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Parallel Hydrogen Injection into Constant-Area, High-Enthalpy, Supersonic Airflow

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Introduction

In principle, the supersonic combustion ramjet offers a means of propulsion for future orbital launch vehicles, and for this purpose, it will be necessary to operate at flight speeds up to 6 km/s. Although mixing and burning of hydrogen injected into the combustion chamber are an essential part of the operation of such a scramjet, experimental investigations of this process have been limited to speeds of less than 2.2 km/s.[1] The experiments reported here were aimed at extending this limit, and were performed at stagnation enthalpies up to 13 MJ/kg, corresponding to a flight speed of approximately 5 km/s.

Experiments

The experiments were conducted in the Free-Piston Shock Tunnel T3[2] at the Australian National University. The tunnel was operated in the reflected shock mode and expanded the shock-heated test gas, from the stagnation region at the downstream end of the shock tube, through a conical nozzle with included divergence angle of 15 deg and an area ratio of 13, to a freejet test section.

The model combustion duct was designed to produce a flow that was essentially two-dimensional. A streamwise section of the duct is shown schematically in Fig. 1. It was of rectangular cross section, 25×50 mm, with the greater dimension horizontal. The intake had sharp leading edges and was located at a point in the test section flow where the Mach number was 3.5 and the static pressure approximately 120 kPa. The hydrogen injector strut had a sharp leading edge, with an included angle of 20 deg, and completely spanned the duct. The injection nozzle was two-dimensional, with a throat width of 1.6 mm, and produced a uniform spanwise mass flow distribution. From a point 18 mm downstream of the nozzle, the sidewalls were made of optical-quality glass.

Hydrogen injection was controlled by a quick-opening valve, which produced a steady flow of hydrogen for 10 ms. By proper timing of the valve trigger, it was arranged that the steady flow of hydrogen was established prior to arrival of the test flow.

Mach-Zehnder interferograms were taken with a light source of 583 nm wavelength and 5 ns duration. Surface pressures also were obtained on the lower surface of the duct, using PCB quartz pressure transducers.

Results and Analysis

The time-resolved pressure records indicated that steady flow was established by 350 μs after shock reflection at the highest stagnation enthalpy tested and by 500 μs at the lowest. Pressure distributions were obtained approximately 100 μs after these times and are presented in Fig. 2.

As shown in Fig. 2a, flow disturbances from the injector gave rise to irregularities in the pressure distribution in the absence of injection, and these persisted when injection took place. Nevertheless, by obtaining the ratio

$$\Delta p = (p_i - p_0)/p_0$$

where p_i and p_0 are pressures with and without injection, respectively, an approximate measure of the pressure rise due to combustion was obtained. This is plotted in Figs. 2b-e. For Figs. 2b-d, estimated airstream temperatures were in excess of 2000 K, and ignition delay times were less than reaction times, which were less than 10 μs (Ref. 3) compared with airstream duct transit times of approximately 50 μs. Therefore, a significant degree of reaction occurred. For Fig. 2e, airstream temperature was 1000 K, ignition delay times were of the order of 100 μs (Ref. 3), and reaction did not take place. The distribution of Δp therefore was similar to that obtained when hydrogen is injected into a nitrogen stream.

Estimates of combustion-induced pressure rise were made, based upon a simplified diffusion flame theory.[4] Pressure gradients were neglected, only the reaction

$$2H_2 + O_2 \rightleftharpoons 2H_2O$$

was considered, and it was assumed that this took place at an infinitely thin flame front. Development of the two-dimensional turbulent jet downstream of the injector was first calculated on the assumption that the density remained

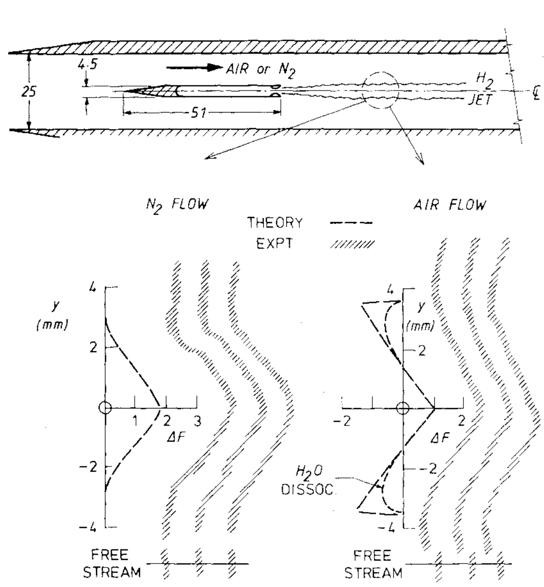

Fig. 1 Injector configuration and jet fringe shifts (stagnation enthalpy = 13 MJ/kg, equivalence ratio = 0.8, ΔF = fringe shift − freestream fringe shift, y = distance from centerline).

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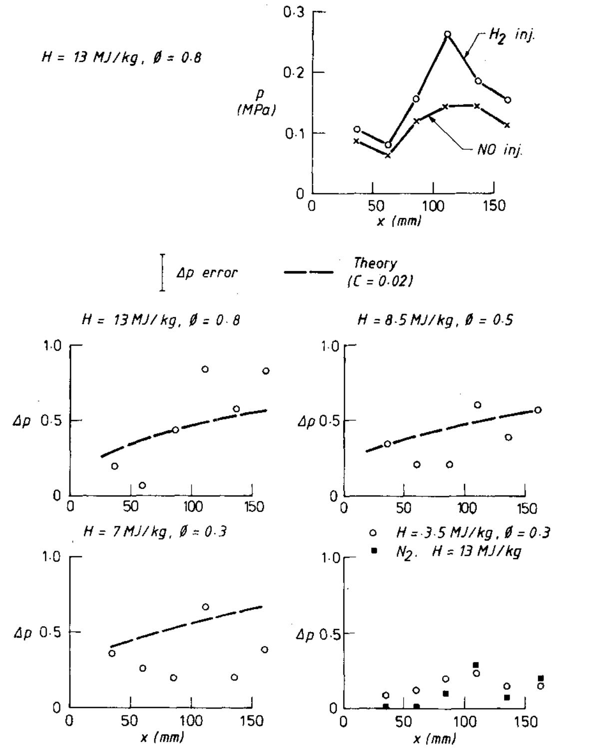

Fig. 2 Combustion-induced pressure distributions (H = stagnation enthalpy, x = distance downstream of injector).

constant at the freestream value, the velocity profile was linear from the centerline to the edge of the jet, and the turbulent eddy viscosity was given by

$$\epsilon = C\delta(u_e - u_m)$$

where u_e and u_m are freestream and centerline velocities, respectively, and C is a constant. At the edge of the jet, δ was put equal to half the width of the jet, and midway between the edge and the center, equal to 0.25 of half the width. The actual density distribution was then calculated by assuming that the Schwab-Zeldovich variables $[c_H + (C_pT + \frac{1}{2}u^2)/\Delta H]$, $(c_O + 8c_H)$, and $(c_O + 0.89\ C_w)$ varied linearly with the velocity. Here T and u are the temperature and velocity; C_p is the specific heat at constant pressure; ΔH is the heat of combustion; and c_H, c_O, and C_w are the mass fractions of H_2, O_2, and H_2O, respectively. Using this density together with the Howarth transformation, it was possible to calculate the displacement thickness of the jet and then, by assuming one-dimensional flow outside the jet, to make an estimate of the pressure rise associated with this displacement thickness.

As a check on the validity of this model, it was used to calculate the fringe shift profile across the jet, as observed by the interferometer at a station 33 mm downstream of the injector. Results are compared with experiment in Fig. 1. The fringe shift profile is adequately predicted for injection into nitrogen flow, when no reactions occur, but when combustion takes place, the strong negative fringe shift that is predicted near the flame front does not occur. As shown in the figure, better agreement can be obtained when dissociation of H_2O in this region is taken into account, especially when it is remembered that the discontinuous change in velocity gradient at the edge of the jet, which is assumed by the theory, is smoothed out to a more gradual change in practice. Taking account of H_2O dissociation changed the displacement thickness by less than 10%, and so this effect was ignored in the calculations.

The pressure distributions calculated by this analysis are presented in Fig. 2. The value of 0.02 for C was suggested by examination of low-speed data,[5] but the results indicate that, at least when the hydrogen injection velocity is much less than that of the freestream, as in these experiments, the same value may be used to obtain rough estimates of jet combustion behavior at high speeds.

Acknowledgment

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Curvature Effects on Heat Transfer in the Free Jet Boundary

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Introduction

A GREAT deal of attention has been given to free jet flows where a pressure differential across the flow profile causes the stream to curve and attach itself to an adjacent wall. Such behavior by the jet is commonly referred to as the "Coanda" effect in fluidic devices, but these fields are also known to exist in flows associated with velocity discontinuities around airfoils. Instances exist as well where high temperatures and thermal radiation can be evident in these flows so that it would be of interest to discover how heat transfer capabilities in the thermal boundary layer are affected by curvature.

A physical interpretation of the steady, two-dimensional, incompressible flowfield and the boundary conditions which apply can be visualized as follows. The moving fluid which has already established a fully developed flow profile possesses a freestream velocity U_{max} and a bulk fluid temperature T_∞ before it reaches a region of stagnant fluid, which has velocity $u = 0$ and a bulk fluid temperature T_s. A short distance, x_0, beyond this point of issue where the curvature is R_0, entrainment of the stagnant fluid causes alteration of the velocity and temperature profiles such that at large negative values of y $(y \to -\infty)$, $u = 0$ and $T = T_s$.

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