Interaction and Penetration of Fuel Jets in Supersonic Crossflows

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Abstract:

The extent of fuel interaction and penetration in a supersonic crossflow governs the ignition and combustion characteristics of a supersonic combustor. A comprehensive series of experiments have been conducted to determine the interaction and penetration characteristics. The cases of injection from a plain wall, stepped wall and wedge strut as well as normal, parallel and parallel/normal injection were considered It was found that the extent of jet penetration at a given distance downstream was governed by the jet/air momentum ratio and the injector port diameter. It was found that jet penetration in a supersonic cross flow was higher than in a subsonic cross flow. For a supersonic cross flow, injection behind a step led to higher jet penetration than injection ahead of a step. Injection ahead of a step yielded a higher penetration than injection from a plain wall, Parallel/normal injection from a wedge strut appeared to indicate good initial mixing.

Introduction

Supersonic combustion shows promise of being more efficient than subsonic combustion for ramjets employed in advanced aerospace propulsion systems operating at flight Mach numbers in the hypersonic range. A programme is now underway at DRDL, Hyderabad to develop a hydrogen-fuelled supersonic combustion ramjet (Scramjet) for the Hyperplane, which is a fully reusable single-stage-to-orbit hypersonic vehicle.

One of the major problems encountered in the design of supersonic combustion chambers for such ramjets is the injection and mixing of fuel in a supersonic airstream in the minimum combustor length while incurring as low a stagnation pressure loss as possible during the short residence time available. Supersonic combustors must of necessity be aerodynamically cleaner than their subsonic counter parts. A typical flow field inside a supersonic combustor would, undoubtedly, be rather complex mainly as a result of the presence of transversely injected fuel jets, fuel injector struts and rearward facing steps. However, the number of possible injector and combustor configuration combinations remains formidable, without there being any sound guidelines for a prior elimination of any of them. In mixing controlled supersonic combustion, fuel injection and mixing can be used to control the rate of heat release in the combustor too. In addition, the mode of fuel injection should be carefully chosen to ensure that the local fuel/air ratio is held within acceptable limits to lead to desirable ignition and combustion characteristics. The results of an experimental study of fuel jet interaction and penetration in a supersonic cross flow are presented.

Fuel Jet Interaction and Mixing

The design of the supersonic combustor requires a knowledge of the fuel-air mixing characteristics. Clearly, methods have to be devised to introduce the fuel into the supersonic air stream in a manner so as to increase the number of mixing initiation sites The desired fuel distribution has to be obtained in a given combustor length within the very short residence time available without incurring a large stagnation pressure loss penalty.

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Presented at the 2nd National Conference on Air Breathing Engines and Aerospace Propulsion, VSSC, Thiruvananthapuram, Dec. 1994.

Supersonic combustor fuel injection systems may be classified into three types. The transverse injector, with fuel injected from the wall into the main supersonic stream, (Figure 1 for gaseous injection), the wall slot injector with fuel injected from a rearward facing step in the downstream axial direction and the immersed or strut injector with fuel injected in the down stream and/or transverse direction.

From the viewpoint of engine performance, coaxial injection has the important advantage over transverse injection, in that the downstream momentum of the injected fuel may contribute significantly to the net engine thrust. With increase in flight speed, it is expected that immersed injectors will give way to wall injectors because of the cooling problems faced. The wall slot injector, however, suffers from the disadvantage that with this mode of injection, mixing is poor. Mixing may be improved by the impingement of oblique shocks on the jets and the addition of normal jets [1]. On the other hand, normal injection of fuel from the wall into the airstream would produce greater penetration and hence better mixing and a higher combustion efficiency. Since transverse injection would in effect cause an obstruction to the supersonic main flow, an oblique shock would be produced. Although this shock will cause a loss in stagnation pressure, the loss would be partially off-set by the smaller loss in stagnation pressure due to heat addition at a lower Mach number behind the shock. It has been pointed out that there is probably, some optimum trade-off between the pressure loss induced by fuel injection and the mixing augmentation process and the resulting increase in combustion efficiency [2,3]. For small scale combustors, radial injection from the wall will be most suitable. Since jet penetration is a function of the port diameter and the jet/freestream momentum ratio, large port diameters or high injection pressures will have to be employed to get adequate penetration. This method has its limitations and consequently, in large combustors, in-stream injection from a strut or other protrusion has been employed to lift the injection ports out into the mainsteam [1]. Improved penetration and mixing can be achieved while incurring a penalty due to the momentum losses caused by the mechanical structure [1]. To obtain good mixing in large combustors, flush wall injection together with injection from swept and tapered struts immersed in the main stream may have to be employed.

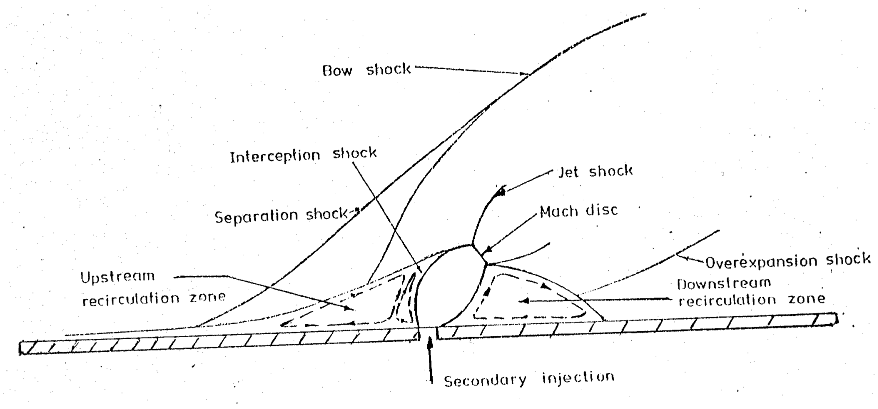

Fig. 1. Schematic of the jet interaction flowfield

The interaction and mixing of a secondary jet injected transversely into a supersonic mainstream may be viewed as a two stage process. In the interaction process, the jet may be considered to substantially retain its identity while penetrating the flow. At the same time, it is accelerated and turned in the flow direction of the mainstream The second stage may be considered to be a substantially coaxial turbulent mixing process.

Correct understanding of the mixing process in supersonic combustors is quite limited. The studies on the growth rate of supersonic mixing layers are limited. The observed decrease in the growth rate at high Mach numbers [4], as well as the decrease with heat release [5] is found to pose serious difficulties in the proper design of combustors to achieve high efficiencies. Clearly, mixing enhancement methods would have to be employed in order that compact combustors could be designed. Among the schemes being currently examined to enhance mixing are combined parallel/transverse fuel injection [6,7], the use of shock waves or expanded waves [1,9] (the strong vorticity induced at the interface between a light and heavy gas by an intense pressure gradient is the mechanism by which mixing is enhanced [8], swept injector ramps [1,10] and injection downstream of a rearward facing step or ramp [1]. Mixing enhancement can be achieved by introducing axial vorticity. Parallel fuel injection and normal fuel injection give rise principally to lateral vorticity [11]. However, in the latter case, streamwise vortices are also generated as the freestream is forced around the jet core and up into the plume [12].

Chemical reaction must be included if the combustion and mixing processes are to be understood in order that attempts may be made for possible enhancement. Currently, fundamental knowledge of the coupling of the combustion and mixing processes in free shear layers is essentially non-existent for supersonic flows and very limited in the incompressible case [13]. Recent evidence indicates that the change in growth rate of mixing layers is marginal in the presence of high speed flows [14]. In general, there is much less influence of chemistry on high speed flows than on low speed flows [15].

Experimental

A comprehensive series of experiments were conducted and the jet penetration, and interaction characteristics determined for various approach stream velocities and temperature.

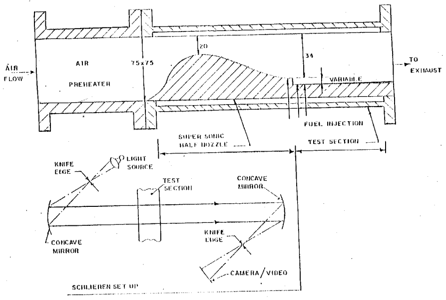

Fig. 2. Flow visualisation set-up

Fig. 3. Test Combustor

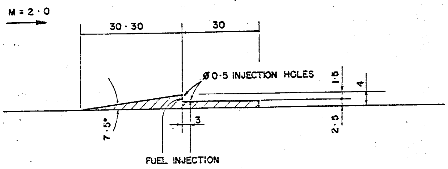

Fig. 4a. Strut fuel injection

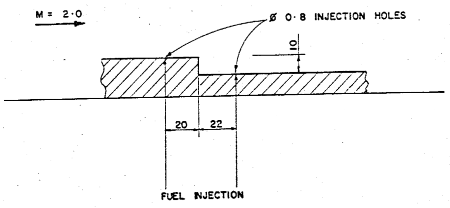

Fig 4b. Stepped wall fuel injection

A flow visuualisation rig (Figure 2-4) was specially set-up to study the interaction and penetration of transversely injected fuel jets in a rectangular stepped combustor. A 36 mm x 77 mm Mach 2 half nozzle was connected to the step combustor, which had a 6 mm rearward step. When necessary, the feed air to the nozzle could be heated with the aid of an air heater built around a kerosene fuelled gas turbine can combustor. Fuel injection from a strut was studied by employing a half wedge (Figure 4).

Hydrogen was used to simulate a gaseous fuelled system and water to simulate a liquid fuelled system. Although liquid hydrogen is proposed to be used to cool the scramjet combustor walls, it is quite likely, from heat transfer considerations that a two-phase hydrogen jet will emerge on injection into the combustor under certain conditions. In a dual mode ramjet combustor, under certain flight regimes, the main stream flow at the fuel injection plane could be subsonic. Consequently, studies of jet interaction have been conducted with both supersonic and subsonic cross flows. Schlieren (Figure 2) and direct photography and video have been employed.

Discussions

A comprehensive series of experiments with water and hydrogen injection transverse to subsonic and supersonic flows were carried out. Direct and schlieren photography as well as video were employed to study the jet interaction process and locate the edge of the jet for determining the penetration.

Jet Interaction

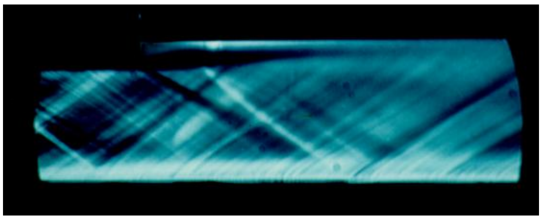

Fig. 5. Flow past a backward step (M=2), transverse injection of hydrogen downstream of step, $P_{oj}/p_a = 20$; h, $d_j = 5.7, 1.2$ mm

Figure 5 shows a schlieren picture of the flow past a backward step. The flow has undergone a strong expansion centred at the step corner as the turbulent boundary separated from the body. The free shear layer geometrically separated the outer flow from the relatively large recirculation zone downstream of the step. A hydrogen jet has been injected 3 step heights downstream of the base and the classic shock bottle and jet induced bow shock are seen.

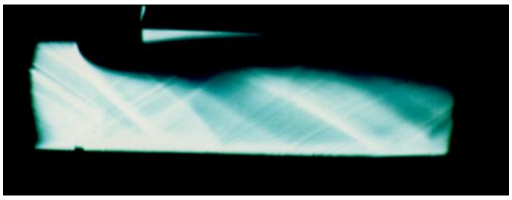

Fig. 6. Flow past a backward step, transverse liquid injection upstream of step, $P_{oj}/p_a = 20$; h, $d_j = 5.7, 1.2$ mm

Figure 6 shows the schlieren picture of the flow past a backward step with large injection of water 3 step heights upstream. The lambda shock system induced by the jet presence, as well as the reattachment shock are seen. The liquid jet is seen to penetrate the air stream quite deeply in contrast to gaseous injection. The penetration is a function of the jet/mainstream momentum ratio. The jet spray is also seen to bend back towards the wall once it flows past the step. The ignition and combustion characteristics are strongly affected by the ratio of the fuel flow rate and the air flow rate which would have passed through the fuel influence zone. Hence, a knowledge of the extent of the zone would be helpful in assessing the optimum location of the injector ports and choice of appropriate combustor geometry.

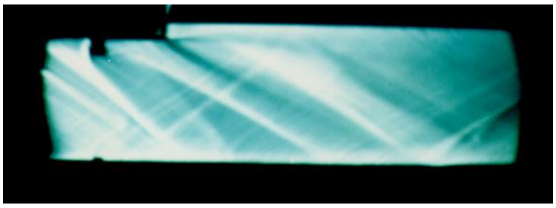

Fig. 7. Flow past a backward step, cylindrical protuberance, M=2; h, H = 5.7, 5.7 mm

Figure 7 shows the schlieren picture of the flow over a backward step with a cylindrical protuberance placed 3 step heights upstream of the step. The same form of the lambda shock or interaction shock shape is repeated and the supersonic stream is seen to be displaced in a similar manner as in the case of the fuel jet (Figure 6). The reattachment shocks are also seen after the protuberance and downstream of the step. This is a clear proof that the jet can be replaced by an equivalent body for the purpose of studying the interaction effects and estimating the influence zones. Wake regions downstream of the jet core and recirculation zones dowstream of the step are critical for ignition and flame stabilisation [11]. Similar recirculation zones are also employed in afterburners for flame stabilisation.

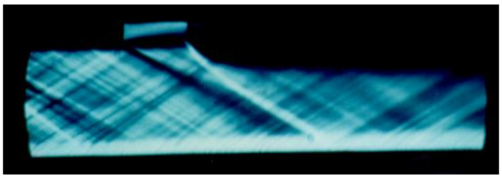

Fig.8. Flow past a backward step, transverse liquid injection downstream of step, M= 2, P_{oj}/p_a = 20; h, d_j = 5.7, 1.2 mm

Figure 8 shows the schlieren picture of the flow past a rearward step with liquid injection 3 step heights downstream of the step. The expansion fan centred at the step corner and the jet interaction shock starting only from the point where the jet has emerged from the step wake region is clearly seen. As expected, there is no bending back of the jet unlike in the case of injection before the step. Normal injection of the fuel jet into a supersonic crossflow causes detached shocks and wakes to form around the jet. These negative effects can overcome, if the jet is allowed to first penetrate a separated region before interacting with the main supersonic flow [11]. The region between the jet and the step base is a likely ignition site.

The corresponding direct photographs of the flow past a transverse liquid jet issuing from a plain wall, transverse liquid jet ahead of a step and transverse liquid jet behind a step are shown in Figures 9-11 respectively.

Fig. 9. Transverse liquid jet from a plain wall ; M=2, P_{oj}/p_a = 20, d_j =1.2 mm

Fig. 10. Transverse liquid injection ahead of step; M=2, P_{oj}/p_a = 20, d_j = 1.2 mm

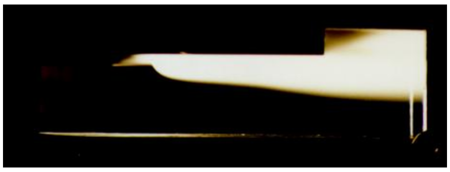

Fig. 11. Transverse liquid jet behind a step; M=2, P_{oj}/p_a = 20, d_j = 1.2 mm

It is seen that the jet penetrates the mainstream rapidly and later follows a shallow trajectory. This is a characteristic of transverse jets in supersonic cross flows. In contrast, the transverse jet will steadily penetrate a subsonic cross flow. These photographs give an indication that the flow past a transverse jet could perhaps be modelled by replacing it with a hemi-cylindrical half body. Wedge shaped injector struts are proposed to be employed for fuel injection in large combustors.

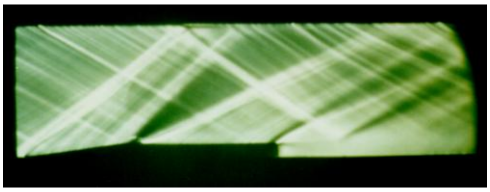

Fig. 12 Flow past a half wedge strut, M=2,

Figure 12 shows the schlieren picture of the flow past a half wedge-plate (Figure 4). The attached shock from the wedge leading edge and its reflection from the wall, the expansion fans centered at the wedge shoulder and the step corner at the strut rear are clearly seen.

Fig. 13. Flow past a half wedge strut, parallel liquid injection, M=2, $P_{oj}/p_a = 20$

Figure 13 shows the schlieren picture when there is liquid injection from the wedge base in a downstream direction.

Fig. 14. Flow past a half wedge strut, transverse liquid injection; M=2, $P_{oj}/p_a = 20$,

Figure 14 is for liquid injection in a transverse direction from a distance (Figure 4) downstream of the wedge base; Figure 15, when there is both parallel and normal liquid injection. The interaction shocks are clearly seen in the normal injection cases (Figures 14,15). It is seen that when there is parallel normal/injection, there is a definite enhancement in the mixing as compared to parallel (Figure 13) or normal injection (Figure 14). In Figures 13,14, the fuel appears to be restricted to a tube whereas in Figure 15, the mixing enhancement is clearly seen, particularly at the strut base end.

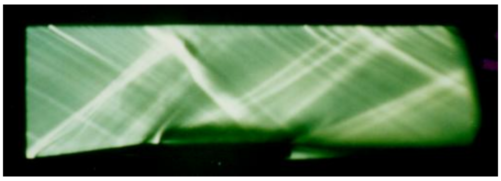

Fig. 15. Flow past a half wedge strut, parallel/transverse liquid injection; M=2, $P_{ojv}/p_a = 20$, $P_{ojh}/p_a = 14$.

Jet Penetration

The penetration of a transverse jet in a supersonic cross flow can be expressed as:

$$\left(\frac{\mathrm{y}}{\mathrm{d}_{\mathrm{j}}}\right) \sim \left(\frac{\rho_{\mathrm{j}}}{\rho_a}\frac{V_j^2}{V_a^2}\right)^{\mathrm{m}} \left(\frac{\mathrm{x}}{\mathrm{d}_{\mathrm{j}}}\right)^{\mathrm{n}}$$

where y is the penetration, x the downstream distance, ρ the density, V the velocity, d_j the injector port diameter and suffixes a, j refer to the air and jet.

The expression may be recast as:

$$\left(\frac{\mathrm{y}}{d_j}\right) \sim \left(\frac{\mathrm{P}_{oj}\ /\mathrm{p}_a - 1}{M^2}\right)^{\mathrm{m}} \left(\frac{x}{d_j}\right)^{\mathrm{n}}$$

$$\sim \lambda^m \left(\frac{x}{d_j}\right)^{\mathrm{n}}$$

where λ is a measure of the ratio of jet to air momenta.

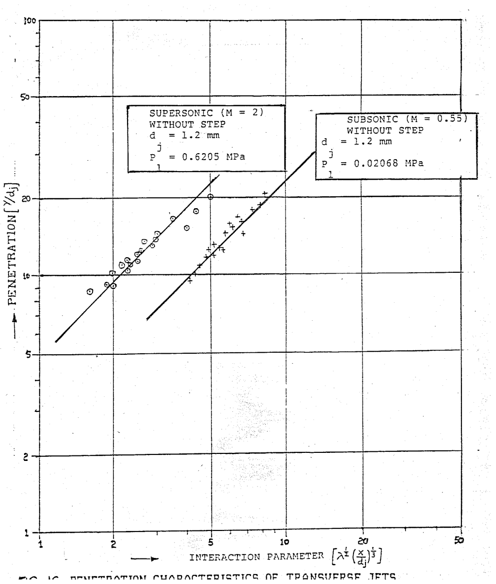

Fig. 16. Penetration characteristics of transverse jets

Figure 16 shows the penetration characteristics of transverse liquid jets in subsonic and supersonic crossflows. The indices m and n were found to be 1/2 and 1/3 respectively.

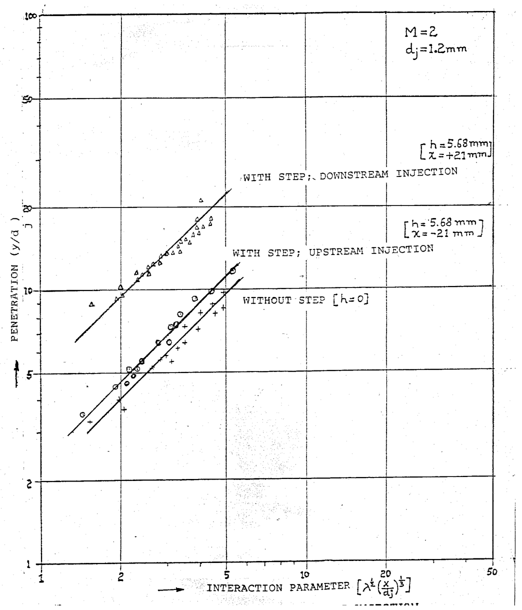

Fig. 17. Effect of step and position of injection

The remarkable similarity between the subsonic and supersonic penetration characteristic is to be noted. For a given jet/air momentum ratio and distance downstream, the penetration in a supersonic cross flow is higher than that in a subsonic cross flow.

Figure 17 shows that for a given jet/air momentum ratio, a higher penetration is achieved with injection behind a step than ahead of the step. The penetration is also higher for injection ahead of a step as compared to injection from a plain wall.

Concluding Remarks

Jet penetration and interaction in supersonic and subsonic cross flows have been studied. The cases of injection from a plain wall, stepped wall and wedge strut as well as normal, parallel and parallel/normal injection have been considered. The penetration of the fuel jet was higher in a supersonic crossflow as compared to that for a subsonic crossflow. The penetration was higher if the fuel was injected downstream of the step than upstream of the step. The penetration was better when injected ahead of the step than without a step. Parallel/normal mixing injection from a wedge strut appeared to indicate good initial mixing.

Acknowledgements

This work was sponsored by the Director, Defence Research and Development Laboratory, Hyderabad. The authors thank him for the permission to publish this paper. The authors also thank Mr. Nataraj, Mr. Ninan Thomas, Mr. S. Praveen and Mr. D. Priyadharshi of the Siddaganga Institute of Technology, Tumkur, Karnataka who carried out the experiments as part of their B.E. Project work.

The authors also thank their colleagues Mr. ATLN Murthy and Mr. M. Satishkumar for their help in the experimental work.

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