Large-eddy simulations of the near field of a swirling turbulent annular jet

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Abstract. We perform Large-eddy simulations of an annular swirling turbulent jet for $S = 0$, $S = 0.3$ and $S = 1$, where $S$ is swirl number. The Reynolds number based on the bulk velocity in the feeding channel and the outer diameter was 8900. The analysis showed that the region around the stagnation point in the end of the recirculation zone has a high level of turbulent kinetic energy. The length of the recirculation zone decreases in case for low swirl ($S = 0.3$) compared to the non-rotating case, while for the higher rotation rate ($S = 1$) the recirculation bubble becomes enormously long. Spectral analysis showed two peaks corresponding to the Kelvin-Helmholtz instability and some low-frequency oscillations of the recirculating zone.

1. Introduction

The flow in a channel between two coaxial cylinders issuing into a larger volume forms an annular jet. This class of flows combine features of jets and wakes due a recirculation zone past the central bluff body and a couple of mixing layers close to the nozzle exit. The first mixing layer is between the recirculation zone and the jet, while the second one is between the jet and the co-flow (ambient fluid). This combination is traditionally employed for burner devices design where the recirculation zone helps to stabilize the flame [1].

Chigier and Beer [2] performed one of the first experiments on annular jets comparing their self-similarity properties with the round counterpart. Ko and Chan [3, 4, 5] considered the near field for various configurations of the geometry of the central bluff body. While the dynamics of the outer shear layer is similar to the one of round jets, the recirculation zone usually introduces low-frequency oscillations of its length and amplitude of turbulent fluctuations [6, 7]. Similar observations were also made for non-swirling annular jets [8].

While for round swirling jets there is a detailed description of the effect of rotation on the flow topology and dynamics including the typical instabilities and the vortex breakdown phenomenon [9, 10, 11] and large-scale coherent structures [12, 13, 14, 15, 16, 17, 19], for annular jets it is much more limited. Sheen et al. [20] performed first experiments and identified several typical patterns depending on the flow parameters including the formation of the vortex breakdown bubble at an intermediate swirl number, which moves upstream as the swirl number increases. The bluff-body recirculation zone and the breakdown bubble merge to form a single recirculation zone at a sufficiently high swirl intensity as was also recently observed using Particle image velocimetry (PIV) [21]. In this paper we use well-resolved Large-eddy simulations (LES) of...
the annular turbulent jet with different several swirl numbers to study the coherent structures populating the near-nozzle area.

2. Computational details and problem
We consider a flow of an incompressible fluid governed by the spatially filtered Navier–Stokes equations:

\[
\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \nabla) \mathbf{u} = -\nabla p + \frac{1}{Re} \Delta \mathbf{u} - \nabla \cdot \tau, \tag{1}
\]

\[
\nabla \cdot \mathbf{u} = 0. \tag{2}
\]

where \( \mathbf{u} \) and \( p \) are the non-dimensional filtered velocity and pressure field, respectively. An extra term \( \tau \) represents the subgrid-scale stresses appearing in the Large-eddy simulation framework. The above described governing equations are implemented in the Nek5000 code [22] with a spatial discretisation based on the spectral-element method using Lagrange polynomials. The Navier–Stokes equations are cast in a weak form and discretised in space by means of Galerkin approximation using \( N \)th-order Lagrange polynomial interpolants on the Gauss-Lobatto-Legendre points for the velocity field and pressure \( (P_N - P_N) \) formulation. In the present work the polynomial order \( N \) is set to 7. The semi-implicit time-stepping scheme is of the third-order accuracy. In the present LES simulations the two highest modes are filtered with parabolic transfer function, and the filter amplitude was 5% in the last mode [23]. The accuracy of simulations has been previously assessed in a number of configurations including the channel flow and the non-swirling annular jet [24, 25].

![Figure 1](image_url)

**Figure 1.** Left: computational domains and boundary conditions. Right: the verification of the inflow boundary conditions produced in the simulation of the flow in a periodic annular channel where the time-averaged axial velocity profile and normal Reynolds stress components are compared with the DNS data [28]. Red and green profiles show the profile of the tangential velocity with is added to the turbulent inflow velocity field in swirling cases.

Numerical simulations of turbulent annular swirling jets of incompressible fluid are performed for the Reynolds number \( Re = 8900 \), based on the bulk velocity \( U_b \) and the outer diameter \( D \), while the ratio of the outer to inner diameter is equal to \( D/d = 2 \). Figure 1 (left) shows two computational domains used for simulation. A periodic annular channel with the length \( L = 2.5D \) and \( 8 \times 32 \times 20 = 5120 \) spectral elements in \( r, \theta, \) and \( x \) directions is used to generate a fully-developed turbulent inflow velocity fields for the main computation of the annular jet. To validate this simulation radial profiles of the time-averaged axial velocity and different components of Reynolds stresses are compared with DNS by Chung et al. [28] showing excellent agreement, see Fig. 1 (right). The main domain represents a cylinder with a diameter \( D_{\text{main}} = 12D \) and length \( L_{\text{main}} = 17D \), which includes a feeding annular channel with length equals to \( 2D \), while the thickness of the outer wall of the channel is 0.03\( D \). The instantaneous
velocity field in some fixed \( r - \theta \) plane from a periodic channel simulation was copied to the feeding channel of the main domain every time step. At this cross-section \( x/D = -2 \) we also add a parabolic tangential velocity profile according to the formula \( u_\phi = \alpha(1 - r^2) \) where \( \alpha \) is a parameter defined below. Previous studies showed that the fully developed rotating annular flow provided by the rotating wall is not efficient to arrange high swirl rates \([26, 27]\), thus, leading to the present way of setting up the rotation. The swirl number is defined as

\[
S = \frac{\int_0^R \frac{R}{r} \pi u_\phi r^2 dr}{\frac{\int_0^R \pi u_x^2 r dr}{R}}.
\]

where \( R = D/2 \). In the present study we consider \( S = 0, 0.3 \) and 1.0 calculated at the inflow section \( x/D = -2 \) corresponding to \( \alpha = 0, 0.45 \) and 1.91, respectively, see Fig. 1 (right). The co-flow in the main domain was set to 0.04\( U_b \) while on other boundaries Neumann boundary conditions were imposed. The main domain was meshed with about 80 thousand spectral elements \((35 \times 32 \times 70 \text{ elements in } r, \theta \text{ and } x)\). Since we used polynomials of the seventh order, there were \( 8^3 \) computational nodes inside each spectral element, so that the total number of computational points was about \( 41.3 \times 10^6 \) for the main simulation and about \( 2.6 \times 10^6 \) for the periodic annular channel. The distance between computational nodes at the outer wall inside the periodic channel was \( \Delta r + = 0.76, (r\Delta \theta)^+ = 6.4 \) and \( \Delta x^+ = 64 \) in radial, azimuthal and axial direction, thus our computational grid satisfied the near-wall well-resolved LES criteria \([29]\). The superscript ‘+’ denotes the non-dimensional units using the friction velocity and viscosity.

3. Results

Figure 2. The instantaneous (top half) and time-averaged axial velocity field is shown for \( S = 0 \) (left), \( S = 0.3 \) (middle) and \( S = 1 \) (right) in \( x - r \) plane.

Figure 2 shows the instantaneous and time-averaged axial velocity fields in \( x - r \) plane for all swirl numbers. For \( S = 0 \) inner and outer mixing layers merge at \( x \approx 2D \), while with an increase of swirl to \( S = 0.3 \) this process goes faster and occurs at \( x \approx 0.8D \). However, close to zero and slightly negative values of axial velocity appears at \( x \approx 3D \) which is the sign of the vortex breakdown as described in the literature. The new bubble grows in size with the further increase of \( S \) and merges with the recirculation zone close to the nozzle. This result is well represented by the instantaneous and time-averaged velocity field for \( S = 1 \) where one can see a very long bubble with the length around 4D.

Figure 3 shows the comparison of radial profiles of the time-averaged axial velocity and its fluctuations at several axial stations along \( x \) from \( x/D = 0 \) to \( x/D = 2.25 \) with step equals to 0.25. The recirculation zone is characterized by the high level of fluctuations in inner mixing layer, especially close to the stagnation point. The peaks of axial velocity and fluctuations move away from the centerline with an increase of swirl. For the case \( S = 0.3 \) the axial velocity decrease after \( x/D = 1.25 \). This fact is the evidence of emergence of the second recirculation zone.

Figure 4 shows the energy spectra for individual velocity components in the inner and outer shear layer at \( x/D = 0.25 \) computed for the time interval around 40 non-dimensional time units.
Two peaks are clearly seen. The first peak corresponds to the Kelvin-Helmholtz instability, which is better pronounced for the radial and azimuthal velocity components with a non-dimensional frequency $f_0 = f D/U_b \approx 1$. A similar effect was observed in the mixing layer for a fully developed round jet [30]. The second peak is connected to the low-frequency oscillations of the recirculating zone and is better detected for axial and radial components of velocity. Further study will concentrate on the spatial form of the velocity fluctuations with low frequency.

4. Conclusion
We investigated the influence of the swirl intensity on statistical characteristics of the near field of the turbulent annular jet. The Reynolds number based on the bulk velocity in the feeding
channel and the outer diameter was 8900. The analysis showed that the region around the stagnation point in the end of the recirculation zone has a high level of turbulent kinetic energy. The length of the recirculation zone decreases in case for low swirl \( S = 0.3 \) compared to the non-rotating case, while for the higher rotation rate \( S = 1 \) the recirculation bubble becomes enormously long. Spectral analysis showed two peaks corresponding to the Kelvin-Helmholtz instability and some low-frequency oscillations of the recirculating zone.

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