16th Australasian Fluid Mechanics Conference
Crown Plaza, Gold Coast, Australia
2-7 December 2007

Effect of Boundary Layer Thickness and Entropy Layer on Boundary Layer Combustion

R. M. Kirchhartz and D. J. Mee and R. J. Stalker

Centre for Hypersonics,
Department of Mechanical Engineering,
The University of Queensland, St Lucia, Queensland 4072, AUSTRALIA

Abstract

This project investigates the possibilities of scramjet combustor performance enhancement by reducing the skin friction through boundary layer combustion. Experiments were conducted in the T4 Stalker tube to investigate the influence of boundary layer thickness and entropy layers on the ignition of a hydrogen air mixture near the wall of a constant area duct. The hydrogen was injected tangentially from a slot of annular cross section after an "injector" of constant area captured flow from a Mach 4 nozzle. Injectors of two different lengths and nose radii were employed to vary the thickness of the boundary layer at the injection location as well as the temperature of the gas near the walls and within the entropy layer created by the leading edge shocks of blunted leading edges. Results are presented of CFD simulations of the injector as well as experimentally measured pressure coefficient profiles along the combustor wall. It is shown that a thicker boundary layer will promote combustion but that heating the gas near the walls through a leading edge shock is more effective for ignition. However, the shocks generated by the leading edge may also influence the core flow of the constant area combustor and possibly cause some main stream mixing.

Introduction

The long, slender design of hypersonic vehicles leads to high ratios of wetted surface to projected frontal area. The large streamwise length of the wetted surface causes thick and mostly turbulent boundary layers, so that the skin friction drag contributes a significant amount of the total vehicle drag [1]. The skin friction is especially high in areas where the oncoming flow is compressed to high pressures and densities, such as in a combustion chamber of a scramjet engine. Despite the relatively short length of scramjet combustion chambers in relation to the overall vehicle length, experiments by Paull et al. [11] have shown that it accounts for up to 60% of the total engine skin friction drag. A reduction of the combustion chamber skin friction drag therefore promises relatively large margins of performance improvement.

Analysis by Stalker [13], based on an extension to the van Driest II analysis [16] to include heat release by combustion, indicates that a reduction in skin friction drag is possible by burning hydrogen in the boundary layer. While the mechanisms that lead to this reduction are still under investigation, it is known that the heat addition reduces the density of the boundary layer gas, lowering the momentum transfer, and the Reynolds stresses. Large Eddy Simulations at the University of Queensland indicate that an alteration of the baroclinic torque is one contributor to the change in Reynolds stresses [2].

Experiments conducted at The University of Queensland have also shown a substantial reduction of skin friction by boundary layer combustion of hydrogen (i.e. [3, 12]). Rowan's experiments were conducted with a cylindrical combustion chamber and normal and tangential injection of the hydrogen fuel. However, results of the experiments with tangential fuel injection indicated that the fuel did not ignite quickly, thereby potentially reducing the beneficial effects of boundary layer combustion. In similar experiments by Suraweera [15] with a thicker boundary layer, ignition of the fuel-air mixture occurred at a shorter distance from the injection slot. Numerical simulations indicate that the boundary layer was indeed too thin in the case of Rowan's experiments and did not supply a sufficient amount of high temperature air for the combustion of hydrogen [14].

In an initial stage of the current project that aims to further investigate the potentials of skin friction reduction in Scramjet combustors, only the axial pressure distribution in a constant area duct are measured. This is done to investigate the influence of boundary layer thickness and entropy layers on the ignition location and combustion pressure rise when fuel is injected tangentially along the duct walls. Rowan's circular combustion chamber setup was therefore tested with different boundary layer states. To investigate the influence of boundary layer thickness, the boundary layer was allowed to grow for the same distance as in Suraweera's experiments and the resulting pressure distribution was compared with that of a boundary layer of one quarter running length. Additionally, the leading edge of the circular duct was blunted for both injector lengths. This produces an entropy layer that contains high temperature gas which may assist fuel ignition.

Model Configuration

The shock tunnel model consists of a circular combustion chamber with an internal diameter of 33.2 mm and a length of 500 mm. Upstream of the combustion chamber is a constant area "injector" of 60.5 or 245 mm length, the end of which features a backward facing step acting as a slot injector for the gaseous hydrogen fuel. A detailed view of the injector is given in figure 1. Figure 2 displays an overall view of the model.

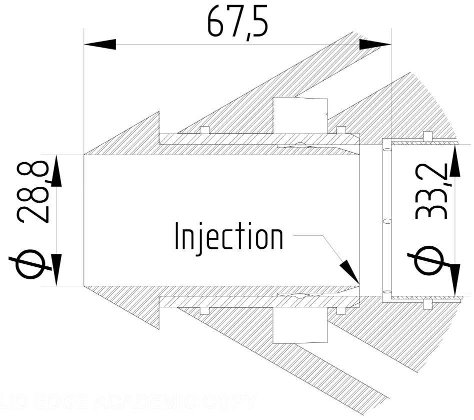


Figure 1: Injection point upstream of the combustion chamber

The fuel injection slot is of annular cross-section with a 17 deg half cone angle at the trailing edge; the first pressure measurement location is located approximately 168 mm downstream of the injection plane. At combustor exit, the flow is guided into

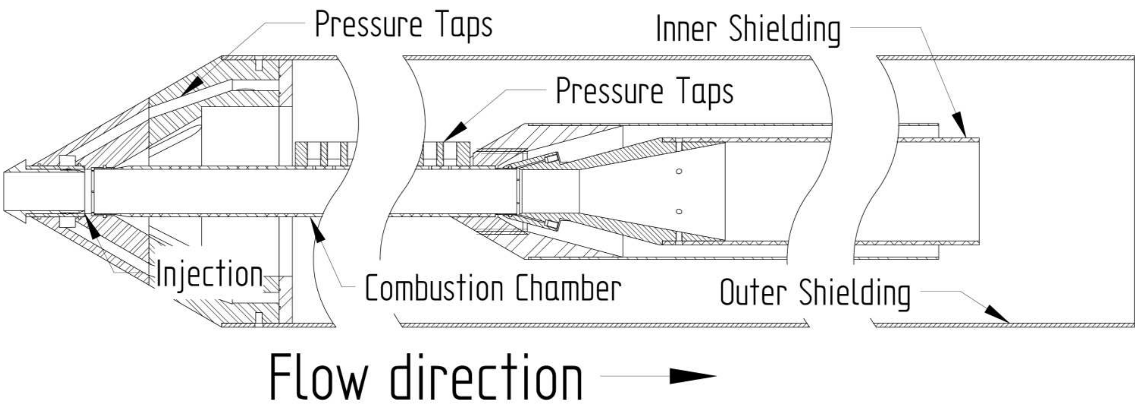


Figure 2: Layout of the stress wave force balance with combustion chamber for pressure measurements

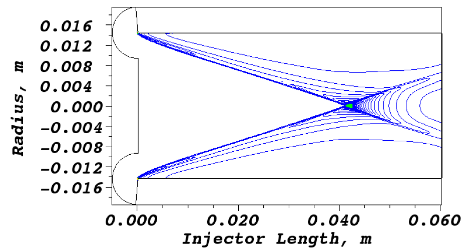
a shielding tube. When conducting force measurement experiments, this tube decouples all flow except the internal combustor flow from the model. The short injector with a sharp leading edge is shown in the figures. Both injector lengths have also been used with a 0.5 mm radius bluntness to investigate the effect of the resulting entropy layer on the ignition of a boundary layer hydrogen air mixture.

Computational Approach

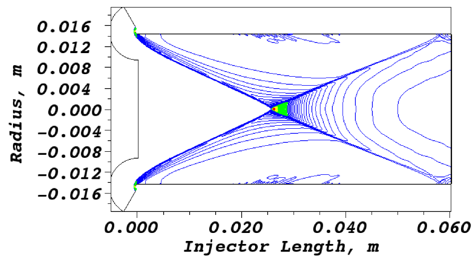
To verify the assumption that a longer boundary layer growing length upstream of the fuel injection or a blunted leading edge can aid ignition of boundary layer hydrogen air mixtures, some simulations have been performed using the multiblock compressible navier stokes solver MB_CNS developed at the Centre for Hypersonics [4]. Only the constant area duct of the injector was modelled to determine the effects of different injector configurations on the flow properties at the injection plane. As an indication for the solved flow fields, some comparisons of pressure contours are given in figures 3 and 4. The calculations for the short injector configurations assume a fully laminar boundary layer while the calculation for the long injector configuration was carried out assuming transition to a turbulent boundary layer at a Reynolds number of approximately two million, corresponding to a wetted length of approximately 120 mm. A total of 80400 cells were used for the simulation of the short blunt injector configuration and 163600 cells for the corresponding long injector configuration. A grid resolution study for these simulations was done to ensure the adequate resolution of the shock layers. It can be seen that the leading edge shocks influence the entire flow field in the injector and that shocks are reflected at the centreline and can form a normal shock in the centre. According to the Korkegi criterion [5], the pressure rise over the reflected shocks impinging on the wall is not large enough to separate the boundary layer.

Of more interest than the pressure contours along the injector are the flow properties at the hydrogen injection point. In particular, the flow field near the combustion chamber and injector walls will determine whether or not boundary layer combustion will occur. Figure 5 shows the radial profile of density and temperature from the centreline (Radius = 0) to the injector wall (Radius = 14.4 mm).

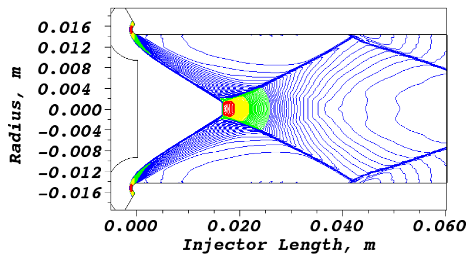
Examination of the contour plots from figures 3 and 4 and these profiles indicates that the abrupt changes in the flow property profiles are caused by interactions of the shocks generated by blunt leading edges. Blunt leading edges and long injectors will result in a broader area along the wall that is of high temperature and yet still contains gas at the same or higher density than the short injector with a sharp leading edge. It is expected that this effect will enhance ignition.



(a) 0.1 mm radius



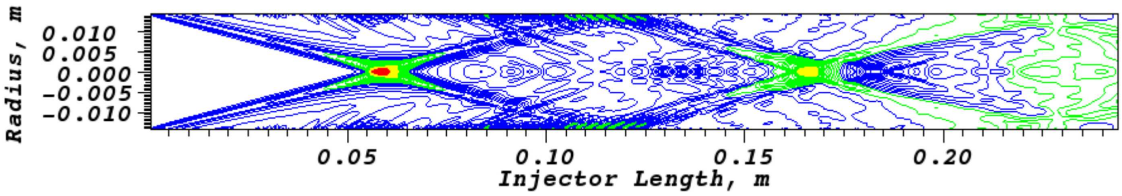
(b) 0.5 mm radius



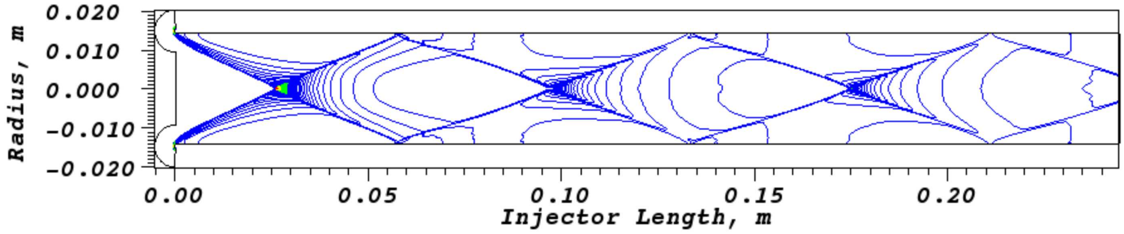
(c) 1 mm radius

Figure 3: Pressure contours for the short injector configuration flow field with various nose radii

The impact of blunting the nose on the flow even close to the centreline is highlighted in figure 6. Results from four simulations are shown. For a stagnation enthalpy of 5.9 MJ/kg results are shown for a sharp leading edge ($R_n = 0$ mm) and a blunted leading edge ($R_n = 0.5$ mm). For the blunted leading edge, results are also shown for a higher enthalpy (7.6 MJ/kg) and for a lower enthalpy (3.9 MJ/kg). It is evident that a blunted leading edge produces a broader region of high temperature gas close to the wall than does a sharp leading edge. The reduced enthalpy case yields higher temperature gas near the wall than the sharp

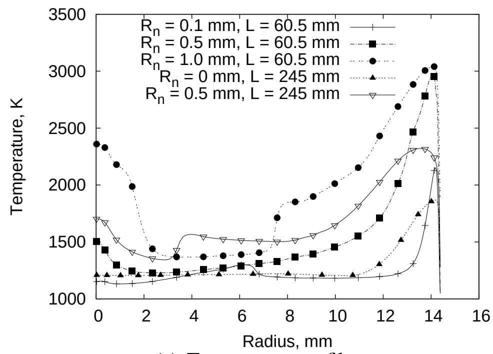


(a) sharp leading edge

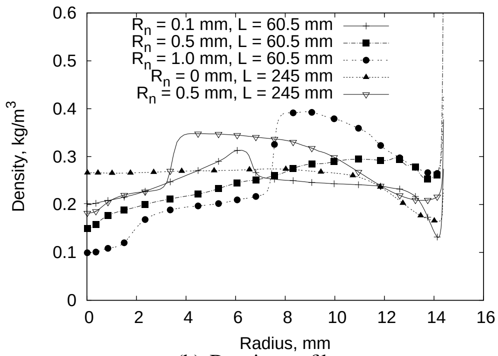


(b) 0.5 mm radius

Figure 4: Pressure contours for the long injector configuration flow field with various nose radii

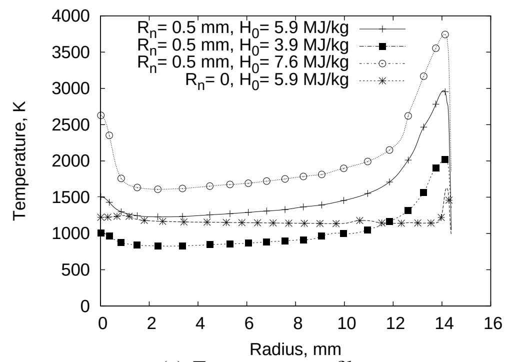


(a) Temperature profile

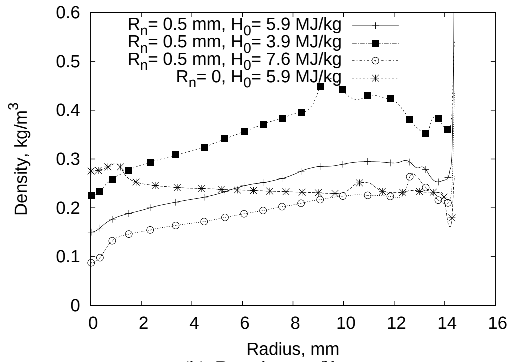


(b) Density profile

Figure 5: Profiles of different flow properties at the fuel injection location for some different injector configurations at H_0 = 5.6 MJ/kg



(a) Temperature profile



(b) Density profile

Figure 6: Variation of temperature and density at the injector exit with bluntness and total enthalpy (short injector)

leading edge case. As its temperature increases, one might expect to see that the gas density is reduced, which could be counterproductive for boundary layer combustion. However, figure 6(b) shows that, for the same enthalpy, the density near the wall increases for a leading edge radius of 0.5 mm compared to that for the sharp leading edge.

Experimental Configuration

The experiments for this project were conducted in the T4 Stalker tube that produced a nominal Mach 4.5 free stream flow. The nozzle-supply enthalpy was varied from 3.6 to 8 MJ/kg with free stream static pressures of 75 to 100 kPa. The nozzle-supply enthalpy was varied within each experimental set for the different injector configurations in order to determine at what flow condition the fuel would ignite in this particular configuration. The nominal free stream conditions are given in table 1. To decouple changes in the free stream flow from the exper-

Cond.	H_0	P	T	ρ	u	M
	(MJ/kg)	(kPa)	(K)	(kg/m^3)	(m/s)	-
A	5.3	82.3	1100	0.257	2900	4.47
B	7.9	100.0	1780	0.197	3380	4.22
C	3.6	84.0	780	0.370	2420	4.36
D	5.0	75.5	1020	0.253	2840	4.51
E	6.4	88.5	1360	0.226	3125	4.38
F	4.3	75.8	875	0.301	2620	4.51

Table 1: Nominal free stream conditions

imental results, pressure measurements are presented as pressure coefficients, relative to the free stream. The free stream properties were estimated with a nozzle expansion of stagnated gas by NENZF [7]. The stagnation conditions were provided to NENZF by ESTCJ, a Python coded version of ESTC [9] using the CEA [8] chemistry database. Shot to shot repeatability of the duct pressure coefficient for identical nominal free stream conditions was established to within $\pm5\%$ for most transducers, although some showed variations as large as $\pm10\%$.

Experimental Results and Discussion

Short Injector with Sharp Leading Edge

The base for the experimental campaign is the original configuration of Lentz and Rowan [6, 12] who used a sharp leading edge configuration with a boundary layer development length of 60.5 mm before injection. Several experiments were conducted with this configuration to determine at what condition the hydrogen fuel contained in the boundary layer would combust. It was found that at a stagnation enthalpy of approximately 5.3 MJ/kg, the first signs of combustion were evident in the measured combustor length. At this nozzle-supply enthalpy, pressure traces showed a significant rise compared to those of nitrogen test gas cases that were conducted to suppress combustion. This rise was not constant for the full duration of the test time and when it decreases, the pressure drops rapidly. Figure 7 shows one of these "unstable" combustion cases while figure 8 gives an example of a steady pressure trace from an experiment with a blunt leading edge. Corresponding fuel off traces are also shown.

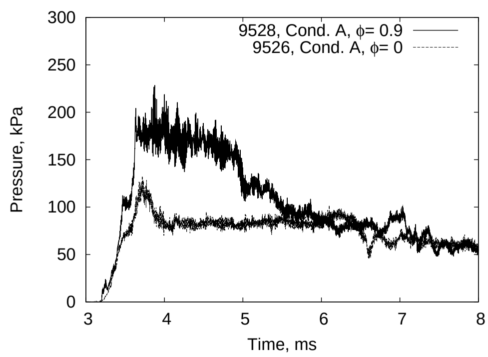


Figure 7: Pressure trace for unsteady combustion, short, sharp leading edge injector

Figure 7 shows that, after a start-up allowance of 1 ms, the pressure level is steady for less than 1 ms and then drops considerably. This indicates that the fuel initially ignited but the flame extinguished quite quickly. One explanation for this could be the arrival of cold driver gas, dropping the boundary layer temperature below the ignition level. However, previous test to measure the time of arrival of driver gas indicate that the driver gas would arrive earlier in higher enthalpy experiments [10].

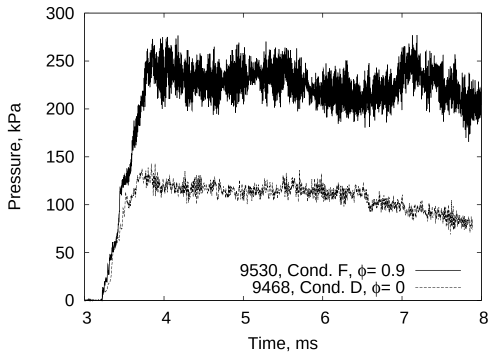


Figure 8: Pressure trace for steady combustion, short, blunt leading edge injector

Therefore, if the flame was extinguished by cold driver gas, the higher enthalpy experiments should display an even shorter time of steady pressure. For enthalpies of 6.3 and 7.9 MJ/kg the pressure level remains steady for more than 1.5 ms after the flow establishment time (2.5 ms after flow arrival which is approaching 10% driver gas contamination). It is therefore concluded that combustion is not steady for the case of 5.3 MJ/kg with a short injector with a sharp leading edge.

The c_p vs. location trace is given in figure 9 together with a trace of a no-injection experiment and that of an experiment with fuel injection into nitrogen. The given equivalence ratio ϕ is the total equivalence ratio using the entire mass flow of air through the combustor. It is noted that not all of the air in the combustor will mix with the injected hydrogen.

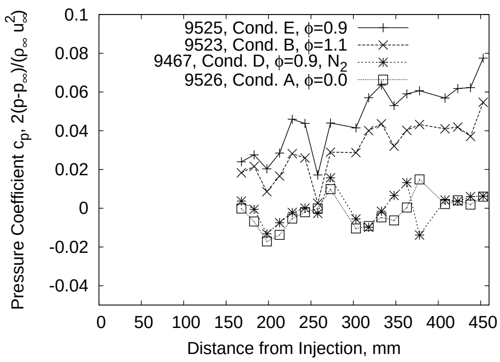


Figure 9: Pressure coefficient for short injector with sharp leading edge

It can be seen that at the upstream end of the profile the pressure coefficient is negative for the no-injection and the nitrogen test gas cases. A pressure coefficient of approximately -0.03 is to be expected due to the expansion of the incoming flow after the backward facing step at the injection location (see figure 1). This effect is somewhat offset at 160 mm downstream of the step because growing turbulent boundary layers compress the constant area flow. The pressure coefficient profile of the injection into nitrogen case and the no-injection case mostly coincide. This is somewhat surprising since the addition of gas into the constant area duct should have some influence on the pressure distribution. However, this result was observed for all no-injection and injection into nitrogen cases with sharp leading edge injectors. No experiments were done with nitrogen test gas and no injection, so that a direct comparison is not possible. It is also shown that the combustion pressure rise diminishes as the stagnation enthalpy rises. This is due to limited heat release in an environment that is already hot.

The pressure distribution of the fuel injection into air case is not shown for the enthalpy of 5.3 MJ/kg because the pressure traces were not steady during the test time throughout the entire length of the combustion chamber. Figure 7 shows a typical trace of a pressure signal at 355 mm downstream of the injection point.

Short Injector with Blunt Leading Edge

As was expected according to the numerical simulations, the blunt leading edge caused combustion in flows with a much lower stagnation enthalpy than the injector with the same length and a sharp leading edge. The pressure coefficient profiles shown in figure 10 indicate that combustion was achieved for the lowest enthalpy of 4.33 MJ/kg and that the pressure rise due to combustion was slightly lower for the enthalpy of 5.2 MJ/kg. The no-injection and nitrogen test gas pressure coefficients are larger than zero as opposed to negative for the sharp leading edge case. This is caused by the leading edge shock compression before the combustor entry. This raised main stream pressure will also promote combustion. It is noted that the leading edge shocks decrease the dynamic pressure in the combustor.

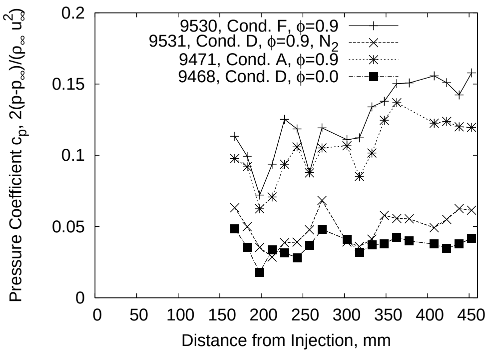


Figure 10: Pressure coefficient for short injector with blunt leading edge

Long Injector with Sharp Leading Edge

The long (245 mm) injector with a sharp leading edge was found to promote combustion earlier and at lower stagnation enthalpies than the corresponding short injector. At an enthalpy of 5.3 MJ/kg a steady combustion pressure rise was detected. A corresponding experiment at an enthalpy of 3.6 MJ/kg did not show any signs of combustion related pressure rise. In fact, as shown in figure 11, the pressure coefficient profile of that shot cannot be discerned from other experiments without fuel injection or with fuel injected into nitrogen. Experiments conducted at stagnation enthalpies between steady combustion and no combustion were found to feature a non-steady pressure levels over the test time, similar to that shown in figure 7 for the short injector. These experiments were conducted at stagnation enthalpies of 4.4 and 4.95 MJ/kg respectively. The c_p profile of both experiments are of the same level as fuel-off cases up to approximately 250 mm and then start rising unsteadily. The lower enthalpy case features the higher pressure rise towards the downstream end of the combustor. Experiments conducted with higher enthalpies than those shown displayed evidence of combustion but featured a smaller rise in pressure coefficient due to smaller heat release at higher mainstream temperatures.

Long Injector with Blunt Leading Edge

The long injector with a blunt leading edge was investigated because it was thought that the shocks forming on the leading edge would create the desired entropy layer near the wall but would not disturb the mainstream and boundary layer flow at

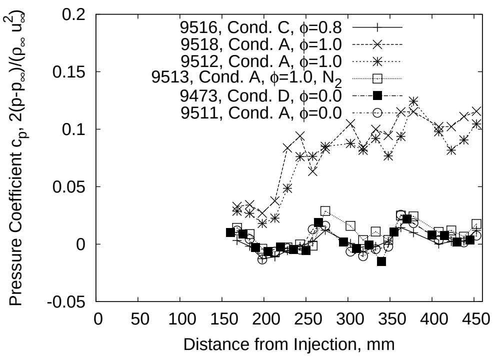


Figure 11: Pressure coefficient for long injector with sharp leading edge

the injection point as much as with the short injector. Likewise for the short injector, combustion was shown for all tested stagnation enthalpies. Figure 12 summarises the pressure coefficient profile for these experiments. As expected, the highest rise in pressure coefficient was found for the lowest enthalpy at which combustion occurred. For this particular case, little pressure rise due to combustion can be seen for a stagnation enthalpy of 7.8 MJ/kg. This can be explained by the high temperatures caused by the leading edge shock. A simulation using MB_CNS suggests an inlet exit temperature of 3000 K close to the wall rather than 2300 K for the 5.3 MJ/kg case. An experiment with the corresponding enthalpy was not carried out for the short blunt injector. It is also noticeable that the blunt leading edge injectors display a difference between the pressure coefficients for fuel injection into nitrogen test gas and no fuel injection with air test gas while the sharp leading edge injectors do not show this effect.

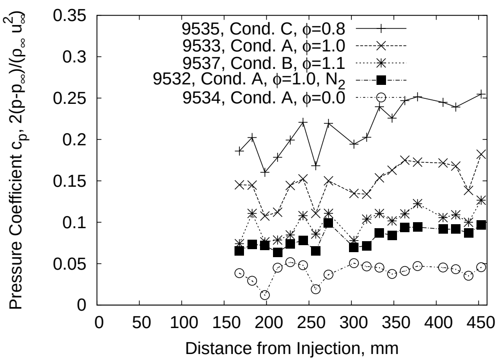


Figure 12: Pressure coefficient for long injector with blunt leading edge

Conclusions

Experiments and numerical simulations have been conducted to investigate the possibility of promoting ignition of hydrogen fuel injected into the boundary layer of a circular constant area combustor. Results show that a boundary layer that is allowed to grow for a longer distance promotes ignition of the injected hydrogen at lower stagnation enthalpies. This is of importance, since the boundary layers on flight vehicles will be growing for a long distance on the vehicle's forebody and the compression inlet. Flight vehicles will also have blunted leading edges in some way to cope with high stagnation point heat transfer rates and it was shown that a blunted leading edge dramatically enhances combustion for boundary layer injected fuel. The effects of the 0.5 mm radius leading edge bluntness were much more noticeable than those of the boundary layer thickness. However, especially since the duct investigated in this study was relatively small in diameter, the leading edge shocks had a large influence not only on the near wall temperature profile but also on the core flow in the combustor. It is also unsure whether the reflected leading edge shocks may have disrupted the boundary layer after fuel injection and caused mainstream mixing. This would increase the combustion efficiency and create a larger pressure rise in the duct but would not be desirable for the reduction of skin friction.

Acknowledgements

The support and funding by the Australian Research Council is greatly appreciated.

References

[1] Anderson, J. D., *Fundamentals of Aerodynamics*, McGraw-Hill Mechanical Engineering Series, McGraw-Hill Higher Education, 1221 Avenue of the Americas, New York, NY 10020, 2001, 3rd edition.

[2] Denman, A., *Large-Eddy Simulation of Compressible Turbulent Boundary Layers with Heat Addition*, Ph.D. thesis, Department of Mechanical Engineering, The University of Queensland, St Lucia, Queensland, Australia, 2007.

[3] Goyne, C. P., Stalker, R. J., Paull, A. and Brescianini, C. P., Hypervelocity skin-friction reduction by boundary-layer combustion of hydrogen, *Journal of Spacecraft and Rockets*, **37**, 2000, 740–746.

[4] Jacobs, P. A., MB_CNS: A computer program for the simulation of transient compressible flows, Departmental Report 10/96, Department of Mechanical Engineering, University of Queensland, St. Lucia, Qld., 1996.

[5] Korkegi, R. H., Lower bound for three-dimensional turbulent separation in supersonic flow, *AIAA Journal*, **23**, 1985, 475 – 476.

[6] Lentz, S., Preliminary investigation of viscous drag reduction on a scramjet combustion chamber, 1998, unpublished Report, Department of Mechanical Engineering, The University of Queensland, Brisbane, Australia.

[7] Lordi, J. A., Mates, R. E. and Moselle, J. R., Computer program for the numerical simulation of non-equilibrium expansions of reaction gas mixtures, NASA Contractor Report NASA-CR-472, NASA, 1966.

[8] McBride, B. J., Zehe, M. J. and Gordon, S., NASA Glenn coefficients for calculating thermodynamic properties of individual species, Technical Report NASA/TP-2002-211556, NASA John H. Glenn Research Center at Lewis Field, Cleveland, Ohio, 2002.

[9] McIntosh, M. K., Computer program for the numerical calculation of frozen and equilibrium conditions in shock tunnels, Technical Note CPD 169, Department of Supply, Australian Defence Scientifc Service, Weapons research Establishment, 1970.

[10] Paull, A., A simple shock tunnel driver gas detector, *Shock Waves*, **6**, 1996, 309–312.

[11] Paull, A., Stalker, R. J. and Mee, D. J., Experiments on supersonic combustion ramjet propulsion in a shock tunnel, *Journal of Fluid Mechanics*, **296**, 1995, 159–183.

[12] Rowan, S. A., *Viscous Drag Reduction in a Scramjet Combustor*, Ph.D. thesis, Department of Mechanical Engineering, The University of Queensland, St Lucia, Queensland, Australia, 2003.

[13] Stalker, R. J., Control of hypersonic turbulent skin friction by boundary-layer combustion of hydrogen, *Journal of Spacecraft and Rockets*, **42**, 2005, 577–587.

[14] Stephensen, D. J., Controlling skin friction by boundary layer combustion, Undergraduate engineering thesis, Department of Mechanical Engineering, The University of Queensland, St Lucia, Queensland, Australia, 2002.

[15] Suraweera, M. V., Mee, D. J. and Stalker, R. J., Skin friction reduction in hypersonic turbulent flow by boundary layer combustion, in *43rd AIAA Aerospace Sciences Meeting and Exhibit*, AIAA, Reston, VA 20191, United States, 2005, number AIAA 2006-613, 13411–13421, 13411–13421.

[16] van Driest, E. R., The problem of aerodynamic heating, *Aeronautical Engineering Review*, **15**, 1956, 26–41.