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Dynamics and geometry of developing planar jets based on the invariants of the velocity gradient tensor*

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Abstract: Based on the direct numerical simulation (DNS), the developing planar jets under different initial conditions, e.g., the conditions of the exit Reynolds number and the exit mean velocity profile, are investigated. We mainly focus on the characteristics of the invariants of the velocity gradient tensor, which provides insights into the evolution of the dynamics and the geometry of the planar jets along with the flow transition. The results show that the initial flow near the jet exit is strongly predominated by the dissipation over the enstrophy, the flow transition is accompanied by a severe rotation and straining of the flow elements, where the vortex structure evolves faster than the fluid element deformation,in the fully-developed state, the irrotational dissipation is dominant and the most probable geometry of the fluid elements should remain between the biaxial stretching and the axisymmetric stretching. In addition, with a small exit Re and a parabolic profile for the exit mean streamwise velocity, the decay of the mean flow field and the magnitude of the turbulent variables will be strengthened in the process of the flow transition, however, a large exit Re will promote the flow transition to the fully-developed state. The cross-impact between the exit Re and the exit mean velocity profile is also observed in the present study.

Key words: planar jet, direct numerical simulation (DNS), velocity gradient tensor, flow transition, joint probability density function (joint pdf)

Introduction

In the fundamental research of turbulence, the free shear flow is often a proper choice of a model to explore the typical instantaneous turbulence structure and the general statistical flow characteristics. As one of the prototypical free shear flows, the planar jet en joys a simple geometry and easily-simulated boundary conditions. Moreover, the planar jet is involved in engineering applications of a broad range, e.g., the combustion, the propulsion and the environmental flows. It is, therefore, meaningful and logical to study the planar jet.

As seen in the past studies, it is quite clear that an integration of the theoretical, experimental and computational methodologies is desirable for the planar jet. Meanwhile, with the progress of the flow measurement technology, mainly, the hot wire anemometry, the laser Doppler velocimetry (LDV) and the particle image velocimetry (PIV), and with the advancement of the computer technology, the understanding and the utilization of the planar jet are much improved, especially with regards to its turbulent characteristics.

Gordeyev and Thomas[1] experimentally examined the topology of the large-scale structure in the self-similar region of the turbulent planar jet by using the proper orthogonal decomposition (POD). The results indicated that the self-similar large-scale structure consists of a dominant planar component including two lines of large-scale spanwise vortices arranged approximately asymmetrically with respect to the jet centerline, resembling the classic Kármán vortex street, however, the fine-scale structure was not revealed in their study. Atassi and Lueptow[2] proposed a model of flapping motion in the transition region of the plane jet based on the linear inviscid analysis near the jet exit and the nonlinear finite-amplitude analysis

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in the further downstream region. This work confirmed that the flapping of the jet could be attributed to a traveling wave instability, which leads to a sequence of coherent structures alternating in signs (asymmetric) on either side of the jet. In 2007 and 2008, Deo et al.[3] published four papers for their experimental work on the effects of initial conditions on the planar jet. In their work, the effects of the exit Reynolds number from 1500 to 16500, the sidewalls[4], the nozzle aspect ratio[5], and the nozzle-exit geometric profile[6] were studied. However, the cross-impact between these factors had not been considered in their work. Suresh et al.[7] studied the transitional characteristics of the planar jet with varying exit Reynolds numbers from 250 to 6 250. The results show that the jet is Reynolds number dependent in the flow development region, on the other hand, the flow features in the fully developed region are independent of the initial conditions. But this was not confirmed in the relevant work of Deo et al.[3], who emphasized that other initial factors may be responsible for the deviation. Terashima et al.[8] developed a new technique for the simultaneous measurement of the velocity and the pressure, and its application to the planar jet produced fine results, but the measurement errors still there, especially, the pressure fluctuation. Based on the work of Gordeyev and Thomas[1], Shim et al.[9] investigated the large-scale coherent structure of the near field of a plane jet using both two-dimensional PIV measurements and POD techniques, in which the presence of anti-symmetrical vortices was confirmed. Sakakibara[10] produced a planar jet excited by disturbances with spanwise phase variations, as a new attempt to trigger the secondary instability at the planar jet exit, where the vortex pairing did not occur downstream and the jet was widened at a low flow rate. In 2013, Deo et al.[11] made a similarity analysis of the momentum field of the planar air jet with varying jet-exit and local Reynolds numbers.

In view of the inevitable measurement errors and the difficult manipulation in some flow experiments, direct numerical simulation (DNS) becomes an important methodology in the turbulence study. Stanley et al.[12], Da Silva et al.[13], Wu et al.[14], and others carried out the DNS for the planar jet. With the DNS, different computational models may be evaluated and compared, meanwhile, some aspects, which are difficult to study experimentally, may be revealed, such as the fine-scale dynamics and the examination of flows under some idealized conditions.

On the basis of the properties of the velocity gradient tensor, the features of the fine-scale motion can be studied properly[15]. Da Silva et al.[13] studied the invariants of the velocity-gradient across the turbulent/nonturbulent interface in the self-preserving region of the planar jet. In their work, the kinematics, the dynamics, and the topology of the flow during the entrainment process were clarified. However, the transition process of the planar jet was not evaluated from this aspect.

Furthermore, it is found that the characteristics of the planar jet at a high Reynolds number or in the self-preserving region were extensively studied in the past, and, on the other hand, related studies at a moderate Reynolds number were relatively few. Meanwhile, the flow transition, in the region after the merging of the shear layers but before the similarity is achieved in the planar jet, deserves to be further evaluated when the Reynolds number is relatively small at the jet exit.

In the present work, we investigate the flow transition process in the developing planar jets according to the results of the DNS based on the finite difference method. The kinematics, the dynamics and the local structure of the planar jet in the fine-scale are studied by analyzing the evolution of the invariants of the velocity gradient tensor. Meanwhile, by setting the different Reynolds numbers and mean velocity profiles at the jet exit, the effects of the initial conditions on the flow evolution are assessed, particularly, the characteristic features of the planar jet in the inhomogeneous transition zone.

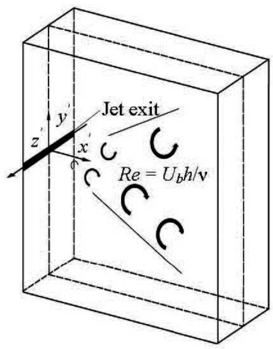

Fig.1 Schematic diagram of the computational domain

1. Problem formulation and simulation details

The DNS of the spatially developing planar jet is performed in a 3-D computational region, which is constructed in the coordinate system nondimensionalized by the height of the jet exit h, as shown in Fig.1, in which x' is the dimensionless streamwise coordinate, y' is the dimensionless lateral coordinate, and z' is the dimensionless spanwise coordinate. The jet exit is set in the middle of the inlet plane, e.g., the plane of $x' = 0$. The dimensionless computational domain covers a region of $14\pi \times 14\pi \times 3\pi$. In our work, the typical Reynolds number of the planar jet Re is defined at the jet exit by the momentum-averaged mean velocity U_b and h.

The continuity equation and the Navier-Stokes equations are used to describe the velocity field, the scalar field is investigated by solving the scalar tran-