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Mechanism of axis switching in low aspect-ratio rectangular jets

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ABSTRACT

In this work we systematically study one square jet ($AR = 1$) and four rectangular jets with an aspect ratio of width over height $AR = 1.5$, 2, 2.5, and 3 respectively using the lattice Boltzmann method for direct numerical simulation. Focuses are on various flow properties on transverse planes downstream to investigate the correlation between the downstream velocity and secondary flow. Three distinct regions of jet development are identified in all the five jets. As the length of the PC (potential core) region maintains about the same, that of the CD (characteristic decay) region strongly depends on the jet aspect-ratio (AR) and Reynolds number (Re). The 45° and 90° axis-switching occur in the CD region, with the former followed by the latter at the early and late stages of the CD region respectively. The half-width streamwise velocity contour reveals that 45° axis-switching is mainly contributed by the corner effect, whereas the aspect-ratio (elliptic) feature affects the shape of the jet when 45° axis-switching occurs. The close examinations of flow pattern and vorticity contour, as well as the correlation between streamwise velocity and vorticity, indicate that 90° axis-switching results from the boundary effect. Specific flow patterns for 45° and 90° axis-switching are identified to reveal the mechanism of the axis-switchings respectively.

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1. Introduction

Noncircular jets attract special attentions due to their enhanced entrainment and mixing properties, relative to those of comparable axisymmetric jets (Ref. [1] and references therein). Depending on initial conditions at the jet inlet, the cross-section of noncircular jets can evolve downstream through shapes similar to that at the jet inlet with its major and minor axis rotated at angles depending on the jet geometry. This phenomenon is called axis-switching. In the last few decades, axis-switching has been observed in various noncircular jets, e.g. elliptic jets [2–12], rectangular jets [13–21], and other more complicated noncircular jets [22–24]. The jet dynamics is of great interest from both fundamental physics and practical application point of view. It has been believed that in elliptic jets, the underlying mechanism of axis-switching behavior results from self-induced Biot–Savart deformation of vortex rings due to nonuniform azimuthal curvature and interaction between azimuthal and streamwise vorticities [1]. Recently, an experiment confirmed the azimuthal vortex deformation in the region of the axis-switching of a lobed orifice jet [23]. Rectangular jets combine the variable aspect-ratio feature of elliptic jet with the corner vortex feature of square jets. The aspect-ratio (AR) is defined as the ratio of major to minor axis of the jet inlet. This combination yields features which do not appear in elliptic jets and are of importance in practical applications. One example is the 45° axis-switching in a square jet and both 45° and 90° axis-switchings in a rectangular jet ($AR = 1.5$) [20].

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The present study is a part of our continuous effort to investigate the mixing properties when a jet entrains with surroundings and enhance our capability to predict physics in turbulent rectangular jets. In our previous works [19], we performed large eddy simulations (LES) of turbulent rectangular jets at relatively high Reynolds numbers using the kinetic-based lattice Boltzmann method (LBM). The LBM has been well established as an alternative methodology of computational fluid dynamics for solving various complex flows [25,26]. It is second-order accurate in time and space and recovers Navier–Stokes equations in the incompressible limit [27]. The main physical and computational advantages of LBM include simplicity of programming, ease of handling complex geometry, suitability of massive parallel computing, etc.; thus, it is well suited for simulating complex flows including various jet flows [19,28,29]. In the previous study of turbulent rectangular jets [19], we obtained various turbulence statistics which agreed reasonably well with experimental data. Peculiar phenomena such as axis-switching and saddle-back velocity profile were observed. The former was well agreed with experimental observation but the latter was less profound than what observed in the experiment. However, the mechanism of them remained unrevealed due to the usage of a laminar velocity profile at the jet inlet, the complexity of turbulent mixing, and the demanding computation cost. We are inspired to study jet development in laminar rectangular jets to find out what causes axis-switching in laminar jets and what the mechanism behind is to gain insights about how to further explore mixing properties in turbulent jets.

In this study, we systematically study axis-switching in five low AR rectangular jets with $AR = 1, 1.5, 2, 2.5, 3$ at relatively low Reynolds numbers through direct numerical simulation (DNS) using LBM. Focus is on the correlations between the primary downstream penetrating flow and the secondary entertainment on transverse planes to reveal the mechanism of axis-switching in rectangular jets. The remainder of this paper is organized as follows. Section 2 introduces the lattice Boltzmann method for DNS of rectangular jets. In Section 3, we show results on the mechanism of 45° and 90° axis-switching through the correlations between the primary downstream velocity and the vorticity on transverse planes. We conclude in Section 4 with a short discussion.

2. Lattice Boltzmann method for rectangular jets

We employ a D3Q19 single-relaxation-time (SRT) lattice model for the simulation. In this lattice model, the 3D discrete phase space is defined by cubic lattice with 19 discrete particle velocities $\boldsymbol{e}_\alpha$ given as

$$\boldsymbol{e}_\alpha = \begin{cases} (0,0,0), & \alpha = 0 \\ (\pm 1,0,0), (0,\pm 1,0), (0,0,\pm 1), & \alpha = 1 \sim 6 \\ (\pm 1,\pm 1,0), (\pm 1,0,\pm 1), (0,\pm 1,\pm 1), & \alpha = 7 \sim 18. \end{cases} \quad (1)$$

The SRT lattice Boltzmann equation is expressed as

$$f_\alpha(\boldsymbol{r} + \boldsymbol{e}_\alpha \delta_t, t + \delta_t) = f_\alpha(\boldsymbol{r}, t) - \frac{1}{\tau}[f_\alpha(\boldsymbol{r}, t) - f_\alpha^{(eq)}(\boldsymbol{r}, t)] \quad (2)$$

where f_α and f_α^{eq} ($\alpha = 0, 1, \ldots, 18$) represent the 19 distribution functions and their equilibria, respectively; δ_t is the discrete time-step, and τ is the relaxation time. The equilibria for incompressible flow are [30]

$$f_\alpha^{(eq)} = \omega_\alpha \left\{ \delta\rho + \rho_0 \left[\frac{3\boldsymbol{e}_\alpha \cdot \boldsymbol{u}}{c^2} + \frac{9(\boldsymbol{e}_\alpha \cdot \boldsymbol{u})^2}{2c^4} - \frac{3u^2}{2c^2} \right] \right\} \quad (3)$$

where $\delta\rho$ is the density fluctuation, ρ_0 is the constant mean density of the system, and $c = \delta x/\delta t$. In LBM the values of ρ_0, δx, and δt are all typically set to unity. The sound speed in this model is $c_s = c/\sqrt{3}$. The total density is $\rho = \rho_0 + \delta\rho$. The weighting factors ω_α for the D3Q19 model are

$$\omega_\alpha = \begin{cases} \frac{1}{3}, & \alpha = 0 \\ \frac{1}{18}, & \alpha = 1 \sim 6 \\ \frac{1}{36}, & \alpha = 7 \sim 18. \end{cases} \quad (4)$$

The mass and momentum conservations are strictly enforced:

$$\delta\rho = \sum_\alpha f_\alpha = \sum_\alpha f_\alpha^{(eq)} \quad (5)$$

$$\rho_0 \boldsymbol{u} = \sum_\alpha \boldsymbol{e}_\alpha f_\alpha = \sum_\alpha \boldsymbol{e}_\alpha f_\alpha^{(eq)}. \quad (6)$$

The fluid kinematic viscosity ν has the following relation with the relaxation time τ:

$$\nu = \frac{1}{3}\left(\tau - \frac{1}{2}\right) c\delta_x, \quad \tau = \frac{3\nu}{c\delta_x} + \frac{1}{2} \quad (7)$$