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Original Research Article

Flow features of confined swirling jets

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Abstract

Assessment of LES models of confined coaxial swirling jets is the aim of this paper. Despite the simple geometrical set-up of the benchmark, the flow pattern shows complex aerodynamic behavior. The case considers two coaxial jets: one axial and another annular swirling jet. The expansion when entering the chamber will produce the Outer Recirculation Zone (ORZ). If swirl number is large enough, an Inner Recirculation Zone (IRZ) is formed. The region between both recirculation zones with high shear is where mixture occurs. Post-process in space and frequency domain supplies useful information of this benchmark. Kernel cores are identified based on the lambda2 parameter. The mesh must be fine enough to capture the inertial regime of the turbulent energy spectrum. Proper Orthogonal Decomposition let identify main flow structures. To sum up, LES models provide more information than conventional RANS models and it is a step forward in any research team to gain an insight of any transitional or fully turbulent process.

Keywords: CFD, LES, Mixing, Vortex, Swirl number

1. Introduction

Combustion with swirling flows in enclosed chambers is common because of advantages such as the flame stability of lean mixtures, combustion efficiency and low NOx emissions. Those have impact on fuel saving, improving quality of products and make process environmentally friendly.

Main characteristic phenomena as recirculation zones and shear layers must be well identified. Hence this paper focuses on gaining insight on flow patterns for the isothermal case.

Large Eddy Simulation (LES) is to describe mixing more accurately than traditional RANS approaches. Traditional Reynolds - Averaged Navier - Stokes (RANS) predicts mean flow fields that are important in the design of combustion chambers. However problems as flashbacks, hot spots, instabilities and quenching are better predicted by the use of Large Eddy Simulations (LES). This is a challenging methodology to achieve accuracy but it requests demanding computational cost.

LES is a state of the art able to provide better accuracy than traditional RANS models. A paradigm of the computer science progress is that LES tools are growing very fast.

The aim of this work is analysing the interaction of two confined non-reacting coaxial swirling jets using the Large-Eddy Simulation approach, [1]. Using the suite of libraries OpenFOAM® the benchmark of Roback and Johnson [2] has been modelled.

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Despite the simple geometrical set-up of the test-case, the flow shows complex behaviour patterns. It is a transitional turbulent the regime with Reynolds number 2400 based on bulk velocity and chamber diameter and swirl number around unity in the annular jet. Test chamber has a sudden expansion ratio of 4 based on area with reference to the annular nozzle. See fig. 1 and table 1 for geometrical dimensions and operating conditions.

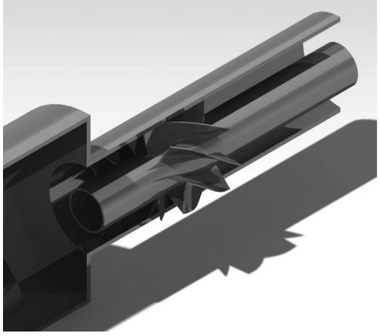

Figure 1 Scheme of the swirling burner of Roback and Johnson [2] with swirler angle 62º

2. Numerical Model

Any LES model requests spatial resolution on the wall should be y+ = 1 such as proposed by [3-4]. Hence a uniform hexahedral mesh with 10.3 million of grid points was constructed using the SnappyHexMesh utility.

Table 1. Boundary Conditions

Variable	**Central nozzle**	**Annular Nozzle**
Radio (inner-outer) (m)	0-0.0125	0.0128-0.0295
Velocity (m/s)	0.66	1.54
Turbulence Intensity	12 %	7.5 %
Density (kg/m3)	1.225	
Viscosity (kg/m/s)	$1.72.10^{-5}$	

The mesh includes the test chamber (Δ~d/190), the central (Δ~d/40) and annular (Δ~d/46) nozzles and an axial swirler formed by eight flat-vanes with pitch angle 62º.

The final domain including two nozzles, swirl generator and test chamber has over 10 million cells. The domain decomposition process was established to minimize the processor boundaries and therefore, saving information transfer time.

The selected implicit LES (iLES) model uses a filter width related to the mesh size and no subgrid model is applied [5-6]. Since the subgrid stress tensor has a dissipative nature, this role is played by the numerical error.

The numerical error is controlled using different kind of limiters and schemes, such a TVD scheme with a coefficient that corresponds with good accuracy.

3. Numerical Results

As for post-process tasks, instantaneous and time-averaged flow fields have been analyzed, see fig. 2.

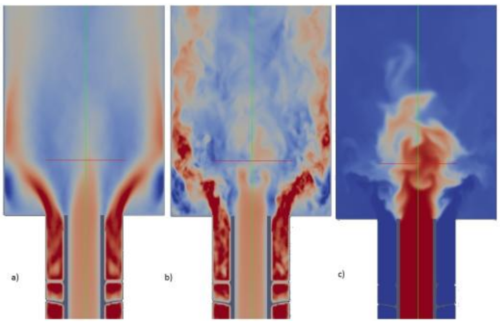

Figure 2 Flow field in a longitudinal plane. a) Averaged axial velocity, b) Instantaneous axial velocity, c) Instantaneous passive scalar

Because the resulting swirl number of annular nozzle is around unity, there is reverse flow in the middle of the chamber. Fig. 3 shows the surfaces of null iso-velocity that represent the limits of the recirculation zones. The outer near the wall chamber is due to the sudden expansion whereas the inner is because of pressure distribution associate to the swirling of the annular jet, [7].

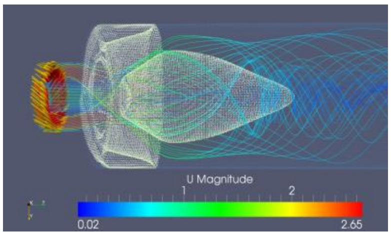

Figure 3 Averaged stream lines with color corresponding the velocity magnitude, diagram of vectors for the annular inlet and isosurfaces of axial velocity zero in white showing two the recirculation zones.

A thorough comparison with experimental data from [1-2] has been carried out in order to validate the model, see a sample of profiles in fig. 4.

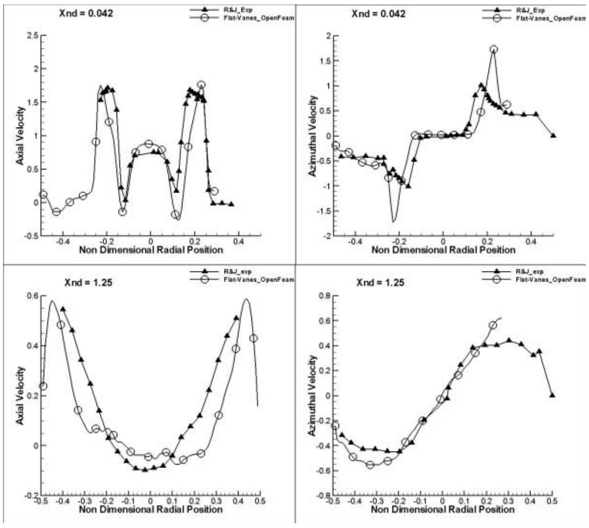

Figure 4 Validation of averaged axial and tangential velocity profiles (m/s) showing the comparison of the OpenFOAM model with experimental results from [2]. Any radial and axial position is made non-dimensional by using the diameter of the test chamber.

Negative values of the axial velocity evidence the existence of recirculation zones. It is clear the presence of ORZ in axial section 0.042 D and the presence of IRZ in axial section 1.25D. Bearing in mind the azimuthal velocity, numerical results show a good agreement with the experimental results.

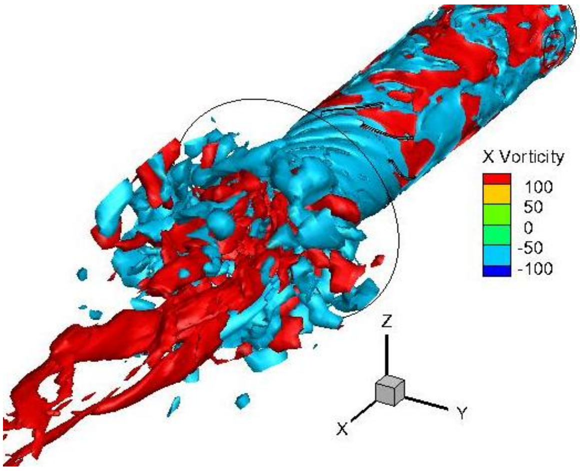

Figure 5. Surfaces of iso-vorticity trying to represent vortex kernels.

An important issue is the procedure to capture small vortices in LES simulations. Conventional criteria based on minimum pressure or maximum vorticity are nor suitable for this kind of results as it is evident in Fig. 5.

Lambda 2 is the second eigenvalue of tensor S^2+R^2 being S and R the strain and vorticity tensors respectively. Lambda 2 is lower than zero inside the vortex kernel, hence it is a useful tool to identify vortex structures such as Fig. 6 depicts.

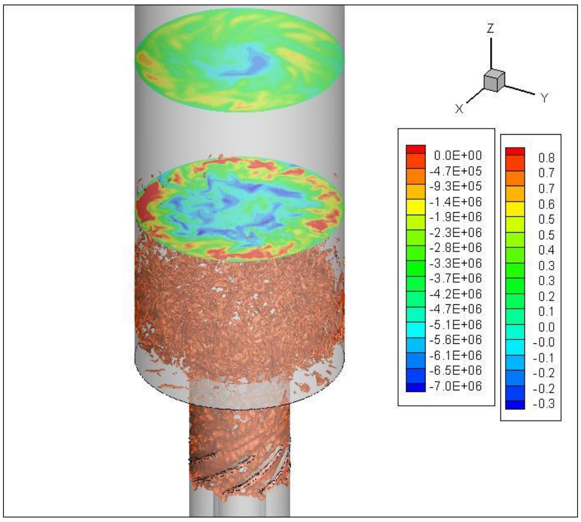

Figure 6. Isosurfaces of Lambda2 equal to -500000 to represent vortex kernels. Slices at axial positions z = 15mm and 25 mm with axial velocity ranging from -0.3 to 0.8 m/s.

Proper Orthogonal Decomposition (POD) supplies information about the most energetic flow structures and let analyze the decay or persistence of swirl structures.

Figure 7 shows the averaged flow and mode 2 that let identify the main vortices of the transversal section as well as the secondary flows generated in the 8 vanes of the swirler.

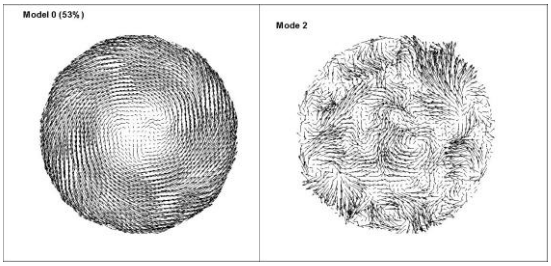

Figure 7. POD results for Modes 0 and 2 in Xnd = 0.42.

Probes located on the free turbulence

region provide information of the energy decay to confirm if fully developed turbulence was achieved and if the grid resolution is fine enough. Figures 8 evidence the correct slope of -5/3 associated to the inertial regime of the turbulence energy spectrum.

4. Conclusions

Large Eddy Simulation has been used to study the flow pattern and mixing of two isothermal confined coaxial jets. Annular swirling jet was generated with a swirl generator composed by 8 flat plates located in the annular nozzle with a resulting swirl number of 1.2.

Averaged fluid field was validated with experimental results provided by Roback and Johnson [2]. Inner and outer recirculation zones where identified on the averaged flow.

In addition, the analysis on the frequency domain let identify energetic vortex structures using Proper Orthogonal Decomposition. Also the energy spectra is obtained verifying the energy decay on the inertial regime.

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