Acta Astronautica 116 (2015) 93–105

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

Numerical investigation on mixing and combustion of transverse hydrogen jet in a high-enthalpy supersonic crossflow

Chaoyang Liu*, Zhenguo Wang, Hongbo Wang, Mingbo Sun

Science and Technology on Scramjet Laboratory, National University of Defense Technology, Changsha 410073, China

ARTICLE INFO

Article history:
Received 20 April 2015
Received in revised form
22 June 2015
Accepted 24 June 2015
Available online 2 July 2015

Keywords:
Transverse jet
Supersonic crossflow
Shear layer
Autoignition
Flameholding

ABSTRACT

Mixing and combustion characteristics of a three-dimensional unsteady reacting flowfield generated by transverse hydrogen jet into high-enthalpy supersonic crossflow are investigated numerically. A hybrid RANS/LES (Reynolds-Averaged /Large Eddy Simulation) method acting as wall-modeled LES is adopted, where the ninth-order WENO (Weighted Essentially Non-oscillatory) scheme is introduced to discretize the inviscid fluxes. The validations of numerical results are performed for the jet penetration height, time-averaged and instantaneous structures of reacting flowfield. It is found that the Kelvin–Helmholtz instability of jet shear layer on the windward side of jet plume discontinuously induces large scale coherent structures, which promote the combustion by enhancing the fuel mixing and enlarging the reacting area. The chain reactions creating OH radical mainly occur in the lean-fuel region and the heat-releasing chain reactions consuming OH radical are in the rich-fuel region. In the boundary layer and windward shear layer where supersonic crossflow stagnates, a diffusion flame with autoignition first occurs and then propagates to the downstream of jet plume, which holds the flame stabilization of total flowfield.

1. Introduction

The scramjet is an essential component of hypersonic air-breathing propulsion technology, which requires enhanced combustion efficiency of fuel and air [1]. Due to the extremely fast incoming airstream, mixing is slow compared to the limited residence time of fuel inside the combustor. Therefore, fast turbulent mixing and flame-holding become the most critical technical issues associated with scramjet [2].

Although different jet-injection configurations have been proposed to enhance the fuel mixing and maintain the stabilization of flame, the fuel injection from a wall orifice becomes one of the simplest but most efficient injection schemes [3]. The complicated structures and mixing enhancement mechanism resulting from the interaction of sonic transverse jet and supersonic crossflow have been investigated by many researchers in previous studies [4,5]. In order to stabilize the flame, wall injection coupled with a downstream cavity flameholder has been shown to be a promising candidate with moderate total temperature. Wang et al. [6] studied the interactions of jet and cavity in a supersonic condition using the large eddy simulation (LES) and pointed that moderate injection pressure may be beneficial to transport more fuel into the cavity to promote the ignition process

* Corresponding author. Tel.: +8615274952697; fax: +86073184512301.
E-mail address: chaoyangliucn@163.com (C. Liu).

http://dx.doi.org/10.1016/j.actaastro.2015.06.023
0094-5765/

under certain conditions. Micka et al. [7,8] experimentally investigated the combustion characteristics in a scramjet combustor with transverse jet upstream of cavity. The results indicated that there were two distinct flameholding modes for upstream fuel injection in the flowfield with high and low total temperature. Most of the previous studies were performed in the conditions with low and moderate enthalpy. However, a real supersonic combustor environment at flight speeds beyond Mach 8 is in high enthalpy. Ben-Yakar et al. [9] experimentally compared the time evolution of large scale vortices with hydrogen and ethylene transverse jet into high-enthalpy supersonic crossflow, and found significant differences of the mixing properties in near-wall region. But the inherent mechanism of mixing and combustion enhancement resulting from large scale vortices was not clearly revealed. Won et al. [10,11] investigated the generation mechanism of large scale vortices and autoignition phenomenon using detached-eddy simulation (DES) in the conditions of Ben-Yakar's experiment, whereas the interaction of turbulence and combustion as well as the physical and chemical mechanism that dominates the stabilization of flame was not answered.

An accurate estimation and a deep physical understanding of the turbulent mixing and flameholding mechanism in the conditions of high total temperature play important roles in scramjet design [12]. The unsteady reacting flowfield is extremely complicated, and consists of multiplicate structures, such as the bow shock, barrel shock, Mach disk, separation shock and combustion wave. Purely experimental approach is not enough to acquire sufficient data to understand their inherent process. To obtain additional insights into the three-dimensional unsteady turbulent process and autoignition with sonic jet into the high-enthalpy supersonic crossflow, numerical simulation with high precision is an attractive choice. Despite the LES and DES have been used to investigate the large scale vortices in the transverse jet flowfield, their structures are somewhat obscure [13]. This primarily stems from the dissipative effect of conventional low-order upwind schemes, which may not be offset by singly increasing grid numbers. The too much dissipation induced by low-order schemes can suppress the actual physical structures. It is difficult for low-order schemes to capture fine structures in the reacting flowfield. Therefore, numerical approach with high-order schemes are urgently required to be applied.

In present study, three-dimensional unsteady flowfield with a sonic jet injected into a high-enthalpy supersonic crossflow is numerically simulated by RANS/LES approach with ninth-order WENO scheme [14]. The ninth-order WENO scheme with high precision and low dissipation can capture the small scale vortices and shock very well in the flowfield [15,16]. The main objective of this paper is to develop further insights into the three-dimensional complex physics of jet mixing and flameholding mechanism.

2. Numerical approach

2.1. Governing equations

The finite difference RANS/LES solver used in present simulation solves the Favre filtered compressible Navier–Stokes equations of continuity, momentum, total energy and species transport for three-dimensional reacting flowfield [17]. For computational purpose, the governing equations are expressed in the conservative vector form as follows:

$$\frac{\partial \boldsymbol{Q}}{\partial t}+\frac{\partial(\boldsymbol{E}-\boldsymbol{E}_v)}{\partial x}+\frac{\partial(\boldsymbol{F}-\boldsymbol{F}_v)}{\partial y}+\frac{\partial(\boldsymbol{G}-\boldsymbol{G}_v)}{\partial z}=\boldsymbol{W} \tag{1}$$

where $\boldsymbol{Q}$ represents a vector of conservative variables required to be solved for; $\boldsymbol{E}$, $\boldsymbol{F}$, $\boldsymbol{G}$ are vectors of inviscid fluxes, and $\boldsymbol{E}_v$, $\boldsymbol{F}_v$, $\boldsymbol{G}_v$ are vectors of viscous fluxes in x, y, and z directions, respectively; and $\boldsymbol{W}$ represents the chemical reaction source term. The specific expressions of above vectors are defined in previous reference [18].

2.2. Turbulence models

With the recent development of computational resources, LES has gradually become an efficient approach to solve turbulent flow and combustion problems, such as the separated flows, chemical non-equilibrium flows. While it is difficult to accurately simulate the flows in the near-wall region at high Reynolds numbers, due to high mesh resolution required. Then a hybrid method [13] blending Spalart–Allmaras RANS model and Yoshizawa sub-grid scale (SGS) model is adopted for capturing large scale turbulent structures in high Reynolds number flowfield. The blended equation can be given as below:

$$\frac{D\rho\tilde{\nu}}{Dt}=\rho P_\nu+\frac{\partial}{\partial x_j}\left[\rho(\nu+\sigma_{\nu1}\tilde{\nu})\frac{\partial\tilde{\nu}}{\partial x_j}\right]+\rho\sigma_{\nu2}\left(\frac{\partial\tilde{\nu}}{\partial x_j}\right)^2-D_\nu+(1-F)\rho P_\Delta \tag{2}$$

where $\tilde{\nu}$ is molecular viscosity, ρ is the density. The specific expressions of P_ν, $\sigma_{\nu1}$, $\sigma_{\nu2}$, D_ν, P_Δ and blending function F in Eq. (2) has been given in our previous paper [19].

2.3. Numerical methods

The finite difference approach is used for the spatial discretization of the governing equations. The inviscid fluxes are discretized by the ninth-order WENO scheme and the viscous fluxes are discretized by fourth-order central difference scheme. In order to improve the computing efficiency, the time advancement is performed by means of a second-order dual time-step approach, the inner iteration of which is achieved by a lower-upper symmetric Gauss–Seidel (LU-SGS) method. An assumed sub-grid Probability Density Function (PDF) closure model is used for turbulence-chemistry interaction adopting a 9 species 19 step chemistry reaction mechanism for H_2–air mixture [17].

3. Code validation

The present simulation is performed to investigate the mixing and flameholding mechanism with the transverse hydrogen jet into a high-enthalpy supersonic crossflow. In order to validate the simulation results, the flow conditions simulated is based on the experiment of Ben-Yakar, which maps the near-field flow characteristics and