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Numerical Investigation of Transverse Hydrogen Jet into Supersonic Crossflow Using Detached-Eddy Simulation

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A three-dimensional unsteady reacting flowfield that is generated by transverse hydrogen injection into a supersonic mainstream is numerically investigated using detached-eddy simulation and a finite-rate chemistry model. Grid refinement with the grid-convergence-index concept is applied to the instantaneous flowfield for assessing the grid resolution and solution convergence. Validation is performed for the jet penetration height, and the predicted result is in good agreement with experimental trends. The results indicate that jet vortical structures are generated as the interacting counter-rotating vortices become alternately detached in the upstream recirculation region. Although the numerical OH distribution reproduces the experimental OH–planar-laser-induced fluorescence well, there are some disparities in the ignition delay times due to the restricted availability of experimental and numerical data. The effects of the turbulence model on combustion are identified by a comparative analysis of the Reynolds-averaged Navier–Stokes and detached-eddy simulation approaches. Their effects are quantified by the production of H_2O, which is the primary species of hydrogen combustion.

Nomenclature

C_{DES}, $C_{DES}^{k\text{-}\varepsilon}$, $C_{DES}^{k\text{-}\omega}$	=	closure coefficients in the detached-eddy simulation model
D_{RANS}^{k}, D_{DES}^{k}	=	dissipation of turbulent kinetic energy
d	=	injector diameter
F_1	=	switching function for Menter's shear-stress-transport model
J	=	jet-to-freestream momentum flux ratio
k	=	turbulent kinetic energy
L	=	distance of the injection port from the flat plate's leading edge
l_{RANS}, l_{DES}	=	turbulent length scale
M	=	Mach number
P_k	=	production of turbulent kinetic energy
p	=	static pressure
Re	=	Reynolds number
T	=	static temperature
t	=	time
x, y, z	=	Cartesian coordinates
y^+	=	nondimensional wall distance
β, γ, $\sigma_{\omega 1}$, $\sigma_{\omega 2}$	=	closure coefficients in the specific dissipation rate equation
β^*, σ_k	=	closure coefficients in the turbulent-kinetic-energy equation
Δ	=	characteristic length based on the maximum grid-size/difference operator
δ	=	boundary-layer thickness at the injector port
ε	=	dissipation rate
μ, μ_t	=	molecular and turbulent dynamic viscosity
ρ	=	density
τ	=	ignition delay time
φ	=	equivalence ratio
ω	=	specific dissipation rate
ω_x, ω_y, ω_z, ω_m	=	x, y, and z vortical components and vorticity magnitude

Subscripts

exp.	=	property based on experimentation
j	=	injector exit value
mix	=	property of the mixing layer
nu.	=	property based on numerical simulation
2	=	property behind the bow shock
∞	=	freestream value

I. Introduction

ONE of the critical issues for a scramjet combustor is the realization of efficient fuel–air mixing and combustion within a short flow residence time. The flow residence time associated with hypersonic flight speeds is typically of the order of milliseconds; therefore, fuel should be mixed with air and burned completely within such a limited time span to reduce the combustor length and weight. A number of research studies have been conducted on this topic. Various injection concepts have been suggested for scramjet combustor configurations to overcome the limited flow residence time. Transverse fuel injection through a wall orifice is one of the conventional and reliable methods that enable rapid fuel–air mixing and high jet penetration into supersonic crossflow.

The configuration of transverse fuel injection is simple, but the generated flow structures are rather complicated, as shown in Fig. 1. The leaving jet expands rapidly and blocks the supersonic crossflow, causing a three-dimensional bow shock ahead of the injector. The bow shock causes separation of the upstream wall boundary layer, where the fuel is subsonically mixed with the air. This region of subsonic mixing is important in transverse injection flowfields, due to its flame-holding capability inside a supersonic combustor. Furthermore, as the fuel jet interacts with the supersonic crossflow,

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