SUPPRESSION OF PREMATURE IGNITION IN THE PRE-MIXED INLET FLOW OF A SHCRAMJET

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This paper addresses the problem of premature ignition in a shock induced combustion ramjet (shcramjet) inlet. Previous studies have developed fuel injectors and inlet configurations that maximize the mixing efficiency in a shcramjet inlet while maintaining inlet losses at a minimum. A chemically reacting study of previously recommended shcramjet inlets finds premature ignition to occur primarily in the boundary layer in the last 15% of the inlet, spreading into the core flow prior to the inlet exit. Both gaseous nitrogen and additional hydrogen are then injected into the inlet flowfield in an attempt to suppress the flame. Various inflow conditions are considered, and injected using various geometries. Premature ignition is suppressed most feasibly by the injection of additional hydrogen through a backward facing step (slot injector) located just before the second inlet shock, such that the global equivalence ratio of the premixed flow exiting the inlet is one. The performance of the original inlet remains unaltered and the frictional force on the inlet wall is reduced by 10% due to the hydrogen slot injection. All turbulent, chemically reacting, three dimensional, mixing flowfields are solved using the WARP code which solves the FANS equations closed by the Wilcox kω turbulence model and the Wilcox dilatational dissipation correction. Chemical kinetics are modeled by a 9 species, 20 reaction model by Jachimowski.

Nomenclature

Roman and Greek symbols

\( c \) = species mass fraction
\( k \) = turbulence kinetic energy
\( \dot{m}_{\text{air, engine}} \) = mass flow rate of air in the engine
\( M_c \) = convective Mach number, \( (q_1 - q_2) / (a_1 + a_2) \)
\( P \) = pressure
\( q \) = magnitude of the velocity vector
\( T \) = temperature
\( x, y, z \) = Cartesian coordinates
\( y^+ \) = non-dimensional wall distance, \( \sqrt{\nu \tau_w} \)
\( FANS \) = Favre-Averaged Navier Stokes
\( \eta_m \) = mixing efficiency
\( \phi \) = equivalence ratio
\( \phi_g \) = global equivalence ratio
\( \omega \) = dissipation rate per unit of turbulence kinetic energy
\( \tau_w \) = wall shear stress
\( \mu \) = viscosity

Subscripts

b = station of interest

Superscripts

S = stoichiometric
R = reacting

Calligraphic symbols

\( \tau_{\text{skin friction}} \) = force vector due to skin friction

Introduction

A
N alternate hypersonic airbreathing propulsion concept to the scramjet is the shock-induced combustion ramjet (shramjet\(^1,2\)), which is depicted in Fig. 1. While scramjet concepts rely on the diffusive burning of injected fuel, the shramjet concept aims to avoid a long combustion chamber by injecting the fuel in the inlet of the vehicle and burning the fuel/air mixture through a shock wave. This reduces the weight of the engine and takes advantage of the typically long inlets found at hypervelocities. In order to establish the shramjet as a viable concept, shramjet research must seriously address 1) achieving adequate mixing prior to the shock-induced combustion, and 2) the prevention of premature ignition in the inlet.

The problem of efficient mixing in supersonic flow has been studied in detail with respect to scramjet combustors.
Reference 3 provides a recent review of this research. In regard to fuel pre-injection in the inlet, Segal et al carried out an experiment where liquid JP-10 fuel was pre-injected through pylons situated in a scramjet isolator.\textsuperscript{4, 5} In addition, Guskov et al performed a similar numerical investigation where pylons were used to inject gaseous hydrocarbon fuel in a scramjet inlet.\textsuperscript{6} Results from both studies show significant improvement in the mixing and burning performance of the scramjets, due to pre-injection of the fuel prior to the combustor. Also, both studies demonstrate how pylon injection keeps fuel out of the boundary layer and thus prevents flashback.

Recently, a new injector has been proposed specifically for fuel injection in a \textit{shcramjet} inlet. Named the “cantilevered ramp injector”,\textsuperscript{7} the injector is based on the standard ramp injector of Marble et al.,\textsuperscript{8} with the noted difference of an air buffer between the fuel and the wall at the point of injection to prevent fuel from being injected in the vicinity of the hot incoming boundary layer. The strong axial vortices generated by the cantilevered ramp injector increase the fuel penetration, while maintaining the injection angle low enough to recover most of the thrust due to the fuel momentum. Studies have been performed to determine the effect of the fuel inflow conditions\textsuperscript{9} and the injector geometry\textsuperscript{10} on the mixing performance of the cantilevered ramp injector over a flat plate.

An “optimal” injector configuration (shown in Fig. 2) was selected and used to study the mixing performance in a non-reacting model of an external compression \textit{shcramjet} inlet flying at Mach 11 and 34.5 km altitude. As a baseline for the study,\textsuperscript{11} the optimized array of cantilevered ramp injectors was mounted on a dual spike (equal shock-strength) inlet resulting in the configuration depicted in Fig. 3. Although the study was non-reacting, the issue of premature ignition in the inlet was addressed by analysis of the equivalence ratio and temperature field. The main focus of the study was to strategically modify the inlet and injector geometry in an attempt to improve the overall performance of the inlet with respect to mixing efficiency, inlet losses, and the risk of premature ignition. Although successful in improving the mixing efficiency by up to 35% over the baseline inlet, all modified inlets exposed a near stoichiometric fuel/air mixture to ignition temperatures either in the core flow or in the boundary layer.\textsuperscript{11} Thus premature ignition (as sketched in Fig. 3) remains very likely.

The primary objectives of this paper are to 1) determine the location of premature ignition and the extent of combus-

**Numerical Model and Error Assessment**

The results are obtained using the WARP code,\textsuperscript{9, 12} in which the multi-species FANS equations closed by the Wilcox \textit{k}\textit{ω} turbulence model\textsuperscript{13} are discretized by the Yee-Roe flux-limited method.\textsuperscript{14} To account for the compressibility effects occurring at high turbulent Mach numbers\textsuperscript{9} the Wilcox dilatational dissipation correction\textsuperscript{15} is used in conjunction with the \textit{k}\textit{ω} turbulence model. The chemical source term is calculated using a 20-reaction, 9 species chemical model from Jachimowski.\textsuperscript{16} Specific heat and specific entropy are determined from polynomials in function of temperature from McBride et al.\textsuperscript{17} Convergence to steady-state is achieved by block-implicit approximate factorization, including the analytical jacobians derived from the chemical model. Convergence is then accelerated by using the marching window acceleration technique.\textsuperscript{12} The use of the marching window decreases the work by 10–20 times and the memory required by 5 times for the inlet.
cases shown herein, and permits the solution of significantly finer meshes hence resulting in a decreased numerical error.

Due to the symmetry of the injector array, second order symmetry boundary conditions are imposed on the sides of the computational domain. For the flow fields analyzed herein, all walls are assumed to be maintained at 500K and wall spacing is set to 30 microns for the 8" wedge and injector surfaces and lowered to 10 microns in the mixing region. This results in a $y^+$ value ranging from 1 to 4 with the maximum value occurring at the domain exit. The hydrogen and/or nitrogen develop an incoming boundary layer before injection via a small 5mm enclosed runway (shown later in Fig. 11) which also reduces the solution's sensitivity to the free-stream value of $u_0$. As suggested by Wilcox, the inflow value of $u_0$ is set to 10 times the inflow velocity, and the free-stream value of $k$ is initially set to zero. The turbulent Prandtl number and the turbulent Schmidt number are set to 0.9 and 1.0 respectively. Finally, the entropy correction term is not used in the Roe scheme as it has no effect on the current inlet flow field other than to increase the artificial dissipation and thus increase the grid induced error.11

These numerical strategies are based on a thorough investigation of the numerical parameters used by WARP and their effects on supersonic mixing flowfields. The same investigation also validates WARP by close agreement with experimental data for a ramp injector by Waitz et al. and an additional study validates WARP with a swept ramp injector by Donohue.21 As previously mentioned, the baseline geometry and grid for the present chemically reacting study are identical to that used in the inert mixing study,11 where the grid induced error with respect to the mixing parameters on a 3.6 million node mesh was verified not to exceed 10%. An upcoming paragraph will verify that the additional chemical processes present in the current study are accurately modeled with the same grid density.

**Ignition Location and Flame Development**

The governing equations with Jachimowski chemical kinetics are solved on a 3.6 million node mesh fitting the geometry detailed in Figs. 2 and 3, herein referred to as the baseline inlet. Figures 4 and 5 depict the flame location and development in the baseline inlet. Figure 4 shows both pressure and $H_2O$ mass fractions on the plane which cuts through the centre of an injector ($z = 0m$) and extends along the dual spike inlet (sketched in Fig. 3). The intersection of the two major shocks indicates the position for the engine cowl and the relative size of the flame. Figure 5 depicts both $H_2$ and $H_2O$ contours on various $yz$ planes starting from the point of first ignition. Ignition is seen to occur at $z = \pm 1cm$ (between injectors) when a near-stoichiometric hydrogen/air mixture ($\phi_{H_2} = 0.02876$) first enters the boundary layer. The initial reactive species are then swept towards the $z = 0cm$ plane by axial vortices and the flame quickly spreads into the core flow. Note that by $x = 1.1m$ the flame has spread throughout most of the hydrogen/air mixture. Analysis of the flow field reveals that the second compression process (in this case the second inlet shock) is the dominant mechanism which causes the fuel/air mixture to enter the boundary layer. The air buffer created by the cantilevered injector is significantly compressed through the shock and because the fuel/air mixture has spread to the symmetry boundary, the axial vortices transport a combustible mixture into the already diminished air buffer. This mechanism is depicted in Fig. 8(a), which also shows the resulting hot spot in the boundary layer between injectors that is not touched by the axial vortices. The diffusion of combustible mixture into this high temperature region is what triggers ignition in the baseline inlet.

The previous inert mixing study suggests two inlet modifications to lower the risk of premature ignition. The first method involves using the Prandtl-Meyer compression fan used in the inert mixing study instead of the second inlet spike. The resulting chemically reacting flow field is shown in Figure 6. Here, the compression process is not as sudden as with a shock. As a result, the air buffer erodes more slowly and ignition in the boundary layer is slightly delayed. The mixture still ignites however, and the axial vortices spread the flame into the core flow before the inlet exit. The second suggested method simply increases the spacing between injectors from 1cm to 2cm. This allows the axial vortices to transport pure air into the buffer area and hence delays the presence of a combustible mixture in the boundary layer. In addition, the hot spot between injectors is now further away from the combustible mixture due to the higher injector spacing. However, as depicted in Fig. 8(b), the unobstructed (and thus stronger) axial vortices entrain hot air from the boundary layer into the mixing layer. The flow field resulting from this modified inlet was solved with Jachimowski chemical kinetics on a 7 million node mesh (to maintain the same grid density). As can be seen in Figure 7, ignition in the boundary layer is only delayed, and in addition, the core flow ignites before the inlet exit. Thus, in all three configurations, premature ignition is found to occur only in the last 15% of the total inlet length. However, at the inlet exit the flame has already spread through a significant amount of the fuel/air mixture. Combustion in the inlet is detrimental to the efficiency of the scramjet engine and must be suppressed. The remainder of this paper will focus on suppressing premature ignition in the boundary layer of the baseline inlet.

**Inlet Performance Parameters**

Although nitrogen or additional hydrogen injection may be necessary to suppress premature ignition in a scramjet inlet, it must not reduce the mixing efficiency or increase the inlet losses substantially. The air-based mixing efficiency $\eta_m$ at the station of interest (here denoted by the subscript "b") is defined as the ratio between the mass flux of oxygen that would react by the mass flux of oxygen entering the engine:

$$\eta_m = \frac{\int b \dot{m}_{O_2} \, db}{0.235 \times \dot{m}_{air, \, engine}}$$ (1)
Fig. 4  Location of premature ignition in the baseline inlet, contour lines represent pressure, contour flood represents $c_{H_2O}$.

Fig. 5  Flame development in the baseline inlet, contour lines represent $c_{H_2}$, contour flood represents $c_{H_2O}$.

Fig. 6  Flame development in the compression fan inlet, contour lines represent $c_{H_2}$, contour flood represents $c_{H_2O}$.
here, the mass fraction of reacting oxygen, $c_{O_2}^R$, corresponds to

$$c_{O_2}^R = \min\left(c_{O_2}, c_{O_2}^S, c_{H_2}^S / c_{H_2}^S\right)$$

(2)

with the stoichiometric mass fraction of hydrogen $c_{H_2}^S$ equal to 0.02876 and the stoichiometric mass fraction of oxygen $c_{O_2}^S$ equal to 0.22824. Inlet losses are captured by the normalized frictional force in the $x$ direction, $\bar{f}_{\text{skin friction}}$, which corresponds to the skin friction force experienced by the inlet in the $x$ direction, normalized by the mass flow rate of air entering the engine, $\dot{m}_{\text{air, engine}}$.

Grid Convergence

A detailed grid convergence study with respect to the mixing parameters on the 3.6 million node baseline mesh found a grid induced error of 10%.$^{9,11}$ In 3D, it is difficult to refine the mesh sufficiently in order to assess the grid induced error accurately. Only the variation of results between different mesh densities is available. The grid induced error was thus approximated by comparing the variation in mixing efficiency between specific mesh densities in 3D to the corresponding variations observed in the same mesh densities in 2D. The mixing efficiency was found to vary by 3% from fine to coarse meshes in 3D which resulted in an approximated grid induced error of 10%.$^{9,11}$ In the present study, the baseline configuration including chemical kinetics is solved on similar mesh densities in 3D to the corresponding variations observed in the same mesh densities in 2D. The mixing efficiency was found to vary by 3% from fine to coarse meshes in 3D which resulted in an approximated grid induced error of 10%.$^{9,11}$ In the present study, the baseline configuration including chemical kinetics is solved on similar mesh densities in 3D to the corresponding variations observed in the same mesh densities in 2D. In order to approximate the magnitude of the grid induced error with respect to combustion processes, the mixing efficiency (an integrated result), along with the maximum $H_2O$ mass fraction on each $yz$ plane, are selected and verified for convergence. Figures 9 and 10 display the results in the region of premature combustion. Figure 9 reveals variations in mixing efficiency (averaged in the combustion region) of 4.3%, 2.4%, and 1.0% for the 1.1, 2.0, 3.6, and 6.5 million nodes. In order to approximate the magnitude of the grid induced error with respect to combustion processes, the mixing efficiency (an integrated result), along with the maximum $H_2O$ mass fraction on each $yz$ plane, are selected and verified for convergence. Figures 9 and 10 display the results in the region of premature combustion. Figure 9 reveals variations in mixing efficiency (averaged in the combustion region) of 4.3%, 2.4%, and 1.0% for the 1.1, 2.0, 3.6, and 6.5 million nodes respectively, when compared with the 6.5 million node mesh. The variation of 4.3% in mixing efficiency from fine to coarse meshes is only slightly higher than 3% for the inert mixing study and so a similar grid induced error of 10% is inferred for the present chemically reacting study. In addition, continued use of the 3.6 million node mesh is also justified as the average variation compared to the 6.5 million node mesh is only 1.0%. Figure 10 shows how all four mesh densities predict the same ignition location and also display convergence of the flame propagation. The ignition location is an important result and is seen to be modeled with sufficient accuracy by the 3.6 million node mesh.

Fig. 7 Flame development in the high-spaced inlet, contour lines represent $c_{H_2}$, contour flood represents $c_{H_2O}$

Fig. 8 Mechanism by which axial vortices affect the air buffer generated by the cantilevered ramp injector.
Grid Convergence Study
Mixing Efficiency on each x-plane
computed on 4 different grid densities.

Fig. 9 Grid convergence of mixing efficiency in combustion region.

Grid Convergence Study
Maximum H₂O Mass Fraction on each x-plane
computed on 4 different grid densities.

Fig. 10 Grid convergence of ignition location and combustion process.

Fig. 11 N₂Window injection, \([q_{N_2} = 750\text{m}^3/\text{s}, p_{N_2} = 10\text{kPa}, T_{N_2} = 100K}\], [dimensions in mm, see Fig. 2 for missing dimensions]

Fig. 12 Post-shock slot injection, \([q_{N_2} = 1500\text{m}^3/\text{s}, p_{N_2} = 15\text{kPa}, T_{N_2} = 100K}\]

Fig. 13 Pre-shock slot injection, \([q_{N_2} = 1500\text{m}^3/\text{s}, p_{N_2} = 6\text{kPa}, T_{N_2} = 100K}\]

Nitrogen Injection Strategies

The high mesh densities used for this study and the inclusion of chemical kinetics are very demanding in terms of computational time. In addition, many different nitrogen injection strategies need testing, as the complexity of the flow field makes the effects of a particular strategy difficult to predict before a full solution is obtained. It is beneficial, therefore, to predict the location of ignition without a chemical model and choose only the most promising strategies for a full chemically reacting study. Prediction without a chemical model is accomplished by comparing the equivalence ratio and temperature fields in the non-reacting mixing flow fields. The flammability limits of hydrogen-air chemistry at atmospheric pressure are approximately \(0.1 < \phi < 7\) (see, for example, Ref. 22). However, this range must be verified for current conditions. The mixture that first comes in contact with the boundary layer is fuel lean, and thus the lower limit on \(\phi\) requires confirmation. A comparison between the equivalence ratio and temperature field of non-reacting cases with identical chemically reacting cases concludes that in the present flow field ignition occurs when a region of \(\phi > 0.8\) is raised above 1000K. This, then, becomes the condition that must be avoided in order for a strategy to be deemed promising in preventing premature ignition.

Three selected strategies are presented. The first is called the “N₂Window” and is detailed in Fig. 11. Here, nitrogen is injected between the hydrogen fuel and the boundary layer without requiring any new protrusions in the flow. The remainder of the inlet remains unchanged from the baseline inlet. The second and third strategies, detailed in Figs. 12 and 13, are called “post-shock” and
“pre-shock” injection respectively. Here, nitrogen is injected through a slot 5mm in height (slightly higher than the incoming boundary layer) both after \( (x = 0.75m) \) and prior \( (x = 0.69m) \) to the second inlet spike of the inlet. In both cases, the pressure of injected nitrogen matches the surrounding flow pressure and the velocity is roughly half that of the surrounding flow.

The resulting non-reacting flow fields, represented as equivalence ratio and temperature fields near the ignition location \( (x = 0.85) \), are shown for each strategy and compared with the baseline inlet in Fig. 14. The region in which \( \phi > 0.8 \) is raised over 1000K in the baseline inlet is consistent with the actual ignition location determined with chemical kinetics, shown previously in Fig. 5. The \( \text{N}_2 \text{Window} \) is seen to actually increase the risk of premature combustion as a large amount of flammable mixture is raised over 1000K. In contrast, both the post-shock and pre-shock slot injection succeed in cooling the boundary layer significantly. As seen in Fig. 14, temperatures over 1000K have been reduced to two small regions which overlap only slightly with the flammable mixture. By injecting the nitrogen prior to the shock, it has a longer distance to mix and cool the boundary layer and hence the pre-shock injection is seen to be more effective. In addition, because the injection pressure is matched to the surrounding flow, the pre-shock strategy injects nitrogen at a much lower pressure which corresponds to approximately 60% less nitrogen (by mass) than the post-shock strategy. Each strategy was verified to have a negligible effect on both the mixing efficiency and skin friction losses.

The chemically reacting flow field resulting from the pre-shock strategy was then computed by including the Jachimowski combustion model. Premature ignition is indeed prevented by this method of nitrogen injection as virtually no \( \text{H}_2\text{O} \) is present at the inlet exit. Figure 15 details the effect of cold nitrogen injection on the maximum temperature at each \( x \) plane. Clearly, the boundary layer is cooled significantly. Although successful, the technical implementation of this strategy poses problems. The pre-shock strategy injects nitrogen at 1500 m/s, which corresponds to a Mach number of 7.4 due to the high density

![Fig. 14 Prediction of premature ignition, shaded region represents a flammable mixture \( (0.8 < \phi < 7.0) \), contour lines represent temperature in Kelvin.](image)

![Fig. 15 Flame suppression via pre-shock nitrogen injection.](image)
and low temperature of the nitrogen. This would put difficult constraints on the nozzle throat of the injector considering the nozzle exit height (slot height) is 5mm. A similar trial injected nitrogen at 750 m/s, corresponding to a Mach number of 3, from the same slot. Here, the temperature of the boundary layer was hardly affected at all and premature ignition occurred in the same location as in the baseline inlet. A high velocity is therefore required, and when coupled with the high density of nitrogen, translates into a significant mass of nitrogen being carried on board the engine. A third disadvantage of nitrogen injection, which is quantified in the next section, is the higher skin friction associated with high density nitrogen in contact with the inlet wall. In contrast, a low density gas such as hydrogen could potentially eliminate all three of these problems while avoiding the complexity of carrying a separate tank of cryogenic nitrogen.

**Hydrogen Injection Strategies**

Based on the results of nitrogen slot injection, it became evident that injecting hydrogen through the slot may also suppress the flame. The cantilevered injector succeeds in keeping the fuel/air mixture out of the boundary layer until the last 15% of the total inlet length. In addition, the nitrogen suppressed ignition solely because it cooled the boundary layer below ignition temperature before the fuel/air mixture arrived (as opposed to diluting the mixture such that it would not ignite). Thus, even though injecting hydrogen will create a new region of combustible flow, as long as the temperature is below that required for ignition, premature ignition will not occur.

Three strategies of injecting hydrogen are selected to portray both the successful suppression of premature ignition, as well as the minimization of addition hydrogen injected such that the global equivalence ratio does not exceed one. The strategies are denoted as $H_2$\_slot1, $H_2$\_slot2, and $H_2$\_slot3. The gas properties at injection for each chemically reacting case are summarized in Table 1. The resultant three flow fields are portrayed as temperature and equivalence ratio fields at the inlet exit ($x = 1.07m$) in Fig. 16 along with the successful $N_2$\_slot pre-shock injection strategy for comparison. Initially, hydrogen is injected in the pre-shock configuration seen in Fig. 13 at the same temperature and pressure as the $N_2$\_slot case, however, at velocity of 5257 m/s matching that of the cantilevered injectors (case $H_2$\_base). As seen in Fig. 16, the high injection velocity of $H_2$\_slot1 results in better mixing and lower temperatures at the inlet exit compared with the $N_2$\_slot case. However, this low temperature hydrogen is not ignited via the shock-induced combustion process and so does not contribute to the heat release in the combustor. For this reason, the $H_2$\_slot2 strategy injects the hydrogen at a higher temperature. Specifically the hydrogen is injected at the same conditions as for the cantilevered injectors with the exception that the pressure is maintained at 6kPa in order to match the surrounding flow. Figure 16 confirms that this strategy also succeeds in keeping the mixture below ignition temperatures but still close enough that the shock-induced combustion process will ignite the new mixture. Thus, the problem of suppressing premature ignition is reduced to adding an additional slot fuel injector. However, as Table 1 shows, injecting hydrogen in this manner results in a global equivalence ratio of 1.3. In order to reduce the global equivalence ratio to one, both the velocity and/or slot height must be reduced. It was determined that if the slot height is maintained at 5mm, the required low injection velocity results in a detachment of the shock from the 12 degree inlet spike. The third strategy, $H_2$\_slot3, reduces the velocity as well as the slot height to 4mm. The inflow conditions are again listed in Table 1 which result in $\phi = 1$. As seen in Fig. 16, the significantly lower mass flow of hydrogen has less capacity to absorb heat from the developing boundary layer than the previous cases. As a result, temperatures over 1000K are just beginning to develop at the inlet exit. Note however, that although this region appears as flammable mixture in Fig. 16 ($0.8 < \phi < 7$), it is still fuel rich ($\phi > 2.8$) and requires a temperature greater than 1000K to initiate combustion. Premature ignition is considered suppressed for this case as the maximum mass fraction of $H_2O$ does not exceed 2 parts per million anywhere in the inlet. This leaves configuration $H_2$\_slot3 as the most feasible configuration for a fully functioning scramjet inlet.

Another potential method of reducing the massflow of additional hydrogen is to use an array of expansion ramp injectors, depicted in Fig. 17, instead of a continuous slot injector. In this configuration, not only is a new flammable region created above the injectors (as with the continuous slot injector), but also on the sides of the ramp injectors. This flammable region is now in direct contact with the boundary layer attached to the inlet wall. In order to determine if premature ignition occurs, the continuous slot injection grid was modified to inject hydrogen through 8.8mm wide, 5mm high expansion ramp injectors at the same location in the inlet ($x = 0.69m$), centered on the same plane as the cantilevered injectors ($z = 0m$). Table 1 shows the hydrogen properties at injection for this case, denoted $H_2$\_ramp, while Fig. 18 displays the temperature and equivalence ratio fields at $x = 0.85m$ and $x = 0.90m$. As Fig. 18 confirms, the newly created flammable mixture on the sides of the injector are exposed to ignition temperatures and premature ignition is found to occur at $x = 0.8m$. Thus, continuous slot injection may be necessary for the sole purpose of keeping a fuel rich region in contact with the inlet wall and the new fuel/air mixing region away from the wall. Note however, that if nitrogen is used as the coolant gas, the initial mixture in contact with the hot inlet wall will no longer be flammable. Thus, the expansion ramp injector configuration may still be a feasible way of reducing the massflow of nitrogen necessary to prevent premature ignition.

In addition to preventing premature ignition in a the scramjet inlet, the injection of cool gas along the inlet wall has the potential to reduce the frictional force felt by the scramjet wall. Table 1 displays the variation in skin friction
Contour lines represent temperature in Kelvin.

Slightly to the frictional force.

In skin friction of roughly 10% is observed. The added sur-

Premature ignition was found to occur in all three previ-
ously recommended "optimal" scramjet inlets. The can-
tilevered ramp injectors do succeed in keeping the fuel/air

Fig. 16 Suppression of premature ignition at inlet exit (x = 1.07m), shaded region represents a flammable mixture (0.8 < φ < 7.0), contour lines represent temperature in Kelvin.

Table 1  Tabulated injection properties for the scramjet inlet cases.

<table>
<thead>
<tr>
<th>case</th>
<th>q [m/s]</th>
<th>T [K]</th>
<th>p [Pa]</th>
<th>M∞</th>
<th>φg</th>
<th>$T_{stag}$ [K]</th>
<th>$P_{stag}$ [kPa]</th>
<th>$\tau_{skin friction}$ [Ns/kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_2$ base</td>
<td>5257.</td>
<td>243.</td>
<td>9600.</td>
<td>1.2</td>
<td>0.82</td>
<td>1216.</td>
<td>2448.0</td>
<td>42.1</td>
</tr>
<tr>
<td>$N_2$ slot</td>
<td>1590.</td>
<td>100.</td>
<td>6000.</td>
<td>-2.0</td>
<td>0.82</td>
<td>1200.</td>
<td>35400.0</td>
<td>40.0</td>
</tr>
<tr>
<td>$H_2$ slot1</td>
<td>5257.</td>
<td>100.</td>
<td>6000.</td>
<td>1.6</td>
<td>1.40</td>
<td>1052.</td>
<td>22670.0</td>
<td>39.3</td>
</tr>
<tr>
<td>$H_2$ slot2</td>
<td>5257.</td>
<td>243.</td>
<td>6000.</td>
<td>1.2</td>
<td>1.30</td>
<td>1216.</td>
<td>1571.0</td>
<td>36.8</td>
</tr>
<tr>
<td>$H_2$ slot3</td>
<td>2500.</td>
<td>243.</td>
<td>6000.</td>
<td>-0.3</td>
<td>1.00</td>
<td>437.</td>
<td>47.0</td>
<td>37.7</td>
</tr>
<tr>
<td>$H_2$ ramp</td>
<td>5257.</td>
<td>243.</td>
<td>4000.</td>
<td>1.2</td>
<td>0.96</td>
<td>1216.</td>
<td>1047.0</td>
<td>38.7</td>
</tr>
</tbody>
</table>

Fig. 17  Expansion Ramp Injector [dimensions in mm]

Fig. 18  Prediction of premature ignition, shaded region represents a flammable mixture (0.8 < φ < 7.0), contour lines represent temperature in Kelvin.

Conclusions

Premature ignition was found to occur in all three previ-

systems. As expected, nitrogen injection creates the same amount of friction as the air boundary layer in the baseline case. The highest mass flux of hydrogen injected, case $H_2$ slot1, is found not to reduce the skin friction. However, as the mass flux is reduced a reduction in skin friction of roughly 10% is observed. The added surface area in the expansion ramp configuration is seen to add slightly to the frictional force.
mixture out of the boundary layer until the last 15% of the inlet. However, at this point the second inlet shock compresses the mixture into the boundary layer where it ignites and quickly spreads into the core flow prior to the inlet exit. Slot injection of additional coolant gas just prior to the second inlet spike was determined to be the optimal configuration through analysis of various non-reacting strategically modified inlets. Chemically reacting simulations then verified that injection of both nitrogen and hydrogen through the slot suppress premature ignition while maintaining the performance of the original inlet.

Finally, numerical simulation yields a feasible configuration for a fully functional scramjet inlet. Hydrogen fuel is injected through an infinite array of cantilevered ramp injectors at a convective Mach number of 1.2 and global equivalence ratio of 0.82. Mixing is enhanced by turbulence, the stretching of the fuel-air interface due to strong axial vortices, and the compression processes in the inlet. Additional hydrogen is injected through a continuous, 4mm high slot injector just prior to the second inlet spike, such that the global equivalence ratio is raised to one. The hydrogen, although injected at 243 Kelvin, is enough to cool the incoming boundary layer before the fuel/air mixture is compressed into this region by the second inlet shock. As a result the flammable mixture does not ignite at any point in the scramjet inlet. The resulting mixture is at an average temperature of 900 Kelvin, a global equivalence ratio of one and mixed at 30% efficiency at the exit of the inlet. In addition, the frictional force experienced by the inlet is reduced by 10% due to the injected hydrogen along the inlet wall.

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