An Experimental Investigation of a Four Inlet, Side Dump Combustor of a Kerosene - Fuelled Boosted Ramjet

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Abstract

An experimental investigation of a four-inlet side dump combustor configuration suitable for a boosted ramjet has been carried out. Combustor characteristics were obtained from water tunnel simulation and direct-connect combustion tests. A perspex, one third scale, model of the ramjet combustor was tested in a water rig. Flow field visualisation was accomplished by employing the hydrogen bubble streak technique. The best placement of the cruciform flameholder relative to the air inlet plane was determined. A similar combustor was made from stainless steel and tested in a combustor test rig. Combustion efficiency, cold and hot total pressure loss and ignition characteristics and lean blow-out limits were obtained. A design methodology for ramjet combustors has been arrived at.

Introduction

For future launch vehicle application, great emphasis has been given to air-breathing engines as they have superior specific impulse characteristics as compared to rockets. However, there is no single propulsion concept which gives optimum performance over the entire flight Mach number range envisaged. The Vikram Sarabhai Space Centre (VSSC) has been carrying out detailed studies of various propulsion options and have planned flight technology demonstrators to evaluate some of the promising candidate engines. Among the options being considered are turbojets, ejector ramjets and liquid air cycle engines (LACE) for the low Mach number range (typially, Mach 0-3) (Ref.1-4). In practically all the studies, the conventional ramjet has been found to be the most promising propulsion option in the Mach 2-6 range (Ref.1-4). Beyond Mach 6, the supersonic combustion ramjet is an obvious choice.

ISRO is actively considering a rocket based combined cycle engine for its Air Breathing Launch Vehicle (ABLV). The development route to be taken would include the design, developement and flight testing of rocket-boosted ramjets, ejector ramjets and scramjets (Ref.4).

Clearly, there is a need to design and develop ramjets and their derivatives and this can be best done by employing and emperimental accelerating ramjet vehicle (Ref.5). The vehicle could have two stages with a conventional solid rocket chosen for the booster first stage and the experimental ramjet for the second stage. Fig.1 is a schematic of a candidate VSSC boosted ramjet. The boosted first stage will take the vehicle upto the ramjet take-over Mach number of about 2.

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Availability of design information on ramjet and scramjet modules, ground and flight tested to date abroad is scarce because of the classified nature of the work. There is a pressing need for the creation of a data base in India so that the design of gaseous and liquid fuel ramjet combustors could be successfully carried out. This experimental investigation of a multi-inlet side dump combustor of a kerosene-fuelled boosted ramjet has been tailored to partially meet this need and as such the emphasis has been on evolving a design philosophy for rapidly attaining a potential combustor configuration. This would also form an input for the development of an Ejector Ramjet.

Boosted Ramjet

The basic cycle of a ramjet is the same as that for a turbojet but the compression obtained is wholly from the ram effect of forward speed. Because the overall pressure ratio must be sufficiently high for good performance, the ramjet is unsuitable for low speeds and, of course, requires boosting to a minimum speed before it is self-driving.

The liquid fuel ramjet consists of an inlet, combustor and an exhaust nozzle (Fig.1). The inlet/diffuser admits free stream air to the engine, reduces the air velocity and thereby develops ram pressure. This air is mixed with fuel, burned in the combustor and the hot gases expelled through the nozzle to produce thrust. The heat release in the combustor should be carefully tailored to the flight speed and the appropriate nozzle opening or else it may lead to poor combustor or inlet performance, and in the extreme, lead even to an inlet unstart.

Dump combustors are usually employed in volume limited ramjets. In addition to co-axial dump combustors, in some cases, the flight vehicle configuration would require that side dump combustors be employed. The free steam air would enter the combustor from the side through multiple inlets. The impingement of jets is an important feature of side dump combustor flow fields. Jet-on-jet impingement can sustain flow instabilities and this could in turn create a mechanism for unsteady heat release. The flow field in a dump combustor is extremely complex. Complex vortex structures will exist between the dome head and the plane of the air inlets to the combustor. On entry to the combustor the air flow will follow a complex trajectory before finally turning in an axial direction. Control of flame stabilisation and flame propogation in such a complex turbulent flowfield represents a key element in combustion chamber design. Combustor configuration and the geometry of the fuel injector/flameholder and its location relative to the air entry points are basic design parameters that govern the performance of a particular combustor. A four-inlet side dump combustor configuration is frequently used. Clean aerodynamics is a characteristic feature of all high performance combustors and this is a definite gaol to strive for.
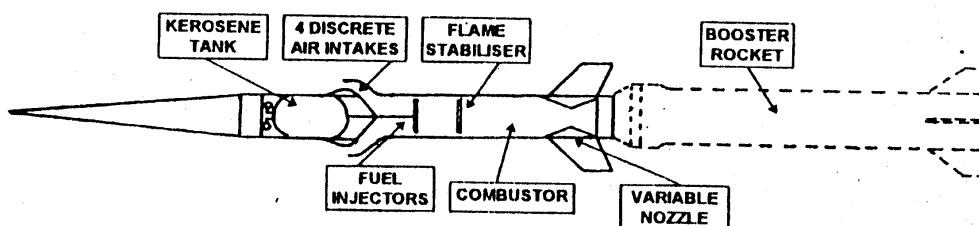

Fig. 1. Schematic of a kerosene-fuelled boosted ramjet

Fig. 2. Water flow visualisation rig

The demand for high performance from ramjet combustors has resulted in the need to meet stringent design requirements. In general, kerosene fuelled ramjet combustors will need to have the following features: High combustion efficiency, low total pressure loss, wide combustion stability, high temperature rise, easy ignition, light weight and compactness. These performance characteristics can only be acquired after a large number of tests on full scale combustors. Such a development process is costly because of the large number of parameters that have to be varied. It is more pragmatic to optimise the combustor configuration before hand with approximate mathematical models, flow visualisation studies and subscale combustor tests. This has been the strategy followed in this investigation.
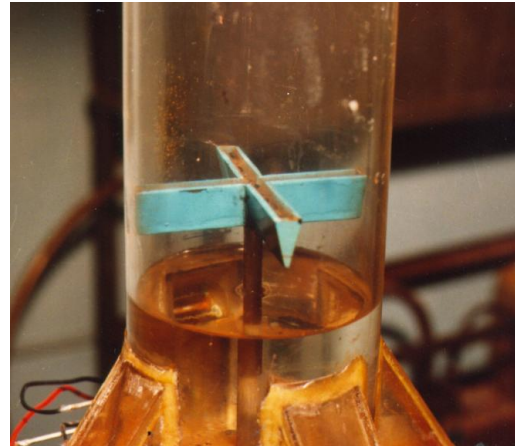
Experimental Approach

Water flow visualisation

Fig. 3. Cruciform flame stabiliser

Fig. 4. Flow past V-gutter, limbs in line with inlets, X=50mm, V=60 mm/s, hydrogen bubble streak technique

A view of the water tunnel is shown in Fig. 2. A 125 mm dia perspex model of a boosted ramjet combustor with 45^0 entry, four inlet arms of rectangular cross-section was fabricated and tested in a water tunnel. The water flow in the tunnel was against gravity and the flow in the four inlets could be controlled separately. A cruciform flame stabiliser (Fig.3), which was mounted on a rod was placed in the tunnel and a provision was made to move the stabiliser, both axially and circumfentially, in the working section of the tunnel. The flow was visualised using a hydrogen bubble streak technique and a He-Ne laser was used as the light source. A typical flow field is shown in Fig. 4 .

Combustor test facility

A schematic of the boosted ramjet combustor test facility is shown in Fig. 5. and views in Fig. 6,7. The rig was fully instrumented and information on pressures, temperatures and flow rates were datalogged. High pressure air at pressures upto 10 bar, is supplied from the NAL Compressor Air Facility was preheated in an Orpheus can combustor, Combustor inlet conditions corresponding to flight Mach number 2-4 and altitude 8 to 15 km were simulated.. A one third scale model of the ramjet combustor, which was similar to the water tunnel model was fabricated from stainless steel was employed in the tests. The pre heated air was passed through a settling chamber (Fig. 5,6) before being admitted through the four inlets to the ramjet combustor for direct connect combustion tests. The chosen ramjet combustor length to diameter ratio was 4. The

combustor terminated in a convergent nozzle which was choked for all the tests carried out. Kerosene fuel was sprayed from a plain opposed jet injector. Ignition was achieved by using a high energy air craft type ignition unit. The ramjet exit temperatures were estimated from the nozzle inlet static pressure by the choked nozzle technique. Combustion efficiency was givrn by the ratio of the actual temperature rise across the ramjet combustor to the theoritical temperature rise, as predicted by the Gordon-McBride method, with allowence made or preheating.
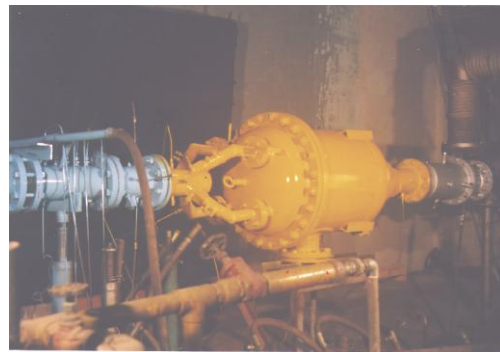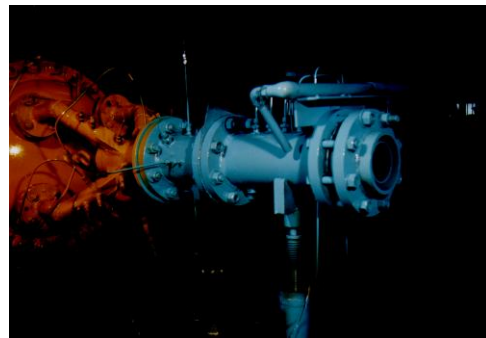

Fig. 6. Test rig - overall view
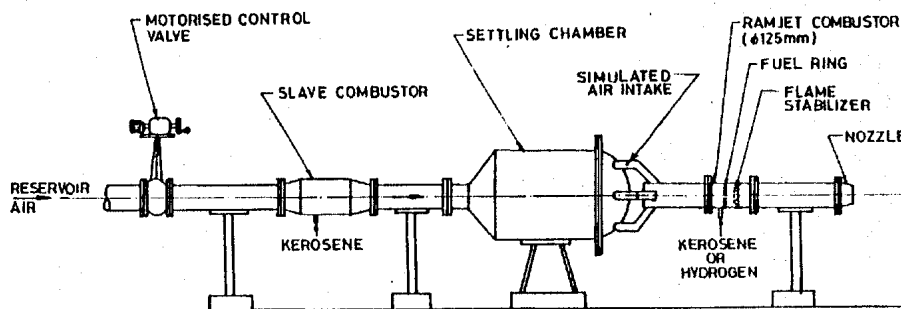

Fig. 7 Test rig - ramjet combustor

Fig. 5. Schematic of the boosted ramjet combustor test facility
Results and discussion

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Water flow visualisation tests

The hydrogen bubble technique was found to be an effective method for water flow visualisation. From the study it was concluded that the best location of the cruciform V gutter limbs was in-line with the inlets and at as large a distance from the inlets, at which the four air streams would have after impinging on each other, aligned themselves in the axial direction. The recirculation zone behind the flame stabilisation is clearly visible and the positive effect of the flame stabiliser in helping to align the flow in the axial direction is to be noted (Fig. 4). The velocities at which these tests were conducted were such as to ensure that the flow was definitely turbulent. It is known that under such conditions, the water flow pattern in the combustor would bear a close resemblance to the flow pattern in a combustor with heat addition. Severe flow non-uniformities were introduced when one or two inlets were deliberately made inoperative. Vortex structures were also observed in the space between the head dome and the air inlet plane. The task of positioning the flameholder in this complex flow field to achieve positive interaction is quite formidable. For the combustion studies it was positioned at 300 mm from the air inlet plane as a compromise to ensure compactness of the combustor, while at the same time achieving good interaction between the stabiliser and the air inlet flow give rise to resonably clean aerodynamics.
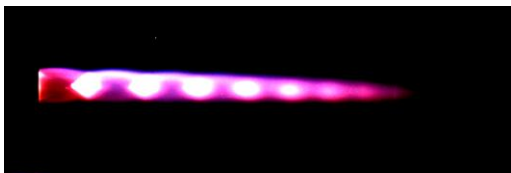
Combustor tests

Fig. 8. Kerosene flame showing shock
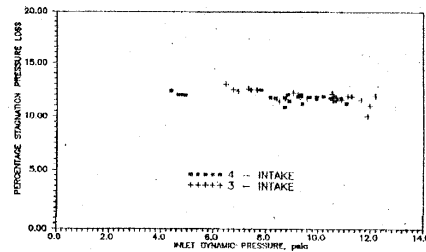   **structure**

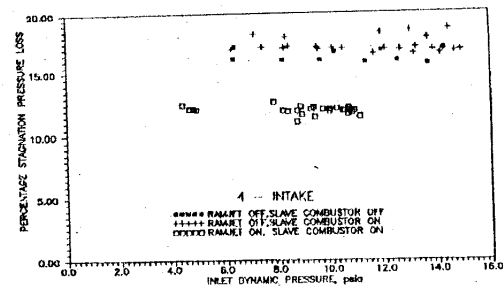Fig. 9. Total pressure loss - ramjet combustor off, slave combustor on

Fig. 10. Total pressure loss - ramjet combustor off / on, slave combustor off / on

The final combustor configuration chosen allowed easy ignition and smooth combustion (Fig. 8) to take place with no appreciable flow oscillation, which could lead to undesirable combustion instabilities. Fig. 9 shows the variation of total pressure loss with inlet dynamic pressure when the ramjet was off but the slave combustor was on. The constant level of percentage total pressure loss indicates that the overall loss coefficient remained unchanged for the range inlet dynamic pressures connsidered. The level of loss was the same even for the case with one intake inoperative (Fig. 9). With a four inlet configuration, there will always be one or two intakes which will be affected by flow disturbances on the leeward side at angle of attack. These disturbances will cause total pressure loss which lead to non-uniform flow in the air inlets. With combustion, the overall level percentage total pressure loss reduced but again remained unchanged for the range of inlet dynamic pressure and heat addition levels (Fig. 10). In both cases, the combustor exit total pressure was estimated from a measure of the nozzle inlet static pressure by employing the choked nozzle

concept. The overall loss coefficient, which now included sudden expansion loss and the generalised Rayleigh heating loss, had changed to a lower, but constant value. The flow structure in the combustor, consequent to heat additon, could have changed.
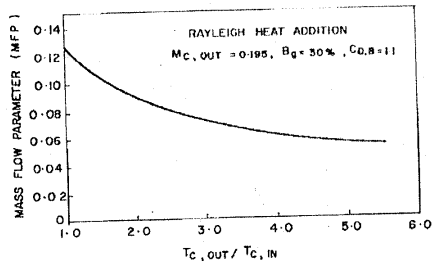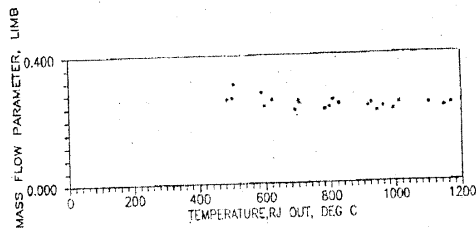

Fig. 11. Mass flow parameter

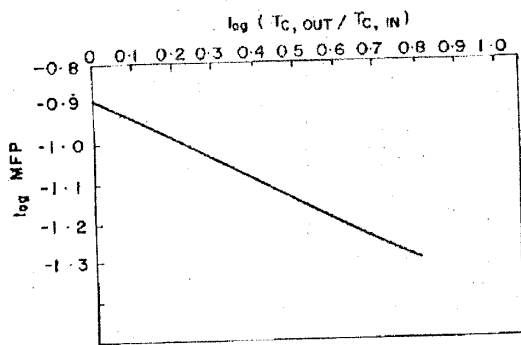Fig. 12. Flow characteristics - ramjet combustor on, intake limb plane

Fig. 13. Mass flow parameter - Rayleigh heat addition

The effect of heat addition on the total pressure loss in a ramjet combustor could be modelled in an analogous manner by considering the Rayleigh heat additon in a constant area duct. The total pressure loss resulting from increasing the gas total temperature and frictional loss of the combustor system can be ob-

tabined by modelling the combustion system as a constant area duct with simple heating and internal drag proportional to the incoming dynamic pressures. Fig.11 shows the variation of the mass flow parameter (MFP) with heat addition. It is seen to decrease with the addition of heat in a constant area duct which terminates in a choked nozzle. It is to be noted that MFP is proportional to the Mach number. Consequently, upstream conditions will adjust (Mach number will reduce) to allow for the heat addition. Even if there is a sudden expansion, as is the present case, ahead of the heat additon zone, the corresponding Mach number in the reduced section would decreased. Fig. 12 shows that this is in true in practice too. The MFP at the inlet limb is found to decrease with heat addition. Fig. 13 it is also seen that MFP decreases in a regular manner (roughly inversely proportional to the square root of the temperature ratio and hence the decrease of MFP at the upstream station (inlet limb) could be used to determine the ramjet outlet temperature and consequently the combustion efficiency, if the tests are carried out in precised manner, and suitable allowance made for the sudden expansion and drag losses.. The MFP at the inlet limb is seen to remain unchanged when there is no combustion in the ramjet and the combustion inlet temperature was varied (Fig.14).
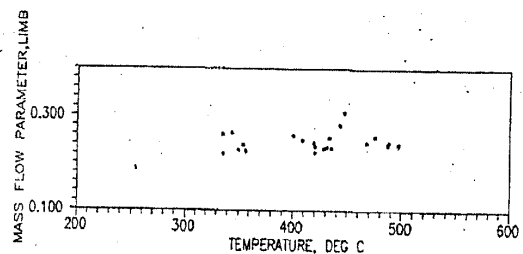

Fig. 14. Flow characteristics - ramjet combustor off, intake limb plane
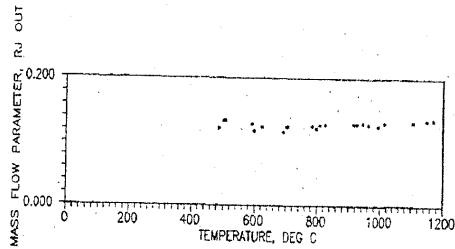
Fig. 15. Flow characteristics - ramjet combustor on, ramjet nozzle inlet plane

The MFP at the nozzle inlet plane has been determined and was found to remain unchange with the heat addition (Fig.15). The Mach number at the nozzle inlet plane will remain unchanged (except for the very small change due to a variation in the specific heat ratio) for a choked nozzle whose area ratio is fixed, even when there is heat additon in the ramjet.
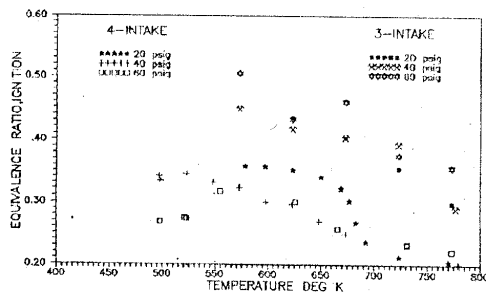

Fig. 16. Ignition characteristics

The ignition and lean blow-out characteristics are shown in Figs. 16 and 17 respectively. If one intake is inoperative, the ignition characteristics are adversely effected. The positive effect of the increase in pressure is to be noted both for blow-off and ignition. The lean limits for blowout and ignition are also widened with increase in temperature.
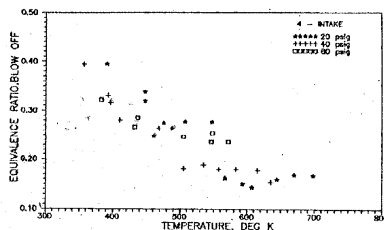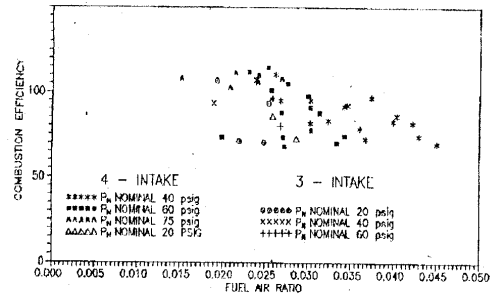

Fig. 17. Lean blowout characteristics

Fig. 18. Combustion efficiency

From the water flow study, a combustor configuration which led to clean aerodynamic was arrived at. Detailed combustion tests were carried with this configuration. The combustion efficiency characteristics are shown in Fig.18 for both four and three inlets. It is seen that the chosen combustor configuration is quite satisfactory as high levels of combustion eficiency have been attained. It must be stressed that these values are only indicative of the trend and more detailed tests require to be done before the final configuration is chosen, after making all necessary corrections, particularly with respect to the estimation of the combustion exit temperatures using the choked nozzle technique The temperature determined in this manner is not only a measure of combustor chemical efficiency but is also a measure of the extent the flow has mixed before it issues from the nozzle. There is a fall in combustion efficiency with increase in fuel/air ratio due to the effect of vitiation..

Concluding Remarks

A sub-scale four-inlet, side dump a subscale combustor for a kerosen - fuelled boosted ramjet has been developed. It has been shown to have good performance. Water flow visualisation studies have provided useful inputs for the design of the combustor. The hydrogen bubble technique was found to be suitable for the visualisation study.

References

1. Kors, D., Design considerations for combined air breathing - rocket propulsion systems, AIAA 90-5216

2. Nagappa, R., Subramanyam, J.D.A. and Shilen, S. , Development of Air Breathing Launch Vehicles, 1st Nat. Conf. Air Breathing Engines and Aero Space Populsions, Bangalore, Dec. 1992

3. Kreiger, R.I., A summary of features and design issues for single-stage-to orbit vehicles, AIAA 90-1932

4. Subramanyam, J.D.A. and Shilen, S., Synergistic combined cycle engine synthesis and its development strategies for air breathing launch vehicles, 2nd Nat. Conf. Air Breathing Engines and Aerospace Propulsion, Thiruvananthapuram, Dec. 1994.

5. Chitilappilly Lazar T., Ravikrishan, M and Subramanyam, J.D.A., Inflluence of design parameters on the overall performance of an accelerating ramjet, 2nd Nat. Conf. Air Breathing Engines and Aerospace Propulsion, Thiruvananthapuram, Dec. 1994.