

Nitrogen Effects on Ignition Delay Time in Supersonic Premixed and Diffusion Flames

A. M. Tahsini

Abstract—Computational study of two dimensional supersonic reacting hydrogen-air flows is performed to investigate the nitrogen effects on ignition delay time for premixed and diffusion flames. Chemical reaction is treated using detail kinetics and the advection upstream splitting method is used to calculate the numerical inviscid fluxes. The results show that just in stoichiometric condition for both premixed and diffusion flames, there is monotone dependency of the ignition delay time to the nitrogen addition. In other situations, the optimal condition from ignition viewpoint should be found using numerical investigations.

Keywords—Diffusion flame, Ignition delay time, Mixing layer, Numerical simulation, Premixed flame, Supersonic flow.

I. INTRODUCTION

THE interests in the development of propulsion systems for high speed aerospace vehicles as scramjets have led to extensive experimental and numerical studies of supersonic combustion processes in recent decades. However, these studies confront many unresolved problems and much research remains to be done. One of the principal difficulties encountered has arisen from the flow residence times being of the same order of magnitude as the ignition delay time within the combustion chamber of supersonic combustors.

The ignition within a supersonic flow give rise to problems related to the coupling between chemical kinetics and compressible, high temperature fluid dynamics. On the other hand, the flow dynamics in an actual combustor is rather intricate due to various flow structures and shock wave interactions arise from complex geometry. So many scientists have concentrated on the reacting mixing layers established between two parallel fuel-air streams, to make fundamental studies in this area.

Ju and Niioka [1] have made studies on supersonic mixing layer of unpremixed oxidant-fuel streams, using three-step reaction kinetics to predict the ignition distance. They have analyzed the effects of free shear, Mach number, and reaction rates on the ignition delay time. They have also numerically predicted the ignition distance for hydrogen-air and methane-air mixing layers using reduced kinetics mechanism [2], [3]. Da Silva et al. [4] have numerically investigated the effect of initial temperature and velocity gradients on ignition distance in supersonic hydrogen-air mixing layer.

Im et al. [5], [6] have analyzed the thermal ignition

behavior in supersonic mixing layer and the effect of Mach number on ignition distance. Nishioka and Law [7] have studied the temperature effect on ignition in supersonic hydrogen-air mixing layer using detail chemistry. Fang et al. [8] have numerically investigated the effect of initial pressure on ignition distance in supersonic mixing layer in the presence of a pressure gradient. Tien and Stalker [9] have studied the effect of the initial conditions on the ignition distance in supersonic hydrogen-air mixing layer using detail chemical kinetics. In addition, some studies have been done to modify the prediction accuracies [10], [11].

Rapid ignition process as well as fast and complete combustion and chemical energy release is significant to decrease the combustor length and weight. So the prediction and reduction of the ignition delay time using different practical techniques is attractive scientific field, which will be applicable to improve practically the scramjets. Recently, the effects of turbulence, chemical additives and using the swirl in both fuel and oxidizer flows on reducing the ignition distance have been analyzed by the author that show they can be significant controlling parameters [12], [13].

Although the existence of the influence of diluents on combustion process in reacting flows is physically obvious, but there is no concentrated precise studies especially for supersonic combustion applications. Some efforts have been done in other situations.

Catoire et al. [14] have investigated the effect of diluents on ignition delay in premixed reacting flows. Phouc and Chen [15] have examined the effect of nitrogen on ignition of hydrogen diffusion jet flames. Prathap et al. [16] have investigated the effect of nitrogen dilution on the burning velocity of fuel under atmospheric condition. Kumgeh and Bergthorson [17] have studied the dilution effects on autoignition of premixed flames.

In the present paper, the hydrogen-air mixing layer has been analyzed numerically using detail chemical kinetics to study the effect of nitrogen concentration on ignition location and gain insight into the practical applications in scramjets.

II. GOVERNING EQUATIONS AND NUMERICAL METHOD

In the present simulation, the two dimensional compressible reacting equations governing the continuum viscous flow representing the conservation of mass, momentum, energy, and species are used. The equations are written in the following conservation form [18].

A. M. Tahsini, Assistant Professor, is with the Astronautics Research Institute, Iranian Space Research Center, Tehran, Iran (e-mail: a_m_tahsini@yahoo.com, tahsini@ari.ac.ir).

$$\frac{\partial U}{\partial t} + \frac{\partial(F + F_v)}{\partial x} + \frac{\partial(G + G_v)}{\partial y} = ST \quad (1)$$

The finite-rate chemical kinetics model which was given by Stahl and Warnatz is employed here as a full chemistry for hydrogen-air combustion [19]. Here, nine chemical species exist within reaction mechanism, and eight conservation equations for species should be considered beside one overall mass fraction equation. Therefore, there are twelve coupled equations to be solved simultaneously and numerically in the flow field.

The cell centered based finite volume method is used to discretize the governing equations. The time integration is accomplished by an explicit time stepping scheme [20]. The viscous terms are calculated using a central scheme and inviscid terms are treated using an AUSM⁺ method (Advection Upstream Splitting Method) to express the numerical flux at cell faces [21]. The present simulation program has been validated using variety of benchmark problems and used successfully to study the reacting supersonic and hypersonic flows [12], [13], [22].

III. RESULTS AND DISCUSSION

Before investigating the nitrogen effects on ignition delay time in supersonic mixing layer which is a practical problem, the premixed flow has been considered. This is simple flowfield and it is expected to expose the uncomplicated behavior. To do this, the hydrogen-oxygen premixed flow diluted by nitrogen has been examined at constant velocity of 3500 m/s and temperature of 1200 K and pressure of 10^5 N/m^2 . Due to the constant velocity condition, the ignition delay time can be directly studied using the ignition distance. The nitrogen mass fraction has been changed in two different ways: first, so that the mixture remains stoichiometry, and then so that the oxygen mass fraction remains constant.

In a stoichiometric mixture, nitrogen addition increases the ignition distance monotonically. Temperature distribution in the flowfield is shown in Fig. 1. Fig. 2 displays the mass fraction of hydrogen atoms in the flowfield where the peaks are good indicator of ignition location in the mixture. Nitrogen addition decreases slightly the product's temperature and increases highly the ignition delay time.

In constant-oxygen premixed flows, the nitrogen effect on ignition is interesting. The results show that in high levels of nitrogen mass fraction, the rapid ignition occurs in stoichiometric condition but decreasing the nitrogen level causes the most rapid ignition in fuel-lean region. On the other hand, the maximum temperature occurs in fuel-rich region. Ignition distance and product's temperature versus the fuel mass fraction ratio are shown in Figs. 3 and 4, respectively. So the ignition delay time and flame temperature are two oppose criteria in choosing the nitrogen level in constant-oxygen premixed flows. It can be concluded that against the simplicity of premixed reacting flows, the nitrogen effect on ignition delay time should be predicted precisely in practical

applications because it cannot be estimated easily.

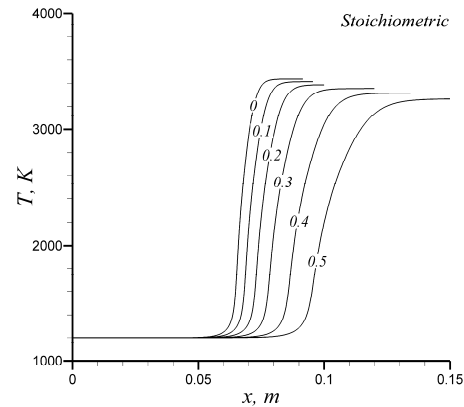


Fig. 1 Temperature change in premixed stoichiometric supersonic flow for different N_2 mass fractions

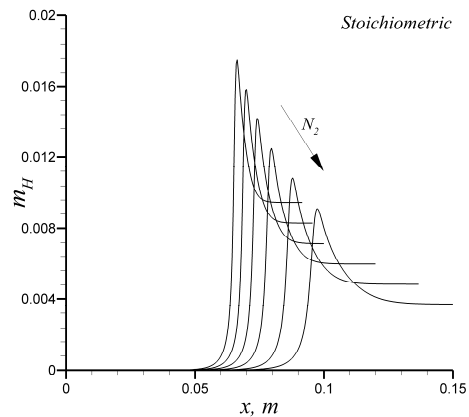


Fig. 2 m_H change in premixed stoichiometric supersonic flow for different N_2 mass fractions

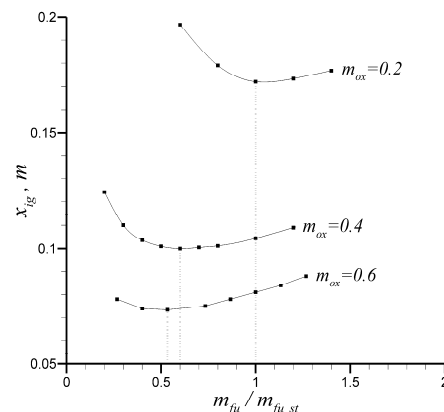


Fig. 3 Ignition distance versus m_{fu}/m_{fu-st} for different N_2 mass fractions in premixed supersonic flow

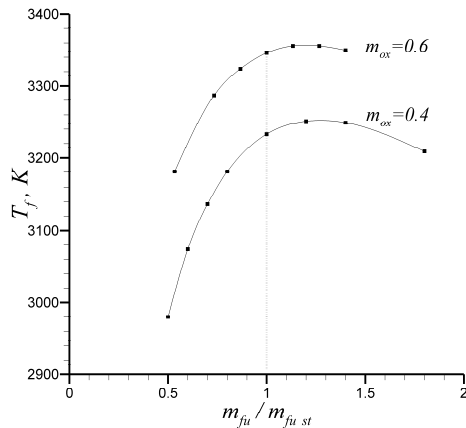


Fig. 4 Flame temperature versus $m_{fu}/m_{fu,st}$ for different N_2 mass fractions in premixed supersonic flow

To study the effect of nitrogen on ignition delay in supersonic diffusion flame, the parallel fuel and oxidizer flows diluted by nitrogen has been examined at constant velocity of 1200 m/s and temperature of 1200 K and pressure of 10^5 N/m² for both streams. The nitrogen mass fraction has been changed here in three different ways: so that the mixture remains stoichiometry at interface and for pure-oxygen and pure-hydrogen flows. In stoichiometric condition, the effect of nitrogen is similar to the premixed reacting flow; nitrogen addition increases the ignition distance monotonically (as shown in Fig. 5). High levels of nitrogen increase extremely the ignition delay time.

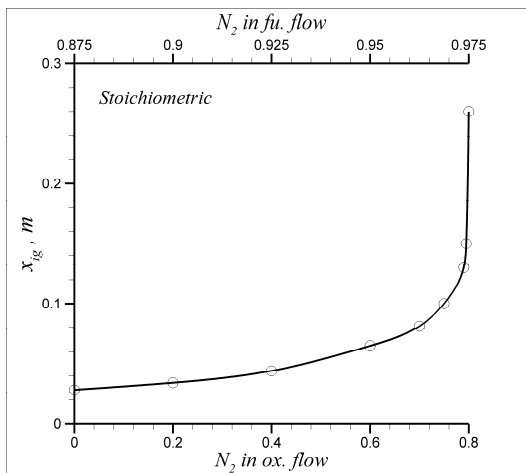


Fig. 5 Ignition distance versus N_2 mass fraction in stoichiometric supersonic mixing layer

In the case of pure-oxidizer stream, nitrogen addition to the fuel stream increases the ignition delay time at low levels of nitrogen mass fraction but the nitrogen role is reversed in higher nitrogen mass fractions (as shown in Fig. 6). From ignition delay viewpoint in this condition, the worse case is nitrogen mass fraction of about 0.2 in fuel stream.

For pure-fuel stream, changing the nitrogen mass fraction

causes more complicated behavior as shown in Fig. 7. Although the overall influence of nitrogen addition to the oxidizer is inappropriate for ignition delay time, but there is local minimum of ignition distance at nitrogen mass fraction of about 0.6 in oxidizer stream. The results show that the effect of nitrogen is more apparent when added to the oxidizer flow in comparison of adding to the fuel flow.

Fig. 8 displays the ignition distance versus nitrogen mass fraction in oxidizer flow for both stoichiometric and pure-fuel conditions. Although the nitrogen addition to the oxidizer stream increases the ignition delay time, but at constant oxygen mass fraction, adding the nitrogen to the fuel stream may decrease the ignition delay except for small region.

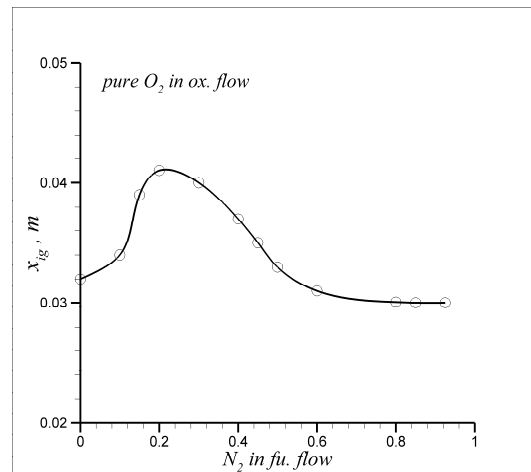


Fig. 6 Ignition distance versus N_2 mass fraction in fuel flow for pure-oxidizer supersonic mixing layer

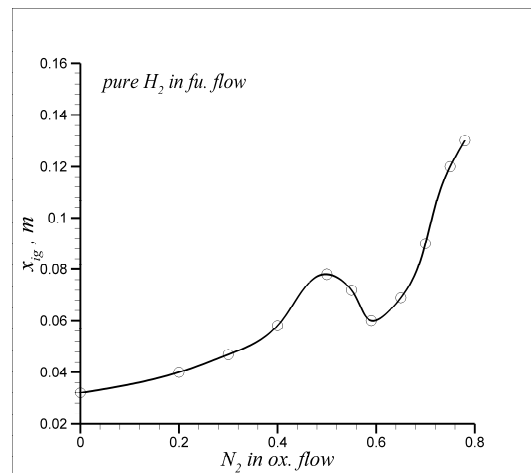


Fig. 7 Ignition distance versus N_2 mass fraction in oxidizer flow for pure-fuel supersonic mixing layer

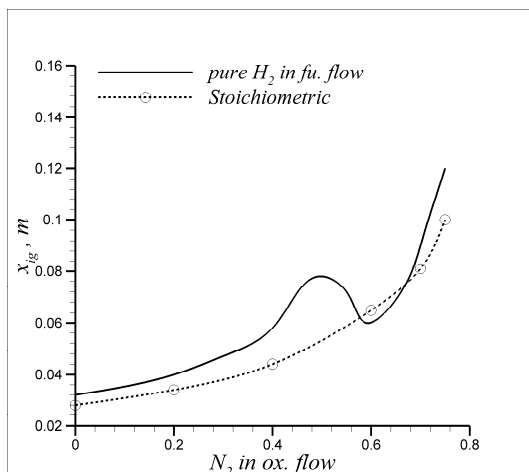


Fig. 8 Ignition distance versus N_2 mass fraction in oxidizer flow for pure-fuel and stoichiometric supersonic mixing layers

Such behaviors in supersonic reacting flows due to the nitrogen addition are related to the balance between the nitrogen properties and its effect on detail chemical kinetics in combustion process. In practical situations, it may be required to using nitrogen as a diluent as it has been done to adjust the streams Mach number in combustion chambers. This study shows that the change at ignition delay time due to such dilution should be considered in supersonic combustors.

IV. CONCLUSION

In the present study, the ignition of hydrogen-air supersonic flow is numerically analyzed using detail chemistry in both premixed and diffusion situations. Attention is paid to the ignition distance estimation and the effect of nitrogen addition on ignition delay time. It is shown that the ignition distance is increased monotonically by increasing the nitrogen concentration in stoichiometric premixed and non-premixed supersonic reacting flows. On the other conditions, different behaviors reveal due to nitrogen addition. Although the nitrogen addition may be used to dilute the fuel in supersonic combustion chambers, it should be analyzed from ignition delay viewpoints.

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