maximas and minimas on the Nu_ϕ/Nu_{CS} profile in the experimental results of helical coils. Nu_ϕ/Nu_{CS} values can be observed greater than one at the circumferential wall from angle range of $\Phi = 45^\circ$ to $\Phi = 315^\circ$ in the tube section till $\theta = 570^\circ$. The percentage of the circumference with a value of $Nu_\phi/Nu_{CS} > 1$ is predominant from section at $\theta = 72^\circ$ to $\theta = 570^\circ$ in Figs. 7(a and b), with a maximum value at $\Phi = 180^\circ$ (OUTER) in the section. In the downstream flow, the locations, at which the Nusselt number had lower value than $\Phi = 0^\circ$, were observed shifted up on the tube wall at $\Phi = 4.5^\circ$ and $\Phi = 351^\circ$, as shown in Fig. 11(a and b). Lin and Ebadian [8] had observed a similar shift of the location with lowest value of the Nusselt number for the helical tubes. The highest value of Nu_ϕ/Nu_{CS} shifts from location at $\Phi = 180^\circ$ to a location at $\Phi = 202.5^\circ$ on the outer circumference in the down stream flow by $\theta = 710^\circ$.

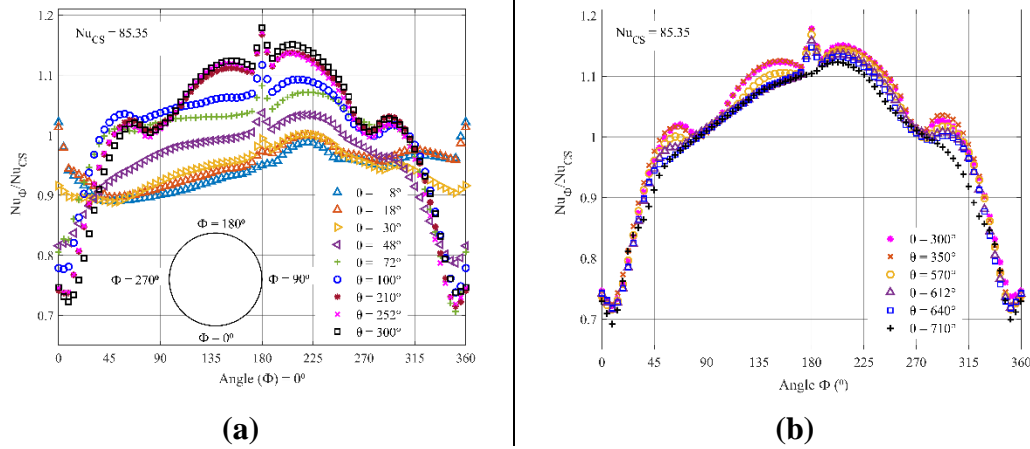


Figure 7: Variation of Nu_{ϕ}/Nu_{CS} around the circumference at various cross-sections of a conical spiral tube with $R_M = 0.2$ m, $d = 0.02$ m and $\alpha = 30^\circ$ for $V_i = 0.5$ m/s.

Fig. 8 presents the influence of α on local Nusselt number variation in a tube section at identical ($\theta = 450^\circ$). It can be observed that values of Nu_{ϕ}/Nu_{CS} marginally vary at the outer tube bend while steep variation was observed in the values at the inner tube bend. Also, the value of Nu_{ϕ}/Nu_{CS} was observed maximum at the outer side of the tube bend (i.e. $\Phi = 180^\circ$) for coils with $\alpha < 30^\circ$ while that for coils with $\alpha \geq 30^\circ$ was observed lesser than adjoining circumference on left and right side of $\Phi = 180^\circ$. However, peripheral average values of Nu_{ϕ}/Nu_{CS} in the tube section of different coils were observed to be unity ~ 1 . The value of Nu_{ϕ}/Nu_{CS} can be observed to vary between 0.6 to 1.2 as shown in Fig. 8. Thus, to develop a correlation to predict Nu_{ϕ}/Nu_{CS} for the coils with different cone taper angle (α), Φ can be considered as a variable.

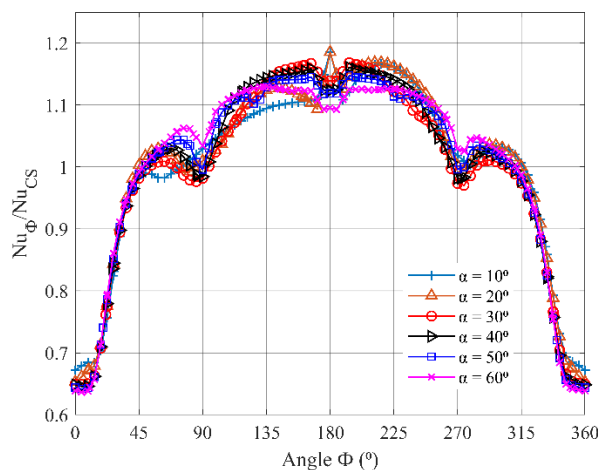


Figure 8: Influence of α on Nu_{ϕ}/Nu_{CS} in a tube section at $\theta = 450^\circ$ of a conical spiral tube with identical d and R_M .

Fig. 9 presents influence of Reynolds number on the local variation of Nu_{ϕ}/Nu_{CS} along the tube wall in a section. Fig. 9 shows that, excluding the small length of inner tube bend (left and right side of $\Phi = 0^{\circ}$), the value of Nu_{ϕ}/Nu_{CS} at a local point on the wall varies marginally with the increase in Reynolds number of the flow. It can be observed that value of Nu_{ϕ}/Nu_{CS} varies between 0.6 to 1.2. Excluding for the $V_i = 0.5$ m/s, Nu_{ϕ}/Nu_{CS} has quite similar value at locations with identical Φ , and hence, Nu_{ϕ}/Nu_{CS} -profiles are very much similar for various inlet flow velocities. Thus, to develop a correlation to predict Nu_{ϕ}/Nu_{CS} for different Reynolds number flows, Φ can be considered as a variable.

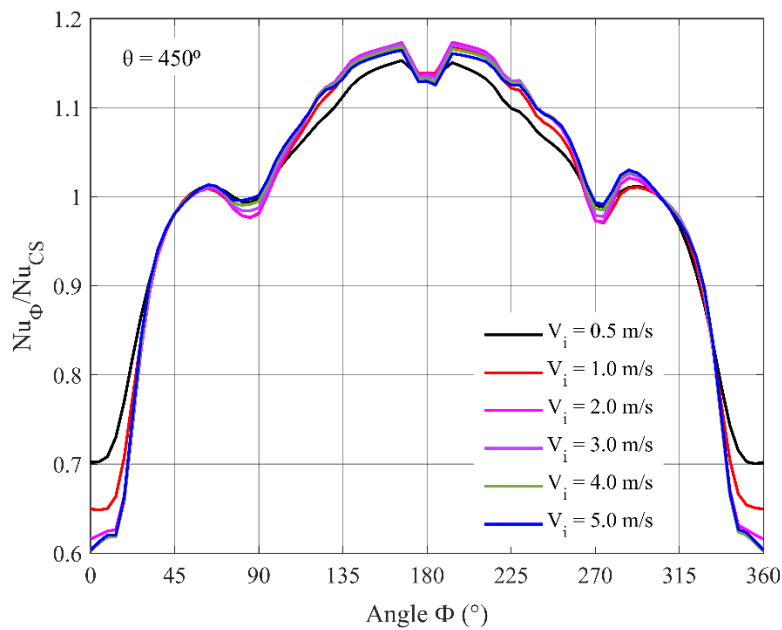


Figure 9: Influence of inlet velocity on Nu_{ϕ}/Nu_{CS} in a tube section of a conical spiral tube.

4. Conclusions

Numerical simulations were performed for studying the heat transfer in conical spiral tubes under turbulent flow conditions for various geometries. The local and total heat transfer characteristics were studied considering the influence of cone taper angle and Reynolds number. Based on the study conducted, the following are the major conclusions:

- The Nusselt number of a conical spiral tube is found to increase with cone taper angle for given Reynolds number due to enhanced intensity of secondary flow.
- When compared to a helical tube with the same tube diameter and curvature radius R_M , the Nusselt number of a conical spiral tube with $\alpha \geq 20^{\circ}$ is observed to have greater value of Nusselt number due to enhanced curvature variation along the tube length.

- The ratio of local Nusselt number in a section to coil Nusselt number (Nu_{θ}/Nu_{CS}) is found to be established (~ 1) by the angular length 210° of the coil. It varies negligibly in the fully developed region along the tube length although curvature varies in a conical spiral tube.
- It is found that in the fully developed region, the value of Nu_{θ}/Nu_{CS} at a section varies marginally along the tube length although the increase in cone taper angle and Reynolds number for given coil with maximum (R_M).
- The variation in the Nu_{ϕ}/Nu_{CS} is steep at the inner tube bend while it is more uniform at outer tube bend in the fully developed region. The value of Nu_{ϕ}/Nu_{CS} is more than unity at the circumference from $\Phi = 45^{\circ}$ to $\Phi = 315^{\circ}$, while it has steep variation between the range 0.7 to 1 for the rest of the circumference.
- The Nusselt number at the outer most edge ($\Phi = 180^{\circ}$) of the tube is revealed to decrease with the increase in cone taper angle of the tube.
- The relative variation in the circumferential Nusselt number (Nu_{ϕ}) is found to increase with Reynolds number, however the profile Nu_{ϕ}/Nu_{CS} curve remains nearly identical, excluding short length near the inner tube bend.
- The ratio of Nusselt number at a location on the tube wall to the Nusselt number of the coil (Nu_{ϕ}/Nu_{CS}) is found to vary between from 0.6 to 1.2 in any section in fully developed region and Reynolds number range considered in the present study.
- The CFD simulation results show that heat transfer in a conical spiral tubes with $\alpha \geq 20^{\circ}$ is more than that in a helical tube for the given coil curvature ratio (r/R_M) and tube radius.
- With an increase in taper angle, the Nusselt number in the conical spiral tube is found to increase up to 9.5% as compared to that in a helical tube with identical geometrical parameters.

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