A Study of Supersonic Combustion of Hydrogen Injected Transversely into a Vitiated Airstream

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Abstract:

An experimental study of supersonic combustion of gaseous hydrogen injected transversely into a vitiated airstream has been carried out. The ignition and performance characteristics of the hydrogen fuelled stepped combustor have been determined. In addition to supersonic hydrogen diffusion flames, hydrogen-aided supersonic kerosene diffusion flames have also been stabilised in the stepped combustor. The flow pattern in a simulated supersonic stepped combustor has been studied. A simple one dimensional gas dynamic approach for heat addition in a sudden expansion has been used to predict the behaviour of the performance characteristics.

Introduction

There have been serious efforts in recent years, both in India and abroad, to develop advanced airbreathing propulsion systems. One such programme is underway at DRDL, Hyderabad to develop a hydrogen fuelled supersonic combustor (Scramjet) for the Hyperplane, which is fully reusable single-stage-to-orbit hypersonic vehicle.

A typical supersonic combustor will have stepped walls followed by a divergent section. Fuel (hydrogen) will be injected transversely from the walls at different locations ahead and/or after the step or from immersed struts. It is clear that a complex flow field will result in such a combustor due to the presence of shocks, recirculation zones and the interaction of the fuel jets with the supersonic cross flow. The ignition and combustion characteristics will be influenced to a great extent by the mode of fuel introduction and the combustor geometry. Practical design information pertaining to supersonic combustors is lacking in the open literature.

An experimental study of supersonic combustion of gaseous hydrogen injected transversely into a vitiated Mach 1.8 airstream was carried out. The specific objective was to study the ignition and combustion characteristics of the hydrogen fuelled stepped combustor and the results of this preliminary investigation are presented.

Supersonic Combustors

In a well designed supersonic combustor (schematic, Figure 1) the amount of permissible heat release would be a maximum and the total pressure loss a

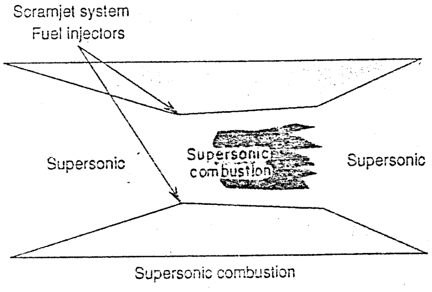

Fig. 1 Schematic of supersonic

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minimum within the given length constraint. To realise this requirement, not only is an understanding of the fuel preparation and injection process necessary, but a thorough knowledge of the processes governing supersonic mixing and combustion as well as those leading to the other losses within the combustor are essential. Flame stabilisation and combustion along with wall friction and heat transfer losses are the major processes governing the effectiveness of a supersonic combustor [1]. In the case of constant area heat addition(Rayleigh flow) to a supersonic stream, the Mach number will tend to unity. To alleviate the severe constraints placed to combustor operation due to the thermal choking limitations on heat addition, the combustor will have to be provided with a divergent portion. Since supersonic combustion is mixing controlled, care has to be taken that mixing takes place in a controlled manner such that thermal choking is avoided. However, if the combustor has only a divergent portion, there will be a rapid decrease in the static temperature, thus reducing the chance of ignition/combustion in the given length. Hence, it is necessary that the supersonic combustor be provided with an initial constant area portion where ignition could be allowed to take place, particularly if the inlet temperatures are low. Once the chemical reaction has been initiated, it will be possible to allow for a combustor wall divergence to offset the thermal choking constraint. Combustor geometry is far more critical in supersonic than in subsonic combustors.

The total pressure loss, which is related to the loss in thrust, should be kept a minimum. The fuel injection process with its attendant shock losses, in the case of transverse injection, and the pressure losses due to heat addition contribute significantly to the overall stagnation pressure loss. Fuel injection should be such that mixing of fuel and air occurs effectively in the combustor length provided. Fuel is conventionally injected transversely from the walls or from immersed struts. It has been observed that parallel injection leads to poor mixing. However, mixing can be enhanced by having immersed injectors, the use of shock waves or expansion waves and injection downstream of a rearward facing step or ramp [2]. Transverse jets pose an obstruction to the flow (Figure 2).

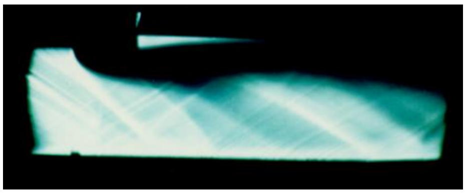

Fig.2. Flow over a rearward step, transverse liquid injection (M=2)

This causes an interaction shock to occur and it also separates the boundary layer. Recirculation zones are then set-up on either side of the jet.

The combustor should have effective flame holding characteristics. The static temperature, static pressure, fuel/air mixture and residence time should be carefully arranged to have appropriate values to accomplish self ignition (and combustion) in the flowing combustible mixure [3].

A backward step will also create a recirculation zone in the flow (Figure 3), An expanision fan, centered on the step corner, also forms. The supersonic flow is deflected towards the wall. Downstream of the recirulation zone the flow again turns in the axial direction setting up a shock wave. It will be advantageous to employ both a transverse fuel jet and a backward step in the supersonic

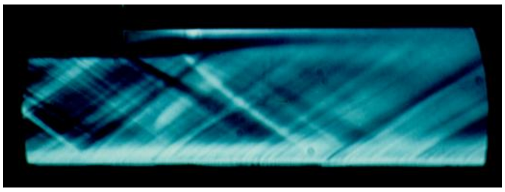

Fig. 3. Flow over a rearward step (M=2)

combustor as their positive flame stabilisation and mixing characteristics could be combined. This is the combustor configuration used in the present investigation.

Experimental

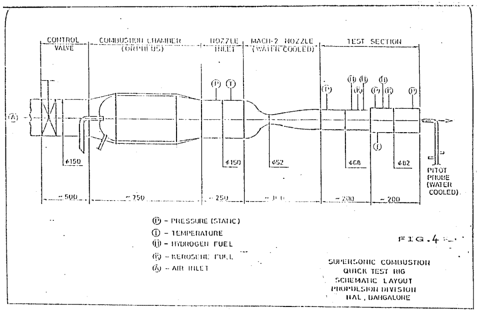

Fig. 4. Supersonic combustor-quick test rig

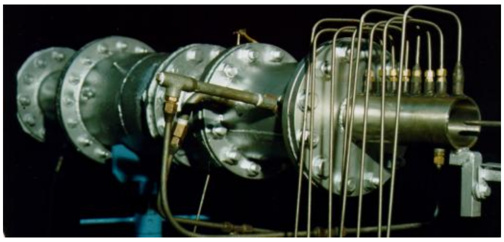

Fig.5. Supersonic combustor test rig

A supersonic combustor test rig was specially setup (Figures 4-5). This incorporated a gas generator built around a kerosene fuelled `Orpheus' gas turbine can combustor. This vitiated air rig was operated in a connected pipe mode. A Mach 1.8 (nominal) water cooled contoured axisymmetric nozzle (exit dia 68 mm) was directly connected to a stepped combustor which had an annular step of 7 mm. No oxygen replenishment was provided and consequently the results had to be carefully examined to allow for the effects of vitiation. With this arrangement, stagnation pressures and temperatures upto 0.8 MPa and 1300K could be provided at the inlet to the water cooled nozzle, thus providing a reasonable simulation of the conditions encountered at the combustor inlet in the high supersonic range of flight Mach numbers of a scramjet. This test rig was set up essentially for quick tests to checkout various concepts and components. All detailed tests will be carried out with a hydrogen burning vitiated air heater with oxygen replenishment, which is being set up.

The main fuel used in the supersonic combustor was hydrogen which was supplied in a regulated manner from cylinders. The hydrogen gas was injected transversely into a combustor from various wall locations.

Because of the volume constraints imposed for missile applications, a strong motivation also exists for the development of kerosene fuelled scramjet combustors. Consequently, kerosene was also used, particularly to checkout the ignition problems due to its lower reactivity as compared to hydrogen.

A Shapiro probe was used to measure the combustor outlet Mach number. The combustor had a number of static pressure tapping on the wall and all measurements were taken using a computer based data acquisition system. The combustor inlet Mach number was deduced from the combustor inlet static pressure and nozzle inlet stagnation pressure.

The flow field inside a supersonic combustor is undoubtedly rather complex mainly as a result of the presence of the backward step and transversely injected fuel jets. This central zone was optically studied as aerodynamics play a major role in the mixing and combustion processes. A flow visualisation rig incorporating a 36mm x 77 mm Mach 2 half nozzle was used to study the flow patterns. Schlieren pictures obtained (typically, Figures 2,3) have helped in the study of the flow processes and in evolving a combustor design.

Discussions

Supersonic hydrogen diffusion flames

In the supersonic range of flight Mach numbers of a scramjet, the static temperature at the combustor inlet is not sufficiently high to ensure spontaneous thermal ignition of the fuel/air mixure to occur or even if thermal ignition occurs, the ignition length may be too long, depending upon the fuel used. In the case of continuous flow systems, unless the combustor geometry is such as to make flame stabilisation possible, some form of a continuous ignition aid is necessary.

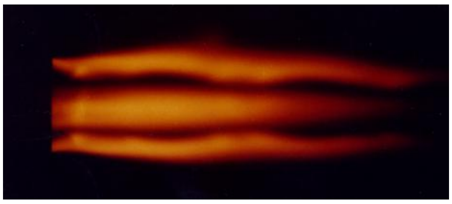

Fig. 6. Supersonic hydrogen diffusion flames (4 port injection)

Stable supersonic combustion of hydrogen (4 port injection) was achieved at combustor inlet static pressures in the range of 0.04 to 1.17 MPa and stagnation temperatures above approximately 1170K in the stepped combustor (Figure 6) The 4 ports were located 90 degrees apart and it is seen that this circumferential spacing has to be decreased for proper flame coverage.

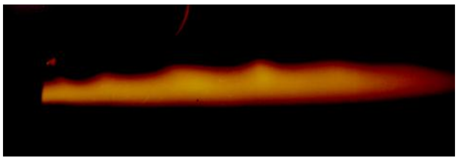

Fig. 7. Supersonic hydrogen flame (single port injection)

Figure 7 shows the supersonic hydrogen diffusion flame obtained with transverse hydrogen injection from a single port. For contrast, a disc stablised subsonic hydrogen diffusion flame is shown in Figure 8. The characteristic compression/expansion zones of an under expanded transverse jet penetrating the supersonic cross flow is seen in Fig 6,7 and this is absent in the subsonic case (Figure 8).

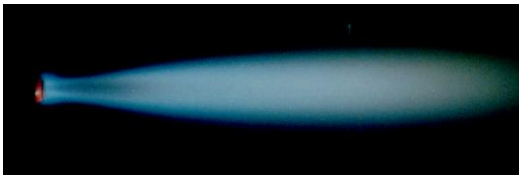

Fig. 8. Disc stabilised subsonic hydrogen diffusion flame

Figure 3 shows a schlieren picture of the flow past a backward step with hydrogen injection downstream of the step. The interaction shock, the shock bottle and the expansion fan centered at the step corner are seen. Figure 2 shows a schlieren picture of the flow past a backward step with transverse injection of fuel (in this case, water injection simulates a liquid fuel like kerosene). The lambda shock ahead of the jet and the reattachment shock are also seen. A combination of expansion waves and shocks as well as the axial vorticity generated from transverse jets which turn into the flow, enhance the mixing process. The recirculation zones are also seen. All these factors along with the approach temperature have combined to allow supersonic combustion of hydrogen to take place in the short stepped combustor. The lengths of the flames indicate that suitable divergent portions have to be arranged to enclose the flame. Figure 9 shows the effect of wall heating when the supersonic hydrogen diffusion flame was stabilised at the step. This brings out one of the disadvantages of a stepped combustor as it dictates the necessity of providing wall cooling.

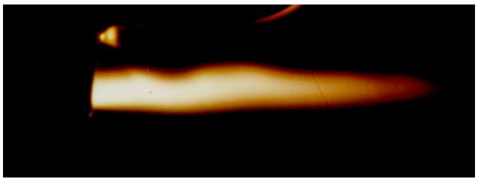

Fig. 9. Wall heating of stepped combustor

Figure 9 proves that the flame was indeed anchored at the step and was not stabilised by allowing hydrogen to pass through, perhaps, a oblique shock system at the combustor exit.

Supersonic kerosene diffusion flame

Unlike hydrogen, it was not possible to ignite kerosene in the supersonic stepped combustor inspite of raising the approach temperature upto 1400 K. The ignition delay of kerosene is much higher than that of hydrogen. It was concluded that unaided supersonic combustion of kerosene was not possible for stagnation temperatures upto 1400K for the given combustor geometry. However, it was found that stable hydrogen-aided kerosene supersonic diffusion flames were possible (Figure 10).

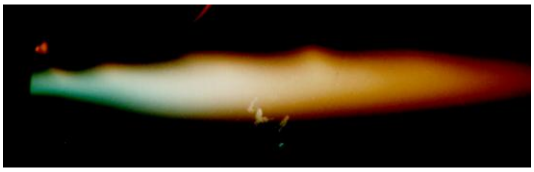

Fig. 10. Hydrogen-aided supersonic kerosene diffusion flame

Hydrogen had to necessarily be injected ahead of the kerosene to avoid hydrogen flame quenching. Hydrogen is an additive which is effective both by chemical and thermal means.

Supersonic combustor performance

The supersonic combustor was operated at various inlet conditions and the ignition and performance characteristics are shown in Figure 11 and Figures 12,13 respectively. The parameter $P_{01} / \sqrt{T_{01}}$ is a measure of the air flow rate at constant Mach number and where hydrogen is injected at constant pressure (0.34 MPa), it is measure of the air/fuel ratio. P_{01} and T_{01} are the nozzle inlet stagnation pressure and temperature. It was observed (Figure 11) that the hydrogen ignition temperature was substantially constant in the stagnation pressure range tested. It was also independent of the number of ports. Increasing the nozzle inlet stagnation pressure should increase the combustor inlet static pressure and hence increase the combustor step pressure (Figure 12).

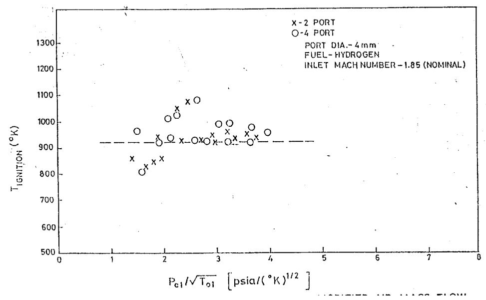

Fig. 11. Variation of igniion tempeature with modiied air mass flow parameter

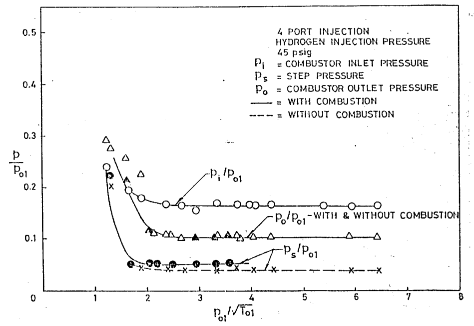

Fig. 12. Variation of combustor pressure with modified air mass flow parameter - stepped combustor, low fuelling rate

This should have led to a decrease in the ignition temperature. The advantage may have been offset. Increasing the combustor inlet static pressure could have reduced the fuel penetration, making the fuel travel close to the combustor wall. This would have led to poor mixing and made the recirculation zone locally fuel rich. In addition, increased combus-

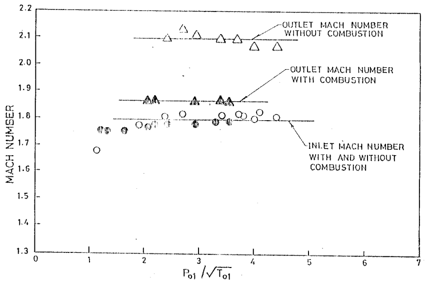

Fig. 13. Variation of Mach number with modified air mass flow parameter

tor inlet static pressure would have led to a smaller equivalent jet induced body (Figure 2) and this would result in poor flame stability as the jet flame stabilisation effect may have been impaired. Increased flame holder scale could be used to offset the adverse effect of decreased pressure and equivalence ratio [4]. Increasing the combustor inlet static pressure would have increased the air mass flow and this would have led to leaner overall fuel/air ratios. Admittedly, the flames are of the diffusion type. The situation is extremely complex and only plausible reasons are offered for the near constancy of the ignition temperature.

Figure 13 shows that the outlet Mach number reduces, as expected, on heat addition in the supersonic combustor. The inlet Mach number, outlet Mach number before and after combustion appeared to be insensitive to the air mass flow parameter, which is a measure of the air/fuel ratio as the hydrogen was injected at a constant pressure of 0.34 Mpa. Figure 14 shows the variation of the outlet Mach number with stagnation temperature ratio for an idealised stepped combustor having the same inlet Mach number and area ratio. This variation has been arrived at by carrying out a one dimensional analysis of the gas dynamics of heat addition in a sudden expansion [5]. There is a tacit assumption that the multidimensional effects due to transverse fuel injection and flow over a rearward step have died down at the combustor exit for the one dimensional assumptions to be valid. It is seen that the outlet Mach numbers, with and without combustion, are close to what have been measured, even though a rather simple model had been employed. The ratio of step pressure to the combustor inlet static pressure is a required input to solve the relevant gas dynamic equations. The step pressure is seen to rise only slightly with heat addition (Figure 12). The fuelling rate was low and the wall pressures were affected only by a change in nozzle inlet stagnation pressure. At low values of P_{01} stable supersonic flow in the nozzle was not possible.

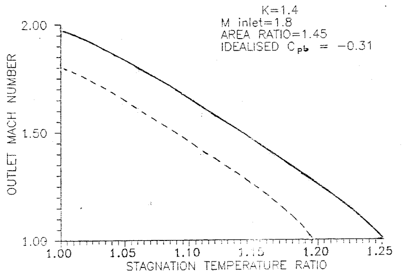

Fig. 14. Variation of outlet Mach number with stagnation temperature ratio, stepped combustor

The base pressure coefficient C_{pb} deduced from the present measurements of step pressure and combutor inlet Mach number was -0.31.This compares reasonably with the value of -0.27 for steps and bases at Mach 1.8 [6].

From Figure 14 it may be deduced that it is possible to add more heat in a stepped combustor than in a constant area combustor. The importance of introducing a divergent section to alleviate the constraints of thermal choking (Figure 14) needs to be stressed.

Concluding Remarks

It has been possible to achieve supersonic combustion of hydrogen and hydrogen-aided kerosene supersonic combustion in the stepped combustor. The ignition and performance characteristics of the hydrogen fuelled stepped combustor have been determined. The flow pattern in the simulated stepped combustor has been studied using a schlieren technique. A simple one dimensional analysis for heat addition in a sudden expansion could be used to predict the behaviour of the performance characteristics.

Acknowledgements

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