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# Fuel Stagnation Temperature Effects on Mixing with Supersonic Combustion Flows

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**An experimental study of the effect of fuel stagnation temperature on mixing in a supersonic hydrogen–air flame is described. The combustor consisted of a constant-area rectangular duct with a centrally located fuel-injection strut that spanned the width. A high-enthalpy stream of air was supplied by a free-piston shock tunnel, and heated hydrogen fuel, supplied by a gun-tunnel, was injected into the freestream as a coflowing planar jet. The freestream total enthalpies were 5.6, 6.5, and 9 MJ/kg, and fuel stagnation temperatures were 300, 450, and 700 K. Raising the fuel stagnation temperature increased the fuel velocity to be near that of the airstream and resulted in a decrease in the mixing rate. Even as the fuel and air velocities became equal, significant mixing still occurred because of a large difference in density. Increasing the freestream enthalpy reduced the difference between the initial air temperature and the adiabatic flame temperature, which in turn reduced the heat addition, and subsequently, the amount of pressure rise in the duct.**

## Introduction

IT is anticipated that future hypersonic air-breathing vehicles will use active cooling of the vehicle surface to maintain structural integrity. Cryogenic hydrogen is a likely fuel for such a vehicle because of its high heat capacity and energy density. The hydrogen will be used initially as the coolant for the vehicle structure and then injected into the combustors. Although the hydrogen is initially cryogenic, the active cooling raises its stagnation temperature significantly before injection. Given the expectation that active cooling will be used, there is a need for data on combustor performance with the fuel having a high stagnation temperature. Since most previous supersonic combustion studies have involved room-temperature fuel injection, a series of parallel-injection experiments was performed to investigate the effect of fuel temperature on supersonic hydrogen–air combustion in a duct. For stoichiometric mixtures, the mass flow rate of hydrogen is small compared to the air, and hence, the initial fuel temperature has little influence on the mixture temperature. It was therefore anticipated that only a subtle variation in ignition properties would occur. The study was therefore designed to concentrate on mixing rate effects where the increase in the initial fuel velocity, caused by the increase of fuel stagnation temperature, was anticipated to have a more significant effect. The freestream conditions, with total enthalpies of 5.6, 6.5, and 8.9 MJ/kg, were chosen to simulate those found in the combustion chamber of a scramjet vehicle flying at an altitude of 38–42 km with approximate flight Mach numbers from 11 to 14. The fuel stagnation temperature range of 300–700 K was chosen to simulate heat absorption from the vehicle structure. A practical fuel stagnation temperature limit has been suggested as 900 K in airborne or ground-based facilities.[1]

In Ref. 2, a review of the effect of the stagnation temperature on the mixing of freejets could establish no clear trend. Following that review, further experiments were performed, but it was concluded that the effect of changing only the jet stagnation temperature was insignificant. The low Mach number ($M \approx 2.2$) supersonic parallel-wall-injection experiments described in Ref. 3 demonstrated that heating the fuel increased its velocity, leading to a smaller difference in velocity between the fuel and air. The reduced velocity gradient through the mixing layer resulted in its reduced growth rate.

This paper discusses a set of high Mach number parallel-central-injection combustion experiments that examine the effect of fuel stagnation temperature on the mixing rate. The experiments were therefore designed such that the initial temperature of the airstream would be sufficient to result in ignition and recombination lengths for the fuel–air mixture that were small compared to the length of the duct. Thus, the flow was mixing-limited in nature. It was anticipated that an increase in mixing rate would result in an increase in the rate of wall pressure rise because the heat release processes will be dependent on the rate of fresh fuel (or oxidant) that is entrained into the mixing layer. Preliminary calculations have shown that, at conditions near the current study, the rate of large-scale entrainment is at least an order of magnitude slower than the molecular mixing rate,[4] and hence, transport by large-scale turbulent eddies is expected to be the rate-determining factor of the mixing process. Further, large-scale entrainment is expected to be dependant on the global parameters of the flowfield, and therefore, the current study will focus on these values.

## Experimental Apparatus

The experiments used a two-part duct of rectangular cross section (Fig. 1a). The first part of the duct (70 mm high by 51.3 mm wide by 150 mm long) cuts a section of flow from the freestream and the fuel was injected as a coflowing planar jet that spanned the width. Shock and expansion waves propagating from the leading-edge section of the injector strut were allowed to pass outside the duct. Wall pressure was recorded in the downstream part of the duct (30 mm high by 51.3 mm wide by 850 mm long), which contained the entire fuel jet and a 30-mm-high section of the airflow. Each transducer was calibrated in situ by first evacuating a small cavity above the transducer and then quickly releasing it to atmospheric pressure, thus producing precisely the same calibration pressure for all transducers. Each transducer's linearity had been tested

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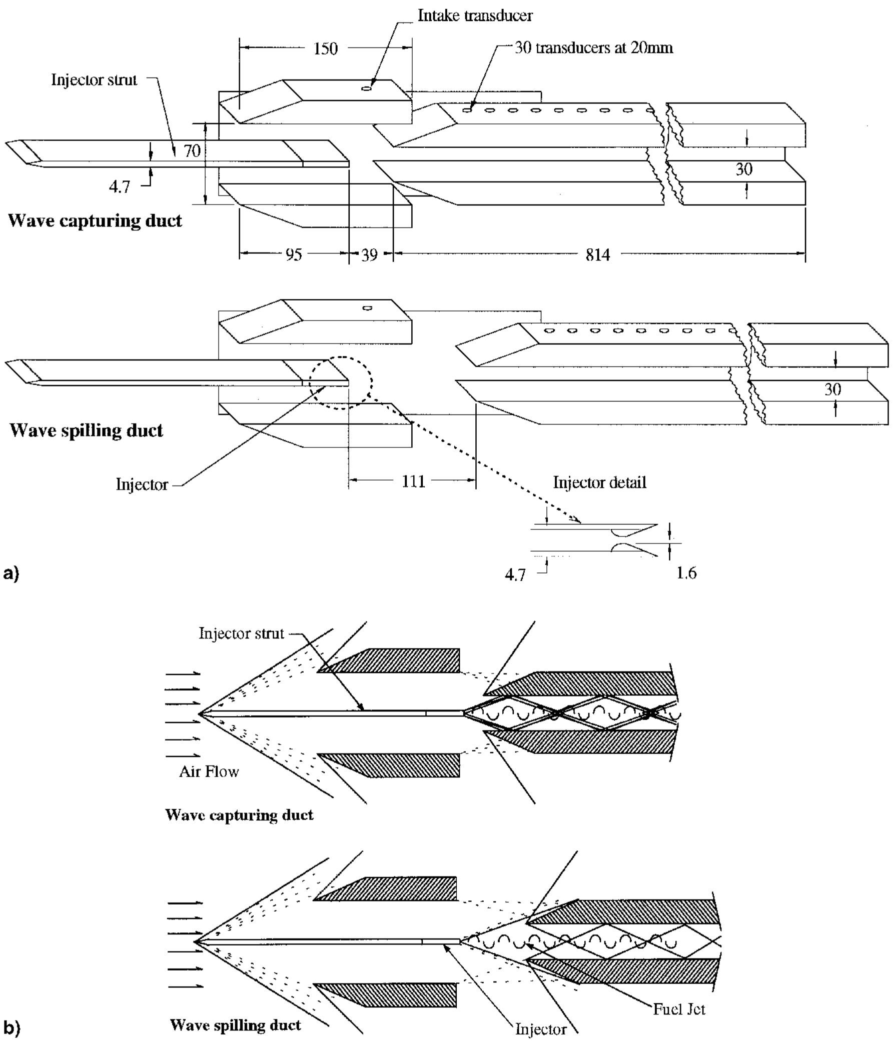


**Fig. 1 a) Oblique view of the wave-capturing and wave-spilling ducts with the side plates removed (all dimensions in millimeters) and b) cross-sectional view of the wave processes in the wave-capturing and the wave-spilling ducts.**

**Table 1 Freestream conditions**

| Condition | Test gas | H, MJ/kg | T, K | P, kPa | U, m/s | ρ, kg/m$^3$ | Mach no. | Dissociation products % | $\gamma_{equil}$ |
|---|---|---|---|---|---|---|---|---|---|
| A9 | Air | 8.9 | 1890 | 62 | 3500 | 0.11 | 4.3 | O ≈ 3, NO ≈ 6.3 | 1.31 |
| N9 | $N_2$ | 9.5 | 1850 | 58 | 3800 | 0.10 | 4.5 | N ≈ 0.27 | 1.31 |
| A7 | Air | 6.5 | 1480 | 66 | 3110 | 0.16 | 4.2 | NO ≈ 0.13 | 1.33 |
| N7 | $N_2$ | 6.8 | 1290 | 58 | 3230 | 0.13 | 4.5 | N < 0.1 | 1.33 |
| A6 | Air | 5.6 | 1230 | 65 | 2920 | 0.18 | 4.3 | NO < 0.1 | 1.34 |
| N6 | $N_2$ | 5.8 | 1110 | 59 | 3020 | 0.16 | 4.6 | N < 0.1 | 1.34 |
| Error | | ±12% | ±12% | ±15% | ±5% | ±10% | ±2.6% | O ± 16%<br>NO ± 0.5%<br>N ± 0.5% | ±0.6% |

previously and this was also taken into account in the error estimate. The largest component of the error in the wall pressure came from the variation in the measurement during the test time. The error was estimated as ±7% and was included in the figures.

The fuel jet was overexpanded because of a practical lower limit on the thickness of the injector strut. Expansion of the airstream toward the overexpanded fuel stream results in the formation of shocks in the fuel stream. This can result in enhanced mixing because the shocks lower the velocity of the fuel jet and increase the velocity difference between the fuel and airstream.[5] The downstream part of the duct could be moved axially to allow the waves propagating from the initial mismatch in pressures to be either captured or spilt as shown in Fig. 1b.

The freestream air conditions, shown in Table 1, were generated by the University of Queensland's free-piston shock tunnel T4. Equivalent conditions with nitrogen as the freestream gas were used to provide noncombusting control data. Typical pressure histories for the transient test flow produced by the shock tunnel are shown in Fig. 2 for the pressure transducer located in the inlet section of the duct (Fig. 1a). The duct wall pressure measurements were averaged from 1.2 to 1.4 ms after the flow had commenced. At the 1.2-ms point, approximately 5 duct lengths of flow had passed through the model, which allowed time for the boundary layers and mixing layers to reach steady state. In the 1.2–1.4 ms time interval, all air conditions had approximately the same static pressure, and thus, a comparison between conditions does not have to allow for a pressure effect on the results. Also, measurement with a mass spectrometer had shown that flow produced by the shock tunnel, at similar enthalpies to the current study, had less than 10% driver gas contamination up to 1.5 ms after the flow had started.[6]

A number of different methods exist to raise the stagnation temperature of the fuel. From a safety aspect it was desirable to minimize the duration for which the fuel remained hot, because the hydrogen was to be heated above its autoignition point. A gun tunnel (Fig. 3a) was chosen because it satisfied these criteria and was relatively inexpensive to construct. A high-pressure nitrogen reservoir (14.8 MPa) drives a light (0.02-kg) piston into a hydrogen-filled compression tube. The light piston allows fast acceleration and causes shock waves to form ahead of the piston in the hydrogen gas. The entropy rise through the shocks, combined with the compression heating, leads to a greater temperature rise than possible with an isentropic process of the same compression ratio. Unfortunately, with a heavy gas driving the piston into a light gas, the shock waves were fairly weak. The piston's low mass also allows a rapid deceleration. The initial deceleration results in an overpressure that bursts the 100-μm-thick mylar diaphragm that separates the compression tube from the combustion duct, and this allows the heated fuel to flow into the duct. After the initial overpressure, the piston oscillates rapidly until it reaches

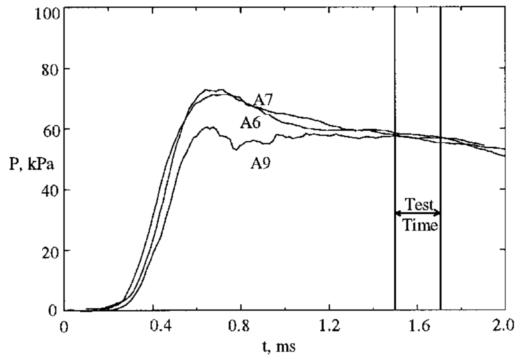


**Fig. 2 Typical static pressure vs time at the duct inlet.**

an equal pressure on both sides. The piston then moves forward to replace the fuel lost to the combustion duct.

The stagnation temperature of the fuel was measured by using a hemispherical thin-skin calorimeter placed at the exit of the gun tunnel. The surface temperature rise should be linear for a constant heat transfer rate,[7] and this is evident in Fig. 3b where the measured surface temperature $T_S$ is linear after the initial overpressure. The stagnation temperature of the hydrogen $T_0$ is calculated from the measured heat transfer rate and a pitot pressure measurement using a theory for blunt body heat transfer. In theory, for a compression heating process, the stagnation temperature should be a function of the stagnation pressure and Fig. 3b shows the stagnation temperature trace $T_S$, is similar in shape to the stagnation pressure $P_S$. Note that most of the noise on the stagnation temperature trace is caused by the coarseness of the digital signal, which leads to large instantaneous changes in slope. Further description of the equipment is available in Refs. 8 and 9.

## Results and Discussion

Figures 4 and 5 show the experimentally measured wall pressure for both the wave-spilling and wave-capturing ducts, respectively. The fuel stagnation temperature increases from left to right and the air enthalpy decreases from the top to the bottom of the figures. In all cases, an increase in the initial fuel or air temperature results in a decrease in the wall pressure in the duct. Either the velocity ratio between the air and fuel streams or the ratio $\rho_f U_f / \rho_{air} U_{air}$ is normally used to nondimensionalize the data.[10,11] However, in the current study with a fixed geometry and an equivalence ratio near unity, the ratio $\rho_f U_f / \rho_{air} U_{air}$ is approximately constant and the significant variation in the mixing rate observed in the experiments cannot be related to this parameter, even if the errors in the freestream conditions are taken into account. Most of the pressure distributions shown in Figs. 4 and 5 were linear with a least-squares correlation coefficient greater than 0.9 for the wave-capturing experiments and greater than 0.95 for the wave-spilling experiments. Figure 6 shows the least-squares slope as a function of the velocity ratio. The nominal velocity of the fuel used in Fig. 6 was calculated by isentropically expanding the fuel to

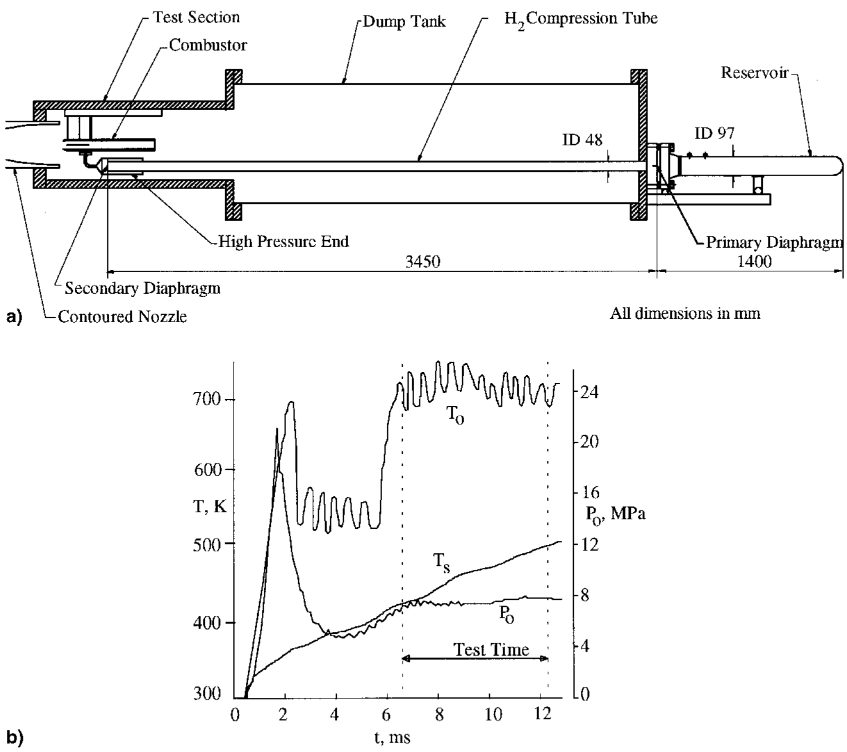


**Fig. 3 a) Layout of gun tunnel (all dimensions in millimeters) and b) stagnation temperature and pressure of gun tunnel vs time.**

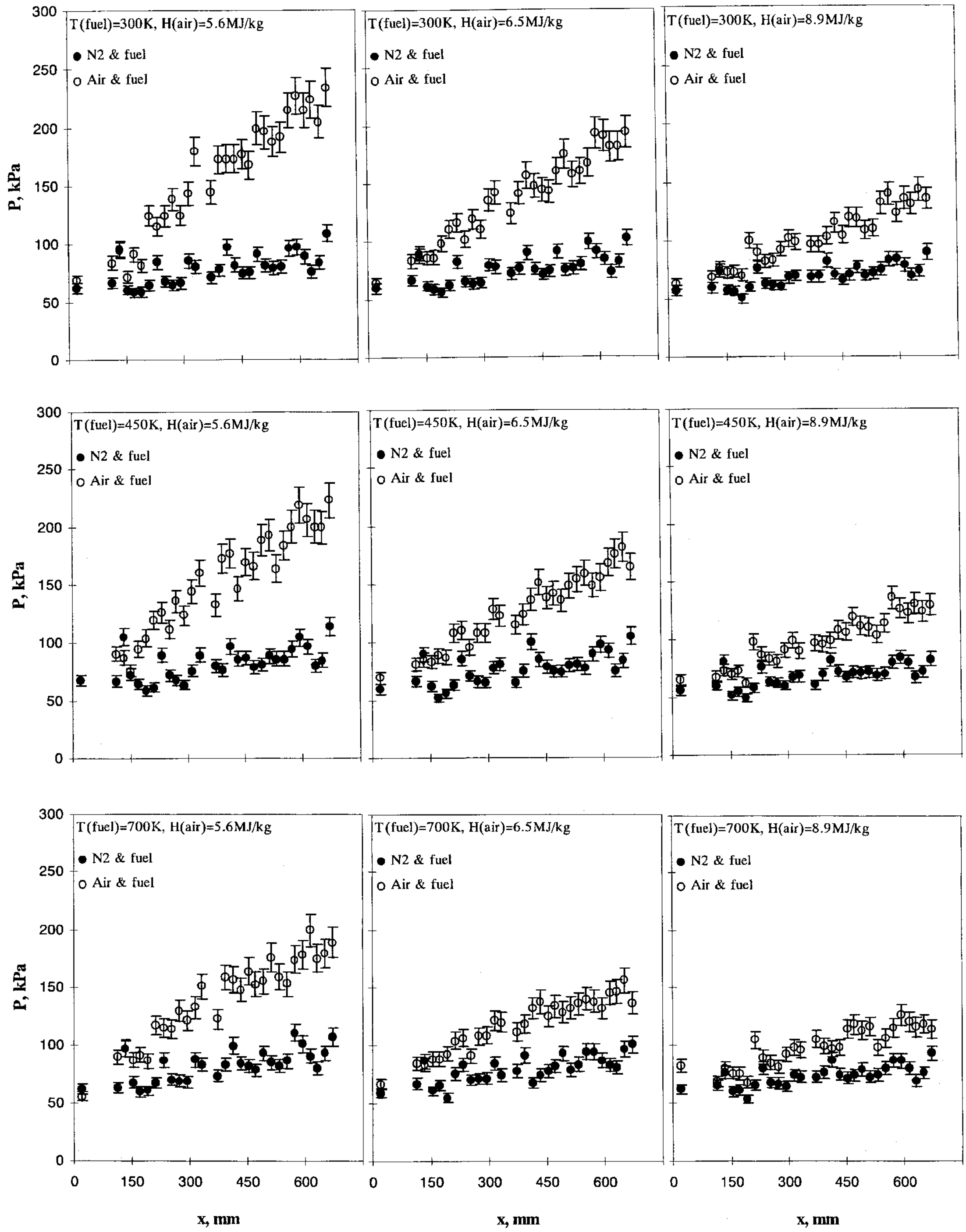


**Fig. 4 Wall pressure distributions for the wave-spilling duct.**

the width of the injector (Table 2) and then passing it through two equal angle oblique shocks so that the final fuel static pressure was the same as the airstream. The equal angle oblique shocks were to simulate the compression of the fuel stream by the airstream and the straightening of the flow at the centerline.

As the fuel stagnation temperature increases, the fuel velocity approaches that of the freestream. This reduces the velocity gradient within the shear layer, and consequently, the mixing rate. Although the error in the velocity ratio is significant, it is still clear from Fig. 6 that as the velocity ratio approaches unity the mixing rate approaches a minimum. It is important to note, however, that in contrast to some recently published observations,[11] significant mixing occurred when the velocity of the fuel and airstreams were similar in value. Coaxial flow experiments[12] have shown that when the velocity of the two streams are equal it is the large difference between the density of the two streams that drives the mixing. The difference in densities, at the equal velocity condition of the current study, is approximately an order of magnitude.

Figures 7a and 7b show calculations for the adiabatic flame temperature and total heat release at the given initial conditions.[13] These calculations were performed by calculating the equilibrium heat release at various equivalence ratios. It was assumed that equilibrium combustion at an equivalence ratio of 0.5 gave the same quantity of heat release as equilibrium combustion at an equivalence ratio of 1 with only 50% of the fuel burned where 100% represents a stoichiometric mixture. That is, the mass of unburnt fuel was assumed to have little effect on the degree of combustion. Although the use of excess

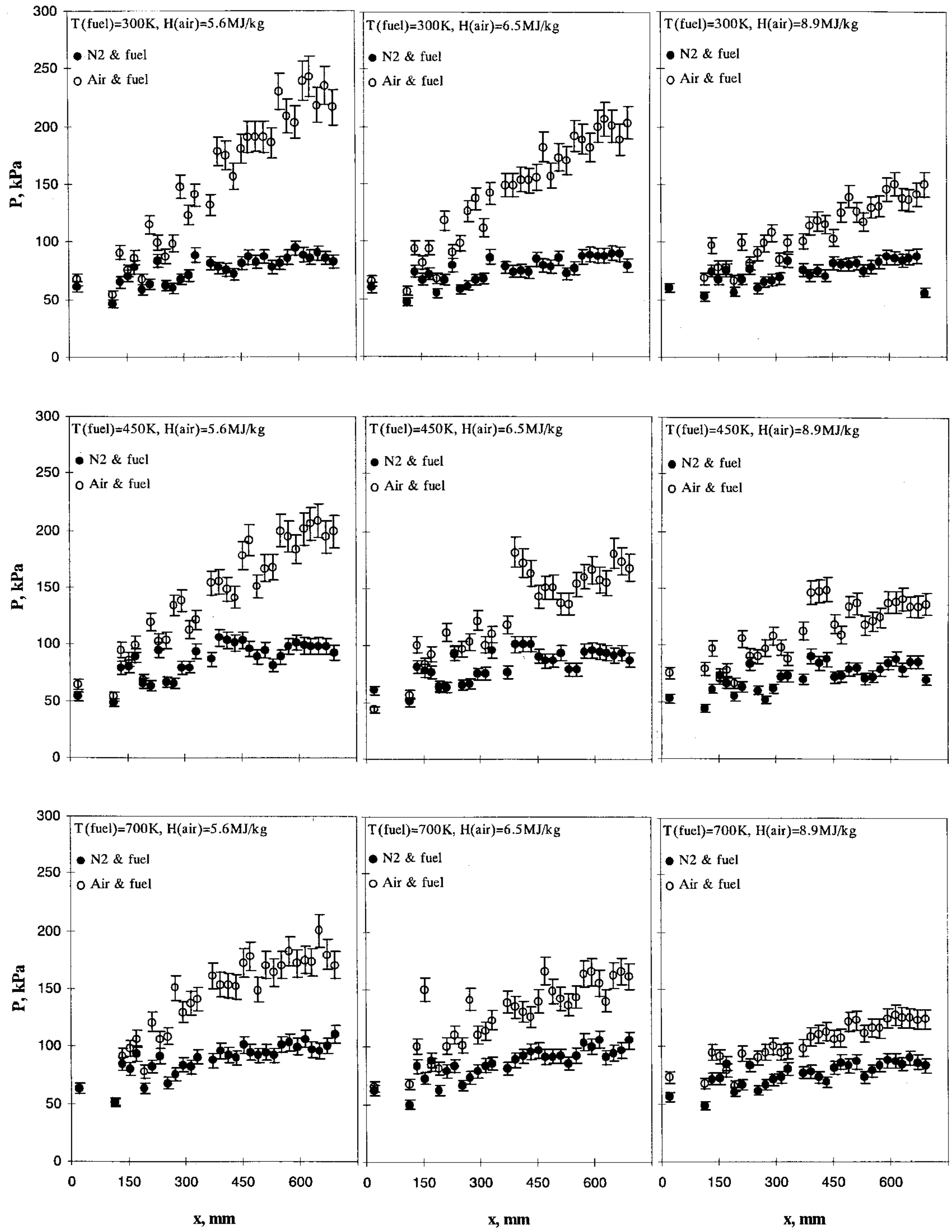


**Fig. 5 Wall pressure distributions for the wave-capturing duct.**

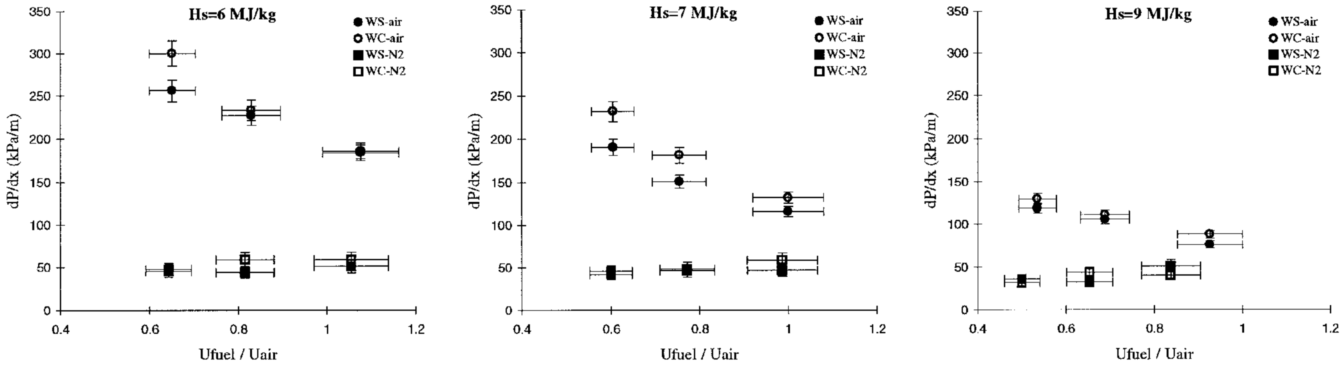


**Fig. 6 Effect of velocity ratio on the rate of pressure rise.**

Table 2 Fuel-stream conditions[a]

| Condition | $T_0$, K | $T$, K | $P$, kPa | $U$, m/s | $\rho$, kg/m$^3$ | Mach no. | $\gamma$ |
|---|---|---|---|---|---|---|---|
| A9/N9 | 300 | 120 | 14 | 2300 | 0.029 | 2.81 | 1.4 |
| A9/N9 | 450 | 140 | 10 | 2990 | 0.018 | 3.31 | 1.4 |
| A9/N9 | 700 | 240 | 15 | 3660 | 0.016 | 3.13 | 1.4 |
| A7/N7 | 300 | 120 | 17 | 2290 | 0.034 | 2.76 | 1.4 |
| A7/N7 | 450 | 150 | 12 | 2950 | 0.02 | 3.2 | 1.4 |
| A7/N7 | 700 | 260 | 22 | 3560 | 0.02 | 2.90 | 1.4 |
| A6/N6 | 300 | 120 | 18 | 2280 | 0.037 | 2.75 | 1.4 |
| A6/N6 | 450 | 170 | 21 | 2820 | 0.03 | 2.82 | 1.4 |
| A6/N6 | 700 | 280 | 27 | 3489 | 0.024 | 2.75 | 1.4 |
| Error | ±15% | ±12% | ±15% | ±4% | ±10% | ±3% | ±0.5% |

[a]Expanded to injector height.

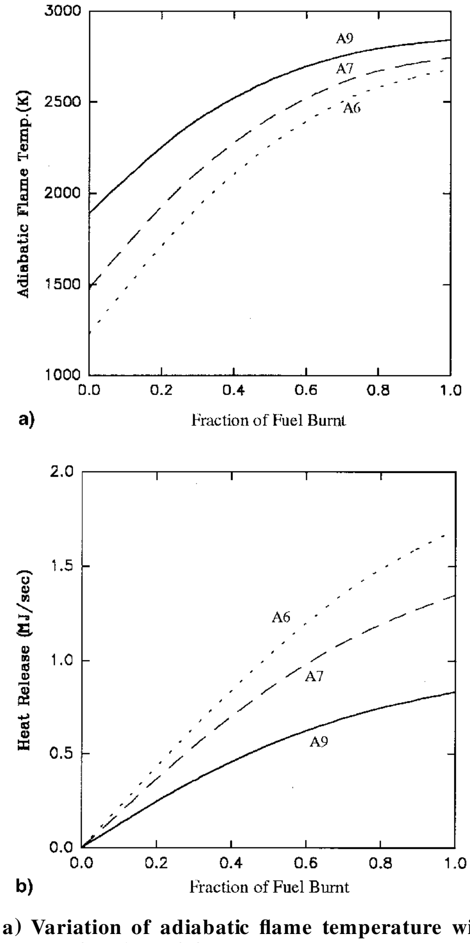


**Fig. 7 a) Variation of adiabatic flame temperature with initial conditions and fraction of fuel burnt. The labels correspond to Table 1 and b) variation of heat release with initial air temperature and fraction of fuel burnt.**

fuel to lower the flame temperature and enhance complex molecule formation have been well documented, this usually involves quantities of fuel well in excess of stoichiometric mixtures. The effect of excess fuel on the initial mixture temperature was less than 1% for each case because the mass flow rate of hydrogen fuel was less than 3% of the air mass flow rate. Figure 7a shows that the highest and lowest enthalpy conditions have similar final flame temperatures when all of the fuel has burnt, because the flame temperature is approaching the limit where complex molecules have difficulty in forming. Figure 7b shows that this results in a significantly higher heat release for the lowest enthalpy case and is consistent with the greater pressure rise shown by the lower enthalpy results in Fig. 6.

To examine the effect of the waves from the overexpanded fuel jet on the wall pressure, the combustion section of the duct was moved downstream to allow the waves emanating from the injector trailing edge to spill, as shown in Fig. 1b. The measured wave-spilling pressure rise in the duct was on average 10–15% lower than the wave-capturing duct. Given that the nitrogen results show similar levels of pressure rise for each duct, it is postulated that the increase in pressure in the wave-capturing duct is not caused by a lowering of the Mach number by the extra shock waves present, but rather by enhanced mixing caused by these waves.

## Conclusions

In conclusion, the experiment with the lowest enthalpy air condition and the coldest fuel injection produced the highest duct exit pressure. Increasing the fuel stagnation temperature increased the fuel velocity, which resulted in a reduced velocity gradient through the mixing layer, and hence, a reduced mixing rate. These results were consistent with low Mach number parallel-wall-injection literature. Differences in the rate of pressure rise between the air conditions were shown to be a result of all the flows tending toward similar final flame temperatures. This resulted in a smaller heat release for conditions with a higher initial freestream temperature. Significant mixing and combustion occurred when the fuel and airstream velocities were matched. Previously published results suggest that this mixing was generated by the order of magnitude difference in the densities of the air and hydrogen streams.

Finally, we comment that when accurate simulation of flight operation is desired, mixing and combustion experiments should use heated fuel as the reduction in the mixing rate, this can result in up to a 40% reduction in duct wall pressure in a combustor of given length. The implication for scramjet-powered vehicles, which must rely on the heating of the fuel to maintain the structural integrity of the engine structure, is the need for longer combustion chambers. However, there is a penalty to pay as the high density and velocity in a supersonic combustion chamber results in a large skin friction drag, which can be a significant proportion of a slender vehicle's total drag. Although it is possible to reduce the axial component of the fuel stream to minimize the increase in velocity, the importance of the fuel momentum to the overall thrust has been well documented. The most promising solution is to design the injection system to generate axial vorticity so that the relative velocities of the fuel and air are not so important.

## Acknowledgments

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