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Large eddy simulation based studies of jet–cavity interactions in a supersonic flow

Hongbo Wang [a], Zhenguo Wang [a,*], Mingbo Sun [a], Ning Qin [b]

[a] Science and Technology on Scramjet Laboratory, National University of Defense Technology, Changsha 410073, China
[b] Department of Mechanical Engineering, University of Sheffield, Sheffield S1 3JD, England, UK

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Interactions of a cavity flameholder with an upstream injected jet in a Ma 2.52 supersonic flow are investigated numerically. A hybrid RANS/LES (Reynolds-Averaged Navier–Stokes/Large Eddy Simulation) method acting as wall-modeled LES is adopted, for which the recycling/rescaling method is introduced to treat the unsteady turbulent inflow. Patterns of the fluid entrainment into the cavity and escape from the cavity are identified using a scalar-tracing method. It is found that the jet–cavity interactions remarkably enhanced the mass exchange between the fluids in and out of the cavity, resulting in reduced residence time of the cavity fluids. Increasing the distance between the fuel injection and the cavity leading edge tends to attenuate the jet–cavity interactions, leading to weaker mass exchange. Raising the injection pressure appears to enhance the jet–cavity interactions, resulting in a shorter residence time of the cavity fluids. Moreover, the mass decay processes for the fuel and air within the cavity are basically the same while the entrainment processes for the fuel and air into the cavity seem quite different.

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1. Introduction

Supersonic combustion ramjet (scramjet) engine lets the air stream enter into the combustor supersonically and organizes combustion within supersonic flow, where robust flameholding schemes are necessary due to the short combustor residence time. One promising candidate for such a flameholder is the wall cavity which has been shown to be effective in stabilizing the flame without excessively decreasing total pressure [1]. When used as an integrated fuel injection/flameholding approach [2], cavity flameholders have become even more attractive in supersonic combustors and received more and more attention. In particular, flush-wall injection coupled with a downstream cavity flameholder is found to be a simple but efficient approach in maintaining combustion in supersonic flows.

Ben-Yakar et al. [3] used high-speed framing schlieren and OH-PLIF (Planar Laser-Induced Fluorescence) to investigate hydrogen normal jet injected upstream of a cavity in air crossflow simulating flight Mach 10 conditions, where autoignition was achieved and OH fluorescence appeared first in the recirculation upstream of the jet and extended along outer edge of the jet plume. Micka et al. [4–7] investigated the combustion characteristics of a dual-mode scramjet combustor with normal fuel injection upstream of cavity flameholder. It was found that the combustion was anchored at the leading edge of the cavity at low stagnation temperature and stabilized a short distance downstream of the fuel injection jet in the jet-wake at high stagnation temperature. Sun et al. [8,9] studied the combustion in a supersonic combustor with normal hydrogen injection upstream of cavity flameholders using OH-PLIF and hybrid RANS/LES (Reynolds-Averaged Navier–Stokes/Large-Eddy Simulation). It was

* Corresponding author. Tel.: +86 13787207654.
E-mail addresses: whbwatch@yahoo.com.cn, whbwatch@gmail.com (Z. Wang).

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shown that an approximately steady flame existed in the cavity shear layer and hot combustion products were transported into the injection jet by the vortex interaction of the jet-with-cavity shear layer, where the counter-rotating vortex induced by the jet and the cavity shear layer played an important role. Kim et al. [10] carried out RANS simulations to investigate supersonic combustion with cavity-based fuel injection, where the cavity effect is discussed from a viewpoint of total pressure loss and combustion efficiency. Jeong et al. [11] studied the combustion characteristics of a scramjet engine using hydrogen injection upstream of the cavity and found the cavity acted as a flameholder. The analyses also indicated that the heat release is mostly initiated by the shock wave from the cavity's trailing face and the ignition above the cavity does not have a strong influence on the downstream combustion. Wang et al. [12] studied the combustion characteristics in a supersonic combustor with hydrogen injection upstream of cavity flameholder both experimentally and numerically. It was observed that the flame or combustion zone spreading from the cavity to the main stream seemed to be dominated not only by the traditional diffusion process but also by the convection process associated with the extended recirculation flows resulting from the heat release and the interaction between the jet and the cavity shear layer.

It is evident that the jet–cavity interactions play an important role in the flame holding and spreading processes, as has been pointed out by the previous studies. This is because the jet–cavity interactions to a large extent determine both the fuel transport from the jet into the cavity and the hot products transport from the cavity recirculation region to the fuel jet or to the main stream. Therefore, both the design of an efficient supersonic combustor and the development of a reliable theoretical model require a deep understanding of these interaction processes. However, there is a lack of detailed studies on this issue in the existing literatures. The present work numerically investigates the jet–cavity interactions in a supersonic flow, attempting to provide a useful understanding of the involved processes, such as cavity mass escape, fuel entrainment and jet–cavity shear layer interaction. First, the theoretical models and numerical methods are briefly presented and validated. Next, the results are analyzed in detail and conclusions are drawn.

2. Physical models and numerical methods

2.1. Turbulence models

LES has been increasingly used to study turbulent flow problems because it is undoubtedly more accurate than RANS in many complex flows, such as non-equilibrium, three-dimensional massively separated flows. However, it is still difficult to use LES in the simulations of wall-bounded flows at high Reynolds numbers due to the high mesh resolution required to resolve the small vortices in the near wall region at high Reynolds numbers. On the other hand, RANS is more suitable for the near wall flows because highly anisotropic meshes can be used to resolve the time-averaged viscous layer with high mesh density only in the wall normal direction. Accordingly, the total grid points required in RANS are much less than that required in LES. In order to combine the advantages of RANS and LES, many hybrid methods were proposed recently. In the present study, a hybrid RANS/LES method [13] blending the S-A RANS model [14] and Yoshizawa sub-grid scale (SGS) model [15] is adopted. The modeling equations are briefly described below.

In the one-equation S-A RANS model [14], the eddy viscosity is directly calculated from the transport equation.

$$\frac{D\rho\tilde{\nu}}{Dt} = C_{b1}\rho\tilde{S}\tilde{\nu} + \frac{1}{\sigma}\left[\frac{\partial}{\partial x_j}\left(\rho(\nu+\tilde{\nu})\frac{\partial\tilde{\nu}}{\partial x_j}\right) + C_{b2}\rho\left(\frac{\partial\tilde{\nu}}{\partial x_j}\right)^2\right] - \rho C_{w1} f_w \frac{\tilde{\nu}^2}{d^2} \tag{1}$$

where ρ is density, ν is molecular viscosity, d is the distance to the nearest solid wall, $f_{v1} = (\chi^3/\chi^3 + C_{v1}^3)$, $\tilde{S} = S + (\tilde{\nu}/\kappa^2 d^2) f_{v2}$, $f_{v2} = 1-(\chi/(1+\chi f_{v1}))$, $\chi = \tilde{\nu}/\nu$, $S = \sqrt{2S_{ij}S_{ij}}$, $S_{ij} = (\partial u_i/\partial x_j + \partial u_j/\partial x_i)/2$, $f_w = g(1+C_{w3}^6)/(g^6 + C_{w3}^6)^{1/6}$, $d\rho/dy$, $r = (\tilde{\nu}/\tilde{S}\kappa^2 d^2)$, $C_{b1} = 0.1355$, $C_{b2} = 0.622$, $\sigma = 2/3$, $C_{v1} = 7.1$, $C_{w1} = C_{b1}/\kappa^2 + (1+C_{b2})/\sigma$, $C_{w2} = 0.3$, $C_{w3} = 2.0$, $\kappa = 0.41$. The turbulent viscosity is obtained as $L/D = 7$.

The one-equation Yoshizawa SGS model [15] for the LES region is

$$\frac{D\rho k}{Dt} = P_k + \frac{\partial}{\partial x_j}\left[\rho(\nu + \sigma_k \nu_t)\frac{\partial k}{\partial x_j}\right] - D_k \tag{2}$$

where $\nu_t = C_\mu k^{1/2}\Delta, P_k = 2\rho\nu_t S_{ij}S_{ij}$, $D_k = C_d \rho(k^{3/2}/\Delta), \sigma_k = 1/\mathrm{Pr}_t . k$ is the sub-grid turbulent kinetic energy, Δ is the spatial filtering width, $\mathrm{Pr}_t = 0.9$ is the turbulent Prandtl number, P_k and D_k are the production and dissipation of the sub-grid turbulent kinetic energy, respectively. Here, the values of C_μ and C_d need to be determined. According to the previous discussion [13], $C_\mu = 0.02075$ and $C_d = 1.0$ are used in the present work.

In order to blend the SGS model with the S-A RANS model, the turbulent kinetic energy transport SGS model is transformed to an eddy viscosity transport model based on the eddy viscosity hypothesis. According to the definition of the eddy viscosity, the k equation can be transformed to that of ν_t as below.

Replacing k with $\nu_t^2/(C_\mu^2\Delta^2)$ in the k equation, one obtains

$$\frac{D\rho\nu_t}{Dt} = \frac{1}{2}\rho C_\mu^2 \Delta^2 S_{ij}S_{ij} + \frac{\partial}{\partial x_j}\left[\rho(\nu + \sigma_k\nu_t)\frac{\partial \nu_t}{\partial x_j}\right] + \rho(\nu/\nu_t + \sigma_k)\left(\frac{\partial\nu_t}{\partial x_j}\right)^2 - \frac{C_d\rho}{2C_\mu}\frac{\nu_t^2}{\Delta^2} + \rho P_\Delta \tag{3}$$

where P_Δ represents the additional terms generated by the grid stretching or the non-uniformity of spatial filtering width:

$$P_\Delta = \frac{3\nu_t}{\Delta^2}(\nu + \sigma_k\nu_t)\left(\frac{\partial\Delta}{\partial x_j}\right)^2 - \frac{4}{\Delta}(\nu + \sigma_k\nu_t)\frac{\partial\Delta}{\partial x_j}\frac{\partial\nu_t}{\partial x_j} - \frac{\nu_t}{\Delta}\frac{\partial}{\partial x_j}\left[(\nu + \sigma_k\nu_t)\frac{\partial\Delta}{\partial x_j}\right] \tag{4}$$

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