Direct numerical simulations of the turbulent annular jet with different diameter ratio

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Abstract. We performed direct numerical simulations (DNS) of the turbulent annular jet flow for the Reynolds number Re = 8900 with three different values of the inner-to-outer diameter ratio (a = d / D = 0.3, 0.5, 0.7). The time-averaged velocity fields and fluctuations were analyzed. The low aspect ratio results in the shortest recirculation zone while for high a value the stagnation point features high level of turbulent kinetic energy. This is the evidence of the accompanying low-frequency oscillations of the recirculation zone.

1. Introduction
The annular jets are of practical interest due to the widespread industrial applications. The main feature of these types of flows is the recirculation zone behind the central bluff body. There are two mixing layers with the first one formed between the recirculation zone and the jet, while the second between the jet and the coflow. Such type of flows are traditionally employed in burner devices since the flow recirculation helps to stabilize the flame [1].

First experiments were performed by Ko and Chan [2, 3, 4], who considered the near field for various configurations of the geometry of the central bluff body and isolated three separate zones: the initial merging, the intermediate and the fully merged zone after the recirculation flow region. In all these regions similarity of the mean velocity and the turbulence intensity profiles in the outer mixing region was observed. Maher Aly et al. [5] experimentally investigated the annular jet with large diameter ratio and showed that the velocity and fluctuation fields are similar to the round jet profiles after the separation point. Davies et al. [6] investigated the influence of the diameter on the flow characteristics behind the disk and the effect of the bluff-body geometry. They showed that the higher the diameter ratio, the more intensive the reverse flow, while the stagnation point moves upstream to the disk.

Various authors [7, 8, 9] among others identified the presence of the low-frequency oscillatory motion of the recirculation zone in different configurations of the separated flows. With the help of Proper Orthogonal Decomposition (POD) Patte-Rouland et al. [10, 11] showed that the first four modes, containing up to 90% of turbulent kinetic energy, are responsible for the oscillatory motion of the recirculation zone in an annular jet. Similar results were obtained by Gentile et al. [12] for flow behind the bullet. They showed that first two POD modes contain the major part of the turbulent kinetic energy (up to 60%). The analysis of the time coefficient of the POD modes revealed the peaks in the very low frequency range with St = 0.0003-0.0005, where St is a Strouhal number based on the
bluff-body diameter. The authors of [13] found out that the angular misalignment led to the switch from the disordered stochastic motion to the oscillation around the axis with small amplitude.

Most of the authors consider high diameter ratios. Sheffer et al [14] showed that the recirculation zone length extends twice compared to the diameter ratio 0.25 while the flame stability is significantly increases. Amelie Danlos et al. [15] used a number of experimental techniques to investigate an annular jet with a large diameter ratio, which was equal to 0.9. They observed an asymmetry in the recirculation bubble. The one of the first who observed and explained this phenomenon was Del Taglia [16]. These results were validated by three-dimensional LDA measurements of the annular jet flow with great diameter ratios (d / D = 0.94). However, the effect of the diameter ratio is not fully explored in the literature. In the present paper we focus on the influence of the diameter ratio of the flow characteristics in the near field region.

2. Computational details and problem

We perform Direct numerical simulations (DNS) of the incompressible Navier–Stokes equations for the annular jet flow using Nek5000 [17]. The Reynolds number Re = 8900, based on the bulk velocity $U_b$ and the outer diameter $D$, while the value of the inner-to-outer diameter ratio $a = 0.3, 0.5, 0.7$. Nek5000 is based on the spectral-element method (SEM) proposed by Patera [18] where the governing equations are cast into the weak form. The spatial discretization is based on the Galerkin approximation, following the $P_N$–$P_N$ formulation. The solution of the Navier–Stokes equations is decomposed inside each element using the orthogonal basis based on Legendre polynomials of the Nth order for velocity and pressure fields. These polynomials are built using the Gauss–Lobatto–Legendre (GLL) quadrature points. The nonlinear terms are treated explicitly by third-order extrapolation scheme (EXT3), while the viscous terms are discretized using a third-order backward differentiation scheme (BDF3). In our group Nek5000 has previously been validated for a channel flow and annular jet using the Large eddy simulations (LES) [19, 20]. The present results have been obtained using comparably high polynomial order ($N = 9$).

Figure 1 shows two computational domains. The small annular channel with periodic boundary conditions (on the left) was used to generate fully-developed turbulent velocity fields, which were copied to the feeding channel of the main domain every computational time step. This part of the simulation was validated using the DNS data provided by Chung et al. [21] showing excellent agreement. The thickness of the nozzle outer wall of the main domain was set to 0.03$D$, while the coflow was chosen to be equal to 0.04$U_b$. No-slip boundary conditions were imposed on solid walls and the Neumann boundary conditions were applied on the open boundaries. The mesh was built to satisfy the DNS near-wall resolution criteria $\Delta r_+ < 0.5, r(\Delta \theta_+) < 5, \Delta x_+ < 10$ [22], where the

![Figure 1](image-url)
Figure 2. The time-averaged axial (top) and radial (bottom) velocity fields for $a = 0.3, 0.5, 0.7$.

Figure 3. Left: The time-averaged axial velocity along the centerline. Right: Turbulent kinetic energy.

subscript “+” denotes the wall unit. The total number of spectral elements was about 7700, 5120, 3200 in a smaller domain (precursor simulation) and 127500, 126600, 129000 in the main domain for $a = 0.3, 0.5, 0.7$, respectively. Since we used $N = 9$, the total number of computational nodes inside every spectral element was $10^3$, resulting in $127.5 \times 10^6 126.6 \times 10^6 129 \times 10^6$, for $a = 0.3, 0.5, 0.7$.

3. Results

In order to get a general impression on the flow we show the time-averaged axial and radial velocity fields in $r-x$ plane for $a = 0.3, 0.5, 0.7$, see figure 2.

The main integral characteristics shown in figure 2 provide information about the size of the recirculation zone and the location of the stagnation point. A high level of fluctuations appears in the inner and outer shear layers and also at the end of the “bubble”. Figure 3 shows the time-averaged axial velocity along the centerline as well as the level of turbulent kinetic energy. The “bubble” length is $x/D = 0.4, 0.58$ and $0.66$ for $a = 0.3, 0.5, 0.7$, respectively.

Figure 4 shows the distribution of time-averaged radial profiles of the axial and radial velocity at several axial positions. The axial velocity in the outer mixing layer behaves similarly for all three cases. At the same time the wide recirculation zone for $a = 0.7$ results in the intensive entrainment according to the high level of radial velocity compared to $a = 0.3$ and 0.5. However at $x/D = 1.0$ the wake-like velocity profiles obtain a similar form.

We further analyze the turbulent kinetic energy inside the recirculation zone in the same manner. Figure 5 contains the diagonal components of the Reynolds stress tensor at different cross-sections. Fluctuations amplitude strongly increases (almost twice) inside the recirculation zone for higher value of the diameter ratio and remains on this level after stagnation points, while in the outer mixing layer the amplitude of the peak is about the same level and shows small decrease. This is confirmed in figure 6 which illustrates the comparison of the dissipation and production of turbulent kinetic energy defined as:
Figure 4. Averaged radial profiles of axial and radial time-averaged velocity at different cross-sections.

Figure 5. Averaged radial profiles of normal components of Reynolds stress tensor.

\[
\text{prod} = \overline{u_i u_j} \frac{\partial U_i}{\partial x_j} \text{diss} = \frac{1}{Re} \frac{\partial u_i}{\partial x_j} \overline{u_i u_j}.
\]

These two terms increase inside the recirculation bubble, while their intensity in outer shear layer decreases with increasing of the diameter ratio. Amplified fluctuations level results in increasing of
period and amplitude of oscillatory motion inside the reversal flow region which is confirmed by the axial velocity oscillation near the stagnation points that are shown in figure 7. This figure shows that for $a = 0.3$ there are short-time oscillation with low amplitude, while for $a = 0.7$ we can see part of one large period of long-wave sine-like oscillation with magnitude almost two-times higher than for the first case.

4. Conclusion
We performed direct numerical simulations (DNS) of the turbulent annular jet flow with three different values of the inner-to-outer diameter ratio ($a = d / D = 0.3, 0.5, 0.7$). The time-averaged velocity fields and fluctuations were analyzed. The low aspect ratio results in the shortest recirculation zone while for high $a$ value the stagnation point features high level of turbulent kinetic energy. This is the evidence of the accompanying low-frequency oscillations of the recirculation zone.

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