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Numerical Validation of a Coaxial and Confined Jet Flow

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The purpose of this study is to investigate experimentally and numerically the flow behavior of a confined coaxial jet flow for two different velocity ratios Ru=0.04 and Ru=0.08. For the experimental analysis a two dimension particle image velocimetry system (2D-PIV) is used to measure the gas behavior in the measurement section. The numerical analysis is developed for four different Reynolds Average Navier-Stokes models: standard k-ε, k-ω, SST and RSM. The experimental and numerical results are presented in radial profiles in two different axial positions (L/D=3 and L/D=6) in terms of axial mean velocity and turbulence kinetic energy. All turbulence models showed a good qualitatively agreement in relation to the axial mean velocity analysis. However, the turbulence kinetic energy analysis showed that the Reynolds Stress model can better describe the flow behavior in the confined coaxial jet.

1. Introduction

Confined and coaxial jet flows are found in several industrial applications such as jet pumps, burners, ejectors, among others. In the confined jet, mixing is achieved mainly due to the velocity ratio, density ratio, compressibility and turbulence levels of the two streams, swirl, pressure gradient and free shear flows. In confined jets the entrainment of sufficient mass from the surroundings mainly depends on the mixture of the coaxial flows, i. e., it is strictly related to the vorticial structures of the flow which may vary according to the velocity ratio $Ru = U_{out}/U_{in}$ (U_{in} is the jet velocity and U_{out} is the co-flow velocity). In order to understand the mixture process in coaxial jet flows several authors are developing successful studies investigating the experimental and numerical behavior of these jet flows. Villermau and Rehab (2000) investigated the stirring and mixing properties of one-phase coaxial jet, with large outer to inner velocity ratio. Kiwata et al., (2006) made experiments to identify the interaction between axisymmetric and streamwise vortices in the unexcited and excited coaxial jet using hot film anemometry, particle image velocimetry (2D and stereoscopic) and laser induced fluorescence. Balarac et al., (2007) performed direct numerical simulations to analyze the flow dynamics and the mixing properties of natural unforced and excited coaxial jets at moderate Reynolds number. Mohmouda et al., (2010) proposed a numerical study of an axisymmetric turbulent jet discharging into co-flowing stream with Ru ranging between 0 and 4.5. More recently, Decker et al., (2010) analyzed with Phase Doppler Anemometry the shear region of a free turbulent jet flow (Ru =0) and observed the existence of consistent large scale coherent structures and mixture in the shear region.

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Thus, in order to investigate the turbulent phenomena in the shear flow region of coaxial jets, the main objective of this work is to study the behavior of four different turbulence models based on the Reynolds Average Navier-Stokes models, and to compare the numerical results with the experimental data obtained by a Particle Image Velocimetry (PIV) system for two velocity ratios Ru=0.04 and Ru=0.08.

2. Materials and Methods

2.1 Experimental Setup

In the test facility showed in Figure 1, a Pitot tube (A) is connected to a differential pressure transmitter in order to measure the mass flow ratio in the known transversal section. As the mass flow ratio inside the chamber is the same in the measurement section, the inlet mean velocity of the gas phase in the chamber (U_{out}) can be calculated. This velocity is maintained constant and controlled using a Programmable Logical Controller with a Proportional Integrative Derivative (PID) algorithm coupled to the radial ventilator located at the end of test facility (B), which is also responsible for maintaining the entire system under negative relative pressure. The velocity inside the jet (U_{in}) is provided by a compressed air system, which is connected to a relief valve and a flow meter (C). The measurements are obtained in the Plexiglass chamber (D) for different axial positions from the jet nozzle by means of a Particle Image Velocimetry (PIV) system (E). In order to measure the gas flow velocity at the jet (U_{in}) and at the chamber (U_{out}), very small TiO_2 (Dioxide Titanium) particles were used due to its ability to follow the gas flow (Stokes number <<<1). The TiO_2 particles are loaded in the flow system through an ejector located in the inlet region of the measurement device (F). All measured data are saved by Software Control and Data Acquisition (SCADA) software in known time steps in a computer.

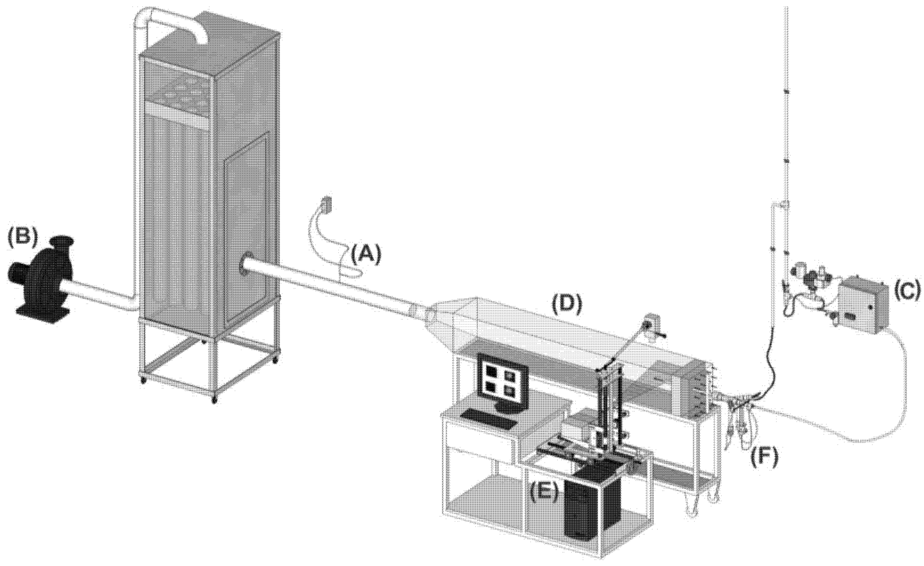

Figure 1: Test facility.

2.2 Operational and Geometrical Conditions

In the test facility, experiments were developed for an initial velocity in the jet (U_{in}) of 10 m/s (Re = 7,415). In the chamber, two different initial velocities (U_{out}) were adopted for the gas phase: 0.4 m/s (Re = 7,738) and 0.8 m/s (Re = 15,476). These two velocities U_{out} were also defined to give a relation between the Reynolds number in the chamber and in the jet around 1 and 2, respectively. Furthermore, the velocity ratios (Ru) obtained for both velocity conditions in the chamber were 0.04 and 0.08, respectively. The experiments were developed at 25°C. The PIV measurements were taken in a single horizontal plane in the middle of the jet nozzle. The measurement area is 140mm length x 100mm width (top view in Figure2), which means from 0 to 140mm from the jet nozzle and 50mm for each radial side from the jet center line. After calibration of the 2D-PIV system, 1000 frames were taken in the measuring region with a time step of 100µs. After the computation of the vector plane by the PIV software Davis 7.2, two different axial positions were selected to investigate the radial profiles in terms of mean velocity and turbulence kinetic energy. These positions are located in a chamber length per jet diameter relation (L/D) of 3 and 6. The geometrical conditions are presented in Figure 2.

Figure 2: Geometrical conditions and measurement section.

2.3 Mathematical Modeling

The objective of this study is to investigate the behavior of the Reynolds Average Navier-Stokes (RANS) equations in a confined coaxial jet flow for different velocity ratios. For this proposal, four different turbulence models were investigated: k-ε model, k-ω model, Shear Stress Transport model and Reynolds Stress Model with version of Lander, Reece and Rodi (RSM-LRR). The three first models are two equation models based on the eddy viscosity hypothesis. In the solution of these models two additional equations are used to represent the turbulent properties of the flow and are used to take account the effects of convection and diffusion of turbulent energy. The last one, RSM-LRR, is a second order turbulence model. It is usually called a Second Order Closure. In RSM-LRR, the eddy viscosity approach has been discarded and the Reynolds stresses are directly computed. The exact Reynolds stress transport equation accounts for the directional effects of the Reynolds stress fields.

2.4 Boundary Conditions

The boundary conditions for physical frontiers of the coaxial confined jet flow are:

Inlet (Chamber and Jet): It is adopted an uniform and constant properties of the gas flow with an initial velocity condition.

Outlet: Constant pressure with continuity conditions considered for all flow properties.

Wall: No-slip conditions and wall logarithm function for the turbulent properties.

2.5 Numerical Modeling

The three dimension and transient numerical simulations were conducted by a CFD commercial package, the CFX 12. The geometrical grid used in this simulation consists in approximately 480,900 hexahedrical elements refined in direction to the jet nozzle. The advective scheme used in the simulation was High Resolution due to the strong convective component of the gas transport. The convergence criterion for all studied cases was 10^{-4} in the Euclidian norm of the residues. The interactions were solved with an adaptive time step varying from 10^{-5}s to 10^{-2}s, totalizing 5s of real time simulation.

3. Results

The numerical and experimental results are presented in Figure 3 and Figure 4 in terms of axial mean velocity profiles and turbulence kinetic energy profiles, respectively. In both situations two velocity ratios are compared (Ru = 0.04 and Ru = 0.08) for two different axial positions from the jet nozzle (L/D = 3 and L/D = 6).

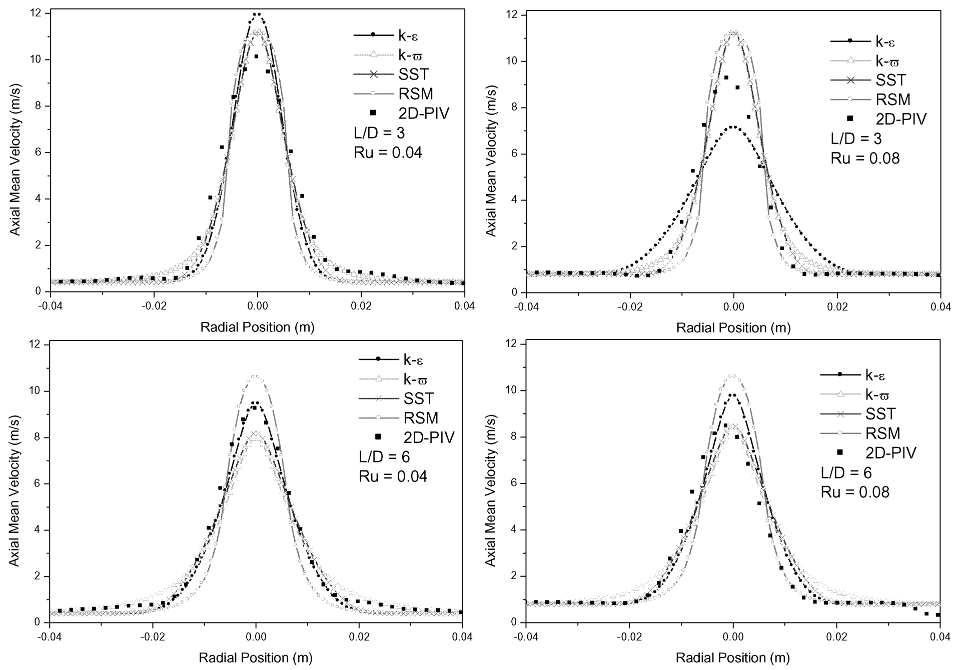

Figure 3: Axial mean velocity profiles for different axial positions (L/D=3 and L/D=6)and velocity ratios (Ru=0.04 and Ru=0.08).

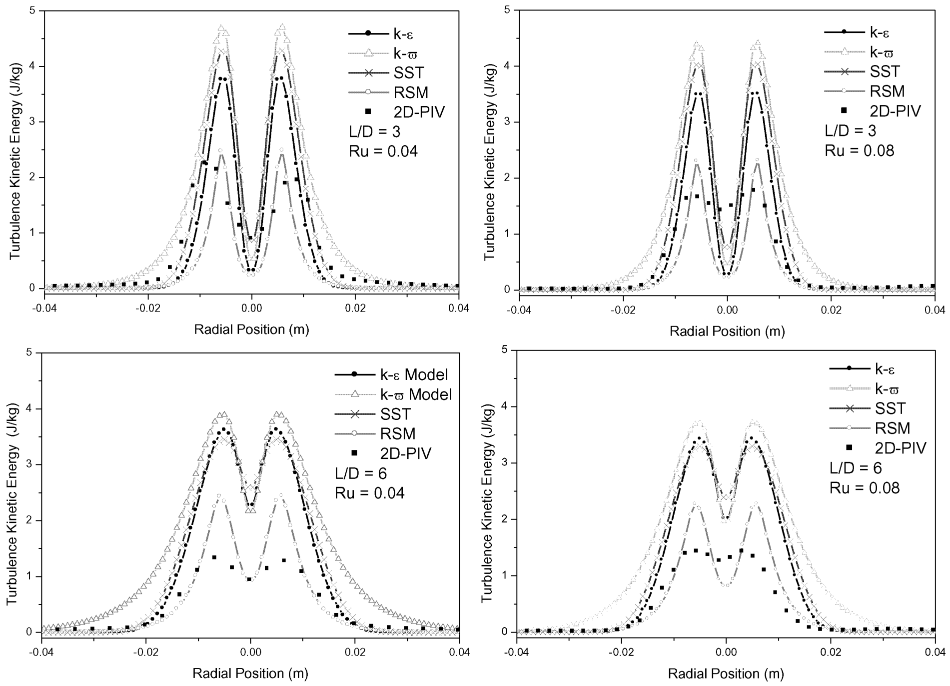

Figure 4: Turbulence kinetic energy profiles for different axial positions (L/D=3 and L/D=6) and velocity ratios (Ru=0.04 and Ru=0.08).

In Figure 3 it is possible to observe for a radial position L/D = 3 and Ru = 0.04 that the numerical results are over estimated in relation to the experimental data. However, with the increment of the axial position (L/D = 6) the k-ε model seems to reproduce the experimental data for Ru=0.04. If Ru is changed from 0.04 to 0.08 at L/D = 6, the model which better predicts the behavior of the flow, according to the experimental data, are the k-ω and SST models.

The RSM-LRR for all analyzed conditions seems to over predict the values of the axial velocity in the centre line of the jet (radial position around 0.0). However, in radial position near the shear region the RSM-LRR showed a good agreement with the experimental data in the same level observed with the others turbulence models.

Based only on the numerical analysis of the axial mean velocity profiles no conclusion can be made because all numerical models described qualitatively the behavior of the coaxial flow. Extending this analysis, Figure 4 presents the turbulence kinetic energy profiles in the same positions and conditions previously detailed. In this analysis the RSM-LRR showed to have results nearly to the experimental ones. These results can be explained by the anisotropic characteristics of the coaxial jet. A second model to be obtained from this analysis is the k-ε model. This model presented over estimated values for turbulence kinetic energy analysis, but in an inferior level when compared to the k-ω and SST models. Figure 5 shows the similarities between the numerical and experimental results in the measuring section for RSM-LRR at Ru=0.08.

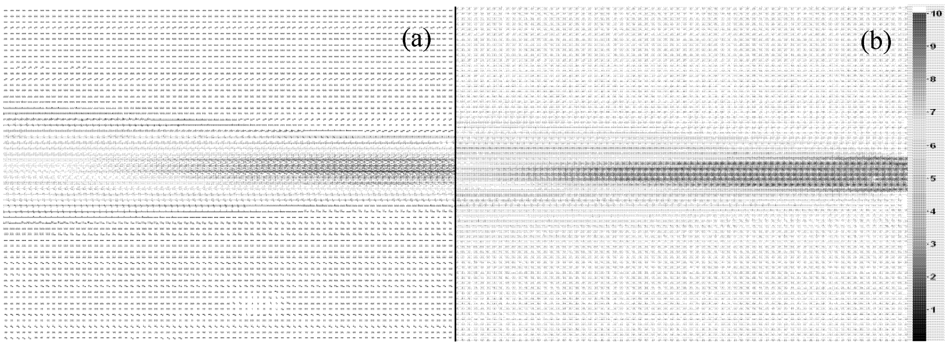

Figure 5:Axial mean velocity (m/s) comparison between 2D-PIV experimental data (a) with RSM-LRR numerical results(b) for Ru = 0.08, in the measurement section.

4. Conclusions

The comparison between RANS models simulations with PIV experimental data showed a good agreement mainly when the RSM-LRR is used. This observation was taken due to the turbulence kinetic energy analysis, once the axial mean velocity analysis showed that the others turbulence models could also be used to predict the mean velocity of the coaxial jet flow. The turbulence coaxial jet flow showed its anisotropic nature due to the better validation with the Reynolds stress model. In this sense, as future works, the gas-solid flow in coaxial jets can be analyzed and the Reynolds stress model can be applied for the CFD simulations. The use of TiO_2 particles with mean diameter of 0.4μm as tracer for the experimental data acquisition showed to be very useful to measure the gas flow.

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