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Impact of rotating and fixed nozzles on vortex breakdown in compressible swirling jet flows

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ABSTRACT

Vortex breakdown of swirling, round jet flows is investigated in the compressible, subsonic regime by means of Direct Numerical Simulation (DNS). This is achieved by solving the compressible Navier–Stokes equations on a cylindrical grid using high-order spatial and temporal discretization schemes. The Reynolds number is $Re = \rho_c^\circ w_c^\circ R^\circ/\mu_c^\circ = 5000$ and the flow is moderately compressible with Mach number $Ma = w_c^\circ/\sqrt{\gamma R_{\mathrm{air}}^\circ T_c^\circ} = 0.6$. The integral swirl number at the inflow is $S_{\mathrm{int}} = 0.85$. The parameters are chosen properly so as to make comparisons with existing experiments at lower Mach numbers possible while still enabling a study of compressible and baroclinic effects. Different from previous numerical investigations, a nozzle immersed in the fluid is included in the computational domain and is modelled as an isothermal no-slip wall, either rotating with the mean azimuthal flow direction or kept at rest. The present investigation aims to clarify the role played by the nozzle wall motion for the vortex breakdown of the swirling jet. We study the nozzle flow as well as the swirling jet flow simultaneously, a novelty for numerical investigations of vortex breakdown in swirling jets. Depending on the nozzle wall motion, the flow differs significantly upstream of the vortex breakdown: for the rotating nozzle, the flow inside the nozzle is purely laminar and the azimuthal boundary layer at the outer nozzle wall gives rise to the axisymmetric mode $n = 0$ and a single-helix type instability with azimuthal wave number $n = 1$. With the nozzle at rest, a transitional flow is observed within the nozzle where a helical instability with azimuthal wave number $n = 12$ dominates, growing in the boundary layer at the nozzle wall. For both nozzle setups, the helical instabilities observed for the nozzle flow interact with the developing vortex breakdown and the conical shear-layer downstream of the nozzle. For the nozzle at rest, this interaction results in a vortex breakdown configuration which is shifted in the upstream direction and which has a smaller radial and streamwise extent compared to the rotating nozzle case and the recirculation intensity is higher. The dominant frequency is highly influenced by the flow upstream of the vortex breakdown and is substantially higher for the nozzle at rest. Although the nozzle flow field differs for the two configurations and therefore alters the vortex breakdown downstream, a single-helix type instability $n = 1$ governing the vortex breakdown is found for both cases. This provides strong evidence for the robustness of the instability mechanisms leading to vortex breakdown.

1. Introduction

The physical phenomenon of vortex breakdown occurs in many technical applications, e.g. on delta wing aircraft [1] and in vortex burners [2], and can also be observed in nature [3]. A field of ongoing research is swirling jet flows undergoing vortex breakdown [4]. For a sufficiently high circumferential velocity relative to the streamwise velocity vortex breakdown occurs. The flow state of vortex breakdown is characterized by a finite region of strong recirculation near the centreline of the swirling flow and a high radial spreading rate [5]. Helical instabilities of co- and counter-rotating type, winding against or in the mean flow direction, dominate the flow field [6]. It is of great interest to understand the fundamental features of vortex breakdown, to know the parameters at which vortex breakdown occurs, and to get insight into possible control mechanisms for this special flow configuration. Although in more than five decades of intense research many attempts were made to explain vortex breakdown,

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a commonly accepted theory of the underlying mechanisms is still missing. For reviews of the vortex breakdown phenomenon, we refer to Lucca-Negro and O'Doherty [7] and references therein.

Experimental investigations reported in the literature vary in the design of the devices used for generating the swirling jet flow as well as whether the nozzle wall itself is kept at rest or rotating. The studies mainly split up in two groups, either utilizing a long rotating pipe with a straight or contracting nozzle attached, e.g. Liang and Maxworthy [8] and Facciolo et al. [9], or a pipe and a nozzle at rest in combination with a rotating honeycomb or guiding vanes to generate swirl, e.g. Billant et al. [5], Gallaire et al. [10], Oberleithner et al. [4] and Leclaire and Jacquin [11].

Liang and Maxworthy [8] and Liang and Maxworthy [12] used a long rotating pipe attached to a large water tank to generate swirling jets. The authors conducted experiments at Reynolds numbers up to $Re_D = 2000$ (based on the bulk velocity). The streamwise velocity profile was initially uniform and laminar. Helical modes $n = +2, +3$ (co-rotating, counter-winding) were found to be dominant before vortex breakdown, while after vortex breakdown modes $n = +1, +2$ competed with each other, with mode $n = +1$ being most unstable. In the post-breakdown stage the dominant modes were suggested to be self-excited/globally unstable, a behaviour identified as a super-critical Hopf-bifurcation: the saturation amplitude of modes $n = +1, +2$ depended linearly on the critical swirl parameter, cf. Huerre and Monkewitz [13]. The flow criticality and shear-layer morphology remained unchanged with Reynolds number. The authors concluded that the swirl difference of the jet to the ambient fluid had only a minor effect on the flow criticality, which depended mainly on the velocity distribution of the vortex core. The effects of the developing boundary layer at the outer nozzle wall on the vortex breakdown of the swirling jet were not discussed.

Oberleithner et al. [4] conducted experiments in air at a Reynolds number $Re_D = 20{,}000$ (based on the bulk velocity) of a turbulent, swirling jet over a range of swirl numbers. The authors focused on the description of three-dimensional coherent structures by means of POD and compared the empirical results to results from a weakly non-parallel spatial linear stability analysis. In this stability analysis the Reynolds number, Re, and the complex axial wave number, α, were assumed to vary in the streamwise direction. The analysis was carried out on subsequent downstream positions to account for the non-parallel base flow assuming the instabilities in the outer shear-layer to be of convective type. A frequency was measured which dominates the entire flow field. The global dominant frequency was used as input parameter for the stability investigation. As in the earlier work by Liang and Maxworthy [8], evidence was found for the existence of a super-critical Hopf bifurcation on which a global mode could get established. The global mode was identified to be a co-rotating, counter-winding single-helix which was triggered by the precessing of the vortex core in the inner region of the jet.

Due to the differences in the experimental setups, the flow upstream of the nozzle end section differs as well. For the first group of experiments, the azimuthal velocity component at the wall is identical to the rotation speed of the nozzle, while for the latter the fluid is at rest at the nozzle wall. Differences in the experimental setups make it difficult to compare results of various studies, especially because the flow state upstream of vortex breakdown within the nozzle is rarely documented. Some discussion is found in Facciolo et al. [9] and Leclaire and Jacquin [11], but is restricted to flows before the onset of vortex breakdown.

Facciolo et al. [9] investigated turbulent swirling pipe flows as well as jet flows, both experimentally and numerically, and focused on the turbulent properties of the flows. Both flow regions – the pipe and the jet flows – were studied separately and an interaction of the pipe flow and the swirling jet flow was neglected in the numerical investigations and not discussed for the experimental results. Since the swirl intensity was below the threshold for vortex breakdown, no upstream effects of the swirling jet on the pipe flow were considered. The authors found that the fully developed flow within the rotating pipe was not in solid-body rotation due to the Reynolds shear stresses, which is in agreement with findings reported in Orlandi and Fatica [14]. A counter-rotating core was observed in the swirling jet flow six-to-eight pipe diameters downstream of its end section. The azimuthal velocity profile of the mean flow changed sign in the vicinity of the jet centreline developing a counter-rotation for $r \leq 0.5$.

Leclaire and Jacquin [11] reported on high-Reynolds number rotating flows in a pipe with a final contraction. The authors found that vortex breakdown within the pipe is suppressed by the contraction at the pipe end and observed instead standing axisymmetric Kelvin waves (see, for instance, Saffman [15]) to be present. The observations made were independent of the employed contraction ratio. The authors observed a high fluctuation level in the pipe exit plane and a spiralling motion, both connected to the flow upstream of the pipe exit plane and its change in criticality from super-critical to sub-critical (see Benjamin [16] and Lucca-Negro and O'Doherty [7] for a review). To avoid this change in criticality already within the pipe and to guarantee smooth flow conditions in the pipe exit, especially at high swirl, Leclaire and Jacquin [11] suggested to exclude a final contraction in swirling jet flow experiments. Although the swirling jet flow was not studied in their investigation, it gave strong evidence of the importance of the upstream flow conditions within the pipe on the vortex breakdown configuration.

Numerical investigations of vortex breakdown in swirling flows in the compressible regime have been published by Melville [17], Müller and Kleiser [18] and Luginsland and Kleiser [19]. Melville [17] solved the compressible Euler equations to study vortex breakdown of a subsonic free vortex of Burgers' type. The suppressing effect of an increased Mach number on the vortex breakdown reported in [20] was reversed leading to a promotion and an upstream shift of the recirculation region. The vortex breakdown configuration was governed by a double-helix type structure, co-rotating with the mean flow and winding in the opposite direction, but different from the structure observed by Sarpkaya [21]. In the study by Müller and Kleiser [18], natural and forced swirling jets at $Re = 5000, Ma = 0.6$ were considered and linear stability analysis was applied to identify unstable modes. The results showed good qualitative agreement with the experimental observations reported in [8]. At sufficiently high swirl the jet broke down and a conical breakdown state established with a pronounced recirculation zone around the jet axis. Counter-rotating, co-winding single- and double-helix type instabilities dominated the flow field. The more rapid breakdown of the jet and the stronger deceleration of the streamwise velocity at the jet centreline compared to results reported in [8] was suggested to be linked to compressibility effects. The swirling jet flow regime was considered only and a nozzle was not included into the computational domain.

In their recent numerical study Luginsland and Kleiser [19] investigated compressibility effects on swirling jet flows undergoing vortex breakdown. The swirling jets were emanating from a rotating nozzle. Compressibility effects were studied for Mach numbers in the range $0.4 \leq Ma \leq 0.8$ at a constant inflow temperature and inflow swirl rate in the nozzle end section (for additional information see also [22]). The authors found a promotion of vortex breakdown for increasing Mach numbers and confirmed the results reported in [17]. The delaying effect of compressibility