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Comparison of turbulence models in simulating swirling pipe flows

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ABSTRACT

Swirling flow is a common phenomenon in engineering applications. A numerical study of the swirling flow inside a straight pipe was carried out in the present work with the aid of the commercial CFD code fluent. Two-dimensional simulations were performed, and two turbulence models were used, namely, the RNG k–ε model and the Reynolds stress model. Results at various swirl numbers were obtained and compared with available experimental data to determine if the numerical method is valid when modeling swirling flows. It has been shown that the RNG k–ε model is in better agreement with experimental velocity profiles for low swirl, while the Reynolds stress model becomes more appropriate as the swirl is increased. However, both turbulence models predict an unrealistic decay of the turbulence quantities for the flows considered here, indicating the inadequacy of such models in simulating developing pipe flows with swirl.

1. Introduction

Flow with swirl finds applications in many engineering areas and has attracted a great deal of research interest. Because of its extensive applications, there has been a great number of experimental and numerical investigations of swirling flow.

1.1. Experimental work on swirling flow

Kitoh [1] experimentally studied turbulent swirling pipe flow. The decay rate of the swirl intensity was obtained, and the tangential velocity profile was classified into three regions: wall, annular, and core. In the wall region, only the centrifugal destabilizing effect appears and a mixing-length model can predict the flow there. There is a flow skewness in the annular region, and a Reynolds stress model (RSM) is recommended to handle the anisotropic turbulence that an eddy-viscosity model will not take into account. In the core region, the centrifugal stabilizing effect becomes important.

Li and Tomita [2] experimentally examined the decay of swirl in a horizontal straight pipe. They developed empirical correlations that describe the decay of swirl and pressure distributions. These correlations can be used given only a discharge velocity and a wall static pressure at any axial location.

Rocklage-Marliani et al. [3] measured the evolution characteristics of swirl in a pipe for moderately high-Reynolds numbers and over a wide range of swirl numbers. The non-intrusive method of three-dimensional laser-doppler velocimetery was used in obtaining measurements. Swirling flow was introduced into the test section via a rotating tube bundle, which yielded solid body rotation of the flow at the inlet. It was found that the evolution characteristics brought out a dominant effect of swirl with a solid body rotation. It was the aim of the authors to obtain "bench-mark" measurements from their experiment. Their data are used in the current research for comparison between the numerical and experimental results.

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1.2. Numerical work on swirling flow

Many numerical studies have also been performed. Kobayashi and Yoda [4] simulated turbulent swirling flow in a straight pipe. They compared the standard k–ε model, a k–ε model with higher order terms, and a modified k–ε model with an anisotropic representation of turbulence. They found that the modified k–ε model with the anisotropic representation of turbulence successfully predicts axial and tangential velocity profile.

Shih et al. [5] studied rotating pipe flow and also complex swirling flow with recirculation. They found that a nonlinear cubic Reynolds stress–strain model was better suited than the standard k–ε model to simulate turbulent swirling flows encountered in aircraft engine combustors.

Jakirlic et al. [6] computationally studied several types of rotating and swirling flows for a range of Reynolds numbers and rotation rates or swirl intensities, including that of the straight pipe configuration. It was found that the Reynolds stress model was superior to other models tested. The major advantage of the RSM model was its ability to capture the stress anisotropy in the near-wall region. The standard k–ε model high-Reynolds number extensions resulted in solid body rotation flow, thus failing to predict the important features of the swirling flows considered.

Najafi et al. [7] modeled the developing turbulent swirling decay pipe flow. They performed investigations both numerically and analytically, and also used RSM model to validate their work. While all three methods were shown to agree quite well, it was concluded that the results of the CFD calculations were more realistic since the full Navier–Stokes equations are solved.

Nickolaus and Smith [8] analyzed highly swirled flows in dump combustors, with and without a downstream contraction. Using Large Eddy Simulation (LES), they captured the flow features that were observed in the experiments they modeled. A Reynolds averaged Navier–Stokes (RANS) model was also used, but was found to be less accurate than the LES calculations. It should also be noted, however, that a tremendous difference in simulation run-time existed between the RANS and the LES models. Using the same mesh, the LES ran for 3 weeks, while the RANS model only needed 1 day for convergence.

1.3. Summary

Much work has been done on swirling flow in straight pipes, both experimentally and numerically. A common numerical finding of several researchers is that the Reynolds stress model is better suited for swirling flow than RANS eddy-viscosity models, such as the k–ε model. This is due to the fact that the RSM handles anisotropy in the flow, whereas the k–ε model does not. This finding will be important to the present work, where a numerical simulation will be employed to better understand the physics of swirling pipe flow.

1.4. Objective

The objective of this research is to use the commercial CFD code Fluent to model the developing turbulent swirling flow inside a straight pipe, and to gain an understanding of such a flow and the turbulence models involved in the simulation. The Navier–Stokes equations will be solved to obtain results that can be compared with the experimental findings in literature. Two turbulence models (RNG k-ε model and RSM) will be compared, and their effects on the simulation results will be determined.

The present paper is organized as follows: the numerical method is presented in Section 2. The numerical simulation for modeling developing swirl will be explained in Section 3. The results from the simulation will be given in Section 4, as well as a discussion. Section 5 provides conclusions of the work.

2. Numerical method

The steady state Reynolds averaged Navier–Stokes continuity and momentum equations are given as

$$\frac{\partial(U_i)}{\partial x_i} = 0, \tag{1}$$

$$\rho\frac{\partial}{\partial x_j}(U_iU_j) = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial U_i}{\partial x_j} - \rho\overline{u_i'u_j'}\right)\right], \tag{2}$$

where ρ is the density of the fluid, t is the time, and U_i is a mean component of velocity in the direction x_i, P is the pressure, μ is the dynamic viscosity, and u' is a fluctuating component of velocity. Repeated indices indicate summation from one to two for 2D problems and from one to three for 3D problems.

As a result of the Reynolds-averaging, additional terms are introduced into the Navier–Stokes equations. These terms, $-\rho\overline{u_i'u_j'}$, are known as the Reynolds stresses, and must be modeled. The Boussinesq hypothesis relates the Reynolds stresses to the mean velocity gradients as seen in the equation below:

$$-\rho\overline{u_i'u_j'} = \mu_t\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right) - \frac{2}{3}\left(\rho k + \mu_t\frac{\partial U_i}{\partial x_i}\right)\delta_{ij}, \tag{3}$$