Diffusive Turbulence in a Confined Jet: A Numerical Study

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ABSTRACT

An investigation of the ability of Reynolds Averaged Navier-Stokes (RANS) models in predicting turbulent situations is conducted. Two RANS models, the k-ε and the second moment closure (Reynolds stress model), are evaluated using FLUENT computational fluid dynamics (CFD) software and the results are compared to the experimental data of Fabre & Risso[1]. The results demonstrate that the Reynolds Stress model is accurate in predicting the second order statistics and significantly more accurate in predicting axial velocity measured on the axis compared to the k-ε model. This implies that the Reynolds Stress model better describes the physics in this kind of diffusive flow.

1 Introduction

This research investigates the ability of RANS (Reynolds Average Navier-Stokes) fluid dynamics models to accurately predict turbulent flows. Two models, k-ε model[3] and Reynolds stress model (RSM)[4][5][6], are considered because of their use in computational fluid dynamics software and applications. RANS models are calibrated by a superposition of effects acting on a flow. In modeling a situation where turbulence is large compared to the mean flow, a better understanding of the influence of the effect on the model can be developed. This occurs in the experiment Turbulence in a Confined Jet (Fabre & Risso)[1] where a region of the experimental setup contains turbulent energy devoid of mean velocity. In this experiment, the behavior of a jet of water in an axisymmetric closed cylinder is explored. Comparing this experimental setup to simulation data, we can obtain a better understanding for how accurate the RANS models are in predicting diffusive turbulence.

2 Materials and Experimental Setup

All of the modeling was performed using Gambit 2.0.4 and Fluent release 6.1.18.

The experimental setup to be modeled was an enclosed tube of length H = 600 mm and inside diameter D = 77 mm. The tube was closed at the top, and the inlet and outlet were both located at the bottom. The inlet consisted of a circular section located at the center of the tube and having diameter d = 10 mm. The outlet consisted of an annular section with an inner diameter D’ = 70 mm and an outer diamer D (see figure 1). The fluid, which was modeled as water, was given an initial velocity of $\overline{U} = 2$ m/s at the inlet, and an initial turbulence level of $\frac{u'}{\overline{U}} = 2\%$, corresponding to a Reynolds number (Re) of 150,000 and a turbulent Reynolds number of 50 (Re_λ).

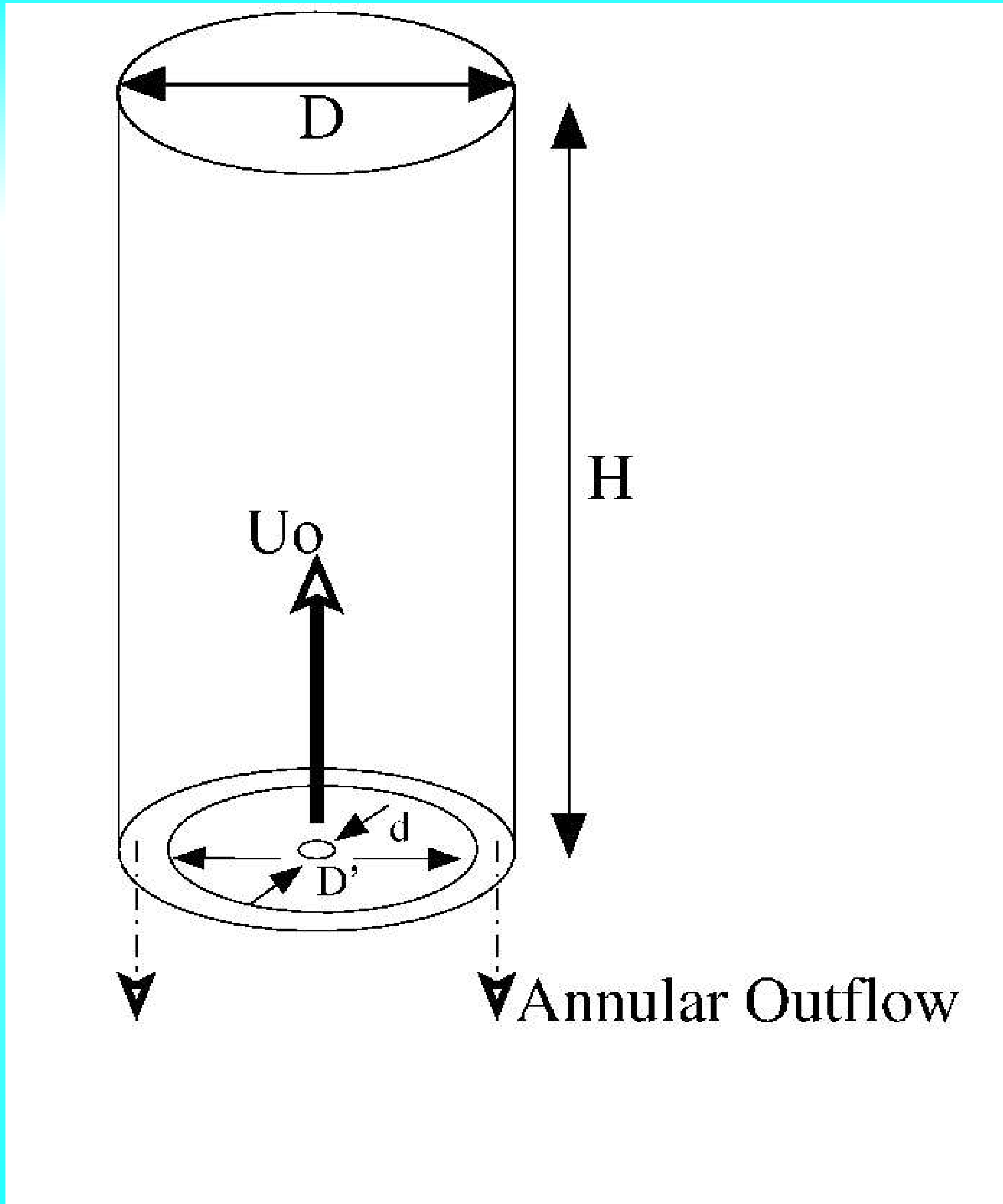

Figure 1: Experimental Setup

3 Convergence of Model

Two separate meshes were used in the model to determine the relative level of convergence. The first mesh used approximately 82,000 nodes. The second mesh used approximately 16,000 nodes. The results for the axial velocity for both meshes are compared in figure 2. The finer mesh was used to obtain the results shown below.

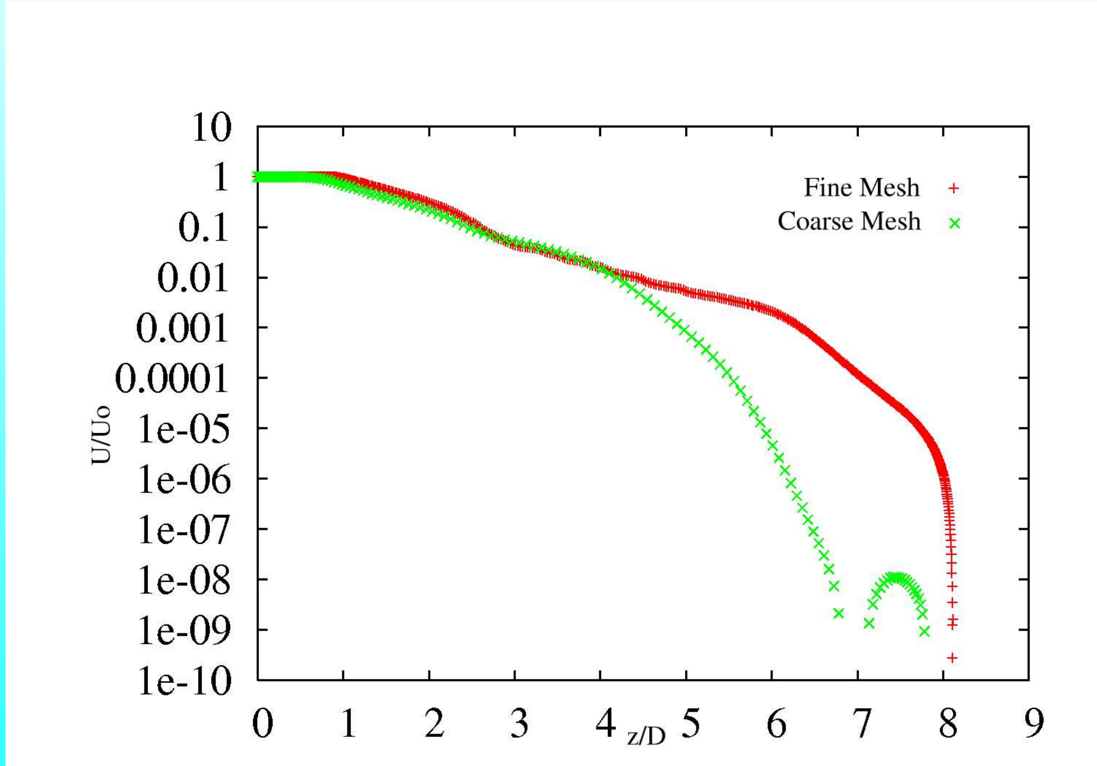

Figure 2: Mean axial velocities of coarser and finer meshes on a linear-logarithmic scale

The effect of the inlet axial velocity on the overall behavior on the model was also examined. The results for initial axial velocities of 2 m/s and 4 m/s ($Re = \frac{DU_0}{\nu} = 150{,}000$ and 300,000, respectively)for the coarser mesh are shown in figure 3 below.

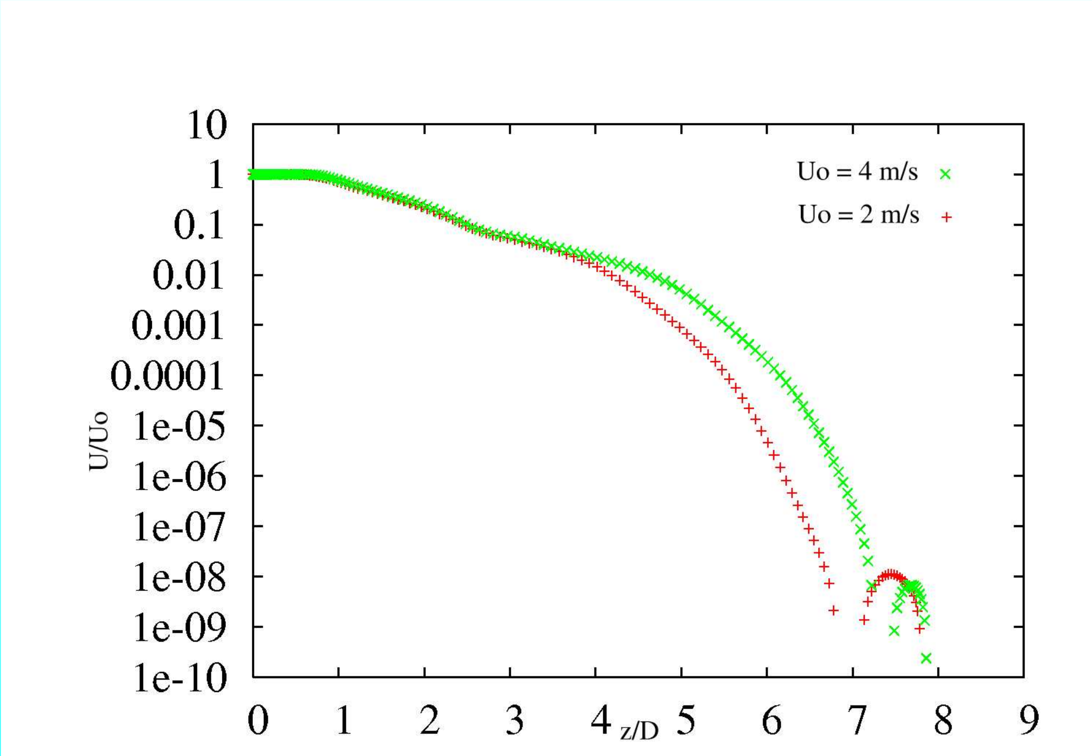

Figure 3: Mean axial velocities for $U_0 = 4m/s$ and $U_0 = 2m/s$ on a linear-logarithmic scale

4 Model Results

4.1 Reynolds Stress Model Contours

The results from the Reynolds stress model are shown below as contour graphs. The geometry used in the axisymmetric model is also shown in these figures. The stream function contour shows the paths that a particle would take if placed on a contour line in the flow. The turbulence kinetic energy contour shows how the kinetic energy decays across the flow, while the dissipation contour shows how the turbulent energy dissipates over the flow. So far, the secondary recirculation reported by Risso and Fabre [1] has not been produced by this model.

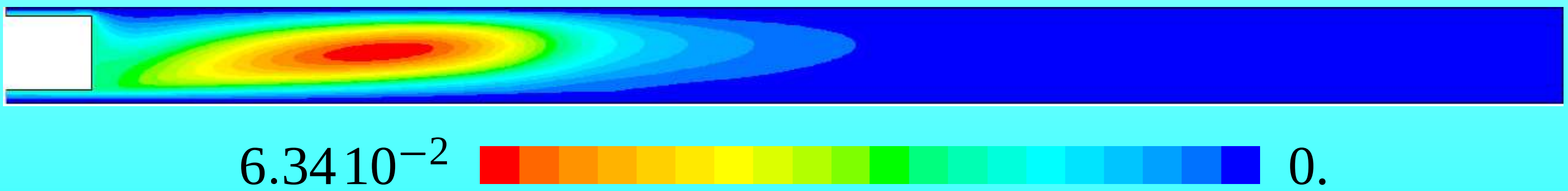

Figure 4: RSM stream function contour Re = 150,000

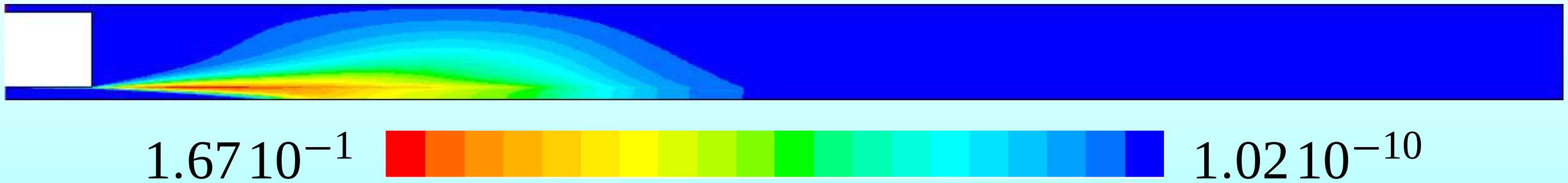

Figure 5: RSM turbulent kinetic energy contour Re = 150,000

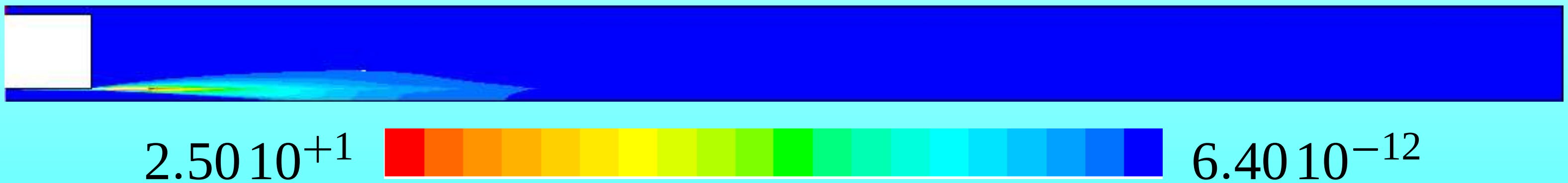

Figure 6: RSM dissipation contour Re = 150,000

4.2 Reynolds Stress Model Results

The results from the Reynolds Stress Model show good agreement with the experimental values, particularly in the region z/D $>$ 4. In the log plot, the RSM axial velocity and $\overline{uu}$ stress show exponential decays consistent with those shown by the experimental data.

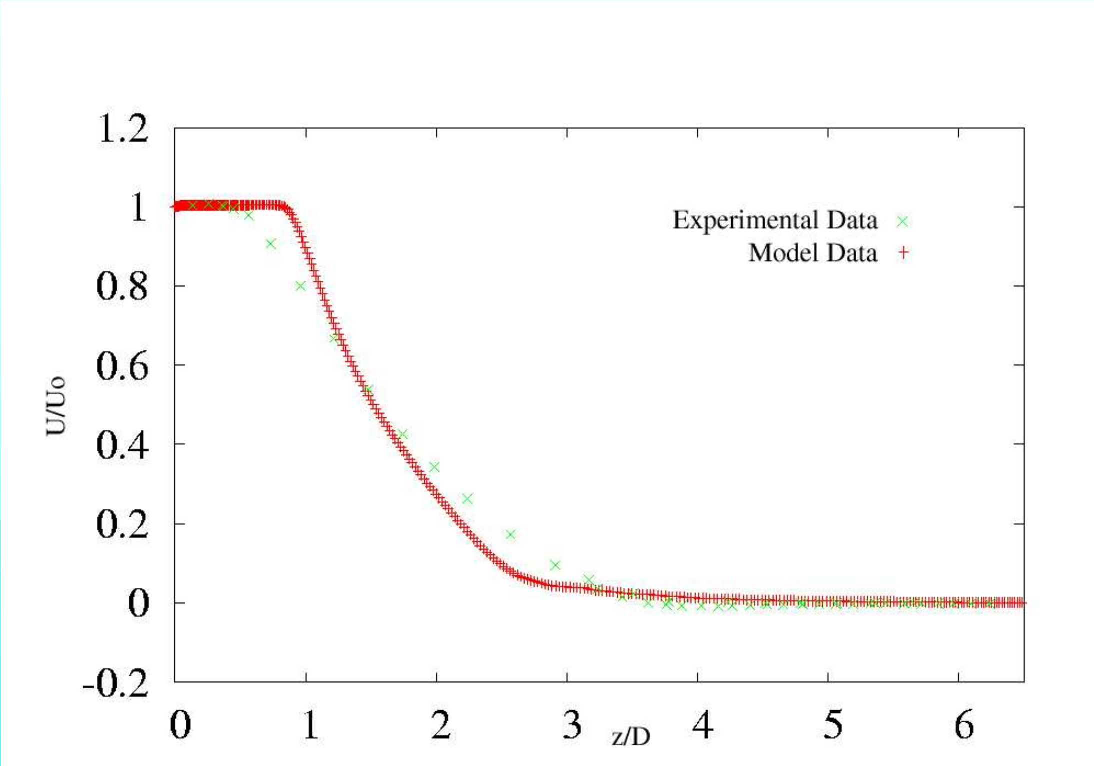

Figure 7: Experimental and RSM mean axial velocities

The log plot of the Reynolds stress model mean velocity and $\overline{uu}$ stress show that the model data decrease exponentially from $z/D \approx 3.5$. Fabre & Risso[1] advance exponential scales of decay for each statistical moment. These scales of decay are driven by the characteristic length scale, $L_n = \frac{L}{n}$, of the nth-order moment. They determined that the law of decay is the same for each moment, with a slightly different length scale, L/D, for each moment, which they determined empirically. These length scales are all close to 1, with, for example, L/D for the first moment, U, equal to 0.96, for the second moment, $\overline{uu}$, equal to 1.00. The general law of decay is expressed as $M_n(z) = M_n(z_0)e^{\left(-n\frac{z-z_0}{L}\right)}$, where z is the axial location in the jet. Therefore, the scales of decay are $y = e^{\left(\frac{-x}{0.96D}\right)}$ and $y = e^{\left(\frac{-2x}{1.0D}\right)}$ for the first and second moments, respectively. The comparison of the RSM and experimental data in Figures 8 and 9 below show the good agreement of the model data with these scales. Also, the shortcomings of the k-ε model are highlighted by a comparison with the experimental data, as well as with the RSM. This is made evident in the mean axial velocity graph in figure 8, where the axial velocity calculated by the k-ε model decays much more quickly than both the axial velocity calculated by the Reynolds stress model and that shown in the experimental data.

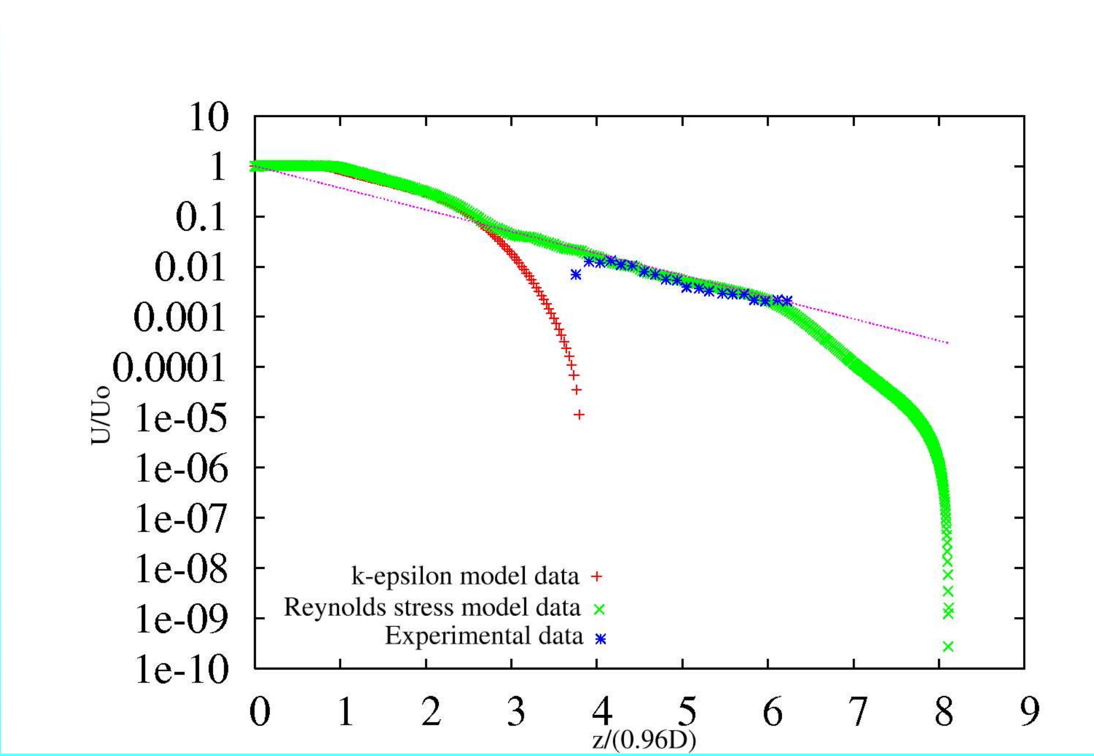

Figure 8: Linear-logarithmic comparison of experimental data, RSM, and k-ε model mean axial velocities with $e^{(-x)}$ decay

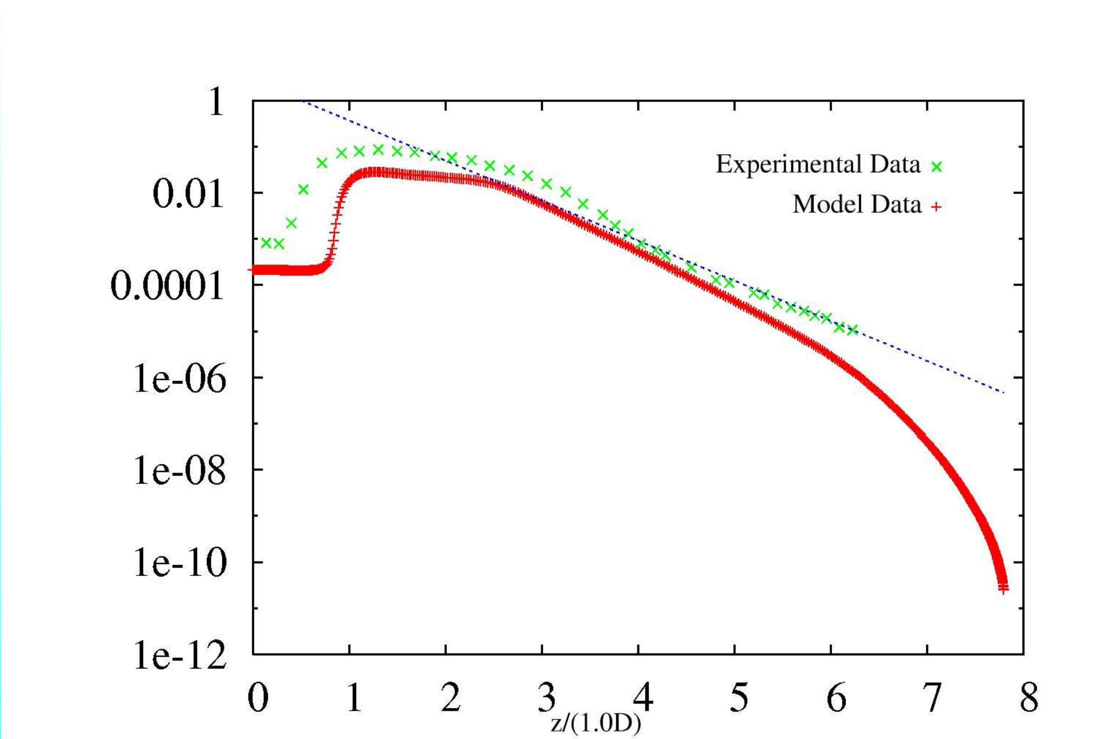

Figure 9: Linear-logarithmic comparison of experimental data and RSM $\overline{uu}$ stress with $e^{(-2x)}$ decay

The relative intensity of turbulence ($\frac{u'}{\overline{U}}$) and isotropy along the axis calculated from the Reynolds stress model is compared in figures 10 and 11 to that calculated from the experimental data by Fabre & Risso[1]. It should be noted that the return to isotropy exhibited by the RSM is slow compared to that shown in the experiment.

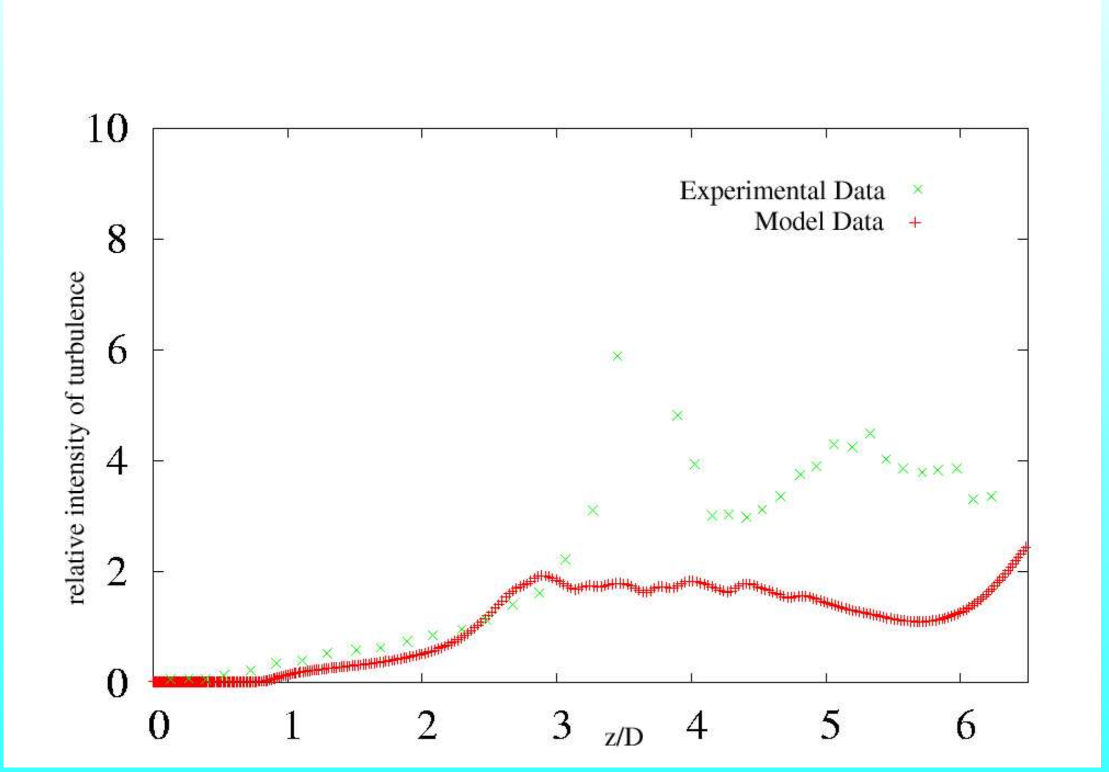

Figure 10: Relative intensity of turbulence ($\frac{u'}{\overline{U}}$) for experimental and RSM data

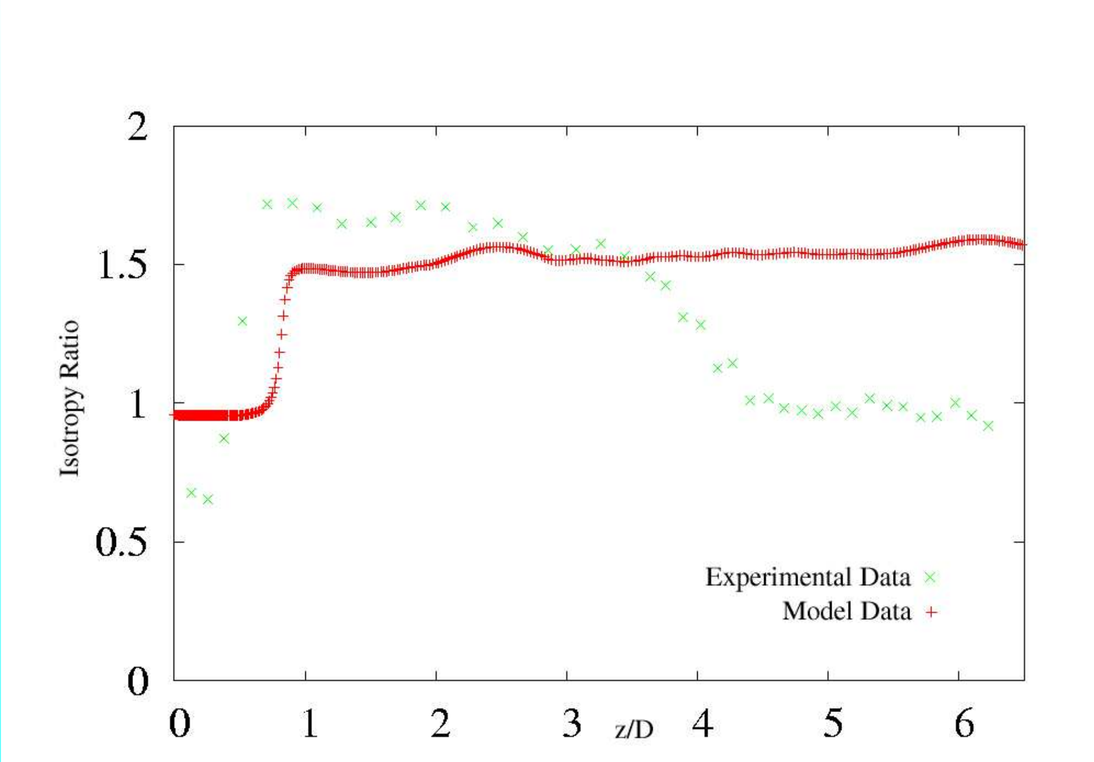

Figure 11: Isotropy of experimental and RSM data

6 Conclusions

- The k-ε model generates predictions that disagree with both Reynolds Stress model predictions and experimental data. This may be due to the assumption of isotropy inherent in the k-ε model.
- Both k-ε and Reynolds Stress models are very sensitive to inlet length and inlet boundary conditions. Small changes in the inlet values of k, ε, and $\overline{U}$ may cause large variations in the resulting data.
- Reynolds Stress models give accurate predictions in situations that are highly turbulent and anisotropic.
- Areas for possible further investigation include an investigation of the effect that varying inlet velocity and turbulence boundary conditions and model geometry has on the results, and an exploration of the effect that anisotropic inlet values would have on results. It would also be interesting to compute a Large Eddy Simulation, (3-D, unsteady, and computationally cheaper than DNS) to study the influence of large-scale unsteadyness on this particular flow.

References

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