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Ignition Time Delay in Swirling Supersonic Flow Combustion

A. M. Tahsini

Abstract**—**Supersonic hydrogen-air cylindrical mixing layer is numerically analyzed to investigate the effect of inlet swirl on ignition time delay in scramjets. Combustion is treated using detail chemical kinetics. One-equation turbulence model of Spalart and Allmaras is chosen to study the problem and advection upstream splitting method is used as computational scheme. The results show that swirling both fuel and oxidizer streams may drastically decrease the ignition distance in supersonic combustion, unlike using the swirl just in fuel stream which has no helpful effect.

Keywords**—**Ignition delay, Supersonic combustion, Swirl, Numerical simulation, Turbulence.

I. Introduction

THERE were a lot of interests in the development of high speed propulsion systems for aerospace vehicles as scramjets which have led to extensive experimental and numerical efforts on supersonic combustion phenomena up to now. However, these studies confront many unresolved difficulties and much research remains to be done.

One of the principal problems encountered has arisen from the residence time being of the same order of magnitude as the reaction delay time within the combustion chamber of supersonic combustors. To decrease the combustor length and weight in this situation, rapid ignition as well as fast and complete combustion is significant. In addition, the fluid mechanics in an actual scramjet is rather intricate due to various flow structures such as shock wave interactions arise from complex combustor 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 analytical studies on a two-dimensional laminar 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 time delay. They have also numerically predicted the ignition distance for hydrogen-air and methane-air laminar mixing layers using reduced kinetics mechanism [2, 3]. Da Silva et Al. [4] have investigated the effect of initial temperature and velocity gradients on ignition in supersonic laminar hydrogen-air mixing layer and found that the flame always starts from the airside.

A. M. Tahsini, Assistant Professor, Aerospace Research Institute, Tehran, Iran; (e-mail: a_m_tahsini@yahoo.com).

Im et Al. [5] have asymptotically analyzed the thermal ignition behavior in laminar supersonic mixing layer using one-step overall reaction. They reported that the ignition distance, for the case where the speed of the air stream is greater than that of the hydrogen, first increases as the Mach number increases. But it decreases with further increment in Mach number by virtue of the increase in temperature in the mixing layer because of friction generated heat. They have also repeated such studies using reduced reaction mechanism [6].

Nishioka and Law [7] have studied the temperature effect on ignition in supersonic laminar hydrogen-air mixing layer using detail chemistry and found that there is a lower limit of the air stream temperature below which ignition in a combustion chamber is not possible and at higher temperatures, radical proliferation causes ignition instead of thermal runaway. Fang et Al. [8] have investigated the effect of initial pressure on ignition distance in supersonic laminar mixing layer in the presence of a pressure gradient. Tien and stalker [9] have computationally studied the effect of the initial conditions on the ignition distance in supersonic laminar hydrogen-air mixing layer using detail chemical kinetics and showed that the initial oxygen atom concentration has serious effect on ignition time delay.

Most of researches have been performed on laminar flow assumption and there are few studies reporting the problem in the presence of turbulent phenomena. Chakraborty et Al. [10] have investigated the supersonic reacting turbulent mixing layer using various empirical DNS data and Zambon et Al. [11] have predicted the ignition distance in similar condition using automatic reduction procedure chemical kinetics, for various splitter lip thicknesses.

It is obvious that ignition distance estimation is one of the most important purposes in scramjet design, and it is better to reduce this. Zabaikin et Al. [12] have experimentally investigated the effect of hydrogen peroxide addition on ignition and combustion in supersonic hydrogen-air flow and found that it becomes possible to decrease abruptly the ignition delay, improve the flame stability, and increase the combustion efficiency by using small amounts of chemically active additives.

Recently, the Author [13] has numerically studied the effect of inlet turbulence and chemical additive on ignition time delay in supersonic combustible mixing layers and showed that they can be significant controlling parameters. On the other hand, in analysis of aero-engines such as gas turbine combustors, some studies have been done to find suitable

methods for achieve acceptable pollutants level and better mixing. One of the best ways especially in premixed combustors is using the swirl. The swirl is also of practical importance in combustion as an agent that can increase combustion efficiency.

The study of swirling flow combustion received considerable attentions in the past decade [14-16]. Most of such studies have been done in subsonic combustors. In the present study, the swirl effect on ignition time delay in supersonic turbulent cylindrical mixing layer has been analyzed numerically using detail chemical kinetics of hydrogen and air. The influences of turbulence and swirl vane angle on ignition distance have been predicted and discussed.

II. Governing Equations

Although the flowfield within a considered geometry is three-dimensional due to the inlet swirling condition, the flow has still angular symmetry ($\partial/\partial\theta = 0$). So the three-dimensional Reynolds averaged compressible equations governing the continuum flow are used with regard to the simplifying condition of this symmetry. The equations representing the conservation of mass, momentum, energy, and species are presented in the following conservation form [17].

$$\frac{\partial U}{\partial t}+\frac{\partial(F+F_v)}{\partial x}+\frac{\partial(G+G_v)}{\partial y}+\frac{G+G'+G_v+G'_v}{y}=ST \tag{1}$$

Where

$$U=\begin{bmatrix}\rho\\ \rho u\\ \rho v\\ \rho w\\ \rho e\\ \rho m_j\end{bmatrix} \quad F=\begin{bmatrix}\rho u\\ \rho uu+p\\ \rho uv\\ \rho uw\\ \rho uh\\ \rho um_j\end{bmatrix}$$

$$G=\begin{bmatrix}\rho v\\ \rho vu\\ \rho vv+p\\ \rho vw\\ \rho vh\\ \rho vm_j\end{bmatrix} \quad G'=\begin{bmatrix}0\\ 0\\ -\rho ww-p\\ \rho vw\\ 0\\ 0\end{bmatrix}$$

$$F_v=\begin{bmatrix}0\\ -\tau_{xx}\\ -\tau_{xy}\\ -\tau_{x\theta}\\ q_x-u\tau_{xx}-v\tau_{xy}-w\tau_{x\theta}\\ -\rho D_{eff}m_{j_x}\end{bmatrix} \quad ST=\begin{bmatrix}0\\ 0\\ 0\\ 0\\ 0\\ \dot{\omega}_j\end{bmatrix}$$

$$G_v=\begin{bmatrix}0\\ -\tau_{yx}\\ -\tau_{yy}\\ -\tau_{y\theta}\\ q_y-u\tau_{yx}-v\tau_{yy}-w\tau_{y\theta}\\ -\rho D_{eff}m_{j_y}\end{bmatrix} \quad G'_v=\begin{bmatrix}0\\ 0\\ \tau_{\theta\theta}\\ -\tau_{y\theta}\\ 0\\ 0\end{bmatrix} \tag{2}$$

The stress tensors are defined as:

$$\begin{aligned}\tau_{xx}&=\mu_{eff}\left(2\frac{\partial u}{\partial x}-\frac{2}{3}\nabla.V\right)\\ \tau_{xy}&=\mu_{eff}\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)\\ \tau_{yy}&=\mu_{eff}\left(2\frac{\partial v}{\partial y}-\frac{2}{3}\nabla.V\right)\\ \tau_{x\theta}&=\mu_{eff}\left(\frac{\partial w}{\partial x}\right)\\ \tau_{y\theta}&=\mu_{eff}\left(\frac{\partial w}{\partial y}-\frac{w}{y}\right)\\ \tau_{\theta\theta}&=\mu_{eff}\left(2\frac{v}{y}-\frac{2}{3}\nabla.V\right)\end{aligned} \tag{3}$$

Here

$$\begin{aligned}\mu_{eff}&=\mu+\mu_t\\ e&=c_vT+(uu+vv+ww)/2+\sum m_j\Delta h^o_{f,\,j}\\ q&=-k_{eff}\nabla T-\rho D_{eff}\sum h_i\nabla m_i\\ h_i&=\Delta h^o_{f,\,i}+\int c_{p_i}dT\end{aligned} \tag{4}$$

The Spalart-Allmaras turbulence model is used here to close the system of RANS equations [18]. Although this model has been developed initially for external aerodynamic flows, it has been used successfully in different reactive flow simulations. The eddy viscosity is determined through a solution of following partial differential equation.

$$\frac{D(\tilde{\nu})}{Dt}=c_{b1}\tilde{S}\tilde{\nu}+\frac{1}{\sigma}\left[\nabla.((\nu+\tilde{\nu})\nabla\tilde{\nu})+c_{b2}(\nabla\tilde{\nu})^2\right]-c_{w1}f_w\left(\frac{\tilde{\nu}}{d}\right)^2 \tag{5}$$

This equation is solved for the variable $\tilde{\nu}$ and the eddy viscosity is calculated as $\nu_t=\tilde{\nu}f_{v1}$ where the damping function f_{v1} is used to treat the buffer layer and the viscous sub-layer. Here

$$\begin{aligned}\tilde{S}&=S+\left(\tilde{\nu}/\kappa^2d^2\right)f_{v2}\\ f_{v2}&=1-X/(1+Xf_{v1})\\ f_{v1}&=X^3/\left(X^3+c_{v1}^3\right)\\ X&=\tilde{\nu}/\nu\end{aligned} \tag{6}$$

The parameter d is the distance to the closest wall, S is the magnitude of vorticity, and $\tilde{S}$ is modified strain rate. The function f_w is given as

$$f_w=g\left(\frac{1+c_{w3}^{\ 6}}{g^6+c_{w3}^{\ 6}}\right)^{\frac{1}{6}} \tag{7}$$

Where

$$g = z + c_{w2}\left(z^6 - z\right)$$
$$z = \frac{\tilde{\nu}}{\tilde{S}\kappa^2 d^2} \quad (8)$$

The constants are: $c_{b1} = 0.1355, c_{b2} = 0.622, c_{v1} = 7.1, \sigma = 2/3$ and $c_{w1} = 3.239, c_{w2} = 0.3, c_{w3} = 2, \kappa = 0.41$. Equation (5) is solved coupled to flow governing equations.

The finite-rate reaction mechanism (Table 1) which was presented by Stahl and Warnatz is used here as a full chemistry for hydrogen-air combustion [19]. There are nine chemical species within reaction mechanism so eight conservation equations for species should be considered beside one overall mass fraction equation. Finally, there are fourteen coupled equations to be simultaneously solved in flow field.

TABLE I
CHEMISTRY MODEL

	Mechanism			A [cm/mol/s]	Exp of T	E [kJ/mol]
1	$O_2 + H$	→	$OH + O$	2.20E+14	0.00	70.30
2	$OH + O$	→	$O_2 + H$	1.72E13	0.00	3.52
3	$H_2 + O$	→	$OH + H$	5.06E04	2.67	26.30
4	$OH + H$	→	$H_2 + O$	2.22E04	2.67	18.29
5	$H_2 + OH$	→	$H_2O + H$	1.00E08	1.6	13.80
6	$H_2O + H$	→	$H_2 + OH$	4.31E08	1.6	76.46
7	$OH + OH$	→	$H_2O + O$	1.50E09	1.14	0.42
8	$H_2O + O$	→	$OH + OH$	1.47E10	1.14	71.09
9	$H + H + M^*$	→	$H_2 + M^*$	1.80E18	-1.00	0.00
10	$H_2 + M^*$	→	$H + H + M^*$	7.26E18	-1.00	436.82
11	$H + OH + M^*$	→	$H_2O + M^*$	2.20E22	-2.00	0.00
12	$H_2O + M^*$	→	$H + OH + M^*$	2.83E23	-2.00	499.48
13	$O + O + M^*$	→	$O_2 + M^*$	2.90E17	-1.00	0.00
14	$O_2 + M^*$	→	$O + O + M^*$	6.55E18	-1.00	495.58
15	$H + O_2 + M^*$	→	$HO_2 + M^*$	2.30E18	-0.80	0.00
16	$HO_2 + M^*$	→	$H + O_2 + M^*$	3.19E18	-0.80	195.39
17	$HO_2 + H$	→	$OH + OH$	1.50E14	0.00	4.20
18	$OH + OH$	→	$HO_2 + H$	1.50E13	0.00	170.84
19	$HO_2 + H$	→	$H_2 + O_2$	2.50E13	0.00	2.90
20	$H_2 + O_2$	→	$HO_2 + H$	7.27E13	0.00	244.33
21	$HO_2 + H$	→	$H_2O + O$	3.00E13	0.00	7.20
22	$H_2O + O$	→	$HO_2 + H$	2.95E13	0.00	244.51
23	$HO_2 + O$	→	$OH + O_2$	1.80E13	0.00	-1.70
24	$OH + O_2$	→	$HO_2 + O$	2.30E13	0.00	231.71
25	$HO_2 + OH$	→	$H_2O + O_2$	6.00E13	0.00	0.00
26	$H_2O + O_2$	→	$HO_2 + OH$	7.52E14	0.00	304.09
27	$HO_2 + HO_2$	→	$H_2O_2 + O_2$	2.50E11	0.00	-5.20
28	$OH + OH + M^*$	→	$H_2O_2 + M^*$	3.25E22	-2.00	0.00
29	$H_2O_2 + M^*$	→	$OH + OH + M^*$	1.69E24	-2.00	202.29
30	$H_2O_2 + H$	→	$H_2 + HO_2$	1.70E12	0.00	15.70
31	$H_2 + HO_2$	→	$H_2O_2 + H$	1.32E12	0.00	83.59
32	$H_2O_2 + H$	→	$H_2O + OH$	1.00E13	0.00	15.00
33	$H_2O + OH$	→	$H_2O_2 + H$	3.34E12	0.00	312.19
34	$H_2O_2 + O$	→	$OH + HO_2$	2.80E13	0.00	26.80
35	$OH + HO_2$	→	$H_2O_2 + O$	9.51E12	0.00	86.68
36	$H_2O_2 + OH$	→	$H_2O + HO_2$	5.40E12	0.00	4.20
37	$H_2O + HO_2$	→	$H_2O_2 + OH$	1.80E13	0.00	134.75

Here, the cell centered finite volume method is used to discrete the equations. Since the flow is axisymmetric, the two-dimensional grid can be used to solve the three-dimensional problem which makes the numerical studies so fast [20]. The time integration is accomplished by an explicit time stepping scheme [21].

Viscous terms are calculated using a central scheme and inviscid terms are treated using an AUSM$^+$ method to express the numerical flux on each cell faces [22]. The developed numerical program has been validated using variety of benchmark problems and experimental data, and used satisfactorily to study the ignition in turbulent flows [23-25]. As an example, the auto-ignition process within two-dimensional mixing layer between a supersonic air and hydrogen stream has been examined. Dimensions of the physical domain were 16 cm length and 1 cm height. At $T_{air} = T_{H2}$=1200 K, M_{air}=1.84 and M_{H2}=1.2, the ignition distance was reported 9.6 cm downstream of the splitter [2]. The present simulation has exact agreement with Ref. 2. Temperature variation along the splitter in this case is shown in Fig. 1. For the main studies under consideration, there are not any experimental data to compare, but due to such validation processes, one can expect that the final results are reliable at least qualitatively, which are represented in next section.

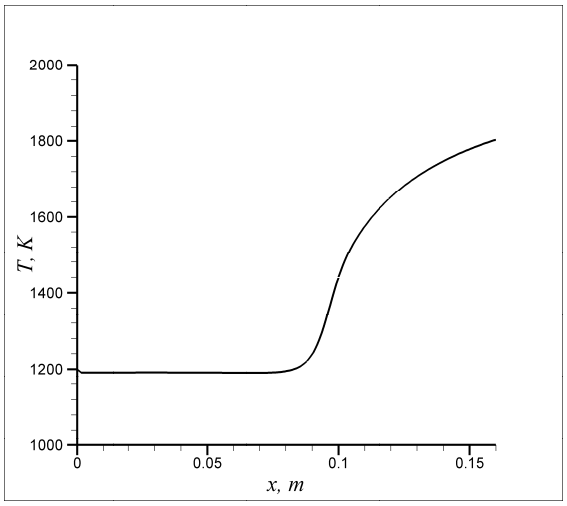

Fig. 1 Temperature variation along splitter

III. RESULTS AND DISCUSSION

The ignition process within cylindrical mixing layer between a supersonic air and a hydrogen stream diluted by nitrogen is considered here (Fig. 2). Dimensions of the physical domain (combustion chamber) are 30 cm length, 6 cm diameter, and 5 mm fuel slot thickness.

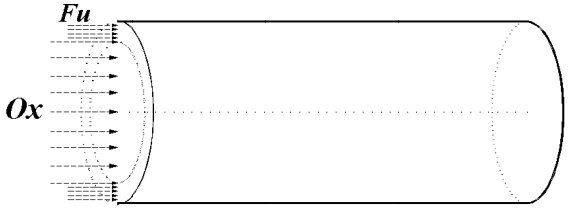

Fig. 2 Schematic configuration of problem

The flow properties are T_{air} = 1200 K, T_{fu} = 500 K, P = 10^5 Pa and M = 2.2. To study numerically this flow field, the selected stretched mesh is used here after proper grid independency studies. Such studies show that the 240*90 grid points which stretched near the combustor wall and mixing layer (as showed schematically in Fig. 3) are proper for this problem.

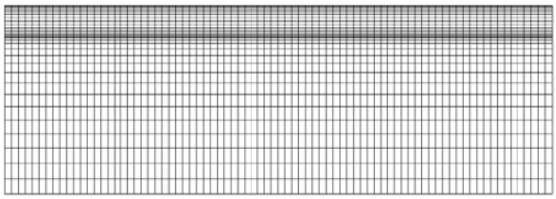

Fig. 3 Schematic grid used in simulations

At first, the problem is examined without any inlet swirling condition where the flow is assumed to be laminar. The results show that the ignition occurs at about 21 cm downstream the splitter. In this study, the inflexion point on the curve of water vapor mass fraction is used as an ignition criterion [3]. Temperature contours show the flame position in flow field in Fig. 4.

Fig. 4 Flame position in combustion chamber

As noted before, the ignition time delay is an important parameter in supersonic combustion systems and its reduction will help scaling down the scramjet engines. The effect of inlet swirl is investigated here. Selecting different deflection angles in fuel stream which make different angular velocities, the computational studies are repeated to predict the ignition distance. It should be emphasized that the laminar flow assumption is still used here. Figure 5 displays the ignition location versus inlet fuel swirl angle.

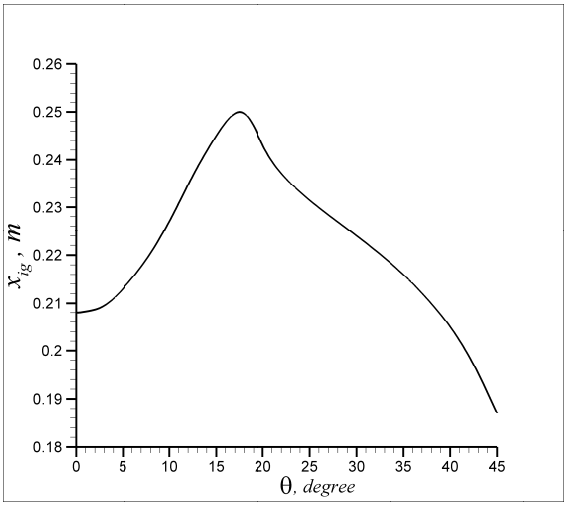

Fig. 5 Ignition distance variation due to inlet fuel swirl angle.

The result is out of the initial anticipations. The fuel inlet swirl enhances the fuel particle path and residence time in a combustion chamber and it is expected that the ignition distance to be reduced by increasing the fuel swirl angle monotonically. But unlike it, the ignition distance rises at first to the maximum value and after that diminishes by enhancing the fuel injection angle. The analysis shows that there are two different phenomena cause this behavior: the effective residence time and the pressure. Although the residence time of fuel particles is increased due to helical motion in combustor which is arisen from the inlet swirl, the effective residence time based on chemical reactions is decreased here. This is a time when the fuel and oxidizer particles remain near each other to encourage the reaction phenomena. Fuel particle rotation around the axial oxidizer flow stream can reduce effective time for combustion, so the ignition time delay is increased initially by enhancing the swirl angle.

Further increase in fuel inlet swirl will augment the downstream pressure due to the centrifugal effect. This pressure growth accelerates the chemical reactions and can compensate the adverse effect of effective residence time. Therefore the ignition delay shows such behavior versus inlet swirl angle.

This study illustrates that the fuel swirl doesn't have useful effect on ignition delay reduction. As mentioned earlier, the presented results are based on laminar flow assumption. So this treatment is valid for the flow and combustor conditions which the turbulence doesn't exist. Using the turbulence model and repetition of recent numerical investigations, the results show that the ignition distance just increases versus swirl angle. In such flowfields, there are two sources of turbulence generation: the velocity gradient near the combustor wall and velocity gradient in rotational mixing layer. The viscosity ratio contours are shown in figure 6 for swirl angle of 20 degrees to represent these sources of turbulence generation.

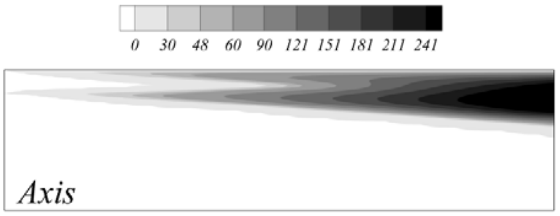

Fig. 6 The ratio of turbulent and molecular viscosities in flowfield

In lower swirl angles, the near wall turbulence is dominant and has no apparent effect on chemical reactions. In higher swirl angles, the mixing layer turbulence is dominant which drastically affect the reaction processes. Increasing the effective conductivity due to turbulence near the reactive mixture doesn't allow the temperature increment and violate the ignition. Therefore the ignition delay behavior is different from laminar case and the fuel swirl is always inappropriate from ignition viewpoint.

Up to now, it is clear that the fuel stream swirl has adverse influence on ignition time delay in supersonic combustible flows. How can the ignition process is improved using the swirl in this situation? The present study shows that using the inlet swirl in both fuel and oxidizer streams, is much helpful. If both flows are rotating, the effective residence time is

increased significantly due to helical motion of O-F particles in combustion chamber. On the other hand, the turbulence generation due to rotating mixing layer is disappeared and there are no turbulent ignition difficulties as mentioned before. Figure 7 illustrates the ignition distance versus inlet swirl angle. It is obvious that the swirling oxidizer-fuel flows have much better chemical reactions emerges in lower ignition distances. Using proper inlet swirlers in scramjet engines may be used successfully to reduce the ignition time delay.

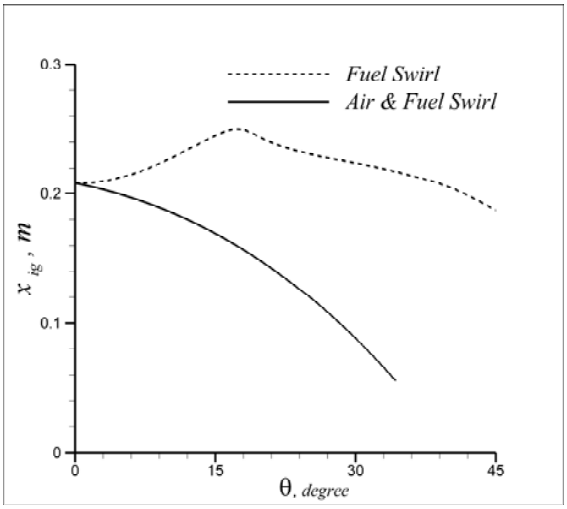

Fig. 7 Ignition distance variation due to inlet swirl angle

IV. Conclusion

In the present study, the ignition of hydrogen-air supersonic cylindrical mixing layer is numerically analyzed using detail chemical kinetics. The focus is on the ignition distance estimation and reduction by inflow swirl in combustor. It is shown that using the swirl just in fuel stream has no useful effect on ignition acceleration. It enhances the ignition distance due to the reduction in effective residence time in lower swirl angles, and reduces it due to downstream pressure increment in higher angles where they compensate each other finally. The studies illustrates that if the swirl is used in fuel and oxidizer streams, the ignition distance is decreased significantly by enhancing the swirl angle, which can be used in supersonic combustion chambers.

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