Large eddy simulation of the vortex breakdown in a turbulent swirling jet

K I Borynyak
Institute of Thermophysics of SB RAS, 630090, Ac. Lavrentiev ave. 1,
Novosibirsk, Russia
E-mail: borisnsk07@gmail.com

Abstract. The paper presents the results of Large eddy simulation of a free swirling jet with Reynolds number $Re = 10^4$ for different swirl numbers. The swirl is organized via the rotation of the nozzle. The case has been divided onto two parts: rotating tube with honeycomb section using dynamic mesh and jet simulation with rotating nozzle using the initial conditions obtained in first part. Simulations were carried for six swirl numbers: 0, 0.15, 0.225, 0.3, 0.46, 0.63. The vortex breakdown with a central recirculation zone formation is observed in the last case.

1. Introduction

There are a huge number of configurations of the jet flows that can be observed. Depending on the swirl organization method, shape of the nozzle, type of initial conditions we can get different flow structure and organization. Swirling flows are often found in nature and also irreplaceable in technical applications, such as reactors, mixers, combustion chambers, cooling systems, etc.

Large-scale structures in the near-nozzle region play a significant role in heat and mass transfer [1,2]. That fact explains the growing interest in the study of the structures arising in the initial part of the jet and control methods to organize these structures. One of the ways to control the vortex structures considered in this paper is swirling.

In [3,4] it was shown that jet swirl leads to more intensive heat and mass transfer in the initial part of the jet. Unlike the non-swirling jet, where the toroidal vortex modes are dominant, in swirled case we can see another flow pattern: typical ring structures break apart into two modes: helical mode and streamwise braid structures [5,6,7,8]. The unorganized turbulence that enhances the turbulent mixing can be generated as a result of interaction of these modes.

The main characteristic of swirling jet flows is the swirl number determined by the expression [3,9]:

$$ S = \frac{2K_\theta}{M_x d} = \frac{\omega R}{2V_s} $$

where the main parameters are jet momentum $M_x$ and angular momentum $K_\theta$:

$$ M_x = 2\pi \int_0^r \pi \rho V_s^2 r dr $$(2)

$$ K_\theta = 2\pi \int_0^r \rho V_r V_\theta r^2 dr $$
Swirled flows can be divided into three categories: low-swirl\((S<0.3)\), for which the effect on the jet-opening angle and on the fluctuations level can be seen; medium swirl \((0.3<S<0.5)\) where the angular momentum conservation leads to the axial deceleration of the jet; high-swirl \((S>0.5)\) where the formation of the recirculation zone, associated with the pressure-gradient influence, can be seen. The mentioned-above phenomenon is called vortex breakdown. There are significant number of publications aimed at the influence of initial parameters such as inlet profiles, swirl number, etc. on the vortex breakdown. Also, this phenomenon can be interesting for burning studies because of sufficient influence of the vortex breakdown on the flame stabilization.

2. Equations

We use LES approach with DKSGS-model\([10]\) with the following momentum-transport equations:

\[
\frac{\partial \overline{u}_i}{\partial t} + \frac{\partial (\overline{u}_i u_j)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{1}{Re} \frac{\partial^2 \overline{u}_i}{\partial x_j \partial x_j} - \frac{\partial}{\partial x_j} \left( (\nu + \nu_{sgs}) \overline{S}_y \right) \tag{4}
\]

\[\nabla \cdot \mathbf{u} = 0\]

where the subgrid-viscosity \(\nu_{sgs}\) is defined by the following equations:

\[
\nu_{sgs} = c_r \sqrt{k_{sgs}} \delta
\]

\[
\frac{\partial k_{sgs}}{\partial t} + \overline{u}_i \frac{\partial k_{sgs}}{\partial x_i} = -\tau_y \frac{\partial \overline{u}_j}{\partial x_j} - c_r \sqrt{k_{sgs}} \frac{\partial}{\partial x_i} \left( \nu_{sgs} \frac{\partial k_{sgs}}{\partial x_i} \right) + \frac{\partial}{\partial x_j} \left( \nu_{sgs} \frac{\partial \overline{u}_j}{\partial x_i} \right) \tag{5}
\]

\[
\tau_y = -2\nu_{sgs} \overline{S}_y + \frac{2}{3} \delta \overline{k}_{sgs}
\]

\[
L_{ij} = \left\langle u_i u_j \right\rangle - \overline{u_i} \overline{u_j}
\]

\[
M_{ij} = -\left( \overline{\delta k_{sgs}} \right) + \frac{k_{sgs}}{2} S_{ij} \overline{\delta S}_{ij} \left( \sqrt{k_{sgs}} \overline{S}_y \right) - \left( \sqrt{k_{sgs}} \overline{S}_y \right) \left( \sqrt{k_{sgs}} \overline{S}_y \right)
\]

\[
c_r = \frac{1}{2} \frac{L_{ij} M_{ij}}{M_{ij} M_{ij}}
\]

Widely-used Smagorinsky model has enough flaws, such as ignoring the historical and non-local effects and also instability of the solution if the Smagorinsky constant is below zero. The main feature of DKSGS-model is that no assumption of local equilibrium between subgrid-scale energy production and dissipation rate has been made. Instead of this we have a direct computation of the kinetic energy, that allows us to account some history and non-local effects.

Also, the equation for passive-scalar concentration was simulated with the momentum-transport equations:

\[
\frac{\partial \overline{C}}{\partial t} + \frac{\partial}{\partial x_j} \left( \overline{C} \overline{u}_j \right) = \frac{\partial}{\partial x_i} \left( \frac{\nu}{Sc} + \frac{\nu_{sgs}}{Sc_r} \right) \frac{\partial \overline{C}}{\partial x_i} \tag{6}
\]

The Schmidt number \(Sc\) and its turbulent analog \(Sc_r\), which characterizes the ratio of the diffusion of the pulse associated with the viscosity to the diffusion of the passive-scalar, was taken equal to 0.9.
3. Computational domain
First of all, this case was set for joint numerical and experimental investigations. So, the geometry of computational domain was modeled as copy of the experimental setup for PIV-experiments at the Institute of Thermophysics of SB RAS.

Assuming the smallness of the reverse effect of the jet on the entrance pipe, it was decided to split the case into two subtasks to reduce the required computational resources. It was rational to carry out the simulations of the flow in a rotating tube with a honeycomb using a dynamic mesh rotating with a constant angular velocity. It was decided to use a static grid for jet flow simulations. It was necessary to interpolate the output fields from the rotating tube case to the static mesh to obtain the time series that can be used as the velocity field for the input section in the second subtask.

Figure 1. Computational domain of two cases with instantaneous velocity field.

The computational grids for both cases were built with the help of GridPro utility[https://www.gridpro.com/]. The numerical grids consisted of $4 \times 10^6$ elements for rotating pipe case and $1.6 \times 10^7$ for rotating nozzle case with the wall-adjacent gridcell width $(y^+)$ of about 10 in wall units in the both cases. The first part of computational domain was set to be a pipe with $D=15$. The honeycomb section length was equal to $10D$. The inlet section of the nozzle has length of $3D$ with the cylindrical domain of $20D \times 20D$ in longitudinal and transverse directions (see Fig. 1).

4. Boundary conditions
Boundary conditions are required to be corrected to get the results via numerical simulations. Thus, the first part of this work is aimed at generation of the inlet cross-section velocity field for the second part of simulations.

Looking through the profiles of the time-averaged longitudinal velocity component in cross sections (Fig. 2a), it can be seen that profiles at the nozzle entrance have a very similar shape. The only significant difference is observed for the maximum considered swirl $S = 0.63$, for which the profile becomes more filled. For the other cases the profiles are rather sloping which indicates a significant effect of flow resistance exerted by the honeycomb.

After the pipe simulations the interpolation from the dynamic mesh to static mesh for rotating nozzle is required. We got the time-series of the inlet cross-section for each case as a result of interpolation-code that was developed for simulations.

For the outlet surfaces, the convective boundary conditions were used. The nozzle surface was set to a solid body rotation, consistent with the chosen inlet azimuthal velocity.
5. Results and discussions

The vortex breakdown was expected for the swirl number $S=0.63$ of all the numbers proposed in this paper. For fair, at the nozzle exit ($x/D=0$, Fig. 2b), the profile for maximum swirl number rearranges with formation of a local minimum of the velocity on the jet axis, which indicates the development of a significant longitudinal pressure gradient due to the swirling effect, resulting in flow deceleration. For the cross-section $x/D=1.5$ (Fig. 2c) and swirl $S=0.63$, the formation of a recirculation region on the nozzle axis can be seen, which indicates the process of vortex decay. At the same time, for the other considered swirls, the structure of the flow remains stable with the visible slowing down and expansion of the flow with increasing swirl number. Also, it can be seen that nozzle outlet profiles have two sections with the different slopes: one of them is associated with the wall-bounded turbulence; the second one which is located at the jet core is associated with the honeycomb mixing. Such structure of the flow gives the coordinate of the mixing layer closure further downstream ($8D$, Fig. 2) for non-swirl task in comparison with the similar case, but without honeycomb where the mixing layer closure is about $4D$, like in shock profile cases. That can illustrate that the using of honeycomb leads to deceleration of jet mixing.

![Figure 2](image-url)

Figure 2. Transverse profiles of the longitudinal velocity component for inlet cross-section (a), for $x/D=0$ (b), $x/D=1.5$ (c), mixing layer closure coordinate depending on swirl number (d)
Figure 3. Transverse profiles of the azimuthal velocity component for nozzle outlet cross-section (x/D=0), and for x/D = 1.5

For the azimuthal velocity component (Fig. 3), it can be seen that for all swirl numbers, the profile at the nozzle outlet has a solid-body rotation behavior. For x / D = 1.5 (Fig. 3, right), it can be seen that the profile vortex breakdown has significant differences from the cases with the other swirl numbers, which have the same structure. For S = 0.63, it can be seen that the decay of the angular velocity is slower than in the absence of vortex breakdown, and an area with counter-rotation appears at the outer boundary of the mixing layer, which is associated with the double-spiral structure at the mixing layer.

This paper was also aimed at the passive-scalar transport analysis. Looking through the mean fields of the longitudinal velocity component and passive-scalar distribution (Fig. 4) it can be seen that mixing layer closure point moves to the nozzle edge with the increasing of the swirl number from x / D = 8 for S=0 to x / D = 2 for S=0.46 (Fig. 2d).

Figure 4. Mean fields of the longitudinal velocity component (a, b, e, f) and passive-scalar distribution (c, d, g, h). (a, c) S=0, (b, d) S=0.225, (e, g) S=0.3, (f, h) S=0.63.
For the high-swirl number \( S=0.63 \) we cannot see the mixing layer closure because of the vortex breakdown, with recirculation zone formation on the jet axis, which can be also seen from the presence of negative velocity on the jet axis (Fig. 4f).

**Figure 5.** Radial passive-scalar transport fields for different swirl numbers (a) \( S=0 \), (b) \( S=0.15 \), (c) \( S=0.225 \), (d) \( S=0.3 \), (e) \( S=0.46 \), (f) \( S=0.63 \).

Considering the radial passive-scalar transfer fields (Fig. 5) it can be seen that with the increasing of the swirl number the reducing of the main transfer region size is observed. Also, we can point the formation of the zone of negative radial transport of the passive-scalar on the jet axis which is directed along the gradient for the high-swirl case as an effect of the vortex breakdown.

The distributions of the second moments of the longitudinal velocity component are shown in Fig. 6. Looking through Fig. 6 it can be noted an increasing of the fluctuations amplitude with the swirl number rises; however, upon reaching \( S=0.3 \), the amplitude of the fluctuations starts to decrease, which indicates the presence here of the effect of suppression of fluctuations due to rotation.

**Figure 6.** Distributions of the second moments of the longitudinal velocity component fields for different swirl numbers (a) \( S=0 \), (b) \( S=0.15 \), (c) \( S=0.225 \), (d) \( S=0.3 \), (e) \( S=0.46 \), (f) \( S=0.63 \).
Conclusions
The simulations with the dynamic mesh and static mesh were combined to carry out the simulations with correct instantaneous inflow data. According to the results of the simulations, the vortex breakdown for swirl number 0.63 was observed. In addition, the influence of this phenomenon on such characteristics as the radial transfer of a passive-scalar and the second moments of the longitudinal velocity component was noted. It was found that the vortex breakdown contributes the formation of a negative radial passive-scalar transfer zone on the jet axis. Also, it is important to point the swirl influence on turbulent fluctuations suppression upon reaching the swirl number 0.3.

The further collaboration with the experimental investigations is planned for this configuration for a more detailed analysis.

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