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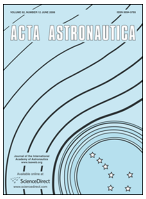

Large eddy simulation of a hydrogen-fueled scramjet combustor with dual cavity

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ABSTRACT

Large eddy simulation (LES) has been carried out to investigate a hydrogen-fueled scramjet combustor with dual cavity, where a Reynolds-Averaged Navier–Stokes (RANS) model is used for near-wall treatment. The recycling/rescaling method is adopted to generate unsteady turbulent inflow conditions for the LES. Experimentally-observed flow and combustion structures are reasonably well captured and explained by the simulation. The results show that the intersection of the bow shock waves and the concentrated heat release generate a high-pressure region between the cavities, which induces great pressure gradients as well as evident flows in the transverse direction, pushing the fuel jets towards the combustor walls. Consequently, strong interactions occur between the fuel jets and the cavity aft walls, promoting the fuel transport into the cavity. Meanwhile, the cavity recirculation regions are considerably extended and distorted, and the mass exchange between the fluids in and out of the cavities may be greatly enhanced. In contrary, these flow structures support the concentrated heat release around the cavity by enhancing the fuel–air mixing and increasing the residence time of the combustible. Then, a positive feedback loop is formed by this close coupling of flow and heat release. It is also observed that the combustion downstream of the cavity is confined within narrow regions near the combustor walls due to the decreased fuel jet penetration in the farfield.

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 [3–14].

Micka et al. [6–9] investigated the combustion characteristics of a dual-mode scramjet combustor with gaseous 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. [11,12] studied the combustion in a supersonic combustor with normal hydrogen injection upstream of cavity flameholders using OH-PLIF (Planar Laser-Induced Fluorescence) and hybrid RANS/LES (Reynolds-Averaged Navier–Stokes/Large-Eddy Simulation).

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It was shown that hot combustion products were transported into the injection jet by the vortex interaction of the jet-with-cavity shear layer. Jeong et al. [15] studied the combustion characteristics of a scramjet engine using hydrogen injection upstream of the cavity and found the cavity acted as a flameholder, where the heat release was found to be 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. [4] observed that the flame or combustion zone spreading from the cavity to the main stream was 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.

Under certain conditions, however, a single cavity may not be able to robustly stabilize the combustion, where multiple cavities could be used [16–21]. In particular, dual cavity arranged both in parallel [18] and tandem [19] were found to provide a better performance when compared with a single cavity, suggesting that the dual cavity flameholder would be a viable option for the future scramjet engines. However, the literature regarding the flow and combustion details of dual cavity configuration is largely unavailable, hindering the efficient design and application of dual cavity in scramjet combustors. In the present study, large eddy simulation is used to study a scramjet combustor with dual cavity mounted in parallel, trying to lay a foundation for understanding more complicated flowfields with multiple cavities.

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 and 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 [22] blending the S–A RANS model [23] and Yoshizawa sub-grid scale(SGS) model [24] is adopted. The modeling equations are briefly described below.

In the one-equation S–A RANS model [23], 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, $f_{v1}=(\chi^3/\chi^3+C_{v1}^3)$, $\tilde{S}=S+(\tilde{\nu}/\kappa^2d^2)f_{v2}$, $f_{v2}=1-(\chi/1+\chi f_{v1})$, $\chi=\tilde{\nu}/\nu$, $S=\sqrt{2S_{ij}S_{ij}}$, $S_{ij}=(\partial u_i/\partial x_j+\partial u_j/\partial x_i)/2$, $f_w=g(1+C_{w3}^6/g^6+C_{w3}^6)^{1/6}$, $d\rho/dy$, $r=(\tilde{\nu}/\tilde{S}\kappa^2 d^2)$, $C_{b1}=0.1355$, $C_{b2}=0.622$, $\sigma=2/3$, $C_{v1}=7.1$, $C_{w1}=C_{b1}/\kappa^2+(1+C_{b2})/\sigma$, $C_{w2}=0.3$, $C_{w3}=2.0$, $\kappa=0.41$. The turbulent viscosity is obtained as $\nu_t=\tilde{\nu}f_{v1}$.

The one-equation Yoshizawa SGS model [24] 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 [22], $C_\mu=0.02075$ 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

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

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

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

Keeping $f_{v1}=1.0$ in the LES region, the ν_t equation can be written in the form of $\tilde{\nu}$ equation using $\nu_t=\tilde{\nu}f_{v1}$

$$\begin{aligned}\frac{D\rho\tilde{\nu}}{Dt}=&\frac{1}{2}C_\mu^2\Delta^2\rho S_{ij}S_{ij}+\frac{\partial}{\partial x_j}\left[\rho(\nu+\sigma_k\tilde{\nu})\frac{\partial\tilde{\nu}}{\partial x_j}\right]+\rho(\nu/\tilde{\nu}+\sigma_k)\left(\frac{\partial\tilde{\nu}}{\partial x_j}\right)^2\\&-\frac{C_d\rho}{2C_\mu}\frac{\tilde{\nu}^2}{\Delta^2}+\rho P_\Delta\end{aligned} \tag{5}$$

Based on the similarity of (1) and (5), these two equations can be blended by using a blending function F, which is equal to one in the near-wall region and approaches zero for the region far away from the wall. The blended equation can be written as below

$$\frac{D\rho\tilde{\nu}}{Dt}=\rho P_v+\frac{\partial}{\partial x_j}\left[\rho(\nu+\sigma_{v1}\tilde{\nu})\frac{\partial\tilde{\nu}}{\partial x_j}\right]+\rho\sigma_{v2}\left(\frac{\partial\tilde{\nu}}{\partial x_j}\right)^2-D_v+(1-F)\rho P_\Delta \tag{6}$$

where $P_v=F(C_{b1}\tilde{S}\tilde{\nu})+(1-F)(\frac{1}{2}C_\mu^2\Delta^2S_{ij}S_{ij})$,