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Characteristic behavior of shock pattern and primary vortex loop of a supersonic square jet

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ABSTRACT

The initial flow fields of the supersonic underexpanded square jets with different nozzle pressure ratios were investigated numerically. The governing equations of large eddy simulation (LES) for compressible flow have been employed and solved numerically with the combination of high-order hybrid schemes. The numerical result provides the 3D shock wave structures embedded in the underexpanded square jet. Moreover, the effect of nozzle pressure ratio on the 3D characteristic behavior of near-nozzle shock wave and the jet boundary are discussed, it is found that the near-nozzle shock wave structure suppresses the jet boundary at the corner position expansion along the diagonal direction, and accelerates the jet boundary near the sidewall position to move in normal direction to the nozzle side, finally resulting in a remarkable cross-shaped jet cross section at the downstream. Besides, the 3D behavior of streamwise vortices during the self-induced deformation of primary vortex loop is identified using the iso-vorticity field, and their role in the axis-switching behavior of supersonic square vortex loop is analyzed in detail.

1. Introduction

Relative to those of circular jets, non-circular jets [1] have been considered as an efficient technique for passive flow control, which attract special attentions due to their enhanced entrainment and mixing properties. The enhanced entrainment obtained with non-circular nozzles is believed to be mainly result of the self-induced vortex deformations. Previous investigations have reported the axis switching of jet cross-section in the near field. The near jet flow visualizations suggest the self-deformation of the corner regions of vortex loops and considerable vortex stretching in the regions aligned with the corners [2–5], where significant streamwise vortices are found and play a significant role during the axis switching [3]. And Grinsterin et al. [6] demonstrated the distortion of the azimuthal vortex structures can lead to streamwise vortices by the computational results, and indicated that the dynamic of azimuthal vortex structures and streamwise vortex pairs are not independent of each other. Thus a set of experiments has been conducted in an attempt to shed light onto these processes. The experimental studies of Zaman [5] and Gutmark and Grinstein [1] have also identified that the 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. Biot-Savart self-induction causes segments with larger curvatures to move faster than those with smaller curvatures, then the vortex structure cannot retain its original shape and remains in a plane, and eventually resulting in the axis switching. However, the underlying fluid-dynamical mechanisms leading to these observations are far from being understood, and detailed studies of the dynamics and topology of the large-scale coherent structures governing the entrainment and mixing in these jets are needed.

Rectangular jets are of great importance in the aerospace community due to the use of vectored thrust on F-35 fighter aircraft and scramjet, and increased mixing of the jet plume with the surroundings which decreases jet detection. The study of square jet has the advantage of allows to isolate the features which are independent of aspect ratio and directly related to the rapid shear layer curvature changes at the corners [6,7]. However, previous studies have mainly focused on the flow structures of subsonic noncircular jets. For the supersonic noncircular jets, another interesting physical phenomenon, such as complicated shock patterns and shock-vortex interaction, appears, but there are not many works reported in this field. Menon and Skews [8] have numerically investigated the rectangular underexpanded gas jets, the results showed the influence of pressure ratio, aspect ratio and Mach number on the

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shock structures of near field, and pointed out the different shock properties between the major and minor plane. Teshima [9,10] studied the structure of underexpanded rectangular jet by laser-induced fluorescence, the results only discussed the cross-sectional jet shape, thus the three-dimensional (3D) shock structure and its correlation with the jet boundary are as yet not fully understood. The PIV results of Zare-Behtash et al. [11,12] provides a 2D analysis regarding the formation and propagation of the different types of shock waves and consequent vortex loops generated when a shock tube with various exit nozzle geometries at a range of flow Mach numbers. Tsutsumi et al. [13] are of the few authors to provide insight into the 3D shock structure inside the underexpanded square jet, but there are obvious differences between the shock structure of jet cross-sectional and corresponding experimental figures. Besides, He et al. [14] numerical results indicate that the overexpanded flow in the four corner region as well as the recompression shock wave may play a domiant role in the interface instalibity. Maeno et al. [15] provided the 3D shock waves discharged from a square open end in a shock tube experiment by used of the interferometric compted temography, which clearly illustrate the 3D flow features of shock waves, contact surface, and the other shape density fronts at the starting flow stage.

In this paper, we aim to determine the detailed flow structure of underexpanded supersonic jet issuing from a nozzle with a square exit. The large eddy simulation (LES) and high resolution hybrid WENO-TCD schemes are used for the numerical simulation. The results illustrated the formation and evolution of the shock wave structures and primary vortex loop. Moreover, the effect of nozzle pressure ratio on 3D shock features has also been carried out to make a better understanding the relevant phenomena and mechanics.

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.

$$\frac{\partial\bar{\rho}}{\partial t}+\frac{\partial}{\partial x_j}(\bar{\rho}\tilde{u}_j)=0, \tag{1}$$

$$\frac{\partial\bar{\rho}\tilde{u}_i}{\partial t}+\frac{\partial}{\partial x_j}(\bar{\rho}\tilde{u}_i\tilde{u}_j)=-\frac{\partial\bar{p}\delta_{ij}}{\partial x_i}+\frac{\partial\sigma_{ij}}{\partial x_j}-\frac{\partial\tau_{ij}^{sgs}}{\partial x_j}, \tag{2}$$

$$\frac{\partial\bar{\rho}\tilde{E}}{\partial t}+\frac{\partial(\bar{\rho}\tilde{E}+\bar{p})\tilde{u}_j}{\partial x_j}=\frac{\partial}{\partial x_j}\left(\bar{\kappa}\frac{\partial\tilde{T}}{\partial x_j}\right)+\frac{\partial\sigma_{ij}\tilde{u}_i}{\partial x_j}-\frac{\partial q_j^{T-sgs}}{\partial x_j}, \tag{3}$$

$$\frac{\partial(\bar{\rho}\tilde{z})}{\partial t}+\frac{\partial(\bar{\rho}\tilde{u}_j\tilde{z})}{\partial x_j}=\frac{\partial}{\partial x_j}\left[\bar{\rho}\bar{D}\frac{\partial\tilde{z}}{\partial x_j}-\rho q_j^{z-sgs}\right]. \tag{4}$$

where the filtered Newtonian stress tensor σ_{ij}, pressure $\bar{p}$ and total energy $\bar{\rho}\tilde{E}$ are expressed by

$$\sigma_{ij}=\bar{\mu}\left(\frac{\partial\tilde{u}_i}{\partial x_j}+\frac{\partial\tilde{u}_j}{\partial x_i}-\frac{2}{3}\delta_{ij}\frac{\partial\tilde{u}_k}{\partial x_k}\right),$$

$$\bar{p}=\bar{\rho}R^0\tilde{T}\sum_{m=1}^{2}\frac{\tilde{Y}_m}{W_m}+\bar{\rho}R^0\sum_{m=1}^{2}\frac{T_m^{sgs}}{W_m},$$

$$\bar{\rho}\tilde{E}=\frac{\bar{p}}{(\bar{\gamma}-1)}+\frac{1}{2}\bar{\rho}(\tilde{u}_k\tilde{u}_k)+\frac{1}{2}\tau_{kk},$$

The subgrid terms including the stress tensor τ_{ij}^{sgs}, turbulent temperature flux q_j^{T-sgs}, scalar transport flux q_j^{z-sgs} and the temperature-species correlation term T_m^{sgs} are given by

$$\tau_{ij}^{sgs}=\bar{\rho}(\widetilde{u_iu_j}-\tilde{u}_i\tilde{u}_j), \tag{5}$$

$$q_j^{T-sgs}=\bar{\rho}(\widetilde{c_pTu_j}-\tilde{c}_p\tilde{T}\tilde{u}_j), \tag{6}$$

$$q_j^{z-sgs}=\bar{\rho}(\widetilde{zu_j}-\tilde{z}\tilde{u}_j), \tag{7}$$

$$T_m^{sgs}=\widetilde{TY_m}-\tilde{T}\tilde{Y}_m \tag{8}$$

The mixture fraction z is defined as: $z=(Y-Y_1)/(Y_2-Y_1)$. 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, z takes the value 0 in the gas of jet and 1 in the ambient air. $\bar{\kappa}$, $\bar{\mu}$ and $\bar{D}$ are the filtered heat conduction, dynamics viscosity and molecular diffusivity, respectively. They are obtained from binary mixing rules and the pure component mixing properties. W_m denotes the molecular weight of component m, and R^0 is the gas constant, R^0 = 8.3143 J/(mol·K).

The subgrid terms (5)–(8) need to be modeled for the closure of the multi-component LES Eqs. (1)–(4). We choose the recently developed stretched-vortex subgrid scales (SGS) model for multi-component, compressible flows to approach the unresolved subgrid terms [16]. The stretched-vortex SGS model which uses stretched vortices to represent the subgrid scales was proposed originally for incompressible flow [17], and has been extended to different purposes [18–20]. The stretched vortex is a physical model for turbulent fine scales which is assumed to be consisted of tube-like structures with concentrated vorticity [21]. 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 subgrid turbulent kinetic energy takes the Lundgren form [22].

The supersonic square jet flow includes shock-vortex interaction and turbulent shear flow etc. complex phenomena, therefore, the spatial and temporal resolution requirement vary largely. The fluid-solver framework AMROC (Adaptive Mesh Refinement in Object-oriented C++) [23] has been proven to be advantageous for the LES of supersonic flows [16,24], it includes the block-structured adaptive mesh refinement (SAMR) method [25] and a hybrid numerical method of tuned centered difference-weighted essentially non-oscillatory (TCD-WENO) [22] for simulating the shock induced compressible flow.

SAMR method in AMROC is one kind of adaptive mesh refinement algorithm designed especially for hyperbolic partial differential equations [26]. The computational domain consists of blocks with rectangular grids, and SAMR uses a hierarchical block data structure, therefore each block can be solved as a single grid which makes the computation more effective than other methods. Further information can be found in Refs. [23,25,26].

AMROC provides an object-oriented framework implementation of SAMR method mentioned above, in which the SAMR method has been decoupled from a particular scheme, therefore, different schemes can be chosen for the solving. It characterizes with the efficient parallelization strategy on distributed memory machines and can run on all high-performance computers with MPI-library installed.

A hybrid TCD-WENO method was initially proposed in Ref. [22] to satisfy the different resolution requirements within the regions with different flow features, such as shock waves, turbulent etc. [21,23,27–29] WENO schemes can effectively eliminate the spurious wave during the calculation, and it has higher order accuracy