Large eddy simulation of two parallel round jets

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Abstract. The results of large eddy simulation of flow dynamics in a system of two parallel round turbulent jets are presented. Twin jets are investigated at Reynolds numbers Re = 5500 and 11000; the cases with different distances between the jet axes s/d = 1.8 and 2.4 are examined. The data are compared with the classical case of a single round submerged jet.

1. Introduction

The study of interaction of parallel turbulent jets is caused, on the one hand, by a wide range of technical applications: ejectors, cooling systems for heat-stressed surfaces and nozzles for gas fuel supply in burners. Optimization of mixing, heat transfer and other characteristics in such devices can lead to significant fuel economy, improvement of environmental friendliness, noise reduction and other positive effects. On the other hand, there is currently no a single theory that would allow us to describe all aspects of this interaction.

A large number of publications deal with the study of a single jet, and the main conclusions of these studies are formulated in the corresponding reviews, for example [1]. For a system of two parallel round jets, there is substantially less information, which is due, among other factors, to the appearance of additional parameters of the problem: distance between the nozzles, ratio of flow rates and ratio of diameters for a system of unequal jets.

A number of works are devoted to the study of interaction of two or more jets, among which experimental works [2-5] should be noted first. In these works, suppression of turbulence in each of these jets due to their interaction is revealed. It is noted that there is a decrease in both the intensity of turbulence and Reynolds stresses, and the magnitude of this effect increases with decreasing distance between the jet axes. Also in the literature, there are the works on numerical simulation of jet systems. So, in [6], a system of three (unequal) parallel round jets was simulated to study flame stabilization in a jet burner using the RANS/RSM approach. The use of two-parameter turbulence models in the problems of jet interaction often leads to a significant difference between the obtained results and experimental data, especially in the region preceding the jet merging point [7]. At the same time, the use of eddy-resolving methods leads to quite satisfactory results, for example [8], which studied interaction of parallel rectangular jets.

2. Computation details

In this paper, we used a finite-difference numerical code developed by the authors to solve the filtered Navier-Stokes equations of an incompressible fluid that are closed using the Smagorinsky model.
Figure 1. Computation domain (a half is shown). Instantaneous distribution of longitudinal velocity at Re=5500.

The equations were solved according to the projection method [9], which had a second order of accuracy by time. The spatial discretization also had a second order of accuracy (central differences). The time step was chosen so that the Courant criterion in the entire range does not exceed 0.5. The computational domain was a cylinder with a diameter of 10d and the same height (Fig. 1). The number of cells in the computational grid varied from $1.5 \times 10^6$ for calculating a single jet at Re = 5500, to $4.5 \times 10^6$ for calculating a two-jet system at Re = 11000. We should note that the number of grid nodes and, accordingly, their size were determined so that at least 80% of the kinetic energy of turbulence fell into the resolvable part of the spectrum. To set the boundary conditions at the nozzle exit, precursor simulation of a fully developed flow in the pipe with the corresponding Re number was carried out.

3. Results

Figure 2 presents a comparison of simulation results for a single jet at Re = 5500 with experimental data from [10]. It can be seen that the simulation results satisfactorily describe the experimental data, both in terms of average and pulsation characteristics.

The transverse profiles of longitudinal average velocity are shown in Fig. 3a. It can be seen that as the flow develops, jet merging is observed, shown, in particular, by an increase in the longitudinal velocity on the axis of the system. It can be also seen that at $z/d = 7.5$ this increase ends, which indicates that the merging point of jets is achieved, and after that the average longitudinal velocity will only attenuate.

The profiles of longitudinal velocity pulsation are shown in Fig. 3b. At the initial stages of interaction, two pulsation maxima, corresponding to the displacement layers, can be clearly seen for each of the jets. With a distance from the nozzles, these peaks degenerate, while the intensity of turbulent pulsations on the symmetry axis of the entire system increases.
Figure 2. The transverse profiles of the average longitudinal velocity (a) and its pulsation (b) for a single round jet at Re = 5500. Lines – simulation results, dots – experimental data [10]. A half of the region relative to the axis of jet symmetry is presented.

Figure 3. The transverse profiles of the average longitudinal velocity (a) and its pulsation (b) at Re = 5500 for a system of two round jets, whose axes are spaced apart by distance s/d = 1.8. Lines – simulation results, dots – experimental data [10]. A half of the region relative to the axis of jet symmetry is presented.

Figure 4. Longitudinal distribution of the average velocity (a) and its pulsations (b) for a system of two jets and a single jet. Line – a single jet, dots – a pair of jets.
The same characteristics in comparison with a single jet are presented in Fig. 4. At that, the data are presented on the axis of symmetry of one of the jets, and not on the axis of symmetry of the entire system. This makes it possible to evaluate the effect of the adjacent jet on the considered one. It can be seen that at small distances from the nozzle the pattern is similar, which indicates weak interaction. As the flow develops, deviation of simulation results obtained for one jet and a system of two jets, shown by pulsations weakening for the last case at the initial stage and their amplification as they approach the merging point, is observed. In this case, slower attenuation of the average velocity on the jet axis can be also noted.

**Figure 5.** Fields of average longitudinal velocity, its pulsations and $u_1u_2$ correlation for $s/d=1.8$ (left) and $s/d=2.4$ (right) at $Re=5500$. 
Figure 6. Fields of average longitudinal velocity, its pulsations and and $u'_{nlc}$ correlation at Re=11000.

Comparisons of average velocity distributions and $u'_{nlc}$ correlations for different distances between the jet axes are presented in Fig. 5. It can be seen that an increase in this distance leads to weakening of interaction and its shift downstream. Figure 6 shows the fields of these values for Re = 11000. Analysis of this figure allows us to conclude that, as the Reynolds number increases, the interaction of jets intensifies.

Conclusion
The results of large eddy simulation of a system of two round parallel turbulent jets are presented. Two different distances between the jet axes $s/d = 1.8$ and $2.4$ and two Reynolds numbers Re = 5500 and 11000 are considered. An increase in the longitudinal velocity on the axis of symmetry of the system is shown, while the velocities on the axis of each of the jets decrease monotonously to the point of jet merging. Simulation results are compared with data for a single round jet, which makes it possible to assess the degree of jet “interference”. It is noted that the intensity of turbulent pulsations on the axis of each of the pair of jets is less than for a single jet and the effect of the adjacent jet increases with increasing Re number and decreases with increasing distance between the jets.

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