20th Australasian Fluid Mechanics Conference
Perth, Australia
5-8 December 2016

Large Eddy Simulation of Flow through a Pipe with Twisted Tape Insert

Parag Chaware[1], **C. M. Sewatkar**[2]

[1]Department of Mechanical Engineering,
Cummins College of Engineering for Women, Pune, Maharashtra, India
[2]Department of Mechanical Engineering
College of Engineering Pune, Pune, Maharashtra, India

Abstract

The flow through a pipe with twisted tape insert is investigated experimentally and numerically by many investigators. However, due to inherent limitations of experimental methods and inadequacy of RANS models in predicting the highly swirling flow in the transitional regions, a little information about the flow physics in transitional regime is found in the literature. The present study investigates the flow through a pipe with twisted tape insert using Large Eddy Simulation (LES) method at Reynolds number 3000 for twist ratio of 6. The results are validated using experimental results from the literature in terms of fiction factor. The present simulation predictions of mean streamwise velocity, root-mean-square velocity fluctuations, the axial, tangential and radial component of the velocity are used to describe the flow physics. The near tape vortex which is primarily responsible for the fluid mixing and decreasing the thickness of boundary layer on the tape, otherwise cannot be captured by RANS models, is analyzed using LES model. It is observed that the LES model can be properly used to obtain the complex flow field in a pipe with twisted tape insert.

Introduction

Swirl flow promoters are used to enhance the heat transfer across many industries. It finds the applications in heat exchangers, chemical industry and casting processes to homogenize the mixture. Twisted tapes are metallic strips twisted along their longitudinal axis at desired dimensions. Twisted tapes are widely investigated by many researchers since the twentieth century. Smithberg and Landis[7] characterized the full length twisted tape generated swirl flow. It consists of helicoidal core flow modified by secondary circulation effects and a twisting boundary layer flow. They found that, except for the near wall region where the boundary layer effects are predominant, the axial velocity remained almost constant over the cross section. Hong and Bergles[2] reported the increase in secondary velocities and reduction in the thermal boundary layer are the reasons for the heat transfer enhancement. Manglik and Bergles [4, 5] investigated the flow with twisted tape in laminar and turbulent regime. Their study proposed that the twisted tape prohibits the transitional jump from laminar to turbulent flow. The monotonic transition from laminar to turbulent is achieved with the twisted tape. Extensive numerical study of heat transfer enhancement using twisted tape was carried out by Lin and Wang [2] for both uniform wall temperature (UWT) and uniform heat flux (UHF) conditions. The study mainly focuses on the effect thermal contact resistance between tape and tube and the conduction of tape. It is concluded that the conduction in the tape is important in UWT conditions. Heat transfer enhancement using secondary flow is strongly dependent on the thermal boundary conditions of the tube wall, the conduction in the tape, and the intensity of secondary flow. The efficiency of heat transfer enhancement is better when UWT is enforced than when UHF is imposed, especially for the nonconducting tape cases. Cazan and Aidun [1] performed the experimental investigation of the turbulent swirling flow downstream the short twisted tapes. Their study proposed that, out of two vortices evolve downstream of the tape, under the influence of the tangential component of the velocity of the main flow, the corotating vortex is accelerated and expands while the counter-rotating vortex shrinks.

Thus, it is noticed that the phenomenon of heat transfer enhancement using twisted tape is widely studied. The investigations done by earlier researchers focuses primarily on the laminar and turbulent regime of the flow. Few attempt has been done for the prediction of the flow behavior in the transition regime experimentally [5, 8]. However due to inherent limitations of experimental measurements and complexity of flow the detailed physical mechanism of heat transfer process in the transition regime of the flow is not found in the literature. All the numerical studies in the literature are performed using RANS turbulence models. The RANS turbulent models are based on the time averaged values of solution variables, so it fails to predict the temporal variations in the flow properties. The information about the critical Reynolds number is also not clear from the literature. Manglik and Bergles [5] have approximately predicted the value of Re_{cr}. Their study emphasizes the need of investigation of Re_{cr} further. Our attempt through this study, is to investigate the factors responsible for high heat transfer like swirl, tangential, radial and axial velocity distribution, with the help of LES modeling in the transition regime of the flow.

Problem Description

The performance of the twisted tape is analyzed using a test section as shown in the fig. 1. The twisted tape of negligible thickness is inserted in the full length of the tube of diameter (D). The tape has a pitch of 'H' for 180° rotation. The width 'W' of the tape is equal to the diameter of the tube so as to ensure the perfect fitness of the tape with tube. Investigations are carried out for twist ratio (H/D) of 6 in the transitional regime of flow regime at Re = 3000. In this work, filtered three-dimensional incompressible continuity and momentum equations are used as governing equations.

$$\frac{\partial \bar{u}_i}{\partial t} + \bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_i} + \nu \frac{\partial^2 \bar{u}_i}{\partial x_j \partial x_j} - \frac{\partial \tau_{ij}}{\partial x_j}. \tag{1}$$

These equations are solved using finite volume method. Subgrid-scale modeling is very important in LES. In this study, the WALE (Wall-Adapting Local Eddy-Viscosity) model is used. In the WALE model the second invariant of stress tensor is zero in the region of pure shear. Therefore the model is able to reproduce the laminar to turbulent transition. The model is sensitive to both the strain and the rotation rate of the small turbulent structures. Because of this, it is well suited for LES of complex geometries, no explicit filtering is needed and only local information is required to build the eddy-viscosity. It produces zero eddy viscosity in case of a pure shear [6]. Velocity inlet and pressure outlet boundary conditions are used at the inlet and outlet. The inlet and outlet are extended beyond the test section to ensure the fully developed flow at the inlet of the test section and zero pressure at the outlet. No slip boundary condition is imposed on tape and tube wall. Water is used as a working fluid. The physical properties of fluid and tape are assumed to be constant and fluid is incompressible.

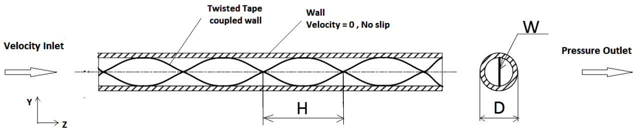

Figure 1: Twisted tape geometry

Solution Procedure

Simulations were carried out by the commercial CFD software FLUENT 15, based on the finite volume approach. Fully developed velocity profile is imposed as an inlet boundary condition. To obtain the inlet velocity profile, a separate simulation is performed for a fully developed flow in a tube. Second-order bounded central differencing schemes were used for advection and diffusion. SIMPLE algorithm is used for pressure and velocity coupling. The CFL number was monitored for the convergence with the continuity and momentum residuals. The grid refinement was used near the walls to ensure the maximum value of $\Delta x+, y+$, and $\Delta z+$ as reported in Table 1. The unsteady statistics is collected for $2 \times l/U_m$ flow time, where U_m is the mean velocity of flow with time step of 1e-4. Data in terms of axial, tangential and radial component of the velocity, RMS and mean values of streamwise velocity is collected over the given time. The results of the simulations are validated with the experimental results by Manglik and Bergles [4] in terms of friction factor. The results shows good agreement with the experimental results by Manglik and Bergles [4].

Table 1: Grid Resolution

Grid Resolution	**Value**
$\Delta x+$	25
y+	1
$\Delta z+$	5

Table 2: Data Validation

	Manglik and Bergles [4]	**Present Analysis**
Friction Factor	0.100728	0.1098

Results and Discussions

The pressure drop in a tube with twisted tape insert is substantially more than in the plain tube. As per the investigations carried out by Lopina and Bergles [3] the pressure drop due to the frictional resistance of the length of the channel is substantially higher than other pressure drops like at the entry entry, the exit and the swirling nature occurring in the tube with twisted tape insert. The pressure drop taking place along the length of the tape can be attributed to the increased length due to the spiral nature of the flow. The pressure drop occurring in a tube is presented in the form of non dimensional friction factor. Friction factor is defined as ;

$$f = \frac{\Delta P}{1/2 \rho V_{z,m}^2} \tag{2}$$

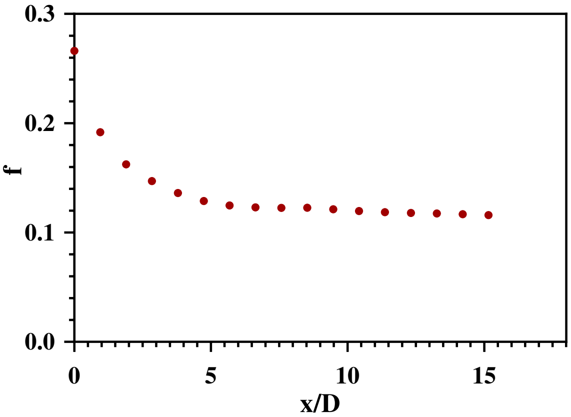

Figure 2: Variation of friction factor along the length of the test section

Figure 2 shows the variation of the friction factor (f) over the length of the domain. It can be observed that the entry length of the flow is substantially reduced with the insertion of the twisted tape. The early turbulence introduction stabilizes the flow. The dominance of the inertial forces and swirling nature of the flow even at lower Reynolds number causes the displacement of the momentum boundary layer. The additional friction factor is a result of friction over the tape and the swirl.

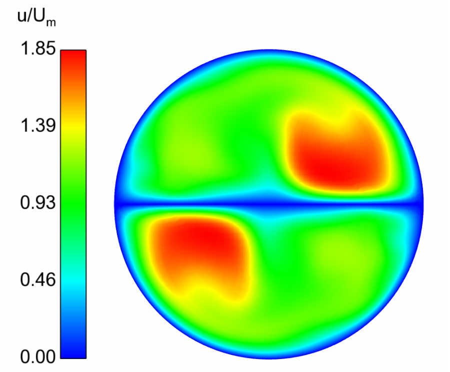

Figure 3: Velocity contours at x/D=10 from the inlet of the test section

Figure 3 shows the contours of the streamwise velocity (u) in the fully developed region of the flow. The maximum velocity is observed at the tube tape contact area opposite to the direction the flow. This results in the asymmetric velocity profile as shown in the fig. 4. The rapid change in the direction of the flow in the tube tape contact area and the assisting direction of the twist increases the axial velocity. The asymmetric velocity profile affects the boundary layer growth over the surface of the tube which in turn increases the heat transfer. The boundary layer thickness is nonuniform in the spanwise direction on the tape. The vortex formation near the tape surface obstructs the sweeping of the boundary layer over the central region of the tape, this in turn gives the non uniform shear stress distribution on the tape surface. Smithberg and Landis[7] reported nearly uniform velocity profile over the cross section of the tube with twisted tape insert. However, a small drop in the velocity magnitude is observed near the tube wall. The higher tangential component reduces the axial component of the velocity and hence such drop in the axial velocity is noticed.

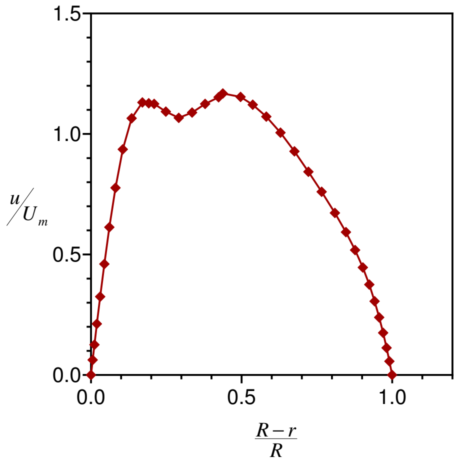

Figure 4: Velocity profile at x/D=10 from the inlet of the test section

The secondary flow is the flow in the direction normal to the main flow. This suggests the existence of velocity components other than the axial velocity at the cross section normal to the flow. Further, for flow in the tube with insert the tangential (U_θ) and radial (U_r) components of the velocity are observed on the cross section normal to the flow direction. Figure 5 and fig. 7 show the streamlines and the velocity vectors of mean velocity on the plane normal to the flow direction. The swirling nature of the flow is evident from the nature of the velocity vectors. The formation of the vortex near the tape can be observed from the streamlines. The RANS models fails to predict this vortex formation near the tape. The strong tangential velocity and increased axial velocity gives rise to the vortex near the tape in the helecoidal region of the flow. The vortex formation occurs over the entire length of the tube. The Q-criterion results from LES can be used to identify the vortex in the flow. Figure 8 shows the isosurface of instantaneous Q criterion. It also shows the generation of the vortices near the tape along the length of the tape. The existence of the corotating vortex is also reported by Cazan and Aidun [1] from their experimental investigations.

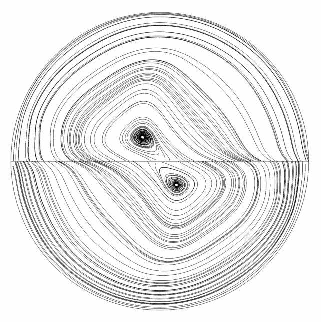

Figure 5: Streamlines of the secondary flow at x/D=10 from the inlet of the test section

The transition to turbulent is generally characterized by fluctuating velocities and flow instabilities. The fluctuating part can be predicted by LES only. Figure 6 shows the RMS values of fluctuating component of the axial velocity (u') at a distance of x/D=10 from the inlet of the test section. The fluctuating velocity increases away from the wall till the center of the section. The highest fluctuations in the velocity is observed at the center as expected where the inertial effects are predominant.

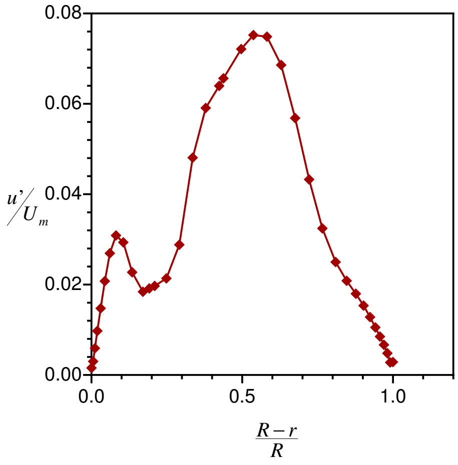

Figure 6: Variation of RMS values of fluctuating component of the velocity at x/D = 10 from the inlet of the test section

There is sudden drop in the fluctuation observed near the wall as a result of highest tangential velocity. Fluctuating velocity increases further beyond this point till the center.

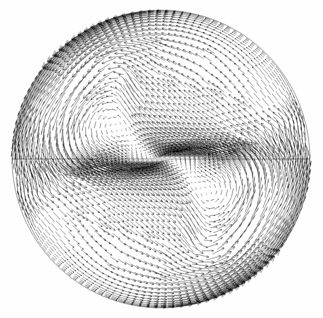

Figure 7: Velocity vectors normal to the flow direction at x/D=10 from the inlet of the test section

Insertion of the twisted tape imparts tangential velocity component (U_θ) to the flow. Figure 9 shows the contours of the tangential velocity on a plane normal to the streamwise direction. The tangential velocity is higher in the area near the tube as a result of the swirl and tube tape contact area due to rapid change in direction. The tangential velocity sweeps the thermal boundary layer on the tape and the tube. The heat transfer augmentation associated with the use of the twisted tape arises from this sweeping. The highest magnitude of the tangential velocity is found to be almost 27% of the mean velocity. The higher tangential velocity makes the twisted tape as preferred heat transfer augmentation device.

The other component of the secondary flow is the radial velocity (U_r). The radial velocity is responsible for the cross flow mixing in the flow. The highest value of the radial velocity is observed at the center of the cross section. The tangential velocity is proportional to the distance from the center hence it is lesser in magnitude at the centre. This causes delayed change in the direction of the flow. This delay allows the buildup of radial velocity. However, the magnitude of this component is less than that of the tangential. The negative radial velocity indicates the movement of the flow towards the tape rather than in the outward direction.

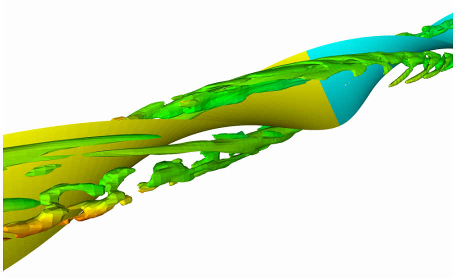

Figure 8: Isosurface of Q criterion

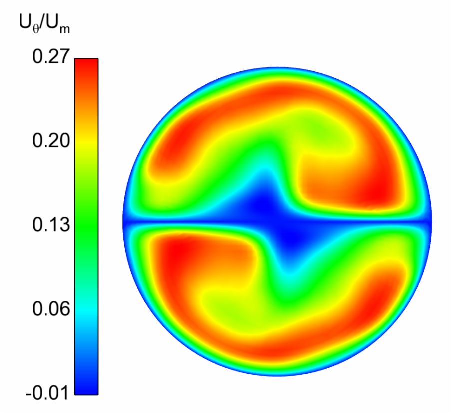

Figure 9: Tangential velocity contours at x/D =10 from the inlet of the test section

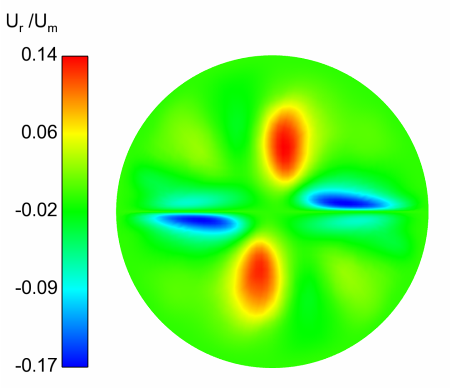

Figure 10: Radial velocity contours at x/D = 10 from the inlet of the test section

Conclusions

The effect of insertion of the twisted tape on the fluid flow in a plain tube is investigated numerically using LES. The study concludes that the insertion of the twisted tape gives rise to the tangential and radial velocity components, which can be considered as secondary flow in the system. The strong tangential velocity produces a vortex near the tape along the length of tape. This vortex formation obstructs the formation of the uniform boundary layer over the tape surface. The highest magnitude of fluctuating component of the velocity is found at the center of the section. The higher tangential velocity suppress the fluctuations near the tube. Twisted tape alters the flow structure by shifting the peak of the axial velocity towards the tube tape contact area with increasing Reynolds number at given twist ratio. This shift alters the boundary layer at the tube wall and assists heat transfer augmentation process.

The present work explains the phenomenon which leads to augmentation in heat transfer and pressure drop. A different viewpoint which gives the systematic understanding of the combined effect of axial, tangential and radial velocity is offered here.

Unlike RANS models which are based on average values, LES method is capable of predicting the instantaneous as well as mean values of the flow parameters. The bifurcation analysis of the the fluctuating component of velocity, and vorticity Reynolds number can be used to identify the critical value of the Reynolds number. The results for the critical Reynolds number and the performance of the twisted tape in the other parts of transitional regime will be presented during the conference.

References

[1] Cazan, R. and Aidun, C. K., Experimental investigation of the swirling flow and the helical vortices induced by a twisted tape inside a circular pipe, *Physics of Fluids*, **21**.

[2] Lin, Z.-M. and Wang, L.-B., Convective heat transfer enhancement in a circular tube using twisted tape, *Transactions ASME Journal of Heat Transfer*, **131**.

[3] Lopina, R. F. and Bergles, A. E., Heat transfer and pressure drop in tape generated swirl flow, Technical Report DSR 70281-47, Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts, 1967.

[4] Manglik, R. M. and Bergles, A. E., Heat transfer and pressure drop correlations for twisted-tape inserts in isothermal tubes: Part i laminar flows, *Transactions ASME Journal of Heat Transfer*, **115**, 1993, 881–889.

[5] Manglik, R. M. and Bergles, A. E., Heat transfer and pressure drop correlations for twisted-tape inserts in isothermal tubes: Part ii transition and turbulent flows, *Transactions ASME Journal of Heat Transfer*, **115**, 1993, 890–896.

[6] Nicoud, F.and Ducros, F., Subgrid-scale stress modelling based on the square of the velocity gradient tensor, *Flow, Turbulence and Combustion*, **62**, 1999, 183–200.

[7] Smithberg, E. and Landis, F., Friction and forced convection heat-transfer characteristics in tubes with twisted tape swirl generators, *Transactions ASME Journal of Heat Transfer*, **86**, 1964, 39–48.

[8] Watanabe, K. Taira, T. and Mori, Y., Heat transfer augmentation in tubular flow by twisted tapes at high temperatures and optimum performance, *Heat Transfer - Japanese Research*, **12**, 1983, 1–31.