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Effects of boundary conditions on vortex breakdown in compressible swirling jet flow simulations

T. Luginsland *, L. Kleiser

Institute of Fluid Dynamics, ETH Zurich, 8092 Zurich, Switzerland

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ABSTRACT

We investigate the sensitivity of numerical simulation results for swirling jet flows undergoing vortex breakdown to inflow and outflow boundary conditions. The compressible regime at Mach number $Ma = 0.6$ and Reynolds number $Re = 5000$ is considered. The swirl velocity is approximately of the same magnitude as the streamwise centreline velocity at inflow. We perform Large-Eddy Simulations using high-order discretization schemes in space and time. A rotating nozzle with isothermal wall is included in the computational domain. Six different combinations of inflow and outflow boundary conditions are investigated. These use a Dirichlet condition at the inflow supplemented with a sponge layer imposing up to five variables and a sponge layer at the outflow acting on several combinations of variables, applied together with non-reflecting boundary conditions. The advantages and drawbacks of each setup are investigated. The qualitative features of the swirling jet undergoing vortex breakdown are robust to changes in the inflow and outflow boundary conditions, i.e., conical shear-layers, a recirculation bubble, the existence of a single-helix type instability, and the occurrence of a dominant frequency, are all captured by combinations of the boundary conditions investigated. However, significant quantitative differences are observed depending on the conditions set at inflow and outflow. In particular, the locations of the stagnation points and the spreading angle of the swirling jet are strongly influenced. The size and shape of the recirculation bubble change as well, as does the intensity of the recirculation flow and of the counter-rotating motion observed at the jet centreline. The dominant frequency in the breakdown region also depends on the setup. As a result of this study, we recommend setting the three velocity components, density, and pressure at the inflow and outflow using sponge layers supplementing non-reflecting boundary conditions as the most suitable choice.

1. Introduction

Vortex breakdown occurs in many technical applications (e.g. delta-wing aircraft [39], vortex burners [9]) and can also be observed in nature (dust devils, tornadoes, hurricanes [8]). A field of ongoing research are swirling jet flows undergoing vortex breakdown. For a sufficiently high circumferential velocity relative to the streamwise velocity, vortex breakdown occurs. The flow state of a vortex breakdown is thereby characterised by a strong recirculation in the centreline region of the swirling flow and a high radial spreading rate [2]. It is of great interest to understand the fundamental features of vortex breakdown, to know the parameters at which it occurs, and to get insight into possible control mechanisms of this special flow configuration. Although in more than five decades of intense research many attempts were made to explain vortex breakdown, a widely accepted theory is still missing. For reviews of the vortex breakdown phenomenon, we refer to Delery [12] and Lucca-Negro and O'Doherty [27].

Recent experimental studies on swirling jet flows in the incompressible regime [25,37] revealed the presence of a globally unstable mode. The global mode overwhelms the entire flow, acting as the wave-maker for the helical shear-layer instabilities of the conical vortex breakdown. These results are supported by linear stability analysis [17], leading to the observation of a maximum of two absolutely unstable flow regions: the first one located directly downstream of the nozzle, and the other one located in the leeward region of the breakdown bubble.

Herrada and Fernandez-Feria [20] and later Meliga et al. [32] investigated the onset of vortex breakdown in the incompressible regime focusing on the mode selection mechanism by means of numerical simulations, linear stability theory and bifurcation analysis, respectively. They found that the early state of vortex breakdown is axisymmetric and the transition to helical

* Corresponding author.
E-mail address: luginsland@ifd.mavt.ethz.ch (T. Luginsland).

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instabilities of single- and double-helix type is due to the presence of a sufficiently large pocket of absolute instability [20] and a series of subcritical bifurcations, respectively [32]. In both investigations, the azimuthal instabilities are identified as co-rotating, counter-winding helical modes.

Published results of numerical investigations are mainly based on solutions of the incompressible Navier–Stokes equations in the low Reynolds number regime ($Re \leqslant 1000$) for swirling jet flows [41], and for moderate to high Reynolds numbers in the context of swirl burners [13] and turbines [45]. To the best of our knowledge, the boundary conditions in these studies were chosen without much further discussion, and only Ruith et al. [42] reported an assessment of the influence of far-field conditions on the flow characteristics. They recommended radiation conditions at the far-field boundary of the computational domain while using Dirichlet boundary conditions at inflow and a convective outflow condition. The flows under investigation were laminar, incompressible low Reynolds number swirling jets and wakes. The results revealed a high sensitivity of the vortex breakdown structure and the entrainment streamlines to the choice of the far-field boundary conditions.

García-Villalba et al. [18] investigated the influence of the inflow boundary location in the context of swirl burners. They found that for certain inflow boundary locations, highly unsteady large-scale coherent structures found in corresponding experiments were not present at all in their simulations. The types of boundary conditions were held fixed for all three simulations performed: a Dirichlet condition at the inflow, a convective condition at the outflow, and free-slip conditions in the far-field.

Leclaire and Sipp [23] theoretically investigated the influence of the upstream boundary conditions on the bifurcation structure leading to vortex breakdown. They varied the streamwise and azimuthal velocity profiles at the inflow in combination with a third condition chosen either as a fixed azimuthal vorticity or as a vanishing radial velocity. At the pipe wall, free-slip conditions were applied. The authors restricted their study to an incompressible inviscid flow in a finite-length pipe of constant cross-section, and found up to six different bifurcation scenarios. Flows with a large rotational core were particularly sensitive to an accurate modelling of the upstream boundary conditions.

Melville [33] studied the breakdown behaviour of an isolated, unconfined Burgers-type vortex in the inviscid, compressible, subsonic regime. He solved the compressible Euler equations under the following boundary conditions: Three velocities were set at the inflow together with the pressure extrapolated from the interior of the domain. At the outflow, all five variables were set, leading to a formal ill-posedness. The upstream effect of this ill-posedness was minimised by choosing the domain size to be sufficiently large.

Herrada et al. [21] investigated the effects of compressibility at $Ma < 1$ on vortex breakdown in pipes solving the axisymmetric Navier–Stokes equations. They set all five variables at the inflow assuming a uniform temperature distribution. At the outflow, zero gradient conditions were imposed and compared to non-reflecting conditions, leading to indistinguishable results.

Liu et al. [26] solved the full compressible Navier–Stokes equations to investigate vortex breakdown of swirling jets in the supersonic regime. The authors found only very little effect of the outflow conditions on the vortex breakdown configuration in bounded and unbounded domains for two reasons: first, the flow field was mainly supersonic at the outflow (due to a bypass flow), and second, the numerical domain was large enough to prevent interactions between the outflow boundary conditions and the vortex breakdown region.

The contributions by Müller [34] and Müller and Kleiser [35] concern swirling jets undergoing vortex breakdown in the compressible subsonic regime. A Dirichlet condition at the inflow was used in combination with a sponge layer [3] for all five conservative variables. The advantages of this choice are the possibility of imposing precise disturbances at the inflow to trigger the swirling jet flow and the ability to damp upstream-travelling waves. At the outflow and far-field boundary, non-reflecting conditions [40] were used in combination with sponge layers for three velocities, density and pressure and for density and pressure, respectively.

Since it is well known that swirling flows undergoing vortex breakdown are highly sensitive to upstream and downstream conditions [14] and especially to any physical or artificial perturbations, it is of great interest to assess the influence of the boundary conditions on computational results for a swirling jet flow. The aim of the present study is to identify the most appropriate combination of inflow and outflow boundary conditions for studying vortex breakdown of swirling jet flows including nozzle modelling. We restrict our investigation to the subsonic, compressible regime at moderate Reynolds number $Re = 5000$.

This paper is organised as follows. In Section 2 the numerical framework is introduced. In Section 3.1 the basic simulation setup is presented, followed by the setup variations described in Section 3.2. In Section 4 the results on the influence of the boundary conditions on flow characteristics are presented. In Section 5 we summarise and discuss our findings. We conclude our study in Section 6 and give a recommendation for the most appropriate setup for simulations of swirling jets undergoing vortex breakdown in the compressible regime.

2. Numerical framework

In this section, we summarise the basic approach and the numerical methods used in the present investigation. An extensive documentation is given in Müller [34]. The radial, azimuthal and streamwise co-ordinates and velocities are denoted by r, θ and z, and u, v and w, respectively. We solve the compressible Navier–Stokes equations in a conservative formulation on a cylindrical grid, see Fig. 1 for a sketch of the setup. The governing equations are non-dimensionalized using the nozzle inner radius R° and centreline quantities, such as streamwise velocity $w^\circ{}_c$, density $\rho^\circ{}_c$, dynamic viscosity $\mu^\circ{}_c$ and temperature $T^\circ{}_c$ ($^\circ$ indicates dimensional quantities). The Reynolds number is set to $Re = \rho^\circ{}_c w^\circ{}_c R^\circ / \mu^\circ{}_c = 5000$ and the Mach number is $Ma =$

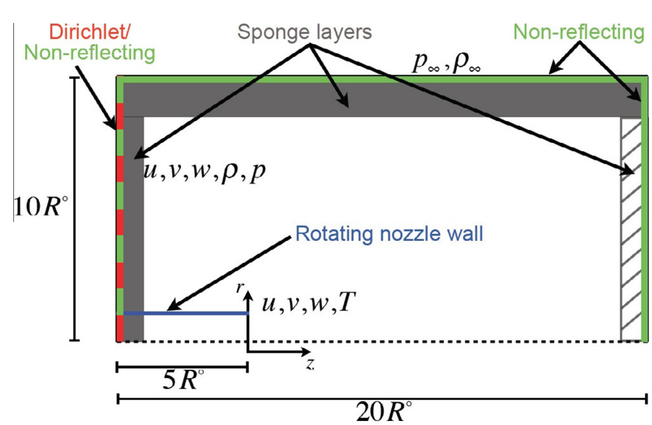

Fig. 1. Computational domain for simulations. Dirichlet conditions marked in red, non-reflecting boundary conditions marked in green. Sponge layers are shaded in grey or hatched. Nozzle wall marked in blue. Dashed boundary conditions at inflow and the hatched sponge layer at outflow are used optionally depending on the specific setup tested. Quantities $(u, v, w, \ldots)$ given are imposed for all setups without exception (inflow/far-field sponge and nozzle wall). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)