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Effects of micro-ramp on transverse jet in supersonic crossflow

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ABSTRACT

The effects of micro-ramp on the characteristics of transverse jet were investigated by the LES simulation at Mach 2.7, with recycling-rescaling method applied to reproduce the turbulent boundary layer. The transverse nitrogen jet in front of micro-ramp and behind micro-ramp were studied by comparison with plate jet. It is found that the micro-ramp can improve the penetration height obviously, while placing jet orifice behind micro-ramp, due to the low freestream momentum in ramp wake. On the other hand, when placing the jet orifice in front of micro-ramp, the improvement in penetration is quite slight, because most injection is above the boundary layer and micro-ramp has little influence on the main flow. It is also observed that unlike the periodic Kevin Helmholtz (K–H) vortices appeared in ramp wake, the periodic K–H vortices are not achieved in jet cases.

1. Introduction

As one of the crucial issues influencing the mixing efficiency, ignition and flame holding in scramjet, the fuel injection has been investigated for many years. Due to its simplest and most conventional design, the transverse jet is the main method applied in scramjet.

Considering requirements in engineering and restriction in study means, researchers mainly focus on time-averaged parameters of jet, such as penetration height, mass fraction distribution, total pressure loss in previous study. And the influence of jet-to-freestream momentum flux ratio [1–5], configuration of injection orifice [4,6], molecular weight [6–8] on the averaged parameters are widely investigated for several years. Plenty of researches prove that the jet-to-freestream momentum flux ratio is the main factor influencing jet penetration height.

With the advancement of experimental equipment, Rayleigh/Mie scattering imaging technique [9], planar laser induced fluorescence (PLIF) [10,11] and ultrahigh-speed schlieren [12] are applied to study the turbulent behavior in transverse jet. Gruber et al. [9] indicated that the compressibility of the mixing layer was the main parameter affecting the behavior of turbulent structures. Ben-Yakar et al. [12] pointed out the velocity difference was the key point influencing the turbulent behavior in shear layer by the stretching-tilting-tearing mechanism. Meanwhile, with the improvement of computational resources, large eddy simulation (LES) has provided further insight into the mixing progress and development of turbulent structures in jet plume [13–17].

According to the former study, two main disadvantages in transverse jet are outstanding. First, large supply pressures is needed to achieve high penetration in transverse jet. Second, some injection is seeded into the boundary layer, which often leads a phenomena know as flashback [18]. In addition, with demand of larger size scramjet emerging, to achieve a higher penetration and better mixing efficiency in main flow is very necessary.

Aiming at improving the jet penetration and mixing efficiency, ramp injector is used as a viable mean, because of the vortex shedding off the edges and a local separation at the base [19,20]. In the traditional ramp jet, the direction of jet is general in streamwise and the configuration of ramp is unswept. Later, to produce a stronger pair of vortex, swept ramp was born [21,22]. Generally, to ensure strong pair of vortices and large separation region, the size of ramp is large. Thus, a thorny and inevitable problem emerges, that is how to minimize the added total pressure loss and drag when the traditional ramp injector is used in scramjet [21,23].

Lately, in the study of the shock-wave and boundary layer interaction (SWBLI), researchers used a micro-ramp immersing into the boundary layer to delay shock-induced turbulent boundary-layer separation [24,25]. The device can produce a counter vortices pairs (CVPs) in the near-wall region and upwash the low energy part of boundary layer into the main flow. Because of the tiny size, the micro-ramp always emerges into the boundary layer. Thus, the total pressure loss is obviously small. Also in the study of film-

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Nomenclature

ρ	density
u_j	velocity exponent in j direction
τ_{ij}^{sgs}	subgrid scale stress
v_t^{sgs}	subgrid turbulent eddy viscosity coefficient
$\bar{\Delta}$	subgrid length scale
S	rate-of-strain tensor
T	time
E	energy
Re	Reynolds number
Sc	Schmidt number
d	boundary layer thickness
P_0	stagnation pressure of inflow
T_0	stagnation temperature of inflow
P_j	stagnation pressure of transverse jet
T_j	stagnation temperature of transverse jet
$\rho_j v_j^2$	the momentum flux of transverse jet
ρu^2	the momentum flux upstream jet orifice
J	jet-to-freestream momentum flux ratio
y_1	mass fraction of injection
Ap	wedge half-angle of micro-ramp
h	height of micro-ramp
c	a chord length
H	height of ramp wake
η	mixing efficiency
ϕ	local equivalent ratio

cooling jet [26,27], researchers placed the micro-ramp downstream the jet to produce CVPs that is in the contrary direction with the CVPs in jet plume. So the lift-off behave of CVPs in jet was much weaken. This application inspired us to using micro-ramp to produce CVPs that is in the same direction with CVPs in jet plume, then the jet penetration can be improved probably. Additionally, in the investigation of traditional ramp, Wilson et al. [28] placed the jet orifice in the front of ramp to enhance the penetration by the inclined ramp surface.

Based on the idea mentioned above, the transverse jet placed in front of micro-ramp and behind micro-ramp are investigated by LES approach in this paper. First, the penetration and mixing efficiency in different jet cases are compared and the factors influencing the penetration are investigated. Then, the differences in injection plume distribution, streamwise vortex in different cases are studied. Last, statistical characteristics, such as time histories of the vortex structures, time correlation, mass fraction probability are analyzed.

2. Numerical methods and the physical model

2.1. LES equations

In the present study, the filtered dimensionless compressible Navier–Stokes equations for an ideal nonreactive gas are solved, with the one equation subgrid scale model (SGS) of Yoshizawa and Horiuti [29] used as below:

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

$$\frac{\partial\left(\bar{\rho}\tilde{u}_i\right)}{\partial t} + \frac{\partial}{\partial x_j}\left[\bar{\rho}\tilde{u}_i\tilde{u}_j + \bar{p}\delta_{ij} - \frac{1}{Re}\bar{\tau}_{ij} + \frac{1}{Re}\tau_{ij}^{sgs}\right] = 0 \tag{2}$$

$$\frac{\partial\left(\bar{\rho}\tilde{E}\right)}{\partial t} + \frac{\partial}{\partial x_j}\left[\left(\bar{\rho}\tilde{E} + \bar{p}\right)\tilde{u}_j - \frac{\kappa_0 T_0}{\mu_0 u_0{}^2\, Re}\left(\bar{\kappa} + \bar{\kappa_t}\right)\frac{\partial \tilde{T}}{\partial x_j} - \frac{1}{Re}\tilde{u}_i\bar{\tau}_{ji} - \frac{1}{Re}\left(\frac{\mu}{Sc} + \frac{\mu_t}{Sc_t}\right)\sum_m \tilde{h}_m\frac{\partial \tilde{Y}_m}{\partial x_j}\right] = 0 \tag{3}$$

$$\frac{\partial\left(\bar{\rho}\tilde{Y}_m\right)}{\partial t} + \frac{\partial}{\partial x_j}\left[\bar{\rho}\tilde{Y}_m\tilde{u}_j - \frac{1}{Re}\left(\frac{\mu}{Sc} + \frac{\mu_t}{Sc_t}\right)\frac{\partial \tilde{Y}_m}{\partial x_j}\right] = 0 \tag{4}$$

where SGS stress τ_{ij}^{sgs} is modeled as below:

$$\tau_{ij}^{sgs} = -2\bar{\rho}\nu_t^{sgs}\left(\tilde{S}_{ij} - \frac{1}{3}\tilde{S}_{kk}\delta_{ij}\right) + \frac{2}{3}\bar{\rho}k^{sgs}\delta_{ij}$$
$$v_t^{sgs} = C_\mu \bar{\Delta}\sqrt{k^{sgs}}$$
$$\bar{\Delta} = \left(\Delta x\Delta y\Delta z\right)^{\frac{1}{3}} \tag{5}$$

In these equations, the laminar and turbulent Prandtl numbers are given as $Pr = 0.72$ and $Pr_t = 0.90$. The subgrid kinetic energy k^{sgs} is solved by the transport equation as expressed in Eq. (6).

$$\frac{\partial\left(\bar{\rho}k^{sgs}\right)}{\partial t} + \frac{\partial\left(\bar{\rho}k^{sgs}\tilde{u}_j\right)}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\bar{\rho}\left(\frac{\nu}{Pr} + \frac{\nu_t^{sgs}}{Pr_t}\right)\frac{\partial k^{sgs}}{\partial x_j}\right] + P_k^{sgs} - D^{sgs} \tag{6}$$

where P_k^{sgs} and D^{sgs} is defined as below:

$$P_k^{sgs} = -\tau_{ij}^{sgs}\left(\partial\tilde{u}_i/\partial x_j\right)$$
$$D^{sgs} \approx C_d\bar{\rho}\left(k^{sgs}\right)^{3/2}/\bar{\Delta} \tag{7}$$

where the model constants are given as $C_d = 1.0$ and $C_\mu = 0.02075$, following the work of Sun et al. [30].

2.2. Physical model and simulation cases

The micro-ramp in this paper is shown in Fig. 1(a), based on the physical model in Wang's paper [24]. Its height h is 3 mm, with a wedge half-angle Ap=24° and a chord length c=7.2 h.

In this investigation, four different cases are simulated by LES. The simulation of transverse jet without ramp shown in Fig. 2 is denoted as ‘platejet’. Based on the different jet locations, there are two cases denoted as ‘front jet’, ‘back jet’. The jet locations are shown in Fig. 1(b). In each case, the origin of the Cartesian coordinate system is at the center of jet orifice. The fourth case is the micro-ramp placed in the flow field without jet, denoted as ‘ramp’.

The mach number of inflow is 2.7 The stagnation pressure P_0 and stagnation temperature T_0 of inflow is 77.6 kPa and 300 K respectively. The corresponding unit Reynolds number Re is 6.95×10^6 The transverse sonic jet is from a circular orifice with diameter d=2 mm on the bottom wall. The stagnation pressure P_j of nitrogen jet is 136 kPa and the stagnation temperature T_j is 300 K with the jet-to-freestream momentum flux ratio J being 2.9. The origin of the Cartesian coordinate system is at the center of the orifice, and the X, Y, Z denote streamwise, transverse and spanwise directions, as shown in Fig. 2.