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Comparative study of turbulence model performance for axisymmetric sudden expansion flow

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1. Introduction

Owing to its computational efficiency, the Reynolds Averaged Navier-Stokes (RANS) approach has been widely used for the prediction of turbulent flows and associated pressure losses in a variety of internal flow systems such as a diffuser, orifice, converging nozzle, and pipes with sudden expansion [1-3]. However, the lack of a general turbulence model often leads to limited applications of a RANS approach, i.e., the accuracy and validity of solutions obtained from RANS equations vary with the turbulence model, flow regime, near-wall treatment, and configuration of the problem [4]. In light of the foregoing, a large amount of turbulence research has been conducted to assess the performance of existing turbulence models for different flow fields. In this paper, the turbulent flow in an axisymmetric sudden expansion is numerically investigated for a Reynolds number of 5.6×10^4, with the aim of examining the performance of several turbulence models.

2. Methods and Results

2.1 Computational Setup

In the present study, the following RANS equations are solved using a commercial code, Fluent 12.0 [5], under an assumption that the flow of constant-property Newtonian fluid is steady, axisymmetric, incompressible, isothermal, and turbulent.

$$\frac{\partial\langle u_i\rangle}{\partial x_i}=0 \qquad (1)$$

$$\rho\frac{\partial\langle u_i\rangle\langle u_j\rangle}{\partial x_j}=-\frac{\partial\langle p\rangle}{\partial x_i}+\frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial\langle u_i\rangle}{\partial x_j}+\frac{\partial\langle u_j\rangle}{\partial x_i}\right)-\rho\langle u_i'u_j'\rangle\right] \qquad (2)$$

The computations are performed using a segregated solver with the SIMPLE algorithm for pressure-velocity coupling and 2nd order upwind method for discretization.

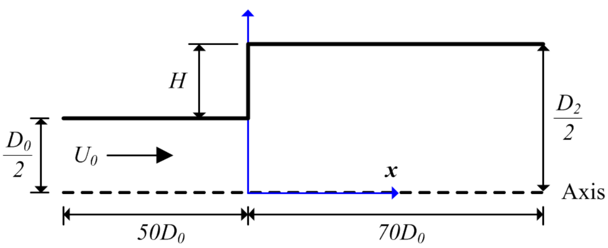

Fig. 1. Schematic of axisymmetric sudden expansion.

For the Reynolds stresses in Eq. (2), six turbulence models frequently used for industrial applications have been tested: standard *k-ε*, renormalization group (RNG) *k-ε*, realizable *k-ε*, standard *k-ω*, shear stress transport (SST) *k-ω*, and Reynolds stress model (RSM).

Figure 1 illustrates schematically the computational domain and corresponding boundary conditions used in this study. The domain is extended from $50D_0$ upstream to $70D_0$ downstream of the expansion, where D_0 is the inlet pipe diameter. The ratio of cross-sectional area of the larger outlet pipe to the inlet (or expansion ratio) is set to 4. Regarding the boundary conditions, a uniform velocity U_0 is specified at the inlet with the turbulence intensity of 3%, and the Reynolds number based on U_0 and D_0 is 5.6×10^4. At the downstream end, a pressure outlet condition is imposed, while the surfaces of the inlet and outlet pipes are treated as a stationary no-slip smooth wall. The simulations are conducted on the mesh composed of 76000 quadrilateral elements with a minimum grid spacing of $\Delta x_{min}=\Delta r_{min}=0.01D_0$. Note that the maximum y^+ at the wall nearest cell is less than 100, lying in a typical bound for the use of a standard wall function.

2.2 Grid Dependency Test

Using the realizable *k-ε* model, a grid dependency test is performed on three mesh configurations with different levels of refinement: $\Delta x_{min}=\Delta r_{min}=0.015D_0$ (M1), $0.01D_0$ (M2), and $0.005D_0$ (M3). The numerical results indicate

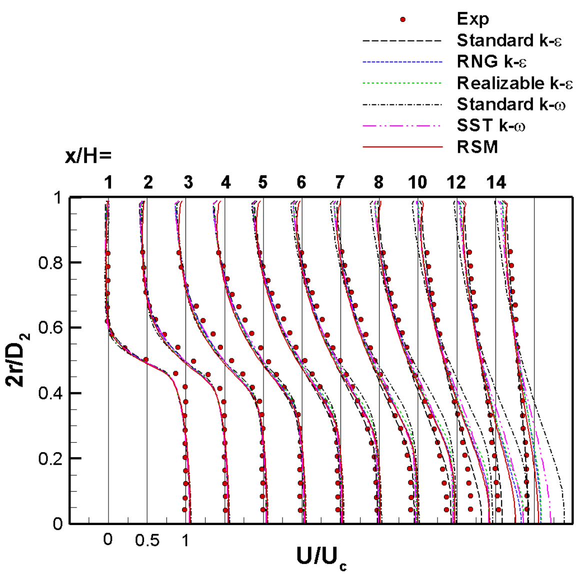

Fig. 2. Comparison of normalized mean axial velocity profiles.

Table 1. Comparison of reattachment length.

Turbulence model	Reattachment (X_r/D_0)
standard *k-ε*	8.783
RNG *k-ε*	10.370
Realizable *k-ε*	9.988
standard *k-ω*	14.374
SST *k-ω*	11.030
RSM	8.554
Experiment [7]	9.356±1.296

that the influence of mesh refinement beyond grid M2 is negligible, i.e., M2 and M3 predict the pressure profile along the axis almost identically. M2 is therefore chosen as the optimal grid resolution in the present study.

2.3 Development of Axial Velocity

Figure 2 compares the mean axial velocity profiles at several axial locations (normalized by the jet centerline velocity U_c at the expansion). It is seen that the standard *k-ε* and RSM models predict well the development of axial velocity in the area following the expansion, while the prediction of the standard *k-ω* model is in poor agreement with the experimental data [6], particularly at x/H>10. It is also interesting to note that predictions of the RNG *k-ε* and realizable *k-ε* models are similar to each other. Table 1 compares the reattachment lengths (normalized by D_0) for various turbulence models with the measurement of Lipstein [7]. The overall agreement between the computed and measured values is found to be favorable, except slight differences in the *k-ω* models.

2.4 Development of Radial Velocity

Figure 3 shows the development of the mean radial velocity profiles in the streamwise direction. It appears that within the uncertainty in the experiment, the results obtained from RANS simulations match well with the measurement for all the turbulence models tested here.

2.5 Development of Turbulent Kinetic Energy

Figure 4 shows a comparison of the turbulent kinetic energy profiles downstream of the expansion. It can be seen that reasonably good agreement exists between the predicted values and the measurements [6]. Similar to the axial velocity distribution, the standard *k-ε* and RSM models provide better agreement than other models, while the standard *k-ω* model considerably under-predicts the turbulent kinetic energy in the jet centerline, and shows a rapid decrease of *k* in the radial direction.

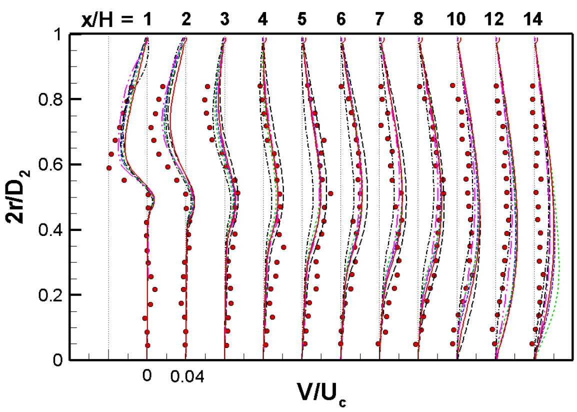

Fig. 3. Comparison of mean radial velocity profiles.

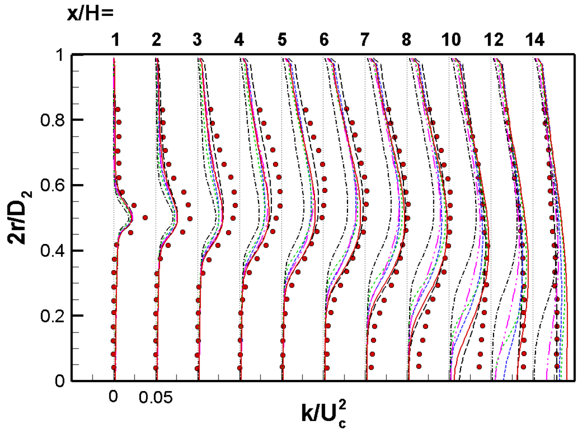

Fig. 4. Comparison of turbulent kinetic energy profiles.

3. Conclusions

In this study, the performance of turbulence models in predicting the turbulent flow in an axisymmetric sudden expansion with an expansion ratio of 4 is assessed for a Reynolds number of 5.6×10^4. The comparisons show that the standard *k-ε* and RSM models provide the best agreement with the experimental data, whereas the standard *k-ω* model gives poor predictions.

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