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Large-eddy simulation of a pulsed jet into a supersonic crossflow

Haitao Shi, Guolei Wang, Xisheng Luo, Jiming Yang, Xi-Yun Lu*

Department of Modern Mechanics, University of Science and Technology of China, Hefei, Anhui 230026, China

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ABSTRACT

Numerical investigation of a pulsed jet injected into a supersonic crossflow was carried out using large-eddy simulation. The corresponding steady jet injection was also calculated for comparison with the pulsed jet injection and for validation against experimental data. Various fundamental mechanisms dictating the intricate flow characteristics, such as multi-scale vortical structures, complex shock systems, mixing properties and turbulence behaviors, have been studied. As the pulsed jet issuing transversely into the supersonic crossflow, the salient shock systems and vortical structures in terms of the instantaneous and phase-averaged flow field are analyzed. The large-scale jet shear vortices are formed along the interface of jet and crossflow due to the pulsation effect, which can promote the engulfing of the crossflow fluid and the mixing of the jet and crossflow fluids. Further we investigate turbulence properties of the jet and crossflow interaction and scalar statistics of the injectant mass fraction to reveal jet penetration enhancement and mixing property improvement for the pulsed jet. Results obtained in this study provide physical insight into the understanding the mechanisms for the interaction of pulsed jet and supersonic crossflow.

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1. Introduction

Owing to the obvious importance in a wide range of fundamentals and applications, the flow characteristics of a transverse jet injected into a supersonic crossflow have been extensively studied [1–7]. Comprehensive reviews on this subject have been given [8–10]. To enhance the jet penetration and its subsequent mixing process, the strategy of forcing jet control has been employed and some work on the forcing control has been carried out experimentally and numerically [11–13]. The pulsed jet has been considered as a control approach for jets in crossflow [14–16]. However, the physical mechanisms dictating the complex flow characteristics are still unclear and are of great interest for detailed studies.

The pulsed jet has been investigated in low-speed and high-speed crossflow by dealing with the influences of the pulsation frequency, amplitude and waveform shape. Experiments indicated that the pulsation frequency may greatly affect the jet penetration [17]. Then the optimal forcing frequency was examined numerically [12] and experimentally [18]. Much lower frequency or much higher frequency may result in a quasi-steady flow field [15,17]. The pulsation amplitude is associated with the jet shear layer evolution and its value around 5% of the mean jet velocity may allow the pulsation frequency to completely dominant the jet shear layer spectra in low-speed flows [19]. Based on the investigation of the effect of pulsation waveform shape, [20] the sinusoidal excitation at high jet-to-inflow velocity ratio can improve jet penetration.

The pulsed jet has a significant effect on the flow field and can improve the jet penetration and mixing process [2,17]. The large-scale vortical structures due to the pulsed jet can induce the deeper penetration and larger mixing zone compared with the counterparts in steady jet case [20,21]. Based on the experimental investigations in low-speed flows, the jet penetration and spread could be enhanced due to the temporally varying jet velocity [19,22]. Moreover, even though turbulent fluctuations have been investigated for steady jet, [23,24] turbulent characters for pulsed jet are highly desired to be studied in detail.

In the present study, a large-eddy simulation (LES) technique, which has provided a powerful tool for studying the dynamics of turbulent flows, is utilized to investigate a pulsed jet injected into a supersonic crossflow. To our knowledge, the relevant work is still limited. The purpose is to achieve an improved understanding the fundamental flow characteristics, including jet penetration enhancement, jet mixing improvement, shocks and pulsed jet interaction, shocks and vortices interaction, and jet shear layer vortices and their evolution.

This paper is organized as follows. The mathematical formulation and numerical method are briefly presented in Section 2. The computational overview and validation are described in Section 3.

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* Corresponding author.
E-mail address: xlu@ustc.edu.cn (X.-Y. Lu).

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Detailed results are then given in Section 4 and concluding remarks are addressed in Section 5.

2. Mathematical formulation and numerical methods

2.1. Governing equations and turbulence modeling

To investigate a jet issuing transversely into a supersonic crossflow, the three-dimensional Favre-filtered compressible Navier-Stokes equations and a transport equation for passive scalar of jet fluid in generalized coordinates are employed. We use the uniform inflow variables including the density ρ_∞, temperature T_∞, speed of sound a_∞, and the jet exit diameter D as characteristic scales to nondimensionalize the equations. Then they are expressed as

$$\frac{\partial \bar{\rho}}{\partial t} + \frac{\partial \bar{\rho}\tilde{u}_i}{\partial x_i} = 0, \tag{1}$$

$$\frac{\partial \bar{\rho}\tilde{u}_i}{\partial t} + \frac{\partial \bar{\rho}\tilde{u}_i\tilde{u}_j}{\partial x_j} + \frac{\partial \bar{p}}{\partial x_i} - \frac{\partial (\tilde{\tau}_{ij} - \tau_{ij}^{SGS} + T_{ij}^{SGS})}{\partial x_j} = 0, \tag{2}$$

$$\frac{\partial \bar{\rho}\tilde{E}}{\partial t} + \frac{\partial [(\bar{\rho}\tilde{E} + \bar{p})\tilde{u}_i]}{\partial x_i} - \frac{\partial (-\tilde{q}_i + \tilde{u}_j\tilde{\tau}_{ij} - Q_i^{SGS} + \sigma_i^{SGS} - H_i^{SGS})}{\partial x_i} = 0, \tag{3}$$

$$\frac{\partial \bar{\rho}\tilde{Y}_k}{\partial t} + \frac{\partial (\bar{\rho}\tilde{u}_i\tilde{Y}_k)}{\partial x_i} - \frac{\partial (\tilde{\theta}_i + W_i^{SGS})}{\partial x_i} = 0, \tag{4}$$

where an overbar denotes the spatial filter and a tilde the Favre filter. The variables ρ, u_i, p and E represent the density, velocity component, pressure, and specific total energy, respectively. The diffusive fluxes are given by

$$\tilde{\tau}_{ij} = 2\tilde{\mu}\tilde{S}_{ij} - \frac{2}{3}\tilde{\mu}\tilde{\delta}_{ij}\tilde{S}_{kk}, \tag{5}$$

$$\tilde{q}_i = -\tilde{k}\frac{\partial \tilde{T}}{\partial x_i}, \tag{6}$$

$$\tilde{\theta}_i = \bar{\rho}D_k\frac{\partial \tilde{Y}_k}{\partial x_i}, \tag{7}$$

where μ and k are the molecular viscosity and thermal conductivity, respectively, $\tilde{D}_k$ is the diffusion coefficient for the passive scalar, and the strain-rate tensor S_{ij} is defined as $S_{ij} = (\partial u_j/\partial x_i + \partial u_i/\partial x_j)/2$. The equation of state for an ideal gas is used and the molecular viscosity is assumed to obey the Sutherland law. Some terms in the Favre-filtered equations arise from unresolved scales which need to be modeled in terms of resolved scales. A detailed description of the mathematical formulation of the subgrid-scale (SGS) models for τ_{ij}^{SGS}, T_{ij}^{SGS}, Q_i^{SGS}, H_i^{SGS}, σ_i^{SGS} and W_i^{SGS} can be found in previous papers [6,25,26].

2.2. Numerical procedure

The Navier-Stokes equations and the transport equation of passive scalar described above are numerically solved by a finite-volume method. The convective terms are discretized by a central and upwind hybrid scheme for shock-capturing and the viscous terms by a fourth-order central difference. The temporal integration is performed using an implicit approximate-factorization method with sub-iterations to ensure the second-order accuracy [27].

To capture the discontinuity caused by shock wave, a second-order upwind scheme with the Roe's flux-difference splitting is introduced into the inviscid flux. Based on the shock detection, [28] the spatial discretization has been constructed explicitly to be shock capturing with the upwind scheme and to revert to a central stencil with a fourth-order central scheme in turbulent flow regions away from shock. The present code is equipped with a multi-block domain decomposition feature to facilitate parallel processing in a distributed computing environment. A detailed description of the formulation has been given in our previous papers [26,29].

3. Computational overview and validation

3.1. Computational overview

We consider a sonic jet issuing transversely into a supersonic crossflow with the free stream Mach number of $M_\infty = 1.6$ with a schematic in Fig. 1. Based on previous experiments, [1,30] an ideal air gas is assumed for the crossflow and the jet. The free crossflow stagnation pressure is set as $p_{0\infty} = 241$ kPa and the stagnation temperature $T_{0\infty} = 295$ K. The circular nozzle has an exit diameter of $D = 4$ mm. The Reynolds number defined as $Re = \rho_\infty U_\infty D/\mu_\infty$ is 1.38×10^5. Both pulsed and steady injections are simulated for comparison. The steady case has a sonic jet with a constant stagnation pressure of $p_{0j} = 606$ kPa and constant stagnation temperature of $T_{0j} = 300$ K as used in the experiment [30]. The corresponding jet-to-crossflow momentum flux ratio $J = \rho_j U_j^2/\rho_\infty U_\infty^2$ is 2.2.

Based on the high-speed [15,17] and low-speed [19,20] studies, the pulsation waveform shape is chosen as sine wave for the pulsed jet. The mean jet stagnation pressure and temperature are equal to the counterparts described above for the steady jet. The pulsed jet-to-crossflow momentum flux ratio can be described as

$$J_p = J_a + J_m \sin(2\pi f t), \tag{8}$$

where J_m and f represent the pulsation amplitude and frequency of the momentum flux ratio, respectively, and J_a is the mean value of the pulsed momentum flux ratio and is chosen as 2.2 which is the same as the steady injection value for comparison.

The parameters for the pulsed case are selected in terms of some typical experiments [2,15,19]. The pulsation amplitude is set as J_m=1. As a result, the jet shear layer response due to the pulsed jet corresponds to the stronger jet excitation type [31] because the jet penetration may be significantly enhanced as observed in the experiments [19,20]. The pulsation frequency is chosen as $f_p = 10$ kHz, consistent with the effective jet frequency [15]. This frequency is also near the target center frequency used in the experiment [17] and the excitation frequency produced by the Hartmann–Sprenger tube [2]. The corresponding Strouhal number defined as $St = fD/U_\infty$ is 0.089 and the pulsed period is described as $T = 1/St$.

In this study, the initial and boundary conditions are set as follows. The initial condition is set as the free crossflow quantities. No-slip and adiabatic conditions are applied on the wall. The far-field boundary conditions are treated by a characteristic method based on Riemann invariants [32]. The mean turbulent boundary layer obtained by a three-dimensional (3D) simulation of flow over a plate as used in previous investigations [33,34]. Then the velocity disturbances at the inlet by means of the random velocity fluctuations are added to the velocity components [35,36]. Then the mean streamwise velocity profile in a semi-logarithmic plot is presented in Fig. 2(a). It is seen that the turbulent inflow velocity profile used here agrees well with the experimental data [1] and the expected linear scaling in the viscous sublayer and logarithmic scaling in the log layer are obeyed. The boundary layer thickness at $x/D = -5$ is $\delta_0/D = 0.775$ and the momentum thickness is $\theta_0/D = 0.065$ as detected in the experiment [1]. Moreover, the previous work [33,34] has confirmed that the turbulence statistical

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