INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 39 (2014) 10284–10292

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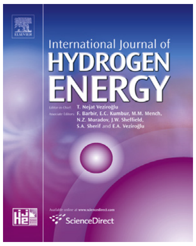

Effects of incident shock wave on mixing and flame holding of hydrogen in supersonic air flow

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ARTICLE INFO

Article history:
Received 24 February 2014
Received in revised form
18 April 2014
Accepted 22 April 2014
Available online 20 May 2014

Keywords:
Supersonic flow
Hydrogen
Mixing
Incident shock
Flame holding

ABSTRACT

The effects of incident shock wave on mixing and flame holding of hydrogen in supersonic airflow have been studied numerically. The considered flow field was including of a sonic transverse hydrogen jet injected in a supersonic air stream. Under-expanded hydrogen jet was injected from a slot injector. Flow structure and fuel/air mixing mechanism were investigated numerically. Three-dimensional Navier–Stokes equations were solved along with SST k-ω turbulence model using OpenFOAM CFD toolbox. Impact of intersection point of incident shock and fuel jet on the flame stability was studied. According to the results, without oblique shock, mixing occurs at a low rate. When the intersection of incident shock and the lower surface is at upstream of the injection slot; no significant change occurs in the structure of the flow field at downstream. However when the intersection moves toward downstream of injection slot; dimensions of the recirculation zone and hydrogen-air mixing rate increase simultaneously. Consequently, an enhanced mixing zone occurs downstream of the injection slot which leads to flame-holding.

Introduction

Scramjet engine is a promising propulsion system for future flights. In order to develop a feasible scramjet engine, obtaining a stable supersonic combustion inside the combustor is necessary. Therefore, the problem of flame-holding in scramjet's combustor seems to play an important role in its design. Since the flow has a very low residence time inside scramjet's combustion chamber, a good mixing enhancement is necessary for obtaining stable combustion.

During the recent decades, many studies have been done on the subjects related to scramjet. For instants, one may refer to the works of Tsujikawa et al. [1–3], Bao et al. [4], Lu et al. [5], Rainey et al. [6], Cecere et al. [7] and Wang et al. [8].

To control the supersonic combustion, interaction among shock waves and fuel-air mixing and combustion process should be studied. Cecere et al. investigated hydrogen combustion in the supersonic air flow [7]. They used Large Eddy Simulation and the detailed chemistry of hydrogen to analyze the fundamental phenomena in mixing and combustion of hydrogen in supersonic air flow. In another research, Wang et al. [8] showed that the flame stability in supersonic flow is not possible using only the geometry induced by injection.

Primitive investigations of the jet-supersonic boundary layer interaction have suggested that the transverse jet can be represented by a solid body of given length and shape in inviscid flow [9]. Therefore, it leads to using the transverse injection of the sonic jet into supersonic cross flow as a geometrical obstacle which can produce a low-speed region upstream of the injector that is dominated with vortex structures, and, can enhance mixing. Therefore, transverse injection is vastly utilized for fuel injection inside scramjet combustors.

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http://dx.doi.org/10.1016/j.ijhydene.2014.04.154

Nomenclature

Cp_0	constant pressure specific heat
Cp_k	constant pressure specific heat for species *k*
$\tilde{D}_t$	average turbulent diffusion coefficient
$\tilde{D}_k$	average diffusion coefficient of species *k*
$\tilde{E}$	average total energy
h_k	enthalpy of species *k*
h_k^0	enthalpy of formation for species *k*
NS	number of species
$\tilde{P}$	average mixture pressure
Pr_t	turbulent Prandtl number
$\tilde{q}_j$	average heat flux in j direction
R	gas constant
$\tilde{R}$	average gas constant of mixture
R_u	universal gas constant
Re_0	reference Reynolds number
R_k	gas constant of species *k*
T	temperature
T_{ref}	reference temperature
$\tilde{u}_j$	average velocity component in *j* direction
$\overline{U}$	average conservative velocity
W_k	molecular weight of species *k*
X_k	mole fraction of species *k*
$\tilde{Y}_k$	average mass fraction of species *k*

Greek symbols

δ_{ij}	dirac delta function
λ	thermal conductivity of mixture
μ	viscosity of gas mixture
μ_k	molecular viscosity for species *k*
$\tilde{\mu}$	average laminar viscosity
$\tilde{\mu}_t$	average turbulent viscosity
ρ	density
$\tilde{\rho}$	average mixture density
σ^2	a unique function of reduced temperature
$\tilde{\tau}_{ij}$	average turbulent shear stress
$\Omega^{(2.2)}$	a unique function of reduced temperature
ξ	computational coordinate

Basic activities on this topic are related to investigation of the flow field induced by injection of a sonic jet in a supersonic transverse flow. Okuyama et al. [10] have done experimental study on mixing phenomenon in supersonic flow with slot injection. Rizzeta [11] performed numerical simulation on the same flow field. Ben-Yakar et al. [12,13] performed experimental investigations on flame holding in supersonic flow. Javoy et al. [14] studied elementary reactions of hydrogen combustion in supersonic flow. Fiorina et al. [15] made investigation on diffusivity method for supersonic reacting flows including shock waves. Kumaran et al. [16] studied the effect of chemistry models on combustion of hydrogen in supersonic flow. According to their results, multi-step chemistry predicts higher and wider spread heat release than what is predicted by the single step chemistry.

Nakamura et al. [17,18] investigated combustion of hydrogen in supersonic flow with transverse injection and incident of oblique shock. Based on their results, flame-holding can only be seen when the direction of incident shock wave meets the jet at downstream of the injection slot. Huag et al. [19] studied the effect of Shock strength on same flow field with a two dimensional numerical analysis.

Although, transverse injection has been established to be an efficient scheme for supplying fuel in scramjet's combustor, and has been greatly studied by researchers [20–25], little work has been done to understand the fundamental mechanism of the interaction between the incident shock wave and the transverse injection [26,27].

More detailed understanding of the near field mean flow structure in a jet-supersonic cross flow interaction has been revealed due to current studies [20–25]. This mean flow structure is illustrated in Fig. 1. Similar flow field has been observed and reported in several experimental and numerical studies [11,17,26–29].

As represented in Fig. 1, the complex flow structure that is formed by jet-supersonic boundary layer interaction is dominated by shock formations and their coupling with the strong vortex structures. It consists of separation shock, λ-shock and bow shock in upstream of injector and approaching barrel shock, mach disk and secondary shock downstream of the injector.

Although the mean flow structure for jet-supersonic cross flow has been studied for different injector's geometries such as circular, elliptic and diamond injectors [24,25], there is no in-depth analysis for mean flow structure formed by a rectangular jet interacting with supersonic cross flow. Since finite slots and the rectangular jets injected from them are used in scramjets' combustor, the aim of current research is in depth analysis of this flow structure. In the present study, the above flow field is studied by a three-dimensional numerical analysis. The effects of incident shock on mixing and flame-holding flow are investigated.

The aim of present project is to study the effects of interaction between the shock wave and transversal injection on fuel-air mixing rate and flame holding. It has been done by investigation of three dimensional flow structure and recirculation zones. This work focuses on experimental studies of Refs. [25,26]. Therefore the presence of incident shock wave and its location are considered as input variables that affect the flame holding characteristics.

The flow structure is numerically simulated by solving three-dimensional Favre-Averaged Navier–Stokes equations. The numerical code incorporates real gas effects and turbulence model for numerical simulation. The numerical solution is first validated with experimental data for a jet injected into

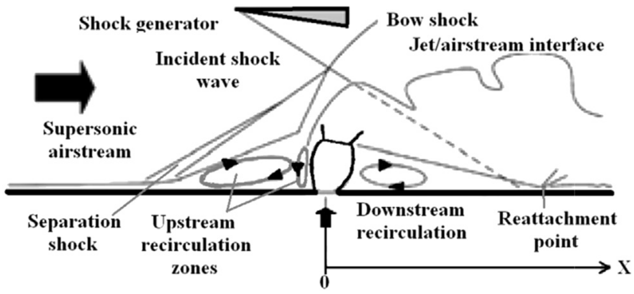

Fig. 1 – Flow field induced by transverse injection in supersonic flow.