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Investigating the supersonic combustion efficiency for the jet-in-cross-flow

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ARTICLE INFO

Article history:
Received 12 October 2014
Received in revised form
25 December 2014
Accepted 29 December 2014
Available online xxx

Keywords:
Chemical kinetics
Combustion efficiency
Jet in cross flow
Numerical simulation
Oblique shock
Supersonic flow

ABSTRACT

The purpose of this paper is to investigate the effect of impinging oblique shock on combustion efficiency of hydrogen injection into the supersonic cross-flow. The two-dimensional finite volume solver is developed to simulate the reacting flow, and the one-equation Spalart-Allmaras turbulence model is implemented to capture the turbulent flow characteristics. The impinging oblique shock is produced by a wedge that is located in the upper boundary of the flow field. Finding the best effective parameters on the combustion efficiency may lead to optimize the supersonic combustion chambers, from technological viewpoints. The variation of combustion efficiency versus various induced shock's collision positions with bottom wall in related to the fuel injection location is presented. In addition, the effect of induced shock strength on combustion process is investigated by changing the wedge's angle. Augmentation an additive, H_2O_2, to the fuel is the other parameter whose effect on combustion characteristics is studied in the disturbed field by impinging oblique shock. Finally, the effects of fuel injection angle as a predominant factor in flow and combustion features is illustrated in this paper. The results show that the shock impinging upstream of the injection slot, tilting the fuel jet to the upstream, increasing the oblique shock strength, and using hydrogen peroxide in fuel stream can effectively increase the combustion efficiency.

Introduction

The injection of a fuel in cross flow has various applications in propulsion systems. Lean-premixed–prevaporized gas turbine combustor and homogenous charge compression ignition (HCCI) are two applications of this type of flow where the flow velocity is not very high. However, supersonic combustion is the inseparable character of promising air-breathing propulsion systems in the future. Hypersonic flight vehicles such as long-range passenger transport planes and reusable launch vehicles for space missions undoubtedly need to enhance their combustion efficiency in supersonic regime.

Rapid macro scale mixing of fuel with air, permission sufficient resident time for fuel heating, destruction of large-scale turbulence structure, promotion of small-scale turbulence generation for micro-mixing when sufficient reactants have macro-mixed, micro-mixing at a rate consistent with chemical reaction times, and controlling pressure rise due to heat generation are subsequent processes that should be done completely in supersonic combustors for the efficient combustion [1]. Hence, numerous researches have been carried

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http://dx.doi.org/10.1016/j.ijhydene.2014.12.124

out to clarify the effects of diverse parameters in supersonic combustion, especially for jet in cross flow physics.

Zukoski and Spaid [2]'s experimental research is among the first published papers about the physics of secondary injection of gases into a supersonic flow. In this research, the authors tried to find appropriate correlations between penetration height—which has been calculated based on the inviscid model of the flow field—and pressure, concentration fields as well as shock shape. They concluded that the correlation of scale parameter, penetration height, with concentration field and shock shape are consistent with experimental data, but penetration height is not able to make an accurate correlation with pressure field, especially at lower Mach number regions. Billig [3] summarized the researches that had been carried out on supersonic combustion at that time, when the paper is published, and suggested some issues or future investigations in order to enhance the efficiency of scramjet engines.

Bogdanoff [4] reviewed the common injection and mixing enhancement methods, and proposed three new injection techniques for better mixing. Curved combustor, pulsation of the fuel injectors, and the injection behind pylons are three suggestions whose performance was assessed by him. Ben-Yakar [5] investigated experimentally the flame-holding capability and the auto-ignition of a hydrogen jet that is injected transversely in high total enthalpy flow, which is a typical condition of flight with Mach number 8, 10 and 13. He used the flow visualization techniques included planar laser-induced fluorescence (PLIF) of OH and Schlieren imaging to study the flow and combustion characteristics.

Ben-Yakar et al. [6] compared experimentally near flow-field properties of transverse hydrogen and ethylene injection into the supersonic cross-flow. They reported that unlike previous researches, the transverse penetration does not depend on jet-to-free stream momentum flux ratio because they observed the ethylene penetration depth is higher than hydrogen's one at the similar jet-to-free stream momentum flux ratio. They stated that development of different large-scale coherent structures in ethylene jet's shear layer due to the steeper velocity gradient could justify this outcome. Huang et al. [7] numerically investigated the effect of injected gas molecular weight and injector configuration on supersonic jet in cross-flow. They studied the influence of these parameters on both low and high jet-to-cross-flow pressure ratio. They concluded that the mixing efficiency decreases with the increase of the jet-to-cross-flow pressure ratio irrespective of the injector configuration.

The Jet in cross flow is a complicated field including vorticities and recirculation regions, so comprehension the origin of these vertical fields helps to enhance the desired phenomena like mixing in this type of flow. Yang et al. [8] studied the two-dimensional, unsteady shock-induced vortical flows numerically. Based on this research and compressible form of vorticity equation, in order to enhance mixing and to generate vorticity in supersonic regime, the baroclinic term of vorticity equation should be increased. The interaction of the density gradient at each light/heavy interface with pressure gradient from the shock wave can generate vorticity, which is the investigated phenomenon in this paper. They concluded that the stretching rate and mixing is enhanced by stronger incident shock or larger density difference. In addition, they generalized their research by investigation the effects of geometrical variations as well as multiple jet configurations on mixing and stretching rate.

Curran et al. [9] reviewed important advances in design and prediction of supersonic combustors' behaviors comprehensively. In addition, they summarized the attempts of various researches to reach this outstanding conclusion “stream-wise vorticity is one the important keys to enhance the fuel-air mixing in supersonic combustors.” VanLerberghe et al. [10] studied the mixing characteristics of an under-expanded sonic jet injection into the Mach 1.6 cross flow by shadowgraph photography and PLIF. They clarified the role of large-scale rolling structures and jet-like plumes in mixing. They stated that the counter-rotating stream-wise vortex pair in the jet plume is one the most effective structures in mixing characteristic of jet in cross flow physics.

Flame-holding is one of the key parameters in combustion, especially in supersonic regime. In general, three techniques are used to achieve sustainable flame in supersonic combustors. First, organization of a recirculation area where the fuel and air can be mixed at low velocities; second, interaction of a shock wave with partially or fully mixed fuel and oxidizer; and third, formation of coherent structures containing mixed fuel and air [11]. The cavity-type flame holders are relatively new and simple way to fulfill this fundamental need. Ben-Yakar and Hanson [11] summarized the flow features of cavities, such as various flow regimes of cavities based on length-to-depth ratio, oscillations, techniques to suppress these oscillations, drag penalties for different cavity geometries, and flow resident time inside the cavity. Moreover, they investigated cavity's effectiveness in flame-holding and ignition in supersonic combustion. Gruber et al. [12] investigated experimentally the flow features and combustion processes of typical cavity-based flame holders in supersonic combustors that use hydrocarbon fuels. Kim et al. [13] numerically studied the effects of a cavity with an angled rear wall on flow and combustion characteristics of hydrogen injection into the supersonic airflow. They investigated the effects of geometrical cavity parameters, such as aft wall angle, the offset ratio of upstream to downstream depth, and cavity length on total pressure loss and combustion efficiency.

Advanced computational techniques in accompanied by modern computers' abilities provide suitable facilities for engineers to investigate the effects of various parameters in complex flow where the experimental tests are unavailable or cannot capture all flow features precisely. Some outstanding numerical researches in jet-in-cross-flow physics are mentioned in the following. Erdem and Kontis [14] simulated the flow field in transverse slot injection into a supersonic flow by k-ω SST turbulence model. They proved the acceptable performance of this model in predictions of transition as well as separation points, surface pressure profile, and flow structures by comparing numerical and experimental results. In addition, they carried out some experiments in sonic round jet injection into free stream Mach number 5; they found that jet penetration is a non-linear function of jet-to-free-stream-momentum-flux ratio.

Cecere et al. [15] simulated the flow and combustion characteristic of hydrogen injection into the supersonic flow