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The starting flow structures and evolution of a supersonic planar jet

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ABSTRACT

The starting flow fields produced by a supersonic underexpanded planar jet are studied numerically with the use of large eddy simulation (LES). The three-dimensional (3D) structures and evolutions of the starting jet flows including compressible main vortex pair, vortex-induced shock waves, shock–vortex interactions and jet mixing have been illustrated and discussed in detail. Our results show that the generation and evolution of the main vortex pair, the initial perturbation and the interaction of vortex-induced shock with jet shear layer can accelerate the instability and mixing of the shear layer. The geometric characteristics of the main vortex for different initial conditions have been discussed. Only at a later stage, the differences between the 2D and 3D structures of the vortex core are obvious, but the interface of the main vortex pair keeps stable even when the vortex cores become turbulent.

1. Introduction

Due to the importance both in the field of fundamental fluid dynamical studies and practical applications, supersonic underexpanded compressible jets have been investigated extensively [1–6]. There are many important physical phenomena, such as free shear layer, shock wave diffraction, turbulence transition, shock–vortex interaction and aerodynamic noise are included in such flows. However, for the starting flow field of a jet, another interesting physical phenomenon, the main vortex loop/pair, appears [7–13], but there are not many works reported in this field.

The starting flow of a supersonic jet is similar to that of a supersonic pulse jet flow. The precursor shock wave exits the nozzle firstly, it diffracts around the corner of the nozzle, then the supersonic gas is discharged to form a shear layer [14–18]. The shock diffraction leads to the misalignment of the pressure and density gradients and makes the shear layer rolls up into a vortex ring which moves downstream like a mushroom head [19]. It also expands immediately through the entrainment of ambient gas into its vortex core, and causes a fast increase of its diameter. For a supersonic jet, some complicated shock patterns, such as shock cells, vortex-induced shock pair and embedded shock, emerge and evolve with the flow field [10], and the flow structures are distinct for different nozzle geometries [10,11]. Ishii et al. [18] investigated experimentally and numerically the supersonic pulse circular jet evolution, in particular the formation processes of Mach disks and shock-cell structures. They found that the vortex ring plays an important role in the formation of shock-cell structures. Radulescu and Law [14] investigated the initial transient hydrodynamic evolution of the highly underexpanded slit and round jet, a closed-form analytic similarity solution for the main parameters (temperature, pressure and density) at the jet head was derived. Based on the high-speed schlieren, shadowgraph, and particle image velocimetry (PIV) techniques, Zare-Behtash et al. [10,11] visualized the structures of shock wave and consequent vortex loop generated by a shock tube with various nozzle geometries, different types of vortex loops were examined. The same research group [20] also studied their structural and propagating features. In addition, the generation mechanism of secondary vortex rings of a supersonic underexpanded circular jet has also been investigated and discussed [17,21,22].

After generation, the vortex ring is self-contained, automotive, and quite longevous [23]. In order to fully describe the vortex loop and its parameters characteristics, Ishii et al. [18] and Kimura and Iwamoto [24] obtained the jet structure and its evolution with the use of both numerical and experimental methods, the variations of the ring diameter and its move velocity have been shown, their numerical results from Euler equations agree well with corresponding experimental results. Zare-Behtash et al. [10] found that the diameter of vortex loop becomes large at high Mach number, while it remains constant after reaching certain value. However, its propagating velocity appears to be constant. In addition, Satti and Agrawal [25] computed the flow structure of an evolving low-density helium laminar starting gas jet, the unsteady flow structures including the mushroom-shaped jet front and multiple vortex rings were captured, their results show significant effects of buoyancy on jet evolution.

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In addition, the generation of vortex loop/pair and vortexlets in such jet flows can also enhance the mixing of jet and ambient gases. Meyer et al. [26] investigated the vortex formation and merging in the near field of a driven axisymmetric jet, and obtained the instantaneous images of molecularly mixed jet fluid fraction. Ribault et al. [27] investigated the passive scalar development in a plane jet with the use of LES. They found that the passive scalar has a Gaussian distribution at the jet centerline with the transport and intermittency sharply increasing near the jet borders. Stanley et al. [28] numerically simulated the flow field evolution and mixing of a planar turbulent jet, they found the mixing process is dominated by large-scale engulfment of coflow fluid into the jet by the rollup of strong vortical structures in the jet shear layers. Moreover, Babu and Mahesh [29] studied numerically the effect of inflow entrainment by providing a buffer region upstream of the nozzle, and found it has influences on the volumetric flow rate near the inflow nozzle. Brownell and Su [30] obtained all the individual mole fractions in a three-species nonreacting turbulent flow by using planar Rayleigh scattering and planer laser-induced fluorescence (PLIF), and investigated the effect of molecular transport properties on the turbulent mixing.

Planar jets have also been investigated due to their engineering applications in the field of combustion, propulsion and environmental flows. Compared to round jets, such non-axisymmetric jets have profound advantages in increasing the mixing with surrounding fluid and reducing noise generation [28,31]. However, there are few studies on the starting flow fields of steady jets or pulse planar jets. Therefore, in this paper, we aim to present a complete description of the 2D and 3D characteristics of the starting flow structures and evolutions of a supersonic planar jet with the use of LES method. The subgrid stretched–vortex model [32] combined with the high order hybrid TCD–WENO scheme [33] are employed to solve the LES equations. The detailed evolution process of the main vortex pair has been illustrated. In particular, the development process of vortex-induced shocks, vortexlets of the shear layers, the interaction of shock with vortexlets and their effects on the mixing of ambient and jet gases have been revealed and discussed.

2. Numerical method and physical model

2.1. Numerical method

The compressible LES equations can be obtained by Favre filtering the compressible Navier–Stokes equations in the Cartesian coordinate system [22]. The mixture fraction f is defined as: $f = (Y - Y_1)/(Y_2 - Y_1)$, where Y_1 refers to the mass fraction of oxidizer (ambient gas), and Y_2 denotes the fuel (jet gas) mass fraction. With this definition, f takes the value 1 in the jet gas and 0 in the ambient air. The filtered heat conduction, dynamics viscosity and molecular diffusivity can be obtained from binary mixing rules and the pure component mixing properties.

The subgrid terms of LES equations are modeled with the stretched–vortex subgrid scales (SGS) model for multicomponent, compressible flows to approach the unresolved subgrid terms [32–35]. The stretched–vortex SGS model is designed for simulating turbulent fine scales and has the capability of predicting subgrid scale quantities systematically. In this model, the stretched-vortices are assumed to be the small-scale structures which consist of tube-like complicated curved and twisted elongated regions of concentrated vorticity, and have a spiral structure. The subgrid turbulent kinetic energy takes the Lundgren form.

The supersonic jet flows include shock–vortex interaction and turbulent shear flow. The hybrid numerical method of tuned centered difference (TCD) – weighted essentially non-oscillatory (WENO) [33] which has been applied successfully for simulating the shock induced compressible flow [22,36,37]. It is proposed to satisfy the different resolution requirements within the regions with different flow features, such as shock waves and turbulence. WENO scheme has high order accuracy and excellent discontinuities capturing ability. However, its ability to distinguish shortwave for dissipation error is lower than the high-order centered-difference methods. TCD uses the Ghosal truncation error as an object function, and optimizes the coefficients of center difference template to eliminate the dispersion error. The hybrid TCD–WENO scheme takes advantage of the virtues of both schemes. The high order WENO scheme is used around discontinuities (such as shock waves and contact surfaces), while TCD scheme is employed to handle the smooth or turbulent regions of the flow. For the hybrid TCD–WENO method, both the WENO and centered-difference methods are specially tuned to minimize dispersive errors at those locations where scheme switching takes place. The WENO stencil coefficients have been adjusted to make it match the TCD stencil. This modification largely eliminates any dispersion errors that result from transitioning between schemes. The derivatives of inviscid fluxes are presently computed using a hybrid numerical method with a 7-point tuned centered-difference (TCD) scheme and a 7-point WENO upwind scheme, this leads to 5th order precision. Time advancement is achieved with the 4th-order Runge–Kutta method.

2.2. Computational domain and cases

The shock wave diffraction and formation of main vortex of the jet flow are dependent on the nozzle shape, Mach numbers, density ratio and the initial conditions of its exit. In this paper, the 3D computational domain is taken as a rectangular cuboid which is shown in Fig. 1. The height of planar nozzle (KI) is $h = 0.01$ m and its width (KM) $L_z = 4h$. The length (AB) and height (AE) of the computational domain are chosen to be $L_x = 8h$ and $L_y = 7h$, respectively.

Initially, the gas within the whole computational domain is chosen to be standard and static ($u_0 = 0$), and its specific heat ratio, dynamic viscosity coefficient, pressure and temperature are $\gamma = 1.4$, $\nu = 1.73 \times 10^{-5}\ \mathrm{kg/m^2}$, $p_0 = 1.0$ atm and $T = 300$ K, respectively. Three different inflow cases shown in Table 1 are taken to be our investigating examples. The jet Mach number and pressure of all cases are $Ma = 1.4$ and $p = 1.4$ atm, respectively, which means all cases are supersonic underexpanded jet flows. Their inflow gas velocities are chosen to be steady and laminar, the corresponding Reynolds number is $Re = 2.8 \times 10^5$. The profiles of inflow velocities in xoy plane are obtained from Ref. [38].

To minimize the amplitude of reflective acoustic waves at the boundaries of the computational domain, non-reflective boundary conditions [39] are applied to the outflow boundaries (including planes of BDHF, ABDC and EFHG), and the viscous wall boundary condition is applied to the upper and lower walls (planes of KMGE and ACJI) of the jet at the inlet end. The uniform Cartesian grid is used for meshing the computational domain. After the grid tests, the corresponding grid numbers for three cases are chosen to be $560 \times 490 \times 280$, $560 \times 490 \times 280$ and 1200×1200, respectively. Case 1 and 2 are three-dimensional (3D) jet flow with the same ejecting Mach number. To accelerate the instability evolution, the perturbation has been superimposed at the entrance ($x = 0$) for Case 2. Case 3 is a two-dimensional (2D) planar jet flow which is used to compare the 3D effects of the flow at a later stage.

Jet flow includes shear layer which is unstable due to the existence of Kelvin–Helmholtz instability, to avoid unnecessary waste of computational resources, it is need to accelerate the instability of shear layer. Linear stability analysis is employed to provide eigenfunctions of unstable waves which can be used as the initial conditions. Therefore, we are able to control the development of a shear layer by initializing the numerical simulation with linear stability eigenfunctions of adequate amplitudes and phases. In this