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Numerical simulation of a low-swirl impinging jet with a rotating convergent nozzle

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Abstract. The paper presents the results of Large Eddy Simulation of a swirling impinging jet with moderate Reynolds number ($10^4$), where the swirl is organized via the rotation of a convergent nozzle. The results show that the effect of the swirl in this configuration leads to an increase of axial velocity, compared to the non-swirling case. It is shown that turbulent stress plays an important role in this effect. The vortex structure of the jet consists of multiple pairs of nearly parallel helical vortices with opposite signs of rotation. The interaction of vortices in the near region of the jet leads to radial contraction of the jet’s core which in turn, causes an increase in the axial velocity.

1. Introduction

Jet flows are used in a wide variety of technical systems: jet engines, cooling systems, mixers, chemical reactors, furnaces and combustion chambers. This makes such flows are perspective for further investigations. The application of swirls to the jet flows is often used for flame stabilization in burners and combustion chambers, since it increases in intensity of heat and mass transfer in the near region of the jet. In particular this is due to the formation of large-scale helical vortex structures that have a significant effect on transport and mixing in swirling flows. For jets with a strong swirl the central recirculation zone is formed as a result of breakdown of the vortex core, which also leads to flame stabilization.

As a drawback, flows with a strong swirls usually show an intensive precession of a helical vortex core, which in a number of cases has negative consequences such as thermoacoustic resonance in combustion chambers and vibrational combustion regimes. The characteristics of large eddies in jets with a weak swirl have not been investigated. The effect of their interaction on the intensity of the heat-mass transfer, mixing and the acoustic noise generated by the jet remains unclear.

Turbulence structure of the flow has significant changes when swirling is applied: instead of ring-structure of the vortices flow in a non-swirling jet case, the variety of helical structures can be seen as the dominant modes. The interaction of helical vortices may be significantly different from the non swirling case, because the mean helicity, being an invariant may affect the spectral energy transfer and dissipation [1]. Swirl is considered as one of the effective ways of passive flow control by many authors[2].

In the recent years due to the development of the optoelectronic technologies and increasing of computational resources for numerical simulation, it has become possible to investigate the effects of the interaction of vortices inside the jet. The identification of parameters that affect the vorticity dynamics enstrophy will allow extending the range of the methods to control the heat-mass transfer in jets.

There are many ways to introduce a swirl to the jet. The most common and well-studied one is by mounting stationary blades inside the nozzle at some angle to the incoming flow. In such setup the drag, induced by the blades in the central part of the flow, leads to the slowing down of the flow in the jet’s core. This effect helps in the formation of recirculation bubble. However, it is possible to introduce the swirl without putting obstacles to the flow by using a rotating nozzle. In the present work we studied, by means of numerical simulation, the rotating nozzle configuration of the impinging jet with a low swirl rate. The vortex structure of the flow and the effect of the swirl on the vorticity dynamics were the main objects of the study.

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2. Equations

We use LES approach with dynamic Smagorinsky model, with the following equations for the momentum transport:

\[
\frac{\partial \tau_{ij}}{\partial t} + \frac{\partial}{\partial x_{j}}(\rho \tau_{ij}) = -\frac{1}{\rho} \frac{\partial p}{\partial x_{i}} + \frac{\partial}{\partial x_{i}} \left( (\nu + \nu_{\text{sgs}}) \tilde{S}_{ij} \right).
\]  

(1)

We use classical form of the subgrid viscosity:

\[
\nu_{\text{sgs}} = (C_{\text{S}} \Delta)^{2} |S_{ij}|^{1/2},
\]

where \(\Delta\) is a grid spacing and \(C_{\text{S}}\) is Smagorinsky coefficient, which should be evaluated dynamically.

The classical dynamic model of Smagorinsky [3] model computes \(C_{\text{S}}\) after applying the explicit spatial filtering to the velocity field and then minimizing the difference between the subgrid and residual stress tensors. However, this procedure may lead to negative turbulent viscosity (i.e energy backscatter from the subgrid to resolved scales). In turn, this is proved to lead to the blow up of the solution because the amount of energy which may be transferred from the small scales is unlimited. It is common to use clamping of Smagorinsky constant only to positive values. But such procedure is an ad hoc and non-physical in nature. It was shown that the Smagorinsky constant averaging over homogeneous directions is a cure-all solution, but only a few types of flow have homogeneous directions for such averaging. Another approach adopted here was introduced in [4] and consists in averaging of the residual tensor magnitude over the lagrangian trajectories. The model has shown a good agreement with direct numerical simulations and can be adopted for almost every flow.

3. Computational domain and numerical scheme

The computational domain covered a short inlet pipe section continued by the convergent nozzle and a cylindrical domain ending with an impact wall (Fig 1). The ratio of the nozzle inlet to outlet diameter \((D_{\text{in}}/D)\) was equal to 4. The inlet pipe section length was 1.6 \(D\), and the convergent nozzle length was 2.5\(D\). The impact wall was placed at the distance of 3\(D\) from the nozzle exit. The geometry of the nozzle was built using the Vitoshinsky equation[5]. The domain around the nozzle was cylindrical and had a diameter of 10\(D\) The numerical grid consisted of 10^7 hexahedral cells, refined toward the solid boundaries, with the wall-adjacent gridcell width (\(y^+\)) of about 1 in wall units.

The momentum transport equation Eq.1 was discretized using the finite volume scheme of the second order of accuracy in time and space. The modified LES solver from OpenFoam[6] package was used.

Figure 1. The computational domain for numerical simulation (left); iso-surface of \(Q\)-criterion \((Q = 5)\), colored by helicity density.
4. Boundary conditions

The numerical simulation of the complex flow requires correct boundary conditions. Nowadays, there are several ways to generate turbulent initial conditions at the inlet. In our work we used the anisotropic divergence-free synthetic turbulence at inflow boundary, introduced in [7]. This method helps to avoid numerical artifacts, as in random fluctuations generation, and costly preliminary simulations for inlet conditions.

![Figure 2](image)

**Figure 2** The profile of axial velocity along the jet axis (a), along spanwise cross-sections $x/D=2$ (b) and $x/D=0$ (c); mean-velocity components (d, f, h) and turbulent intensities (e, g, i) in longitudinal cross-section of the jet.

In our case the swirl is introduced by the rotating convergent nozzle with inlet to outlet diameters ratio of 4. It was shown in [8] that for convergent nozzle the azimuthal and axial velocity components will be affected differently by the contraction. From an inviscid analysis one obtains that the axial velocity will increase in proportion to the contraction ratio (CR) whereas the azimuthal one - only as a square root of CR. In our case we expected the 16 times increase of axial velocity and only 4-times increase of azimuthal velocity. We chose the Reynolds number at the nozzle outlet to be $10^4$ this means that the nozzle inlet Reynolds number should be 2500. The azimuthal velocity of the nozzle inlet pipe surface was set to be two times larger than the mean axial velocity of the nozzle inlet: that gave the swirl number $S\approx0.3$ (based on the ratio of azimuthal and axial fluxes) at the nozzle outlet. We used the rotating pipe
velocity and fluctuations amplitude profiles (taken from [9]), for the inlet conditions of the rotating pipe section placed before the nozzle. 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. At the impact wall, simple no-slip conditions were used.

5. Results and discussion

Applying the swirl to impinging jet it is expected to intensify the spanwise spread through the effect of the centrifugal force. This behaviour was observed in experiments with stationary blade swirlers [2]. However the evolution of the jet strongly depends on the radial organization of the swirl. In our case the effect of centrifugal force in the contracting part of rotating nozzle induce the negative axial force component. This leads to the formation of recirculation bubble inside the nozzle, which affects the velocity profiles at the nozzle outlet.

The time-averaged fields of velocity and turbulent fluctuations obtained in the present simulation are presented in Fig.2. The comparison with non-swirling case with the same nozzle (Fig.2 a,b) shows that swirl affects the axial velocity. It can be seen that maximum of axial velocity detaches from the nozzle plane and shifts in streamwise direction to $x=0.65D$. The spanwise profile of axial velocity shows that in the swirling case the mixing layer is wider, which leads to a slower growth of Kelvin-Helmholtz type instabilities, compared to a non-swirling case.

Because of its shape the rotating nozzle accelerates the flow rotation in its widest part, and decelerates in the narrowest part close to the nozzle outlet. This leads to generation of axial vorticity of the opposite sign to the main swirl close to the nozzle surface and the formation of secondary vortices in the boundary layer. This is reflected in the azimuthal velocity profile at the nozzle exit. The maximum of azimuthal velocity is shifted from the wall towards the jet core. The positive part of radial gradient of azimuthal velocity is observed to be lower than the negative part, which is located at the outer boundary of the jet. This behavior is pronounced for the distance of about a jet diameter ($D$) downstream from the nozzle exit. This means that there exist two concentric vortex systems with opposite signs of axial vorticity, one at the jet core and the other one at the jet periphery. Below it will be discussed in more detail.

The radial velocity profile shows negative values which means that the jet is contracting in the radial direction in the region close to the nozzle exit. This contraction is reflected in the growth of axial velocity after the jet exits the nozzle shown in Fig. 2a.

5.1 Turbulence characteristics

The components of turbulence energy are presented in Fig 2 c, e, g, i. At the nozzle exit the highest are the axial velocity fluctuations, but the azimuthal fluctuations are of almost the same magnitude, while the radial fluctuations are much lower, and their maximum is closer to the jet axis. This reflects the fact that the main modes of fluctuations are helical vortices. While moving downstream the radial fluctuations grow up to the same level as azimuthal ones, which might be the reflection of the development of Kelvin- Helmholtz type instabilities.

![Figure 3](image_url)

**Figure 3** The components of mean radial momentum equation for $x/D=0.65$ (left) and the distribution of $-\frac{\partial u_r^2}{\partial r}$ in longitudinal cross-section (right).
One of the most interesting questions of the study is to search for the mechanism of jet radial contraction as it exits the nozzle.

We consider now the equations of mean radial momentum balance to see which term contributes the most to the negative radial force component. Neglecting the viscous terms one can write

\[
U_x \frac{\partial U_x}{\partial x} + U_r \frac{\partial U_r}{\partial r} - \frac{U_y^2}{r} = - \frac{1}{\rho_0} \frac{\partial P}{\partial r} \left( \frac{\partial(u'_x u'_x)}{\partial x} + \frac{\partial(u'_r u'_r)}{\partial r} - \frac{u'_r^2 - u'_r^2}{r} \right)
\]

where the first four terms are the effect of the mean flow characteristics while the last three are the effect of turbulent fluctuations. From Fig. 3a it can be seen that the most positive radial forcing is provided by the centrifugal force, while the significant part of negative forcing is provided by the effect of radial velocity fluctuations. The pressure gradient acts to counterbalance these two parts. This means that the effect of radial contraction at the near region of the jet is caused by the effect of turbulence.

![Figure 4](image)

**Figure 4** Distribution of axial vorticity component in the nozzle cross-section (a), the schematics of vortex interaction (b), the main vortex modes of the jet shown by iso-surfaces of \(Q\)-criterion, colored by helicity density (c)

From the axial distribution of \(-\frac{\partial u'_r^2}{\partial r}\) it could be seen that it causes the positive radial forcing at the jet periphery, and negative forcing closer to the jet’s core.

We will now discuss the vortex structure of the jet. As it was mentioned above, the most energetic modes of the mixing layer are helical vortices (Fig 4). The axial vorticity distribution is shown in Fig 4a. It can be seen that the distribution consists of two parts with opposite signs, one with negative (same as the main swirl) sign in the jet core and the other with positive sign close to the nozzle boundary. Due to the growth of instabilities, the substantial part of vorticity volume is organized in separate counter-rotating vortices, represented as red and blue spots in Fig 4a. Spatially these vortices have helical shape. After exiting the nozzle the positive axial vorticity becomes amplified because of the generation of instabilities in the mixing layer. After that the two-part helical structure is established with checkerboard pattern of positive and negative axial vorticity. In three dimensions these leads to generation of parallel
helical vortex pairs, in which the vortices with negative axial vorticity are located closer to the jet axis and with positive axial vorticity around them at the jet periphery. The interaction of such vortices may lead to the radial contraction of the jet as shown schematically in Fig 4b.

It is also noticeable that when reaching the impact surface the helical structure of the jet evolves into two separate helical “sleeves”, each having about a half of the jet core vorticity. These sleeves form a “Y” shape and split near the wall.

6. Conclusions

The impinging jet with a rotating convergent nozzle was simulated. It has been found that in the near region of the jet the axial velocity intensifies, compared to the non-swirling case. The point of maximum axial velocity is shifted by 0.65 nozzle diameters downstream from the nozzle edge. The turbulent stress is found to have a sufficient contribution to the effect of radial contraction of the jet that leads to the growth of axial velocity. Possible explanation of such influence of turbulent vortices on the mean flow is proposed based on the dynamics of helical vortex pairs, evident in the simulation.

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