Effects of Curvature on the Turbulent Flow in a Helical Tube

Dong-Hyeog Yoon*, Kwang-Won Seul
Korea Institute of Nuclear Safety, 62 Gwahak-ro, Yuseong-gu, Daejeon, 305-338
**Corresponding author: dhyoon@kins.re.kr*

1. Introduction

Helical tubes are commonly used for engineering equipments such as heat exchangers. The centrifugal force generated by such a helical tube causes the pressure gradient from the helical axis toward the outer side of the tube, while inducing the secondary flow. The secondary flow increases the movement of fluid in the tube and increases the fluid velocity outer side of the tube as well. Due to such effects, the heat transfer greatly increases in the tube. Therefore, many different kinds of industrial heat exchangers use helically-coiled tubes, and recently it is even adopted for once-through steam generators of integral type pressurized water reactors (PWRs) such as SMART (System-integrated Modular Advanced ReacTor).

The secondary flow induced by centrifugal force in the helical tube increases the outer axial velocity and decreases the inner axial velocity of the tube, while increasing the pressure drop inside the tube. Thanks to those characteristics, there have been a great many of researches conducted on the pressure drop and friction factor [1-2], through which many related correlations are suggested under several different flow conditions [3]. However, most of the researches are focused on the change of averaged friction factor inside the tube, and there are not sufficient researches on the turbulent characteristics.

For engineering designs that strict safety standards should be applied, such as the steam generator of integral type pressurized water reactors, turbulent characteristics and the wall stresses in the local region are very important elements for safety evaluations. In this study, the effect of Reynolds number and radius ratio of coil on the turbulent flow characteristics of a helical tube is investigated by using ANSYS-CFX [4].

2. Numerical Method

To analyze the three-dimensional incompressible steady flow in a helically coiled tube, continuity and Reynolds-Averaged Navier-Stokers equations are solved using a finite volume solver [4], which is a commercial computational analysis code. The shear stress transport (SST) turbulence model [5] is used as a turbulence closure. In case of a helical tube, the centrifugal force induced by the curvature comes to have effect on the turbulence model. Thus, Spalart and Shur[6] attempted to consider the effect of curvature and flow rotation on the two-equation models by modifying the turbulent production term, and even this study applied Spalart and Shur[6]'s model provided from CFX as well.

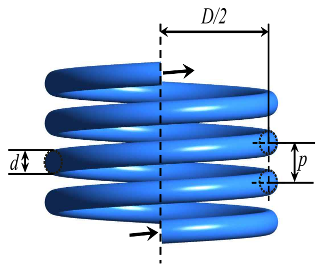


Fig. 1 Geometry of a helically-coiled tube.

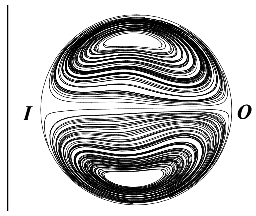
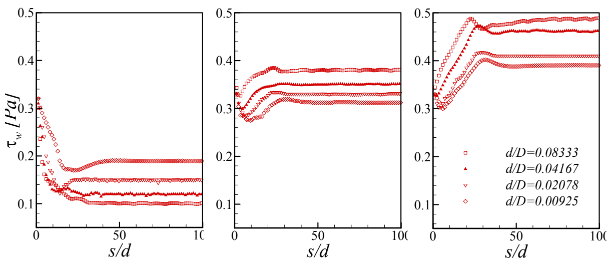


Fig. 2 Streamlines of the secondary flow in a helically-coiled tube.

Figure 1 shows the geometry of a helical tube used for this study. We investigated the effect of centrifugal force in the helical tube on the turbulent characteristics by changing d/D to 0.08333, 0.04167, 0.02078 and 0.00925 on the basis of Re=25000, while having helical pitch fixed as p/d=1.667. As for the axial length of the tube, L/d=150 was used in consideration of an entrance region where flow is fully developed. For the boundary conditions, uniform velocity was used for the inlet, and no-slip condition was imposed for the tube wall. Hexahedron-structured grids were used for the numerical analysis, and 6,555 cells were used to compose each grid for the cross section of the tube, a total of 2,097,600 elements were used.

3. Results and Discussion

Figure 2 shows the secondary flow induced by the centrifugal force in a helically-coiled tube. A pair of the counter rotating vortices is observed in Fig. 2. These vortices in the tube increase the outer axial velocity and decrease the inner axial velocity of the tube. As d/D increases, that is, as the effect of centrifugal force increases, the intensity of the secondary flow increases.



(a) (b) (c)

Fig. 3 Variation of the wall shear stress along the axial direction, Re=25,000; (a) the inner side of the tube, (b) averaged wall shear stress, (c) the outer side of the tube.

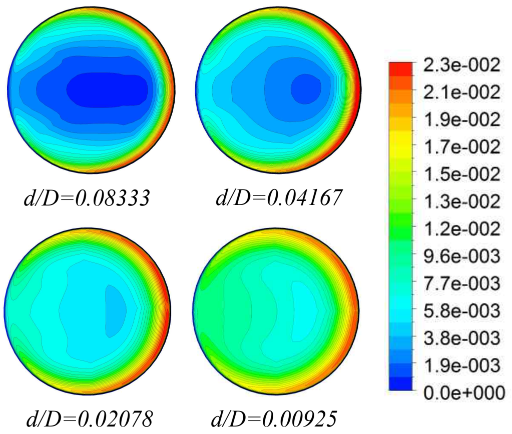


Fig. 4 Turbulent intensity in the fully developed region, Re=25,000.

Figure 3 shows the variation of the local wall shear stresses along the axial direction. As s/d increases from the inlet of the tube, the centrifugal force gets developed, further making the increased outer velocity of the tube and inducing the secondary flow. Because of this, the wall shear stress on the outer side of the tube greatly increases, but the wall shear stress on the inner side decreases. As the centrifugal force in the tube is rapidly developed in the region below s/d=30, it is observed that the wall shear stress on the outer side of the tube increases due to the secondary flow and the increased outer velocity of the tube, while the wall shear stress on the inner side greatly decreases to the contrary. As d/D decreases, the wall shear stresses are observed to decrease and gradually approach to shear stress of the straight tube.

Figure 4 shows the turbulence intensity according to variation in d/D at Re=25,000. It is seen that the maximum value of the turbulent intensity does not greatly change by the variation of d/D, but, turbulent fluctuations in the center region of the tube greatly decrease. As d/D increases, the effect of centrifugal force gets higher, and this leads to the increasing pressure gradient from the helical axis toward the outer side of the tube. The increased pressure gradient stabilizes the turbulence in the center region of the tube.

4. Conclusion

In this study, the characteristics of the turbulent flow in a helical tube are numerically investigated by the variation of d/D by using RANS (Reynolds Averaged Navier-Stocks). Since the centrifugal force induced by the curvature of the tube increases the movement of fluid particles, it increases the wall shear stress. Furthermore, the wall shear stress of the outer side wall shear stress of the tube is much higher than that of the inner side of the tube, which will have effect on the safety of tube materials. It is also seen that turbulent fluctuations become weaker in the center region of the tube as d/D increases because of the increased pressure gradient from the helical axis toward the outer side of the tube. Overall, it is expected that the results of this study can be used as important data for safety evaluation of the helical steam generator.

REFERENCES

[1] H. Ito, Friction factors for turbulent flow in curved tubes, Trans. Am. Soc. Mech. Eng. J. Basic Eng., D81, pp.123-134, 1959.
[2] S. Ali, Pressure drop correlations for flow through regular helical coil tubes, Fluid Mech. Res., Vol. 28, pp.295-310, 2001.
[3] P. Naphon and S. Wongwises, A review of flow and heat transfer characteristics in curved tubes, Renewable and Sustainable Energy Reviews, Vol. 10, pp.463-490, 2006.
[4] Ansys CFX-13.0, Ansys Inc, 2010.
[5] F. F. Menter, Two-Equation Eddy-Viscosity Turbulence Models for Engineering Applications, AIAA Journal, Vol. 32, pp. 1598-1605, 1994.
[6] P. R. Spalart and M. Shur, On the sensitization of turbulence models to rotation and curvature, Aerospzce Sci. Tech., Vol. 1, No. 5, pp. 297-302, 1997.