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The Effects of Pressure Fluctuations on the Hydrogen Jet Combustion in a Supersonic Cross Flow

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Abstract

The aim of the present paper is to analyze the effect of pressure fluctuations on the combustion efficiency of hydrogen fuel injected into the supersonic oxidizing cross flow. The existing pressure fluctuations at inlet oxidizer flow and also at fuel jet flow are considered with different frequencies, and for two different situations: with and without inlet standing oblique shock wave. The two-dimensional finite volume unsteady flow solver is developed to simulate the compressible reacting supersonic flow field in the combustor, and to predict the time-variation of the combustion efficiency due to the imposed fluctuations. The results show that the response of the considered reacting flow field depends on the fluctuations' frequency and the existence of the inlet shock wave.

Keywords: *Combustion efficiency; Frequency; Hydrogen; Jet in Cross flow; Pressure fluctuations; Response; Supersonic; Transient simulation*

Nomenclature

D_{im}	effective mass diffusivity of species i in a mixture
E	total internal energy
p	local pressure
q	heat flux
T	local temperature
V_{ij}	the j^{th} component of the diffusion velocity

Greek symbols

μ	molecular dynamic viscosity
μ_t	turbulent dynamic viscosity
ρ	gas local density
$\dot{w}_i$	mass rate of production of species i

1. Introduction

The fuel injection in a cross flow has various applications especially in propulsion systems. In addition, the supersonic combustion is the promising air-breathing propulsion system in the future. So, the high speed vehicles undoubtedly need to enhance their combustion efficiency in supersonic regimes. There are numerous experimental and numerical researches which have been carried out to investigate the effects of different parameters in the supersonic combustion, especially for the jet in cross flow configuration.

Billig [1] suggested some issues in order to enhance the efficiency of scramjet engines. Bogdanoff [2] reviewed the common injection and mixing-enhancement methods, and proposed new injection techniques for better mixing. Ben-Yakar [3] investigated experimentally the auto-ignition of a hydrogen jet injected transversely in high enthalpy flow. Huang et al. [4] numerically analyzed the effect of injected gas molecular weight and injector configuration on the mixing efficiency. Curran et al. [5] reviewed comprehensively the important advances in design and prediction of supersonic combustors' behavior. Cecere et al. [6] simulated the flow and combustion characteristic of hydrogen injection into the supersonic flow.

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The incidence of an oblique shock near the fuel injection hole may increase the mixing features of such flow fields [7]. The author recently studied the effects of the shock strength and its collision position on the combustion efficiency [8].

One of the most interesting phenomena in the reacting flow field arises due to the pressure fluctuations, and may lead to the combustion instabilities. There are a lot of researches which have been performed to analyze the combustion stability in different reacting systems. The author investigated recently the effects of pressure fluctuations on the burning rate response of the solid fuels [9], and also on the supersonic reacting mixing layer [10]. In order to illustrate the effects of an inlet and fuel jet pressure fluctuations on the combustion efficiency of the jet in supersonic cross flow fields, this research has been carried out numerically.

2. Governing Equations and Numerical Procedure

The governing equations of two-dimensional and compressible continuity, momentum, and energy equations are used at this study. The conservative forms of the governing equations are presented here as

Continuity,

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j}\left(\rho u_j\right) = 0 \tag{1}$$

Species Continuity,

$$\frac{\partial(\rho Y_i)}{\partial t} + \frac{\partial}{\partial x_j}\left(\rho Y_i\left(u_j + V_{ij}\right)\right) = \dot{w}_i \tag{2}$$

Where Y_i is the mass fraction of the species i, u_j is the j^{th} component of local bulk mass-average velocity, V_{ij} is the j^{th} component of the diffusion velocity of species i, and $\dot{w}_i$ is the chemical reaction rate of species i.

$$\rho V_{ij} = -\rho\left(D_{im} + \frac{\mu_t}{\rho\, Sc}\right)\frac{\partial}{\partial x_j}(Y_i) \tag{3}$$

μ_t is the turbulent viscosity, and D_{im} presents effective binary mass diffusivity for the diffusion of species i in a mixture, and Sc is designated to represent the Schmidt number. Chemical reaction rate for each species is computed by mechanism of H_2-O_2 reaction that is presented by Stahl and Warnatz [11]. In this mechanism, 9 species (H_2, O_2, H_2O, H_2O_2, OH, O, H, N_2, and HO_2) and 37 elementary reactions are considered as a full chemistry.

Momentum,

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}\left(\rho u_i u_j\right) = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\tau_{ij} \tag{4}$$

Where

$$\tau_{ij} = (\mu + \mu_t)\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{2}{3}\left[(\mu + \mu_t)\frac{\partial u_k}{\partial x_k}\right]\delta_{ij} \tag{5}$$

Energy,

$$\frac{\partial}{\partial t}(\rho E) + \frac{\partial}{\partial x_j}\left(\rho u_j E\right) = -\frac{\partial}{\partial x_j}\left(P u_j\right) + \frac{\partial}{\partial x_j}\left(\tau_{ij} u_i\right) - \nabla . q \tag{6}$$

Here, E is the total energy and q is defined as below

$$q = -\left(k + \frac{\mu_t C_p}{Pr_t}\right)\nabla T + \rho \sum_{i=1}^{N} h_i Y_i V_i \quad (7)$$

$$h_i = \Delta h_{f,i}^{\circ} + C_{p,i} T \quad (8)$$

$\Delta h_{f,i}^{\circ}$ is standard heat of formation of species *i*, and Pr_t represents the turbulent Prandtl number. Turbulent viscosity is computed by the one-equation S-A turbulence model. The transported variable in this model is $\tilde{\upsilon}$ and turbulent viscosity is computed from $\mu_t = \rho\tilde{\upsilon} f_{\upsilon 1}$, where $f_{\upsilon 1}$ is a viscous damping function. The transport equation for $\tilde{\upsilon}$ and the coefficients as well as constants can be found in Spalart and Allmaras [12]. The combustion efficiency is calculated here with the below definition where $\dot{N}$ represents the molar flux.

$$\eta_c = \frac{\dot{N}_{H_2O\ at\ exit} - \dot{N}_{H_2O\ injected}}{\dot{N}_{H_2\ injected}} \quad (9)$$

The cell-center finite volume scheme is used to solve the governing equations. Viscous terms are calculated using a central scheme and the inviscid fluxes are computed based on the AUSM$^+$ (Advection Upstream Splitting Method) [13]. The developed numerical program has been validated using different benchmark problems and experimental data, and used satisfactorily to study the reacting flows [8, 9, 14-16].

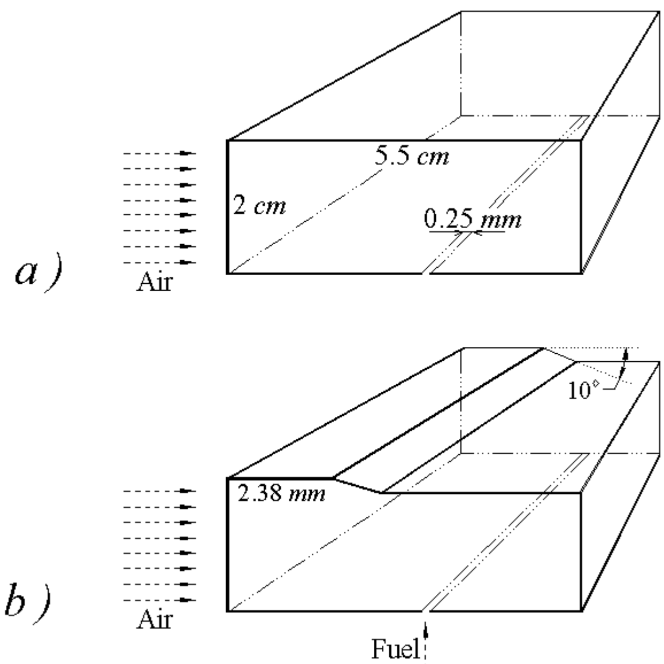

Figure 1: Problem geometry a) without inlet shock, b) with inlet shock.

Here, two different flow fields are considered: the fuel jet in supersonic oxidizer flow with and without an inlet standing oblique shock wave. The schematics of geometry and the dimensions are shown in Figure 1. The grid resolution of 240x80 is used in these simulations, after grid independency studies. The pre-burned hydrogen/air gases whose equivalence ratio is 4.5 are injected from a slot with 0.25 *mm* width. The Mach number and the total pressure of the injected fuel are set to 1.0 and 12 *bar*, respectively. The free stream Mach number, the total pressure and temperature are set to 2.5, 5 *bar*, and 673 *K*, respectively.

3. Results and Discussion

The existing structures in the flow field of the fuel jet injection in to the supersonic cross flow are comprehensively described, and the effects of an inlet standing oblique shock on the combustion efficiency of the combustor are parametrically studied recently [8]. In that numerical investigation, the steady state solution of the reacting flow was important and studied. The streamlines of such flows are shown in Figure 2. The combustion efficiency is increased from 0.123 to 0.388 due to the inlet shock wave in the considered problem.

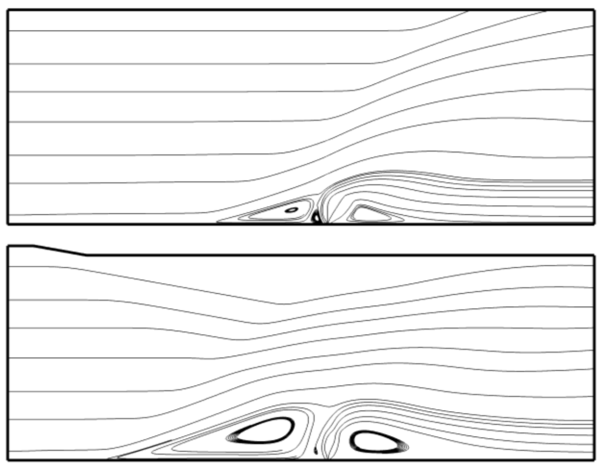

Figure 2: Streamlines for the flows without and with inlet shock.

In order to investigate the effect of pressure fluctuations on the combustion efficiency, transient simulation should be performed. To do this, after the computation of the steady state characteristics of the flow field, the unsteady simulation is continued by applying the considered fluctuations to the boundary condition. Here, the harmonic pressure fluctuations in an oxidizer inlet flow or in the fuel stream are applied. The amplitude of the oscillations is 5% of the mean pressure, and the frequencies are changed (Figure 3).

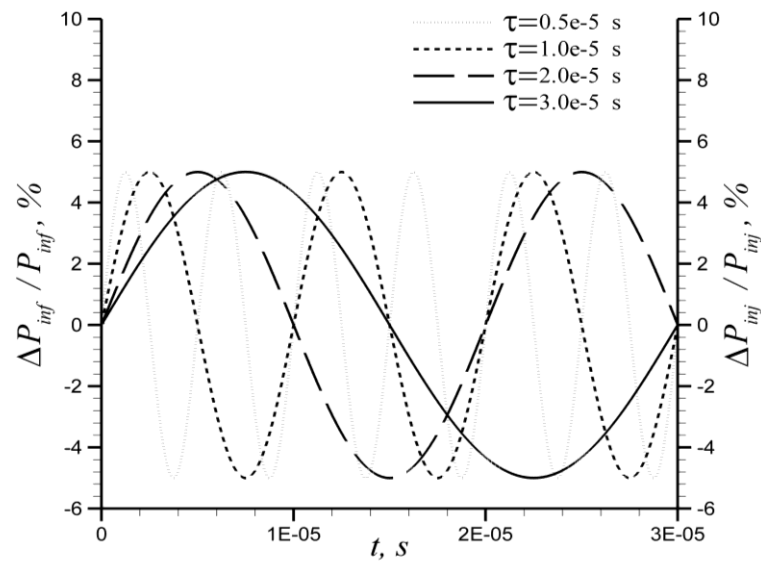

Figure 3: Applied pressure fluctuations.

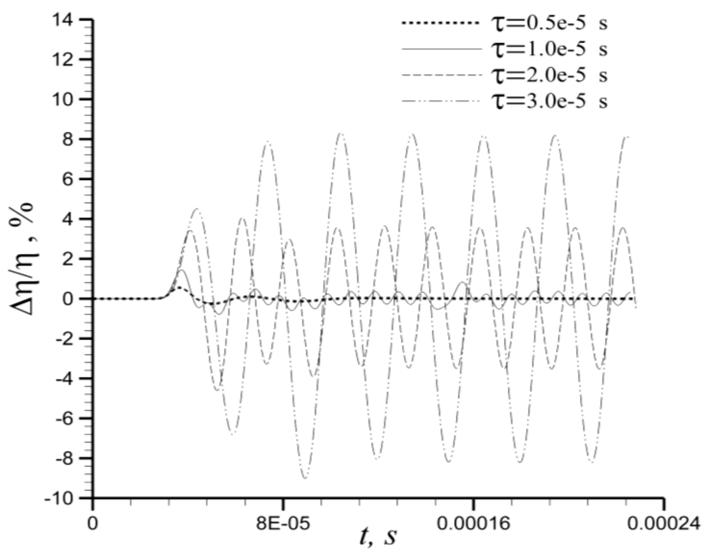

Figure 4: Combustion efficiency versus time due to the inlet fluctuations, without inlet shock.

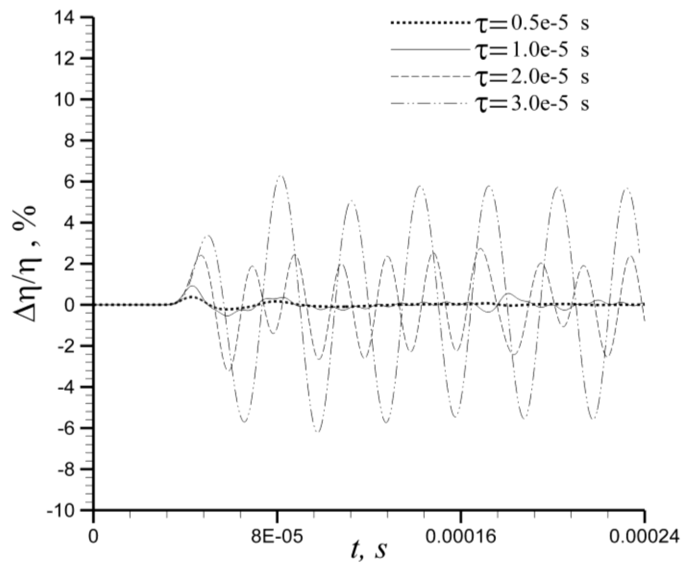

Figure 5: Combustion efficiency versus time due to the inlet fluctuations, with inlet shock.

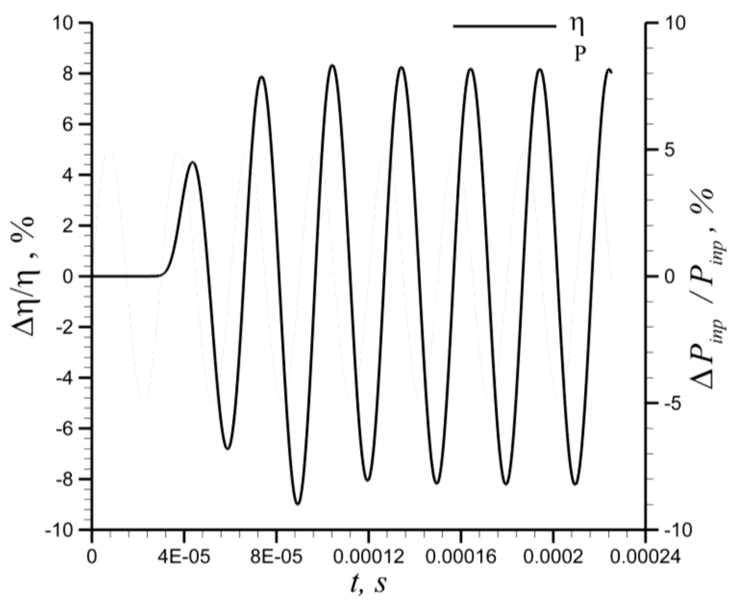

Figure 6: Response and excitation time histories, τ=3e-5 *s*, without inlet shock.

By applying the fuel jet pressure fluctuations, the response is always oscillatory even with high frequencies of excitations. The periods of the excitation and the response are also equal in this situation. The amplitude of the response is larger again for the case without inlet shock than the other case, and the amplification features of the flow field are stronger than when the excitation is applied to the inlet flow, as illustrated in Figure 7.

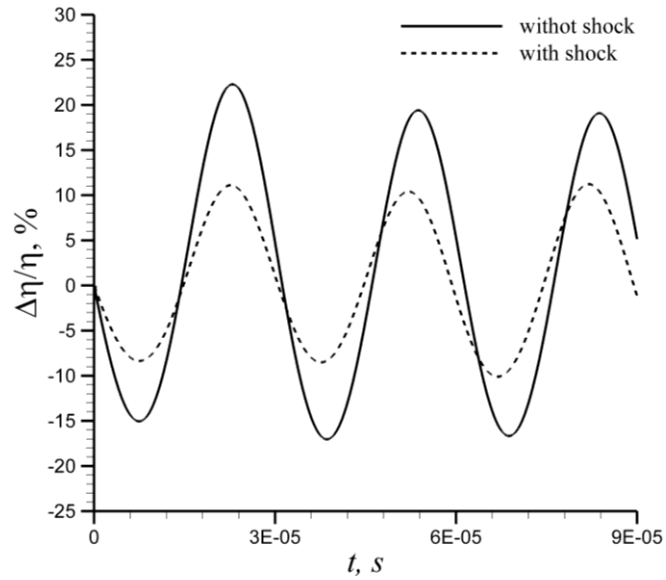

Figure 7: Combustion efficiency versus time due to the jet pressure fluctuations, τ=3e-5 *s*.

As a final step of this analysis, the excitations are applied in both inlet and jet pressures, for the case without the inlet shock wave. The results show that when the excitations are in anti-phase condition, the amplitude of the response is greater, and applying the amplitude of 5 % in excitation leads to amplitude of about 25% in the response (Figure 8).

The amplification features which sometimes observed in this reacting flow field may result in combustion instabilities and must be considered in practical situations.

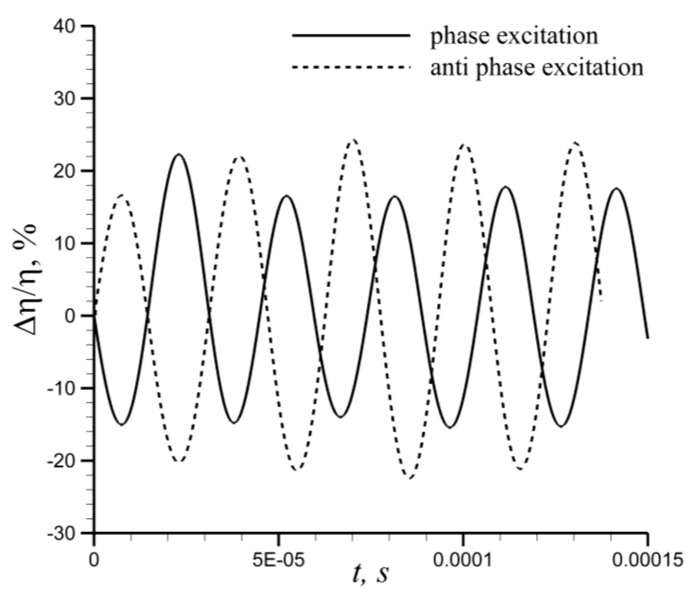

Figure 8: Response time-history due to both pressure fluctuations, τ=3e-5 *s*.

4. Conclusions

The effect of pressure fluctuation on transverse injection of fuel jet in supersonic oxidizer cross flow is investigated numerically. The excitations are applied on the oxidizer and fuel streams, and for two different situations: with and without inlet standing oblique shock. The results show that if the high frequency excitations are imposed at inlet pressure, the oscillatory response is damped, but it is not true for the jet pressure fluctuations. Increasing the period of excitations lead to amplification of the response, and it is stronger for the case without inlet standing oblique shock wave. The considered reacting system sometime indicates amplification features, and applying the excitations in both streams shows strong amplification when they are in anti-phase condition. Such behavior may lead the combustion instabilities which is much important phenomena and should be analyzed in practical situations.

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