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Premature Ignition in Scramjets with Intake Injection: A Preliminary Laminar Mixing Layer Simulation

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Abstract

Injecting fuel on the intake of scramjet engines is one strategy that might be used to minimize the required length of scramjet combustion chambers. Premature ignition must be avoided for the strategy to be viable. Premature ignition is not normally observed in shock tunnel experiments with compression ignition scramjet configurations even though local regions of elevated temperatures sufficient to support combustion would have been present on the model scramjet intakes. However, for full scale flight vehicles, we cannot conclude that ignition will generally be delayed until the combustion chamber based on limited empirical results from shock tunnel ground-testing. Reliable intake/injection design correlations for premature ignition avoidance in a flight scramjet are yet to be developed. Numerical simulation offers an approach for the investigation and identification of premature ignition regimes which should be avoided in compression-ignition scramjets. A particular case of hydrogen injection in the presence of a laminar boundary layer is simulated numerically. The location of the stoichiometric mass fraction of hydrogen occurs very close to the peak mixing layer temperature which is also within the lowest speed region of the mixing layer. An ignition delay correlation is used to demonstrate that ignition will almost certainly occur. This case is offered as an example to highlight the potential problem and perhaps stimulate further study in the area of premature ignition with intake injection.

Keywords: Scramjet, Intake injection, Shock induced ignition, Compression ignition scramjet.

1. Introduction

For scramjet propulsion at flight Mach numbers below about 8, efficient and stable combustion is likely to be achieved through inclusion of an isolator (a backwards facing step) between the intake and the combustion chamber [1]. The isolator prevents destabilization of the intake flow by the coupled heat release and fluid mechanics of the combustion chamber. For flight at speeds beyond Mach 8, the presence of large recirculation zones within the combustor is likely to cause unacceptably large pressure loss. However, with high speed flow through the combustion chamber and no recirculation zones, the residence time will be short so combustion efficiency may be limited by the rate at which the fuel and air streams mix. Compensating the short residence time by using long combustion chambers may be unviable because of skin friction, heat load and engine weight penalties.

To minimize the required combustion chamber length, fuel injection within the scramjet intake has been proposed, Fig. 1. Provided the flow conditions within the intake are sufficiently mild, ignition of the fuel will be delayed until the combustion chamber. Shock waves which compress the fuel and air streams on entry to the combustion chamber induce combustion and may also enhance further mixing of the fuel and air. Experiments using this compression-ignition approach have been performed on a number of occasions using shock tunnel facilities and the approach appears to have merit [2-6]. Recent theoretical work by [7] with the compression-ignition scramjet configuration has focused on the so called 'radical farm' concept [6]. With this technique, localized hot pockets of gas are generated within the combustor (see Fig. 1) and combustion proceeds at mean combustor conditions that would normally be too mild to support ignition.

A major concern with the compression-ignition scramjet strategy is the possibility of premature ignition of the fuel on the intake rather than in the combustion chamber. Premature ignition would reduce the net engine thrust and may unstart the inlet, either of which could render the scramjet inoperable. There is sufficient certainty in the chemical kinetics of hydrogen combustion to confidently design bulk flow conditions what would not support auto-ignition on the inlet. However, local regions of very hot air flow adjacent to the fuel stream can arise on the intake. Scramjet designers need to be confident that these regions will not support premature ignition of the fuel when using a compression-ignition strategy.

Shock tunnel experimenters using the compression-ignition strategy rarely observe premature ignition effects and yet temperature and pressures sufficient to support combustion do locally exist in the intake in the vicinity of the injected fuel. For example, Gardner et al. [2] and Kovachevich et al. [4] used port hole injection on cold and hot-wall intakes and did not observe any combustion on the intake using shadowgraph visualization, pressure measurements, and fluorescent imaging of OH. Gardner et al. [2] conclude that although boundary layer temperatures are sufficient to support combustion, the port-hole injection delivers the fuel to the free stream: mixture residence time and/or

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composition in the hot boundary layer region is insufficient for combustion.

Huber et al. [8] compiled data from a number of supersonic injection and combustion experiments and developed some preliminary correlations for hydrogen ignition in a range of configurations. While it is encouraging that premature combustion was not observed in the ground-based (shock tunnel) experiments [2-6], further investigation is warranted because there appears to be some disparity with the work of [8]. For example, the recirculation region upstream of transverse jets on plane surfaces appears a prime ignition location, particularly for injection conditions where the fuel penetrates a long way into the flow relative to the boundary layer thickness [8]. Therefore it seems imprudent to conclude at this stage that intake injection is a viable strategy for scramjet propulsion in general.

In this paper, we consider the case of fuel injection from a slot in the presence of a laminar boundary layer to demonstrate via numerical simulation that, premature ignition remains a significant concern for compression-ignition scramjet technology.

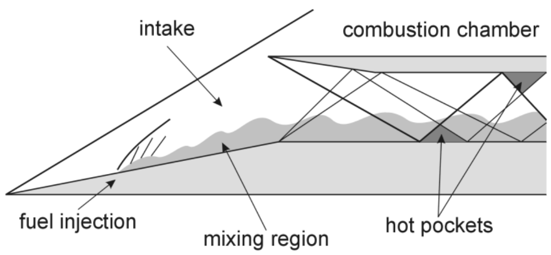

Figure 1. Schematic illustration of a scramjet intake and combustion chamber.

2. Boundary Layer and Mixing Layer

Figure 2 illustrates some profiles of velocity (u) and temperature (T) within a mixing layer which develops between an injected fuel stream and an air stream which includes a relatively thick boundary layer. Although previous experimental investigations have often focused on port-hole injection, we consider slot injection as a model for injection from a dense matrix of discrete port-holes with injection static pressure approximately matching the free stream static pressure.

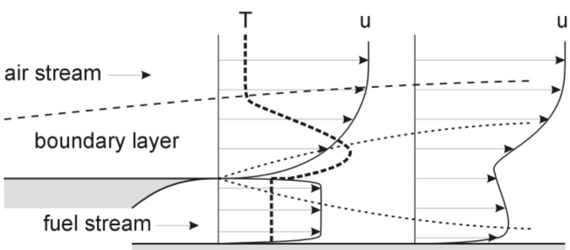

Figure 2. Illustration of mixing layer development in the presence of a boundary layer.

In the case of high speed flow, the static temperature within the boundary layer is generally higher than the free stream static temperature (T_e). In the case of an adiabatic wall, the static temperature peaks at the wall itself and has a value given by [9]

$$T_{aw} = T_e + \frac{r}{2C_p} u_e^2 \quad (1)$$

where u_e is the flow speed external to the boundary layer, c_p is the constant pressure specific heat, and r is the recovery factor which, for a laminar boundary layer is given by

$$r = \sqrt{\mathrm{Pr}} \quad (2)$$

If heat is transferred from the boundary layer to the wall, which is the case we are considering as illustrated in Fig. 2, the peak temperature within the boundary layer will be somewhat less than the adiabatic wall temperature (T_{aw}) and will occur at a point some distance from the wall. We are considering a condition for which the wall temperature $T_w < T_{aw}$, but the peak temperature in the intake boundary layer is still sufficient for combustion if other mixing layer conditions are suitable.

If regions of high temperature within the mixing layer dissipate rapidly or if the mixture in the high temperature regions is not combustible, then ignition will be delayed until further compression occurs or until further mixing occurs. However, if the mixture in the region of the high temperatures is combustible, then ignition is expected to occur after some delay. In this case, the mixing layer velocity in combination with the ignition delay time will determine if combustion occurs prior to the flow reaching the combustion chamber.

3. Numerical Simulation

3.1 Solver and Domain Configuration

Numerical simulation of the mixing layer configuration was achieved using a multi-block compressible Navier Stokes solver described in [10]. The domain considered in the present simulations is illustrated in Fig. 3. The development of a flat plate laminar boundary layer over a length of 1 m was simulated using the two blocks with an in-flow boundary condition on the left as illustrated in Fig. 3. Fuel (hydrogen) was injected parallel to the air stream using an in-flow boundary condition. The downstream edge of the domain was 500 mm from the injection boundary and this position is still considered as being within the scramjet intake.

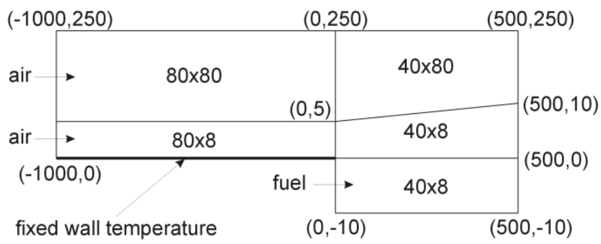

Figure 3. Blocks used in numerical simulation, not to scale. Number of cells in each block is given by $n_x \times n_y$ near the centre of each block and the position of selected corners are given by (x, y) with numerical values reported in mm.

Finite rate chemistry was not used in the present calculation. The likelihood of ignition was deduced based on the distribution of temperature, composition, and velocity.

3.2 Flow and Boundary Conditions

Table 1 presents the in-flow boundary conditions for the air and the hydrogen used in the numerical simulations. The air flow conditions were chosen to replicate one of the conditions used by [7] in their premixed compression-ignition scramjet simulations. The hydrogen injection conditions were selected on the assumption that the hydrogen would be hot (having been used for vehicle cooling prior to injection) and would be supersonic, once expanded to the local static pressure of the air stream. For the hydrogen conditions listed in Table 1, the corresponding Mach number is 1.9 and for the air conditions, the Mach number is 5.9. The temperature of the wall beneath the laminar boundary layer was 1000 K. An adiabatic, slip-wall boundary condition was adopted for simulating the wall beneath the fuel layer.

Table 1. In-flow conditions used in simulations

	Air	Fuel (hydrogen)
Velocity (m/s)	2500	4000
Pressure (kPa)	20	20
Temperature (K)	450	800

Laminar flow was assumed for the development of both the boundary layer and the mixing layer. There is considerable scatter in transition data from flight experiments (see [11] as cited by [9]). However, the air flow conditions (Table 1) correspond to a unit Reynolds number of $Re_u = 1.56 \times 10^7$ 1/m which places the boundary layer condition at the point of fuel injection towards the upper end of the reported transition Reynolds number spectrum.

4. Results

4.1 Mixing Layer Properties

Transverse profiles of hydrogen mass fraction at 3 streamwise locations within the mixing layer are presented in Fig. 4. As expected, the steepest gradients of concentration are closest to the injection location. The stoichiometric mass fraction of hydrogen (0.0285) is indicated on each profile with the square symbol.

Transverse profiles of temperature at the same 3 streamwise locations within the mixing layer are presented in Fig. 5. The transverse location of the stoichiometric mass fraction for each profile (as identified in Fig. 4) has been plotted in Fig. 5, again with the square symbols. It is noted that for each profile, the peak temperature occurs very close to the location of the stoichiometric mass fraction. Furthermore, the peak temperature at each streamwise location exceeds 1000 K. Although the ignition of hydrogen-air mixtures is a relatively weak function of composition within certain limits [8], the coincidence of peak temperatures and stoichiometric mass fractions contributes to the prospects for premature ignition.

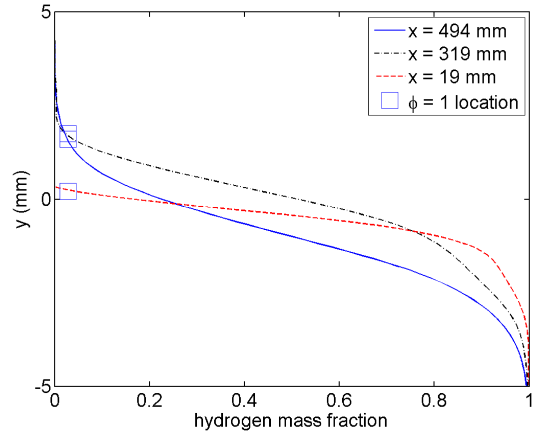

Figure 4. Profiles of hydrogen mass fraction at 3 locations downstream of the splitter plate.

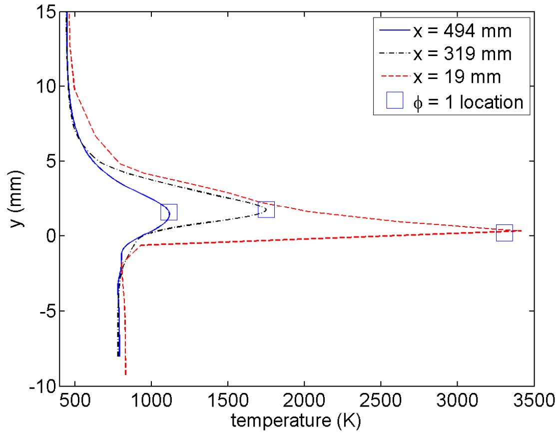

Figure 5. Profiles of temperature at 3 locations downstream of the splitter plate.

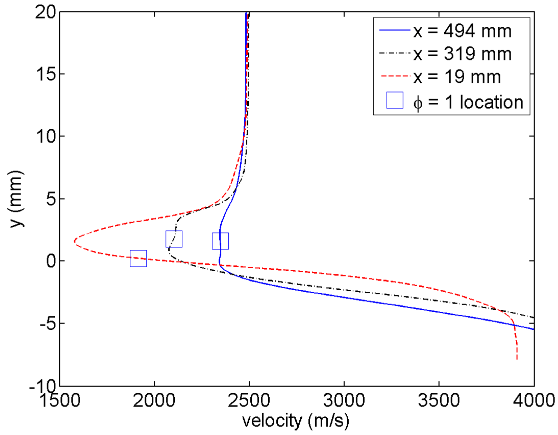

Figure 6. Profiles of velocity at 3 locations downstream of the splitter plate.

Transverse profiles of velocity at the same 3 streamwise locations are presented in Fig. 6. Locations of stoichiometric mass fractions are again presented as square symbols on each profile. Stoichiometric mass fractions (and peak temperatures) occur in the wake region of the mixing layer. The wake region of the mixing layer, where the velocity is lower than the free stream value, persists to a distance of more than 0.5 m downstream of the injection point in the present case. The slightly lower speeds in the wake region will tend to increase residence time on and hence the mixing layer velocity profile contributes to the prospects for premature ignition.

4.2 Ignition Delay

For hydrogen-air mixtures, the ignition time delay correlation of [12] as cited by [8] is given as

$$\tau_i = \frac{8\times10^{-9} e^{9600/T}}{p}. \quad (3)$$

where τ_i is the ignition time in seconds, T is the mixture temperature in K and p is the mixture pressure in atm. According to [8], this correlation can be applied for $1000 < T < 2000$ K, and $0.2 < p < 1$ atm.

Results from the application of the ignition delay correlation (3) to the mixing layer simulation at the three streamwise locations are presented in Table 2. For the location nearest the point of injection, the mixing layer temperature is beyond the range of correlation (and indicating near instantaneous ignition). Ignition within the mixing layer appears very likely for quite a large region of the mixing layer. For example, at the location x = 319 mm the calculated ignition distance is only a further 21 mm downstream.

Table 2. Ignition delay results

x (mm)	T (K)	u (m/s)	τ_i (μs)	Δx_i (mm)
19	3306	1915	0.74	1.4
319	1750	2102	9.78	20.6
494	1118	2346	217	510

5. Conclusion and Further Work

Development of a fuel-air mixing layer in the presence of a laminar boundary layer has been simulated for conditions relevant to the compression-ignition scramjet configuration. Results show that premature ignition on the intake is likely for the chosen configuration and conditions. Laminar boundary layers are likely to occur on the forebody of scramjet vehicles. Fuel injection in the presence of these boundary layers could be problematic.

To avoid boundary layer separation within scramjet intakes, boundary layer transition to a turbulent state will need to occur. Boundary layer transition would tend to promote mixing and may also promote ignition, depending on the magnitude and the rate of dissipation of the boundary layer recovery temperature. Given the theoretical likelihood for ignition but the lack of evidence for such ignition in current shock tunnel experiments, further investigation of injection and ignition in the presence of turbulent boundary layers is warranted. Further numerical simulations with a chemistry model for hydrogen-air combustion are planned in the near future.

7. References

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