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EXPERIMENTS ON A SIMPLE SCRAMJET MODEL

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SUMMARY The results of a shock tunnel study of the performance of a 2 dimensional scramjet combustion chamber and exhaust nozzle are presented. Thrust measurements were obtained with combustion chamber inlet static temperatures ranging from approximately 700 to 3500 K. Inlet Mach number and pressure were approximately constant at 3.5 and 1 bar respectively for all test conditions and the equivalent flight speeds ranged from 2.5 km/s to 5 km/s. A dramatic ignition phenomenon was observed between 700 and 900 K when the specific impulse rose from zero to values exceeding 1000 sec. At higher temperatures the specific impulse dropped again reaching values of 500 sec at 3000 K. This is shown to be consistent with calculations performed for one dimensional equilibrium flows and comments are made on the significance of these results for flight propulsion.

1 INTRODUCTION

A scramjet, Ferri (1973), is an air breathing engine designed to operate at high speeds and high altitudes. Ambient air is compressed through the engine intake and is supplied to a combustion chamber where the injected fuel mixes and burns spontaneously with the shock heated supersonic flow. The combustion products are expanded through an exhaust nozzle which produces the thrust.

Potentially the scramjet may operate at flight speeds up to 6 km/sec, Swithenbank (1967), Ferri (1973), but it has not yet been studied experimentally at speeds in excess of 2.2 km/sec. In this paper experiments are reported in which a shock tunnel is used to study a two dimensional scramjet combustion chamber and exhaust nozzle at conditions equivalent to flight speeds up to 5 km/sec.

At the flight speeds and air densities corresponding to scramjet flight, high volumetric flow rates to the combustion chamber are required, and this necessitates large intake and exhaust geometries. If a scramjet is to be competitive with rocket propulsion, then the reduction in take off weight produced by not having to carry an oxidiser must not be offset by the additional engine mass required. For this reason current concepts for scramjet propulsion, Henry and Anderson (1972), envisage an engine integrated with an air frame which provides the intake and exhaust nozzles. A schematic of such a system is shown in Fig. 1. A bow shock from the leading edge compresses the incoming air before it enters the combustion chamber. The exhaust nozzle is formed by the air frame after body, and the expansion must start before mixing and combustion of the fuel are complete in order to minimise overall dimensions and weight. Thrust is produced by the interaction of the reacting flow with the expansions propagating from the exhaust nozzle countour, and this is the region of interest to the present study.

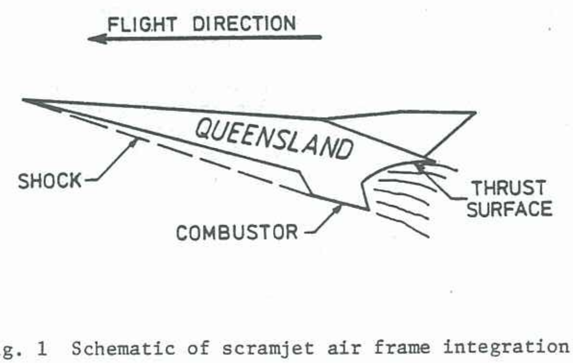


Fig. 1 Schematic of scramjet air frame integration

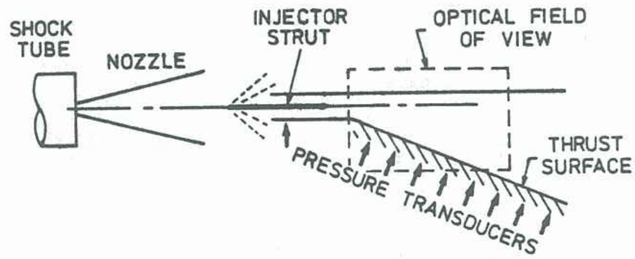


Fig. 2 Schematic of experimental equipment

2 EXPERIMENTS

The experiments were performed in the ANU free piston shock tunnel T3, Stalker (1972), which supplied shock heated test gas to the combustion chamber intake through a conical nozzle. A schematic of the experimental set up is shown in Fig. 2.

The model was two dimensional with an internal width throughout of 50 mm, and consisted of a constant area section where hydrogen fuel was injected parallel to the free stream flow, followed by an asymmetric exhaust nozzle. The upper surface of the exhaust nozzle was parallel to the intake, and the thrust surface was straight and could be set to any desired divergence angle up to 20°. The thrust surface was instrumented with PCB pressure transducers, and another transducer on the intake monitored the inlet pressure. The pressure traces were recorded on a digital data store and processed on a microcomputer to yield the total thrust in the exhaust nozzle. The difference between fuel-on and fuel-off total thrusts was taken as the net thrust due to fuel injection. The model walls were fitted with optical glass so that schlieren photographs of the flow could be taken.

Hydrogen was injected uniformly across the duct from a strut located midway between the upper and lower surfaces of the constant area section. The hydrogen supply was controlled by a pulsed valve described by Morgan and Stalker (1983).

The experiments were performed for a range of intake conditions with static temperatures ranging from 700 K to 3500 K. The conditions at intake are presented in Table 1 and were calculated using a one dimensional nozzle program, Lordi, Mates and Moselle (1966). For each shock tunnel operating condition the thrust was measured over a range of equivalence ratio and exhaust nozzle divergence angle.

3 RESULTS

To understand the significance of the results it is helpful to compare the specific impulse measured to that which would be achieved in the 'ideal' case of a one dimensional premixed hydrogen and air flow expanding through the same area ratio with equilibrium combustion throughout. However, because of the two-dimensional nature of the flow, there is some difficulty in defining the effective area ratio applying at any given cross section in the nozzle.

Fig. 3 shows a schematic of the flow field in the presence of hydrogen injection as determined by schlieren photography. The expansion produced by the exhaust nozzle starts at the corner and propagates into the flow as a Prandtl-Meyer expansion fan. When the expansion reaches the hydrogen jet the density gradients encountered cause it to partially reflect as a compression. The effects of the compression accumulate over the fan so that a strong compression wave is produced which propagates back to the thrust surface. When the compression wave reaches the thrust surface it reflects back into the flow with the result that downstream wall static pressures increase. This effect produces a larger thrust than would be realised in the fuel-off case.

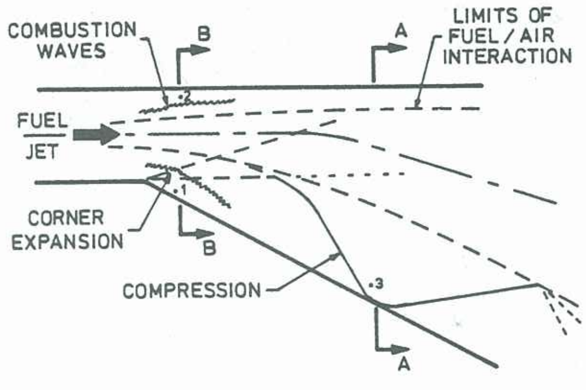


Fig. 3 Fuel on flow field

TABLE 1 TEST CONDITIONS

INTAKE TEMPERATURE K	INTAKE PRESSURE kPa	INTAKE VELOCITY km s^{-1}	STAGNATION ENTHALPY MJ kg^{-1}
3500	103	4.18	15.4
3040	114	3.76	12.1
2370	124	3.30	8.7
1790	132	2.88	6.1
1160	99	2.46	4.3
1010	93	2.34	3.8
900	92	2.23	3.4
670	75	1.98	2.7

Thrust is also increased due to compression waves produced by the expansion of the jet cross section due to combustion, but the interaction of the corner expansion with the fuel jet is the main thrust producing mechanism.

Consider the section BB, Fig. 3, taken just downstream of the corner. The nominal area ratio based on duct height is small, however streamtubes passing through point 1 will have experienced the full effect of the corner expansion and would see a large local area ratio. Conversely point 2 on the same transverse section will not have been affected by the expansion and would see a local area ratio of 1. Intermediate points on section BB within the expansion fan will see varying local area ratios. The wall static pressure at section BB is not affected by the presence of the jet, but the section is contributing to the net thrust through the compression which is propagating towards the thrust surface and which increases downstream pressures. Any comparisons made of the measured net thrust upstream of section BB with the ideal net thrust produced by expansion through the geometrical area ratio at BB would therefore be misleading.

A theoretical technique is used to modify the experimental results and to calculate an effective area ratio so that a useful comparison can be made with an ideal expansion. It is first noted that an ideal one dimensional expansion produces a uniform, parallel outlet flow from the exhaust nozzle, and therefore can be compared with a two dimensional contoured nozzle which produces the same outlet flow. The area ratio of the nozzle is determined by the initial thrust surface divergence angle. When the fuel jet is introduced, reflection of compression waves from the nozzle surfaces would produce a non-uniform outlet flow.

However, it would be possible to use experimental surface pressure measurements to calculate how to modify the profile of the thrust surface so that whenever a compression reaches the surface it is cancelled out and no reflection is produced. This would change the thrust produced by an amount which can also be calculated from the surface pressure measurements, and it would change the jet flow downstream of the point where the reflected compression from point 3, Fig. 3, interacts with the fuel-air mixing region. However, it is noticed experimentally that no net thrust is produced downstream of the point where the reflected compression from point 3 interacts with the jet. Therefore it is concluded that the thrust producing portion of the jet would not be affected by the change in contour. The contour adjustments would produce uniform, parallel outlet flow, and for the conditions of the experiments, are found to be of a magnitude such that they change the nozzle area ratio by less than 10%. Incorporating these changes, the calculated thrust for a contoured nozzle can then be directly compared with the premixed equilibrium combustion over the same area ratio.

These arguments can be extended to apply to the straight nozzle used in the experiments and it can be shown that the calculated net thrust, as obtained above for a contoured nozzle is equal to that for a straight nozzle. Thus the measurements on the straight nozzle can be used to obtain a calculated net thrust which can be compared with an ideal expansion.

The results are presented in terms of the internal jet specific impulse, derived from the calculated net thrust values. Also shown is the internal total specific impulse, calculated from the difference in fuel on and fuel off thrusts measured for the straight profile.

The first series of experiments were performed over a range of divergence angles to ascertain which condition produced maximum thrust. For these tests the distance from the hydrogen injector nozzle exit to the start of the corner expansion fan was fixed at 5 cm. These results are presented in Fig. 4 for inlet static temperatures of 3040 K and 2400 K at an equivalence ratio of 1. Also shown in Fig. 4 is the specific impulse predicted by the premixed equilibrium theory.

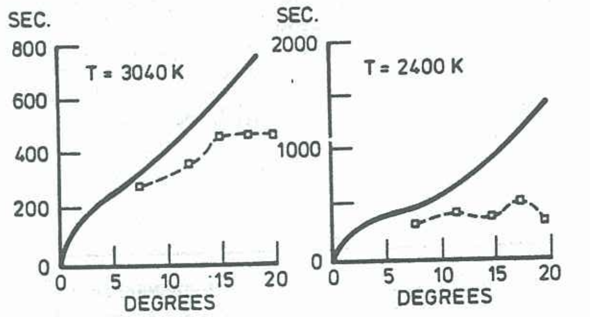


Fig. 4 Internal jet specific impulse/divergence

The experimental results follow the shape of the equilibrium curve up to approximately 18°, above which the measured specific impulse begins to fall. The behaviour is explained by noting that, as the divergence angle increases, the expansion fan extends downstream, interacts with a larger section of the jet and so produces more thrust. However, this is partially offset by the fact that the increased thrust surface angle weakens the reflected compression. At large angles of divergence the second effect dominates, causing the experimental results to drop away from the equilibrium theory.

A fixed divergence angle of 15° was chosen for the remaining experiments in which inlet conditions and equivalence ratio were varied. These results are summarised in Fig. 5 for an equivalence ratio of 1. Two sets of experimental data are presented, corresponding to constant area mixing lengths of 5 cm and 20 cm between injection and the start of the corner expansion fan.

For the 5 cm mixing length the internal jet specific impulse rises from zero at 900 K inlet static temperature to a value of 600 sec at 1160 K. A similar effect is observed for the 20 cm mixing length where the internal total specific impulse rises from zero at 700 K to 1300 sec at 1000 K. Only the internal total specific impulse is shown for the 20 cm mixing length, as the large pressure rises in the constant area section meant that the jet specific impulse could not be calculated.

At low temperatures the ignition delay time increases and the duct transit time is not sufficient for significant combustion to take place. Increasing the mixing length allows more time for combustion and therefore combustion can be maintained at a lower inlet temperature. For given inlet conditions combustion will be more complete with the extended mixing length and this explains the higher thrusts produced.

The highest measured specific impulse for the short mixing length is less than the premixed equilibrium values due to incomplete fuel and air mixing, and also due to the incomplete combustion produced by finite reaction rates. As the temperature rises reaction rates increase and the combustion process approaches equilibrium. However dissociation of combustion products reduces the available heat release and the net result is that specific impulse is approximately constant between 1800 K and 3500 K. At high temperatures combustion is nearly complete with the short mixing length and no thrust increase is expected or measured with added mixing length. However the failure of the mixing length to increase thrust at 2400 K where the experimental results are far from the equilibrium values is as yet unexplained.

At higher temperatures a lower hydrogen mass flow rate is required to maintain a stoichiometric mixture and mixing takes place within a shorter downstream distance from injection. This is thought to explain the fact that the experimental results agree well with the equilibrium predictions at higher temperatures.

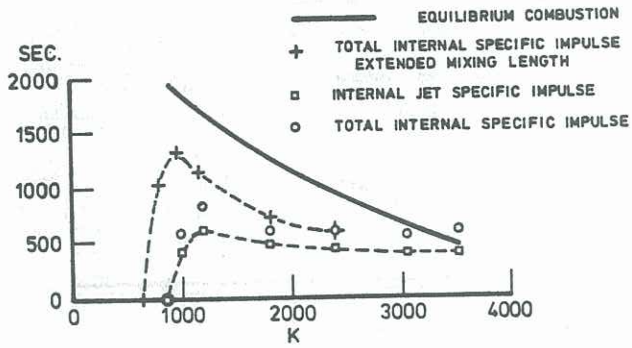


Fig. 5 Specific impulse/inlet static temperature

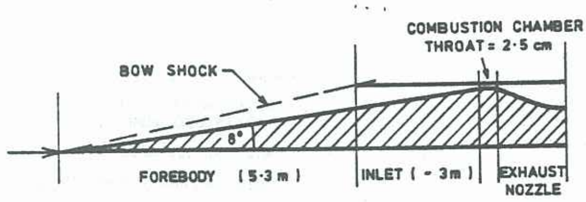
4 CONCLUSIONS

The experiments have shown that a simple two-dimensional scramjet model can produce useful thrusts at conditions corresponding to flight speeds up to Mach 16. Because of the two dimensional nature of the flow, thrust levels are higher than would be predicted by a one dimensional equilibrium combustion model based on the geometrical expansion ratio. This is the most significant finding of the work to date. Previous parametric studies of a scramjet propelled vehicle have assumed dimensions allowing for complete combustion followed by a gradual one dimensional expansion to achieve the full potential thrust. This leads to a very large and heavy engine which could not form a practical propulsion system. The possibility of developing thrust in a compact combustion chamber-exhaust nozzle configuration would change the situation.

Approximate calculations have been made for the two dimensional scramjet shown in Fig. 6. Viscous forces have been neglected and an intake kinetic efficiency of 0.98 was assumed. Conditions corresponding to Mach 12 flight at an altitude of 40 km were used, and the intake geometry was chosen so that a temperature of 2000 K, a Mach number of 3.5 and a pressure of 1 bar would be achieved in the combustion chamber. The duct height was the same as used in the shock tunnel model so that a direct comparison with the experimental results may be made.

The calculations show that a specific impulse of 600 sec would be sufficient to offset the net drag and maintain flight speed. The experimental results with a short mixing length achieved a specific impulse of 450 sec with a combustion chamber intake temperature of 2000 K. When the thrust contribution from the momentum of the injected hydrogen jet is added, appriximately 170 sec, a specific impulse in excess of 600 sec is realised.

If these results were reproduced under real flight conditions then a scramjet propulsion system could produce enough thrust to maintain Mach 12 flight at an altitude of 40 km. Bearing in mind that these results were obtained using the simplest possible model, then the prospects for developing an optimised nozzle geometry and injection system which approached the idealised performance are good. The problem of low theoretical specific impulse at high temperatures remains. The probable solution would be to raise the combustion chamber intake Mach number by adjusting the geometry at high speeds so that the intake temperature can be kept below 2000 K. No facility exists at present to provide experimental data under these conditions.



MACH 12 PRESSURE DRAG AT 40 Km ALTITUDE:

	(N PER M WIDTH)
Forebody drag	1140
Intake drag	4340
Fuel off nozzle thrust	-3820
Net fuel off drag	1660

Specific impulse of 600 sec required to off set drag

Fig. 6 Approximate scramjet model

These calculations illustrate some of the engineering problems that would confront the application of a scramjet propulsion system. For a scramjet combustion chamber height of 2.5 cm, which might produce a net thrust of 1500 - 2000 Newtons per metre width, an overall aircraft length in excess of 8 m is required. To maintain an acceleration of ½ G then the total mass including fuel remaining at an altitude of 40 km, thermal protection system, payload etc. would have to be kept below 400 kg per metre width. The major component of the drag is produced in the intake, the design of which is likely to be critical.

If a scramjet could be developed to produce specific impulse above 1000 sec from Mach 3 to 20, and if it could be successfully integrated into the air frame structure with the compact exhaust nozzle geometry suggested by this paper, then the potential would exist for a single stage to orbit vehicle.

5. REFERENCES

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