STREAMWISE PORTHOLE FUEL INJECTION FOR BOUNDARY-LAYER COMBUSTION INSIDE A SCRAMJET ENGINE

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Abstract

Due to its low practicality, an alternative to slot injection is desirable for boundary layer fuel injection in scramjet engines. An array of porthole injectors in the face of a backward step is examined as a possible alternative. Skin friction drag reductions predicted through CFD are compared to slot injection for a variety of porthole spacings with constant fuel mass flow. While the fuel did not ignite within the domain of the simulation, film-cooling induced drag reductions show that porthole injection can provide comparable performance when injectors are spaced sufficiently close. Mixing of the fuel and mainstream air is shown to increase as jet spacing goes up; after ignition, wider jet spacing may lead to improved combustion and therefore further improvements to skin friction drag reduction.

1 Introduction

Supersonic combustion ramjet (scramjet) engine research has recently seen a surge in popularity, driven in part by their potential for economical space access. It is envisioned that scramjets would provide thrust to launch vehicle stages without the need to carry on-board oxidizer, freeing up mass for larger payloads or enhanced system reliability. Because scramjets operate entirely in the supersonic and hypersonic flow regimes, developing an engine that can generate sufficient thrust to propel a space-access vehicle is a problem of considerable difficulty. At the speeds necessary for space access, the net thrust a scramjet is capable of generating is highly dependent on factors beyond just the engine's combustion efficiency; reducing the drag generated by the engine surfaces can have a significant impact on the engine's performance [1].

One proposed method for drag reduction in a scramjet is the injection and burning of fuel (usually hydrogen) in the boundary layers which develop along the engine's internal walls. This is similar to the well-known phenomenon of film cooling, (e.g. [2], [3]) where skin friction drag is reduced through lowering near-wall momentum and viscosity. Boundary layer combustion achieves larger reductions via the heat release of combustion acting on the (turbulent) Reynolds stresses in the boundary layer to decrease momentum transport to the wall. This has been demonstrated for hydrogen combustion both analytically [4] and experimentally ([5], [6]), where downstream of the fuel injection point, skin friction was reduced by as much as 70%.

To date, all published studies on hypersonic boundary layer combustion have employed parallel slot injection of fuel next to a wall, forming a mixing shear layer behind a backward facing step, as illustrated in Fig. 1.

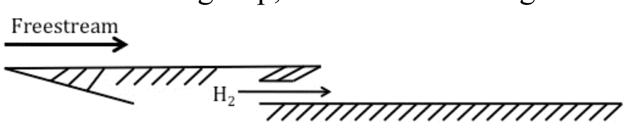

Fig. 1. Typical boundary layer injection slot geometry

While this injection geometry yields excellent drag reduction, it would be difficult to build a slot injector with sufficient structural strength and manufacturability to be useful in a practical engine design. For this reason, recent studies of combustion inside a Rectangular-to-Elliptical Shape Transition (REST) engine have replaced the slot injector with an array of discrete portholes spaced along a backward-facing step. While this geometry still shows robust combustion of boundary-layer-injected fuel [7], to date there has been no investigation comparing its effectiveness relative to that of slot injection. Of particular interest is the required spacing for porthole injection; while [7] provides a single example of porthole geometry, there is little information on the potential existence of an "ideal" spacing for this application.

2 Methodology

Flow over a backward-facing step at conditions analogous to a scramjet operating at Mach 8 flight conditions was simulated using the US3D code developed by the University of Minnesota [8].

US3D is capable of solving a variety of hypersonic flow applications with both Reynolds-Averaged Navier-Stokes (RANS) and Detached-eddy Simulation methods, with full chemistry and vibrational temperature models. Turbulence is modeled with the one-equation Spalart-Allmaras model [9] with the compressibility corrections of Catris and Aupoix [10]. This code has been successfully applied to the simulation of transverse jet injection into a supersonic cross-flow [11], which bears some similarity to the injection case presently being examined.

The geometry simulated is shown in Fig. 2. The entire domain has a physical length of 100mm, with a 2.5mm height (H) backward facing step located 25mm downstream of the inlet. The top boundary of the domain is set as an outflow plane.

The domain side walls are set as symmetry conditions, thus simulating an array of portholes behind a step, similar to the geometry employed in the REST engine of [7]. The actual domain width was determined by the method of injection, and is indicated by the shaded regions of each injection schematic in Fig. 2. The smallest porthole spacing is identical to the spacing employed in the REST engine of [7], and consists of 1.5mm diameter (D) portholes spaced approximately 3.4mm (~2.25D or 1.36H) center-to-center. The porthole area for the 1.5 times (x) and 2x injector spacing cases (and slot height in the slot injection case) were chosen such that the fuel mass flow rate per unit of spanwise width was constant.

Multiple RANS simulations were run to examine the effect of the variations in injection geometry on skin friction drag. A simulation without fuel injection was also performed to establish the baseline skin friction drag generated along the wall downstream of the step. In all cases, flow chemistry was modeled using the twelve-species model of Evans and Schexnayder [12].

2.1 Grid Generation

The grids used in this simulation were generated using the commercial grid generation software Pointwise [13]. Both two- and three-dimensional (2D and 3D) grids were employed. 2D grids were generated for the baseline drag case (no injection), and the slot injection case, where the flow is uniform in the spanwise direction.

Grid spatial resolution was determined by proximity to both the step and injector. Cells

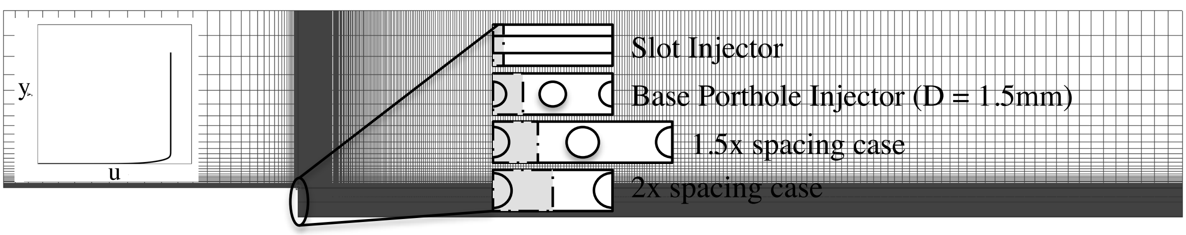

Fig. 2. Model geometry used in the study with various injection configurations

were clustered close to the corner of the step to accurately capture the expected expansion of the supersonic flow as it passes over the step lip, as well as to resolve any recirculation zones established. The grid resolution was also kept fine downstream of the step for a length of ten step heights before gradually relaxing grid spacing in the streamwise direction for this reason.

In the porthole injection cases, grid was clustered close to the porthole edge to accurately capture the behavior of the jet as it enters the flow. A low-resolution example of meshing around a porthole is shown in Fig. 3 below.

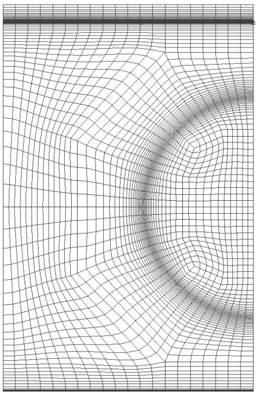

Fig. 3. Typical grid topology around porthole injector

2.2 Flow Conditions

The inflow condition was chosen to match the conditions at the entrance to the combustion chamber of a REST engine operating at Mach 8 flight conditions. To account for the effects of the engine inlet, the computational inlet flow was given a turbulent boundary layer profile extracted 1000mm from the leading edge of a flat plate flow simulation with freestream conditions identical to the core flow expected in the REST engine. These free stream conditions are for air (79% N_2, 21% O_2) with a speed of 2595m/s, flow density of 0.3135kg/m^3, and temperature 912.8K. Hydrogen injection conditions were chosen to approximate conditions from [7], leading to a uniform fuel inflow speed of 1203m/s, density 0.7181kg/m^3, and 248.96K static temperature. The injector flow exits at a 10^o angle away from the wall.

2.3 Grid Convergence

Since this study focused on the reduction of skin friction drag due to film cooling and boundary layer combustion, the integrated shear stress along the wall downstream of the step was chosen as the grid convergence index (GCI) parameter. Following the method of Roache [14], coarse, medium, and fine grids with a refinement factor r = 1.25 were simulated for the smallest porthole case. After multiple iterations, it was found that for a fine mesh with 12 Million cells, run on 256 CPUs, a GCI of ~6.5% for integrated skin friction was achieved. It should be noted that other traditional measures of grid convergence, such as wall pressure, were grid converged to a much higher degree of accuracy for far coarser grid resolutions. This emphasizes just how important the choice in grid convergence parameter is: a convergence study done on a parameter other than that of greatest interest may generate results of questionable accuracy.

Due to time and computational restraints, it was decided to compare the finest mesh with only the similarly scaled 2D cases to establish the baseline comparison between porthole and slot injection performance in skin friction reduction. Different porthole spacing meshes were run on the medium-refinement meshes of ~6 Million cells, to provide an approximate magnitude of the change between various porthole configurations.

3 Results and Discussion

Given the relatively unknown nature of the flow characteristics of parallel porthole injection from backward step, it is worthwhile spending some time to understand the steady flow structures predicted to occur for this case. In order to guide the discussion, the relative performance of each injection configuration is presented first.

3.1 Drag Reduction Performance

The skin friction drag acting on the wall downstream of the step is estimated by

integrating the local magnitude of wall shear stress over the area of the wall. Dividing by the spanwise width of the domain, an average drag force per unit width is obtained. Normalizing this to the drag per unit width of the surface without fuel injection, the relative performance can be plotted as shown in
Fig. 5.

As expected, all injecting cases provide some level of reduction to the skin friction drag. For reasons that will be discussed later, all three porthole cases exhibit some lesser ability to reduce the skin friction drag generated along the surface downstream of the step, with the closest porthole spacing providing performance nearest to that of the slot injector. Notably, the 1.5x and 2x porthole spacing cases both show a marked difference from baseline porthole injection case, but similar performance to each other.

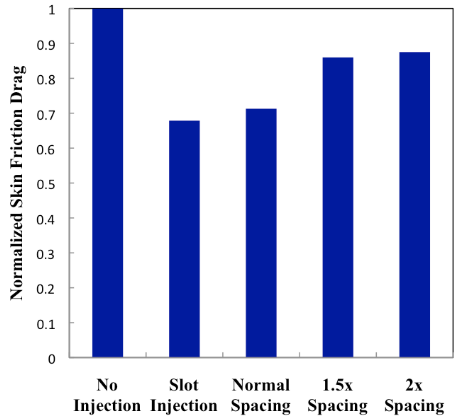

Fig. 5. Reductions in skin friction drag relative to the no-injection case

Perhaps of greater interest is the magnitude of the reductions: as was previously mentioned, prior studies have demonstrated far greater

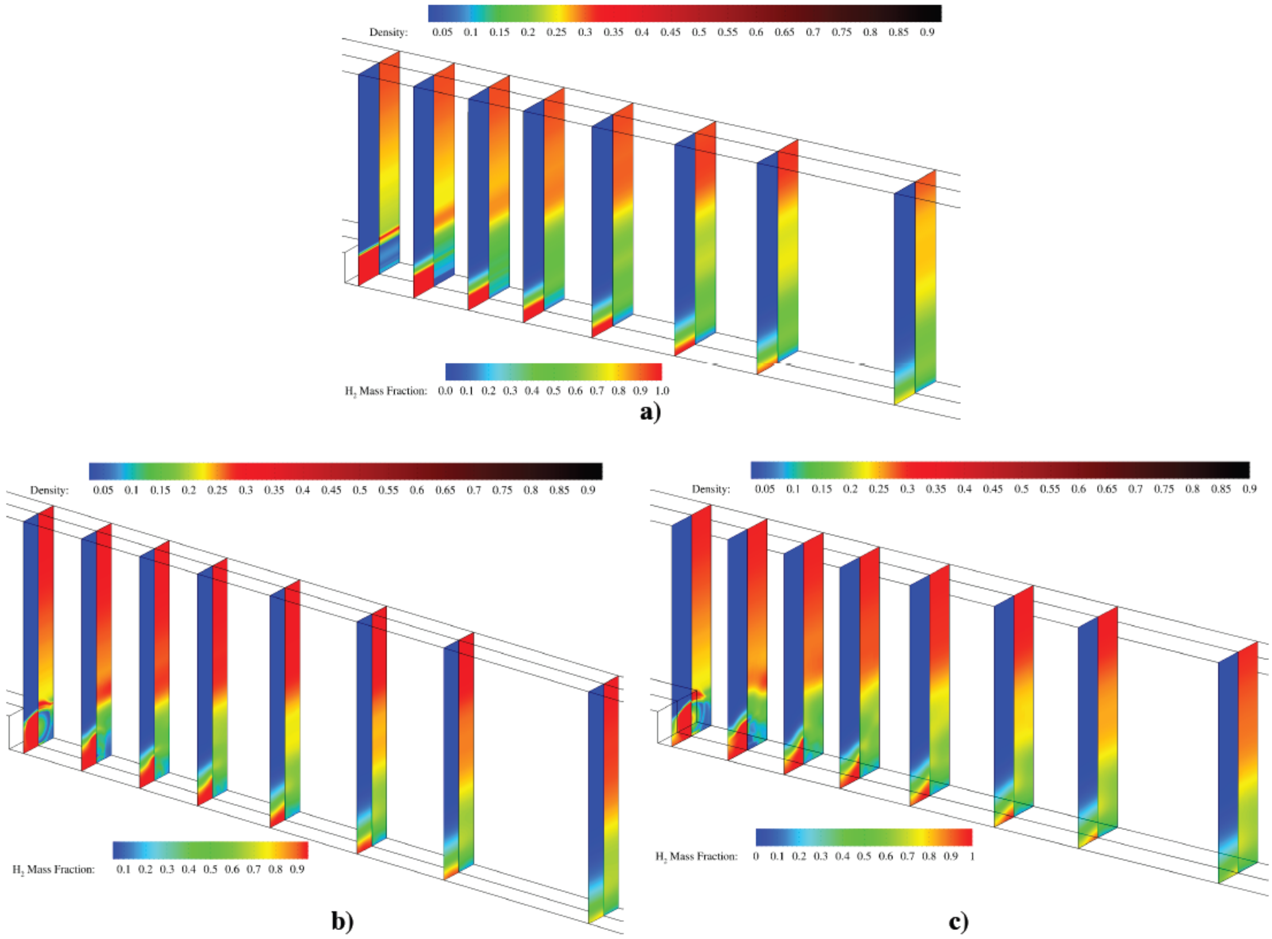

Fig. 4. Hydrogen mass fraction and bulk density contours for a) 2D slot injection, b) baseline porthole injection, and c) 1.5x injector spacing

reductions to skin friction than are seen in Fig 4. This can be explained by the apparent lack of burning fuel in the flow. The simulations run all show the beginnings of OH radical production to some degree, but none indicate sufficient OH concentrations to exhibit combusting flow. Thus the global skin friction reductions seen are due to the film-cooling effect, and are consistent with prior analytical results for integrated drag reduction in a scramjet combustor [15].

3.2 Flow Structure

In order to fully understand both the lack of combustion and why the porthole injector cases exhibit such different degrees of skin friction reduction, the structure of the flows must be understood. A series of spanwise slices of flow downstream of the step for representative flow cases are presented in Fig. 4.

Differences in the development of hydrogen mass fraction profiles downstream from injection are of great importance in film-cooling. When the injection is switched from slot to porthole injection, flow isotropy is lost. The hydrogen contours shift from the flat fuel layer of the slot injection case, to a more "corrugated" hydrogen layer with thicker "ridges" of fuel centered along the porthole axis. This change in the fuel layer allows the air coming over the step to penetrate closer to the wall surface between each injector. While this effect is minor for the baseline injector spacing, a simple 1.5x increase in spacing (and jet area) greatly increases the mixing of fuel and air between the jets: 20 step heights downstream of the step, the fuel has begun to coalesce into streaks of fuel moving downstream along the porthole centerline. In the case of the 2x injector spacing (not shown), the effect is even more pronounced. While undesirable from a film-cooling perspective, if the flow was to ignite, the enhanced mixing characteristics should provide more robust combustion inside the boundary layer, leading to further skin friction reduction.

The density profiles indicate another major change: the simple shock structures of the slot injection case have given way to a far more complex flow structure. The intersection of the injector flow has changed from the linear shock of the slot injector case, to a curved shock around the fuel jet that bears a striking resemblance to the bow shock seen upstream of a transverse porthole injector. This shock is the hottest region of the flow, and is likely responsible for the generation of most the radicals that seed the ignition process further downstream.

Behind the step, the simple wall-reflection of the jet expansion wave has been replaced with a series of 3D shock interactions between not only the jet and the wall, but also between individual jets. The complexity of the flow is further demonstrated by the wall shear distribution and streamlines visible in Fig. 6.

The complicated structure of the recirculation zones and wall-shock interactions are plainly visible for all three porthole injection cases. While showing a great degree of similarity in the region ten step heights downstream of the step, the baseline porthole spacing produces a far more persistent low-shear-stress region between the jets. This reinforces the point that the closer porthole spacing is advantageous to cases where the boundary-layer flow does not ignite; the stress profiles for the slot and baseline porthole spacing show similar levels of growth in the wall shear stress magnitude downstream of the step, while the larger porthole spacing cases show faster return to non-injection stress levels.

The porthole injection cases also show other flow features that would contribute to increasing skin friction drag. The first is the presence of high shear regions where the jet expansion impinges on the wall, seen as a ``bar'' of high shear that is symmetric about the jet centerline ($z/H = 0$). Another high shear region is present closer to the between-jet symmetry plane, where the expanding jet flow is turned downstream and back inward to toward the injector centerline. Both the size of these zones, and the magnitude of the shear stresses within them, increase with injector spacing and cross-sectional area.

Similarly, the size and location of recirculation zones (bounded by regions of zero shear and indicated by streamlines) change greatly from case to case. In all injecting cases, there is a recirculation zone in the region 2-3 step heights downstream of injection. These recirculation zones are bounded by the reflection of waves emanating from the injector region. In the case of porthole injection, this region is confined to an area immediately underneath the hydrogen jet, and moves further downstream as injector diameter increases. In the baseline spacing case, there is also a small separation zone along the centerline between two injectors, located downstream of the primary recirculation zone. This separation shrinks with injector spacing, and has subsided entirely in the 2x spacing case. This is most likely due to the greater ability of the mainstream flow to influence near-wall flow between the injectors, dominating the flow between two injector axes to a point where the 3D shock patterns can no longer establish a separation zone in this region. In the 2D case, there is a second large region of low shear stress along the jet centerline that is not indicative of recirculation. It is simply a region of slow, low-density flow.

3.3 Flow chemistry and Shock-Boundary Layer Interactions

The lack of combustion in the flow is of some concern, as experiments at similar conditions suggested robust combustion should be present by the end of the computational domain [7]. Fig. 7 shows that the flows are merely beginning to ignite by this point. There is a minor increase in radical concentrations at the jet "bow shock," but not sufficient to improve overall ignition characteristics downstream. The produced radicals appear to be swept downward

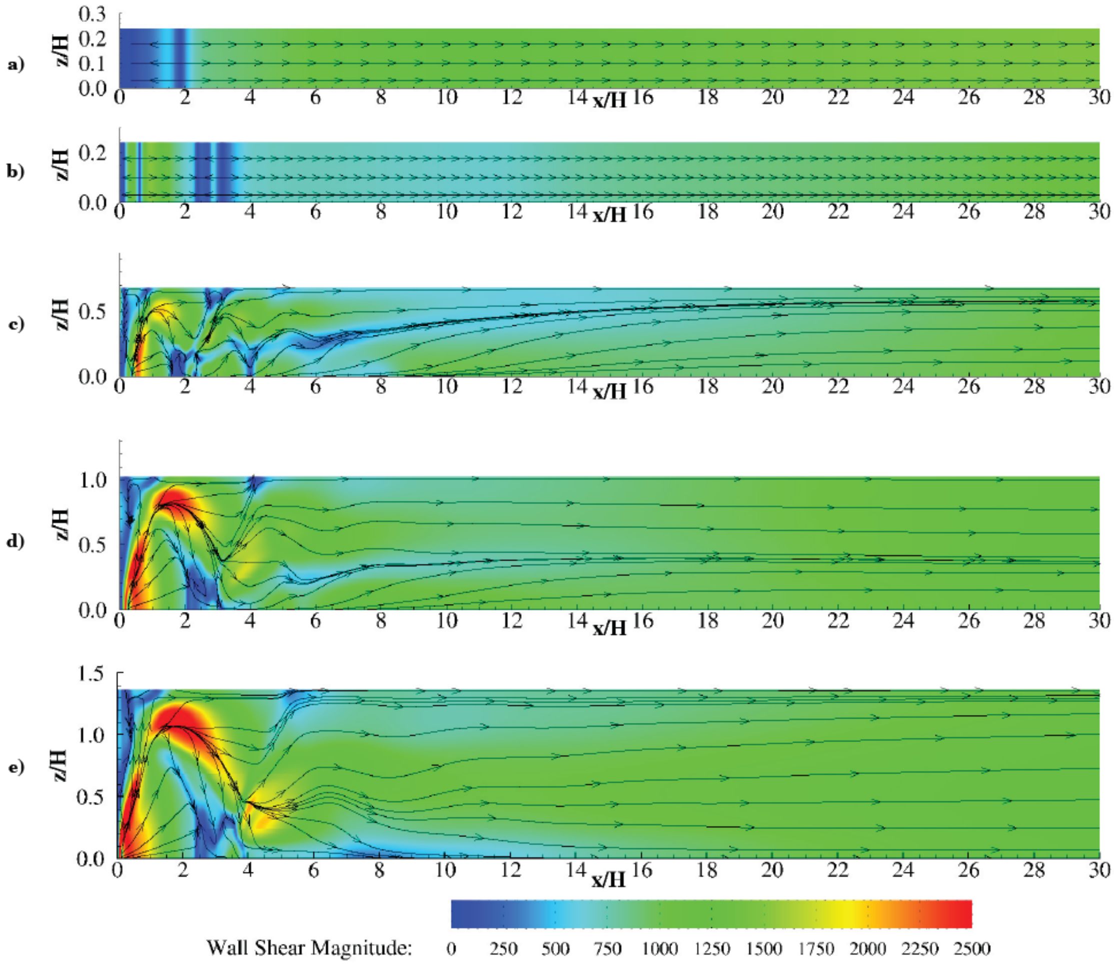

Fig. 6. Wall shear stress distributions and streamlines for a) no fuel injection, b) slot injection, c) porthole injection, d) 1.5x injector spacing, and e) 2x injector spacing

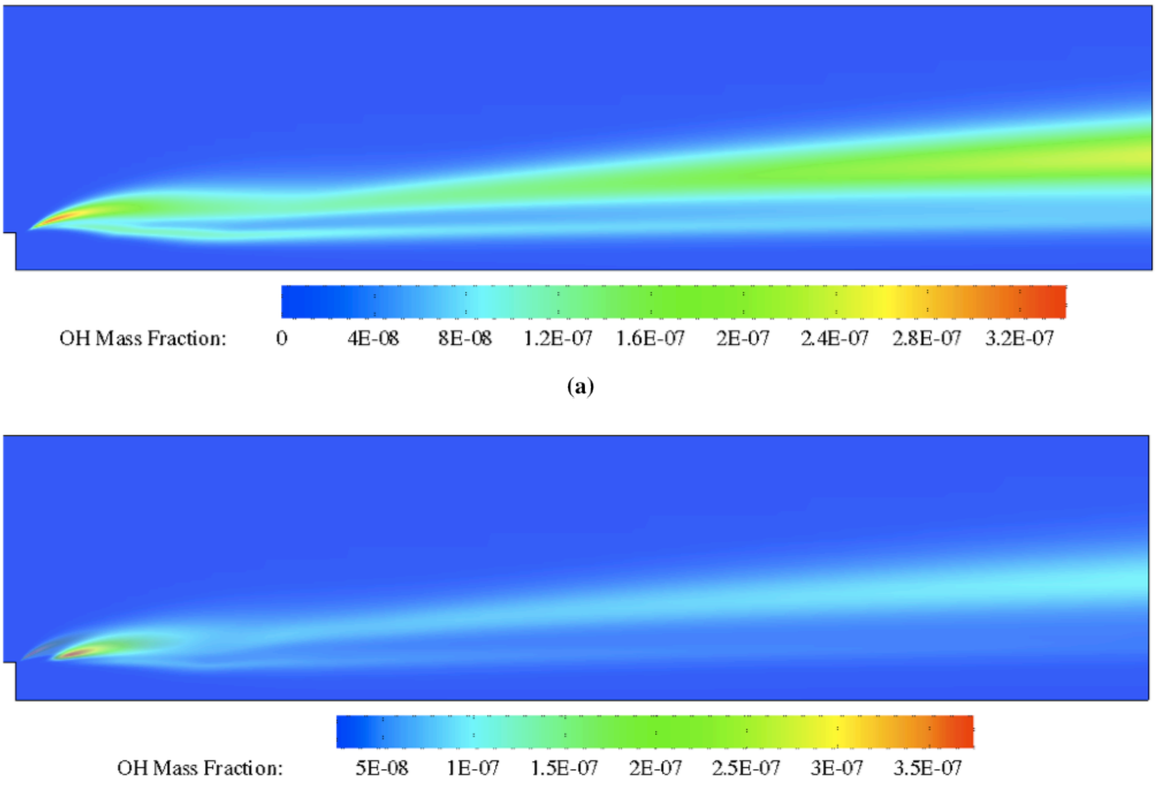

Fig. 7. Typical OH radical mass fraction contours for a) 2D slot injection and b) porthole injection (1.5x spacing)

into the colder fuel/air mixture close to the wall, and so overall OH radical concentration is lower by the end of the domain.

These simulated flows do, however, lack one key feature of the flows studied in [7]: shock-boundary layer interactions. Oblique shocks generated by a scramjet inlet operating at flight conditions significantly lower than its design Mach number typically result in a shock train propagating through the entire engine flow path. These shocks impinge onto the boundary layers developing along the engine walls, and often can enhance mixing or create zones of radical production (the so-called "radical farming" technique described in detail by McGuire [16]). Either of these effects may lead to enhanced ignition and combustion inside a scramjet. In the absence of these interactions, the hydrogen fuel must rely entirely on turbulent mixing and diffusion to reach zones in which there are favorable conditions for ignition. Depending on the flow, these mechanisms alone may lead to ignition times longer than the flow residence time in the engine combustor.

4 Conclusions

Despite the lack of combustion, valuable insight has been gained into the relative drag-reduction performance of parallel porthole injection from the face of a backward step compared to slot injection. For a constant fuel mass flow rate, narrower spacing of smaller-diameter injectors gives the closest performance to that of slot injection. As injector spacing (and area) increases the drag reduction is diminished, but greater mixing between the freestream and fuel occurs as the fuel layer behind the step takes on a corrugated cross-sectional shape. Complex patterns of expansion waves and reflecting shocks dominate the regions of flow just behind of the step, but do not lead to any appreciable change in ignition time in the absence of external shock interactions.

Overall, porthole injection is a viable alternative to slot injection for boundary layer film-cooling and combustion, provided the porthole spacing is kept relatively small. Based on the geometries studied, a centerline spacing of ~2.25D is a conservative upper boundary for reasonable film-cooling-based drag-reduction performance, though smaller injector spacing may be more advantageous in applications where the flow is not expected to ignite. In cases where ignition is expected, the enhanced mixing a wider spacing affords may be desirable.

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