The asymmetry of the recirculation zone of the annular jet with different diameter ratio

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Abstract. We performed direct numerical simulations of the annular turbulent jet flow for the Reynolds number based on the bulk velocity inside the nozzle and its outer diameter Re = 8900 with three different values of the inner-to-outer diameter ratio $a = d / D = 0.3, 0.5, 0.7$. The size of the reversal flow region, the fluctuation level and mixing rate increase with the increase of the diameter ratio. For all the cases of geometry parameters the symmetry breaking phenomenon was detected. The degree of asymmetry increases with the increase of the diameter ratio resulting in the displacement of the global stagnation points from the axis of symmetry and the deflection of the averaged streamlines from the jet axis.

1. Introduction

Annular jets have a simple axisymmetric geometry that consists of two coaxial cylinders with the inner one acting as a bluff body. Thus there is a recirculation zone that leads to the formation of two shear layers. The first one is between the recirculation zone and the jet, while the second one appears between the jet and co-flow. In case of gas combustion a recirculation bubble due to the bluff-body helps to stabilize the flame and reduce the pollutant emission [1,2]. This feature is widely employ in burner facilities.

The near field of annular jets consists of three zones depending on a shape of radial velocity profiles, i.e. the wake profile with negative and positive axial velocity and gaussian-like profile [3,4]. In all the zones velocity profiles has self-similarity properties. While the far field velocity profile is similar to the one in a round jet. In the near field a number of numerical [5,6] and experimental [2,7,8] investigations shows the spontaneous break of symmetry of the reversal flow area. In turbulent flows this asymmetry may be explained by the low-frequency oscillations observed in experimental works [7,9,10] as well as in numerical simulations [2,11]. However this phenomenon occurs also in laminar jets [5]. The symmetry breaking phenomenon was also observed for a number of configuration including the flow over a disk [12,13], a bullet-like obstacle [14] and a rectangular Ahmed bluff body [15,16].

One of the possible mechanisms of transition to asymmetry was proposed by Del Taglia [8]. Perturbations from the boundary layer near the inner cylinder of the nozzle are convected downstream the flow to the stagnation point and cause a shift in its location. Whereas these perturbations are random the choice of an appropriate time-averaging interval must provide axisymmetric flow fields, but for the real flows this asymmetry is observed for time-converged statistics.

In present paper we use the Spectral element based code Nek5000 [17] and Direct numerical simulations to perform the three-dimensional unsteady calculation of the Navier-Stokes equation. The
results of the simulations are carefully analyzed. We show the time-converged flow fields that reveal the asymmetry of the reversal flow for all the values of the diameter ratio.

2. Methods and problem formulation

We perform Direct numerical simulations (DNS) of the annular turbulent incompressible jet in a cylindrical domain with a co-flow (see Fig. 1). The size of the domain is 12D × 17D and the magnitude of the co-flow is Uc = 0.04Ub, with D and Ub being the supplying pipe outer diameter and bulk velocity, respectively. The pipe length is 2D and the diameter ratios are d / D = 0.3, 0.5, 0.7, while the wall thickness is 0.03D. The Reynolds number Re = Ub D / ν is 8900. A turbulent velocity profile for the supplying pipe is generated using an auxiliary simulation of a periodic annular 2.5D channel. The instantaneous fully developed velocity profile from some r – θ plane of the auxiliary channel is copied to the inflow boundary of the main domain every timestep. On the other boundaries the Neumann boundary condition was imposed. We use the cylindrical coordinates system (x, r, θ) and place the origin in the center of the bluff body at the end of the supplying pipe.

![Figure 1. The main computational domain with the axial instantaneous velocity field for the case d / D = 0.7. The purple isosurface of the time-averaged zero axial velocity indicates the asymmetric reversal flow region.](image)

The total number of the spectral elements was about 7700, 5120, 3200 in the auxiliary channel and 127700, 124400, 122400 in the main domain for the cases d / D = 0.3, 0.5, 0.7, respectively. We use polynomial order N = 7 providing 103 computational nodes inside the spectral elements thus the total size of the computational mesh of the main domain was about 127.7 × 10^6, 124.4 × 10^6, 122.4 × 10^6. The distance between the computational nodes near the outer wall inside the auxiliary channel was ∆r⁺ = 0.5, r(∆θ)⁺ = 4.9 and ∆x⁺ = 10 for radial, azimuthal and axial directions satisfying the near-wall resolution criteria [18]. The superscript + denotes the distance units non-dimensionalized with the friction velocity and viscosity. The comparison of time-averaged auxiliary channel flow fields with DNS data base [19] shows good agreements.

To perform the DNS we use Nek5000 [17] which is based on the Spectral–element method (SEM) [20]. The Navier-Stokes equations are discretized in space with the use of the Galerkin approximation.
with \( P_{N} \) - \( P_{N} \) formulation). The time discretization is performed by means of the semi-implicit third-order accuracy scheme. The accuracy of Nek5000 was previously validated for a number of configurations including the channel flow and non-swirling annular jet [21,22].

3. Results

We collect time-averaged data (the first and the second moment) during 100 non-dimensional time units in term of the outer diameter and the bulk velocity \( (t \times U_b / D) \). The isosurface of the axial time-averaged velocity corresponds to the zero value and represent the reversal flow region providing a general impression on the flow topology. The flow shows asymmetric behavior in this area for all the geometry parameters (see Fig. 2).

Figure 2 shows the time-averaged axial velocity distribution in the \( r \) – \( \theta \) plane that corresponds to the end of the supplying pipe. The blue isosurface indicates the reversal flow region. White and red points correspond to the axis of symmetry and the global stagnation points, respectively. With the increase of the diameter ratio the stagnation point shifts from the symmetry axis with the reversal flow region becoming asymmetric. In the near field of the jet we look at two main cross-sections. We call the “asymmetric” plane the cross-section passing throw the axis of symmetry and the stagnation point while the orthogonal plane is referred to as “symmetric”. Figure 3 shows the time-averaged streamlines and axial velocity field in these two planes. In the asymmetric plane (the upper row) the reversal flow is nonparallel to the axis of symmetry and this angle increases with the increase of the diameter ratio. In the symmetric plane (the bottom row) the streamlines are mostly parallel to axis but the flow is slightly asymmetric near the bluff body.

The asymmetry can be caused by low-frequency oscillations of the reversal flow region [7]. To exclude this possibility we investigate convergence of the averaged axial velocity. The convergence is presented in Fig. 4. A changing of streamline directions (the upper row) corresponds to a chaotic motion of the recirculation area inside the first quadrant. In the bottom row where the time-averaging interval smoothly increases the averaged velocity field is converging. The reversal area stays in a specific point up to 100 nondimensional time units.

![Figure 2. The axial time-averaged velocity fields in the \( r \) – \( \theta \) plane with \( x / D = 0.0 \). The blue isosurface indicates the reversal flow region.](image-url)
Figure 3. The axial time-averaged velocity in the near field with streamlines.

Figure 4. Streamlines and averaged axial velocity field in $r - \theta$ plane with $x / D = 0.42$ for $d / D = 0.7$. The upper row shows the axial velocity averaged during 5 consecutive time units, in the bottom row the time averaging interval increases on 5 units.
Conclusion
We performed Direct numerical simulation of the incompressible annular jet flows for different diameter ratios using Nek5000. The averaged fields show the increase of the fluctuation level and mixing rate while the diameter ratio increases. Thus one can easily provides a higher mixing level of reagents with increasing of the inner cylinder diameter without adding moving parts to facilities. The symmetry breaking phenomenon was observed for all the values of the diameter ratio, however for a = 0.3 the asymmetry is not so pronounced. The global stagnation point displaces from the jet axis with the increase of the diameter ratio and the angle between the axis and the direction of time-averaged streamlines increases.

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