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Numerical (CFD) studies in twisted square duct

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ABSTRACT
CFD analysis of steady fully developed laminar flow inside twisted duct of square cross section flow area is studied for Re range of 100 - 2000. A commercially available software is used for the analysis. Twist ratio used are 2.5, 5, 10 and 20. Maximum average f.Re values were observed for a twist ratio of 2.5 and Re of 2000. It is observed that the average f.Re values are not constant rather are function of Re and twist ratio. Average f.Re values are correlated with swirl parameter. Local distribution of f. Re across a cross-section is further analysed. Comparison of average f.Re values of twisted square duct with straight square duct is also done.

Keyword: *Twisted duct, laminar flow, twist ratio, Periodic flow, swirl parameter.*

I. INTRODUCTION

Economics of any heat transfer equipment is decided by its size. Among other means, the heat transfer enhancement can be achieved by twisting the flow in tubes. One of the emerging techniques is to use twisted tubes, instead of straight tubes. Secondary flow generated inside twisted tube contributes towards enhancing the heat transfer coefficient as compared to straight tubes. Twisted duct when used in heat exchanger not only enhances heat transfer inside the ducts but also outside the duct to duct space, thus mixing of fluid is significantly improved. Swirl induced flow inside the duct is expected to enhance the heat transfer coefficient by an amount similar to that of twisted tape or turbulator inserts. The higher heat transfer results is however accompanied by higher pressure drop (higher friction factor) compared to straight tube. In this study, the friction factor characteristics for fully developed single phase laminar fluid flow through twisted square tube at different twist ratios have been numerically analysed. Todd (1975) investigated a general problem of twisted tube. He simplified the Navier-Stokes equations under small twist ratio assumption in the rotating coordinates which was solved by a regular perturbation method. He derived a fourth order partial differential equation for the stream function and showed that it is identical to the equation for the small transverse displacement of a clamped elastic plate under a constant loading. Although this analysis is applicable for a pipe of any cross section with proper boundary conditions, its validity is limited only to a slightly twisted elliptic pipe. Masliyah and Nandakumar (1981) numerically studied the fully developed steady laminar flow through twisted square ducts with rotation coordinates system. They presented average friction factor values for twist ratios of 2.5, 5, 10 & 20 for *Re* up to 2000. Later Xu and Fan (1986) however pointed out some discrepancy in the viscous dissipation term adopted by Masilyah and Nandakumar (1981). Chang *et al*. (1985) studied laminar flow in a twisted elliptic tube for large twist ratio (*H* = 20, 50, 100) using finite difference method. The effect of twist ratio and aspect ratio of ellipse is investigated with respect to their role in determining the axial and circumferential velocities and streamline patterns. Bishara (2002) numerical studied laminar, periodically fully developed single phase flow of a Newtonian fluid in elliptical twisted tube with constant wall temperature boundary condition for *Re* range of 10-1000 and *Pr* of 3. Elliptical tubes with aspect ratio 0.3, 0.5 & 0.7 and twist ratio of 3, 4.5 & 6 were considered. Solution for fluid flow and heat transfer were presented. Twisted elliptical tube showed considerable heat transfer enhancement compared to straight tube. In the present study, an effort is made to verify the claims made in literature regarding pressure drop data by using a CFD analysis. Fluent is used as the CFD tool to generate the fluid flow distribution in a square twisted duct for a range of twist ratios. Common terminologies associated with twisted duct have been highlighted in Fig. 1.

- Pitch (*S*): The distance between two consecutive points along the length of tube where the orientation of tube cross section exactly coincides to each other. Cross section rotates by 360° through one pitch distance.
- Twist Ratio (*H*): is the geometrical parameter used to describe flow through the twisted ducts. It is defined as the ratio of the pitch (*S*) to hydraulic diameter (*d*) of the duct.

II. CALCULATION METHODOLOGY

Fluent software has the ability to provide solution of fluid flow and heat transfer by using periodic flow concept. Periodic flow

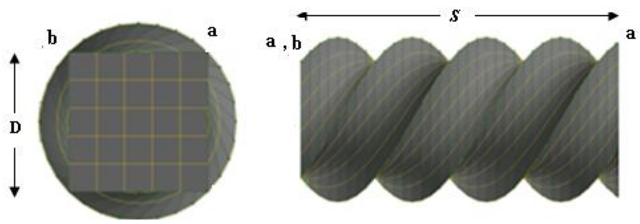

Figure 1 CFD model for twist ratio 2.5

condition exists when the flow pattern repeats over some length *l*, with a constant pressure drop across each repeating module along the flow direction. In the case of twisted duct, as the geometry of duct repeats, a suitable modelling length of twisted duct was considered and periodic flow concept was utilized to obtain the solution. As for periodic flows, such problems can be analyzed by restricting the numerical model to a single module of periodic length. This permits the use of scaled model and reduces the preprocessing time. Common calculation methodology adopted for all case of solution is as follows.

- Three dimensional models were used in the analysis with hexahedron mesh elements.
- Laminar flow solution had been obtained for *H* = 2.5, 5, 10, 15 and 20.
- Shear stress (τ_w) data had been obtained from fluent at different location along the length of the duct.
- Friction factor can be obtained from wall shear stress as

$$f = \frac{\tau_w}{\left(\frac{\rho V^2}{2}\right)} \qquad 1$$

- Grid independence check had been performed for each case by refining the grid till the results are constant.
- Convergence criteria for velocity components, continuity equation and Energy equation was set as 1×10^{-6}.

III. VALIDATION WITH LITERATURE

Fluent solution are first obtained for flow in a twisted square duct (H = 2.5) at Re = 709. The results are compared with Masliyah and Nanadakumar (1981) and presented in Table 1. The results compare reasonable well with that reported in the literature.

Table 1 Comparison of solution with literature

Re	***f.Re***	
	CFD	**Masilya & Nandakumar (1981)**
709	25.76	26.08

IV. AVERAGE FRICTION FACTOR

Average friction factor results for Re 100 to 2000 are obtained for fully developed internal flow in twisted square duct. Twist ratio of 2.5, 5, 10 and 20 are considered. Average $f.Re$ values obtained for different twist ratios are presented in Fig. 2. It is observed that $f.Re$ values for twisted duct are function of Re and H. Maximum value of $f.Re$ is 47.7 obtained for a twist ratio of 2.5 at Re = 2000. Numerical data for average $f.Re$ can be correlated in terms of swirl parameter Sw for twisted duct as shown in Fig. 3. Sw is modified form of swirl parameter used by Manglik and Bergles (1993) for twisted tape. Correlation obtained is given by Eq. (2)

$$f.\mathrm{Re} = 0.0217\,Sw + 14.2 \qquad (\pm 5\,\%) \qquad 2$$

Valid for $100 \le Re \le 2000$ & $2.5 \le H \le 20$

where Sw is defined by Eq. (3)

$$Sw = \frac{\mathrm{Re}}{\sqrt{H}} A_r \qquad 3$$

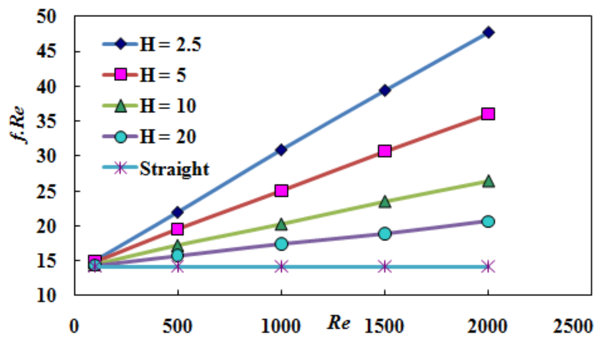

Figure 2 Average *f.Re* variations

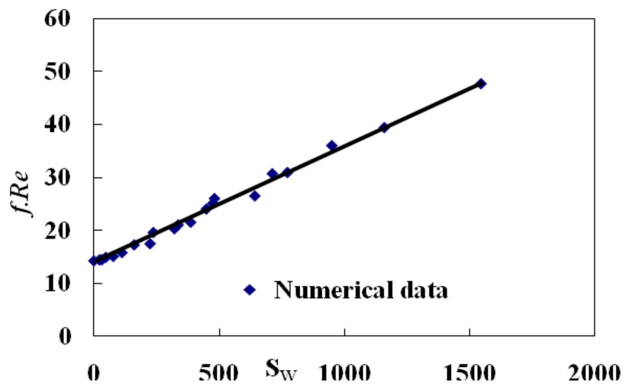

Figure 3 Correlation fit for *f.Re* and swirl parameter

$$A_r = \frac{A_{st}}{A_{tw}} \quad (4)$$

$$A_{st} = 4 d_h^2 \quad (5)$$

$$A_{tw} = 4\pi d_h \left[0.5\left(1+\frac{H^2}{\pi^2}\right) + \frac{H^2}{2\pi^2}\ln\left\{\frac{\pi}{H} + \left(1+\frac{\pi^2}{H^2}\right)^{\frac{1}{2}}\right\}\right] \quad (6)$$

A_r from Eq. (4) for *H* = 20 is 1.004, hence not much advantage is obtained by employing twisted duct having *H* greater than 20 for heat transfer enhancement. Therefore study is restricted to *H* = 20.

V. RESULTS AND DISCUSSION

In the previous section, average *f.Re* values calculated for twisted square duct were dependent on *Re* and *H* values, which is contrary to straight square duct for which average *f.Re* remains constant in laminar flow regime. In this section, local variation of *f.Re* is studied. Figure 4 shows cross section of straight tube. Z axis is the flow direction and X & Y axes are in plane of cross section. Line cb represents half edge of square side. Line oc & line ob are half side and half diagonal of cross section with o as center of cross section.

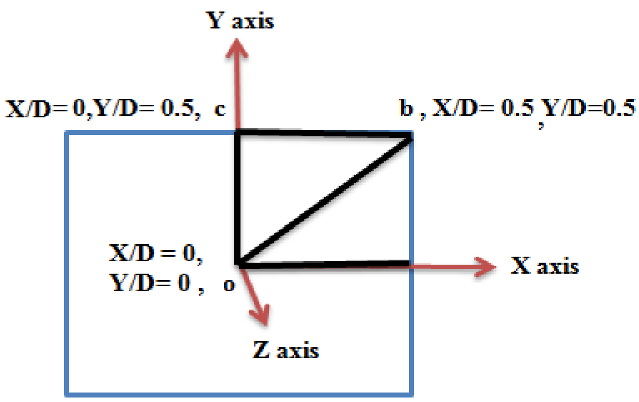

Figure 4 Cross section of square duct

Local Friction factor variation

In case of flow through duct, wall surface of duct will oppose the motion of fluid by exerting forces called friction forces. Fluid will also exert equal magnitude and opposite direction shear force on duct wall surface. This friction forces will cause pressure drop in fluid whereas shear force on duct will decide the thickness and material of duct wall. In case of square duct (Fig.4) there is zero flow at corners of duct, e.g point b which results in zero shear stress (no contact between fluid and wall surface) and hence zero *f.Re* values. Figure 5 shows local *f.Re* variation along half edge cb for twist ratio 10. In Straight tube maximum *f.Re* occurs at centre of side of duct and zero at corner. However for twisted duct, location of maxima is function of *Re* and its location shift away from centre of side with increase in *Re*. Figure 6 and Fig. 7 shows V_x and V_z component of velocities respectively along line ob . Velocities are non-dimensionalized with respect to mean inlet velocity (V_{mi}). From Fig. 7 it is observed that maximum V_z occurs at center of tube and it is 2.1 times that mean inlet velocity or mean velocity at given cross section for Re = 2000. Figure 6 shows V_x (same as V_y) component of velocity which is cause of secondary flow. Contrary to straight square duct where V_x and V_y component of velocities are zero compared to V_z component, twisted duct shows comparable values of this components. V_x and V_y components of velocities observed are maximum for H = 2.5 and is about 2.56 % of inlet mean velocity. It is also seen from Fig. 6 that location of maximum value of V_x and V_y velocity component is in region of X/D = 0.3-0.5, which is near wall region. For a given twist ratio, as *Re* is increased, location of maximum value of x & y component shifts towards wall. For given Reynolds number as twist ratio is decreased location of maximum of x & y component shifts towards wall. X & y components of velocity generated (also referred as secondary flow) are result of swirling motion occurring inside the twisted tube. As magnitude and location of secondary flow are function of *Re* and twist ratio, Shear stress at wall and hence *f.Re* values will also be function of the same. Observation leads to conclusion that swirling motion (secondary flow) is responsible for higher *f.Re* values and it distribution at given cross section in case of twisted duct.

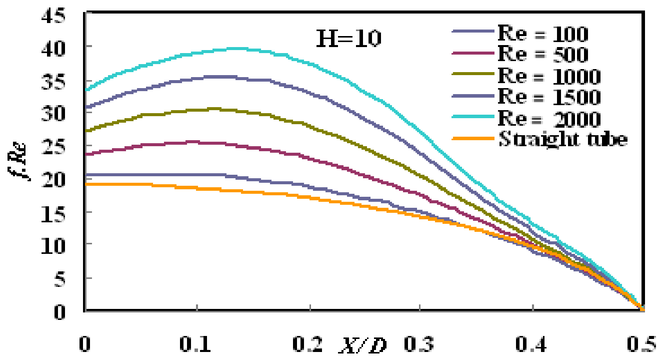

Figure 5 Local *f.Re* variations along cb

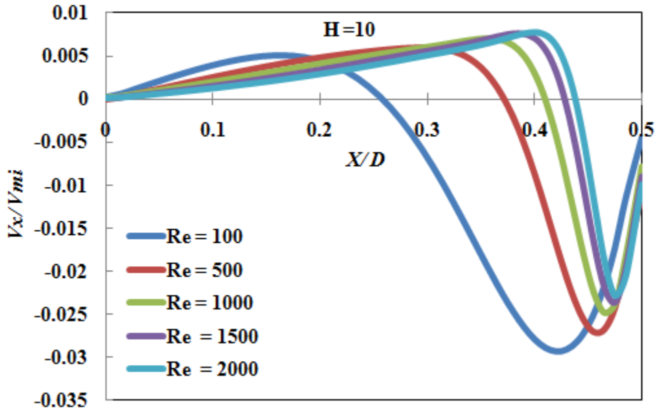

Figure 6 *Vx* variations along ob

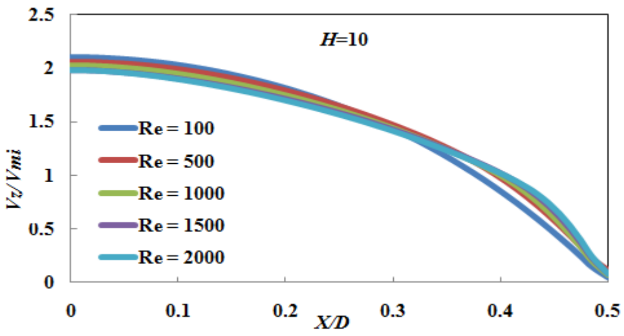

Figure 7 Velocity components in flow direction along ob

VI. CONCLUSION

In the earlier sections it is realised that average *f.Re* values in twisted duct are higher than straight duct. Table 2 shows average friction factor values compared to straight square duct. Maximum friction factor observed is for *H* = 2.5 & *Re* =2000 and it is 3.36 times that straight square duct. To estimate suitability of twist tube in heat exchanger application corresponding heat transfer enhancement is to be computed. Utilizing twisted duct for heat transfer applications e.g. Heat exchanger will result in compact and economical equipments.

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Table 2 Friction factor comparison with straight square duct

	((f.Re)tw/(f.Re)st)				
Re / H	**2.5**	**5**	**10**	**20**	**Straight**
100	**1.06**	**1.04**	**1.01**	**1.00**	**1.00**
500	**1.54**	**1.37**	**1.21**	**1.11**	**1.00**
1000	**2.17**	**1.76**	**1.42**	**1.22**	**1.00**
1500	**2.77**	**2.16**	**1.65**	**1.32**	**1.00**
2000	**3.36**	**2.53**	**1.86**	**1.45**	**1.00**

NOMENCLATURE

A	Heat transfer area , m^2
D	Side of Square, m
d	Hydraulic diameter, m
E	Suitability factor for twisted tube
f	Friction factor
H	Twist ratio, dimensionless
l	Periodic length , m
Re	Reynolds number
S	Pitch of twisted tube, m
Sw	Swirl parameter, dimensionless
V	Flow velocity (Twisted Tube) , m/s

Greek Letters

τ	Shear stress N/m^2

Subscript

b	Bulk temperature , fluid
mi	Mean inlet
r	Area ratio
st	straight tube
tw	Twisted tube
x	x coordinate - direction
y	y coordinate - direction
z	Z coordinate - direction

Abbreviations

CFD	Computational fluid dynamics

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