An Experimental Study of the Performance of a Subscale Kerosene - Fuelled Ejector Ramjet at Simulated Takeoff

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Abstract:

The ejector ramjet is a rocket based combined cycle propulsion system in which a rocket and ramjet are integrated to accrue synergistic benefits. A proof-of-concept experiment to augment the thrust of a simulated rocket by the induction of air through an ejector and the subsequent afterburning of kerosene fuel in it is described. Ejector ramjet thrust augmentation ratios of upto around 1.1 at the simulated take off conditions have been achieved. The critical effect of the operating conditions and the ejector ramjet geometry, in particular the afterburner configuration, for achieving thrust augmentation ratios greater than one have been demonstrated.

Introduction

The best features of rockets and air breathing engines can be combined in composite engines. Studies at the Vikram Sarabhai Space Centre (VSSC) have revealed that a Rocket Based Combined Cycle (RBCC) engine is an attractive choice for the propulsion system of an Air Breathing Launch Vehicle (Ref.1). It is envisaged that a high performance ejector ramjet could be employed in the propulsion system's low speed mode (typically, Mach 0-3). VSSC has plans to develop a flight demonstrator vehicle which employs an ejector ramjet (Ref.2). A liquid rocket and ramjet can be integrated into a light weight, highly flexible engine in an ejector ramjet. Such a combined cycle engine can operate in several modes. It has the advantages of rocket propulsion during take off as a rocket ejector and in the all-rocket mode after the space vehicle has left the atmosphere. At intermediate vehicle speeds, it could achieve high performance as a ramjet/scramjet. There is a clear need for the creation of a data base for the design of an ejector ramjet with specific reference to the transition from ejector to ramjet mode and eventually, even the transition from ramjet to scramjet mode, during which it would operate in a dual mode. This preliminary experimental investigation has been carried out to explore the performance bounds of a subscale kerosene-fuelled ejector ramjet at simulated takeoff. The specific area of interest was the ramification of the afterburner design on the ejector ramjet performance. Incorrect release of heat in the afterburner along with unsynchronised opening of the exit nozzle will lead to poor ejector and afterburner performance and may even result in intake unstart.

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Ejector Ramjet

The function of a thrust augmenting ejector is to enhance the thrust of a primary exhaust by allowing transfer of energy from the primary jet to the low speed secondary jet. The ejector is a mechanically simple device in which turbulent entrainment by a jet of primary fluid is used to pump a secondary fluid through a mixer duct (shroud). The ejector could be considered analogous to a low pressure ratio compressor. The ejector ramjet is an improved derivative of this type of ejector. Basically, an ejector ramjet consists of a primary rocket, air intake, mixer duct, diffuser, secondary combustor (afterburner) and nozzle.

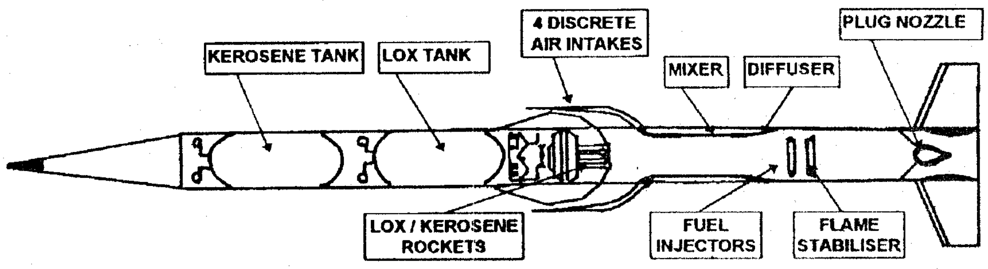

Fig. 1. Schematic of a kerosene-fuelled ejector ramjet

Fig.1 is a schematic of a candidate VSSC ejector ramjet. The secondary combustor will be similar to a standard afterburner or conventional ramjet combustor. The intake compresses the free stream air to the desired pressure at the mixing chamber inlet. The exhaust gases from the primary rocket are injected into the mixer and they will entrain and mix with the incoming air. Additional compression and flow deceleration occur in the diffuser section. The flow then enters the afterburner section where additional fuel is sprayed into the main flow and combustion allowed to take place. The resulting high energy gases are finally expelled through the exhaust nozzle to produce thrust. The afterburner must be so configured that it will allow the ejector ramjet to operate as an air-augmented rocket at takeoff and continue its operation upto Mach 2 in an ejector ram rocket mode. The engine will gradually undergo a transition to a ramjet mode in the Mach number range 2-2.5 and continue further operation as a pure ramjet (primary rockets shutoff) upto about Mach 5.5.

At very low forward speeds, the ejector ramjet thrust is partially due to the suction forces exerted on the contoured portion of the air inlet, as the secondary flow is ingested and accelerated. At higher flight speeds, air is induced through a diffusing intake and the pressure is increased. Thrust augmentation can be realised in an actual ejector ramjet only by adding energy to the flow by combustion. The mixing is limited only to a level to promote combustion (Ref.3).

Ejector ramjets must simultaneously achieve two key objectives: High performance and critically, for flight applications - Compactness. The engineering issues to be addressed are many.

Thrust augmenting ejector performance improves considerably as the mixing between the primary and the secondary streams become more complete within the cylindrical shroud. In theory, complete mixing requires a long ejector and this high performance objective clearly conflicts with the compactness objective. Various methods such as multiple primary jet configurations and the provision of hypermixing primary nozzles, which introduce streamwise vortices (Ref.4) have been employed to improve the mixing. It is essential that combustion be avoided during mixing as it leads to a deterioration in the mixing process (Ref.1, 5-7).

The ejector length is restricted in many practical applications. In such designs, wide angle diffusers necessarily have to be used but they are very susceptible to flow separation. The effectiveness of the diffuser cannot be augmented by employing inserts. However, the wall boundary layer could be energised by the influx of primary gas. The diffuser will only amplify the skewness if presented with a skewed profile due to incomplete mixing (Ref.8). In addition to recovery of velocity head, the diffuser is also required to reduce the flow Mach number at afterburner inlet in order to decrease the drag losses and ensure good ignition and flame stability characteristics. Low afterburner inlet Mach numbers are also required to ensure low Rayleigh heating total pressure losses.

A large number of geometric configurations of the ejector ramjet are possible. The designer has at his disposal a choice of the primary fluid at a given flow rate, pressure and temperature. Consequently, the primary throat can be determined. The remaining free parameters to achieve good thrust augmentation are the primary nozzle exit Mach number, the mixing tube diameter and length, relative location of the primary nozzle exit, the afterburner exit nozzle size and type, the afterburner configuration, the extent of heat release in the afterburner and the secondary fluid inlet total temperature and pressure.

Several modes of operation are possible for ducted mixing/combustion systems. Moreover, the afterburner (or ramjet combustor of the ejector ramjet) should be configured to be aerodynamically clean so that the overall system will give acceptable performance in the ejector ram rocket mode as well as in the ramjet mode and eventually, in a later phase, in the scramjet mode. The second throat (afterburner exit nozzle) will radically alter the starting characteristics of the ejector and this process will be further complicated by the release of heat, in addition to the presence of the normal shock which should eventually be disgorged out of the exit nozzle throat. An exploratory investigation was conducted to identify the parameters which have significant effects on the performance of the kerosene fuelled ejector ramjet.

Experimental approach

For the complete experimental programme, heated high pressure air discharged from an aeroengine can combustor has been used in place of a rocket jet as this would simplify the process of investigation. The tests closely simulated the primary jet pressure ratio but only partially simulated the primary gas temperature and properties.

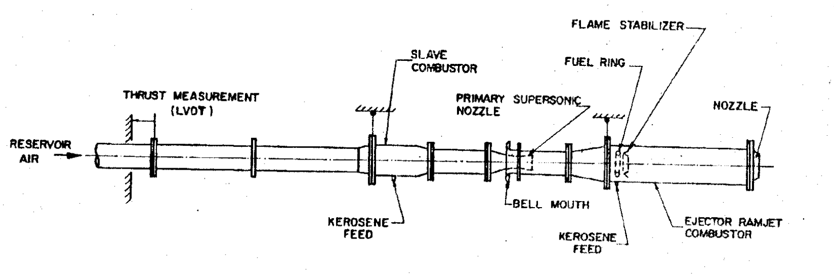

Fig.2. Schematic of the ejector ramjet test rig

Fig.2 is a schematic of the test rig and Fig.3-5 are views of the test rig. The axisymmetric one third scale ejector ramjet module consisted of a bellmouth intake, diffuser, interchangeable primary nozzles, mixing tubes, afterburner and exit nozzles. The model was mounted horizontally and the axial thrust generated by the ejector ramjet system could be determined through the deflection, as measured by an LVDT, of the load carrying member.

Primary air, at pressures upto 10 bar was heated upto 1600 K, depending on the test requirement, with the aid of an aeroengine can combustor. This heated, pressurised air was fed to uncooled primary nozzles. A range of tubes (diameter 53, 81, 105 mm) to simulate choked nozzles and Mach 2.73 conical nozzle (exit dia 86 mm) were used. The ejector shroud diameter was kept constant at 156 mm but its length was varied. The ejector used a bellmouth inlet which is suitable for static conditions. A blunt inlet with elliptic profile would be more suitable for forward speeds (Ref.9). It may be noted that VSSC plans to employ four discrete rectanguler air intakes and a cluster of eight primary engines in the proposed ejector ramjet (Ref.2).

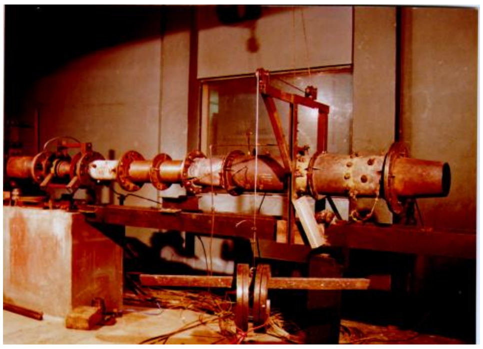

Fig.3. Test rig - overall view

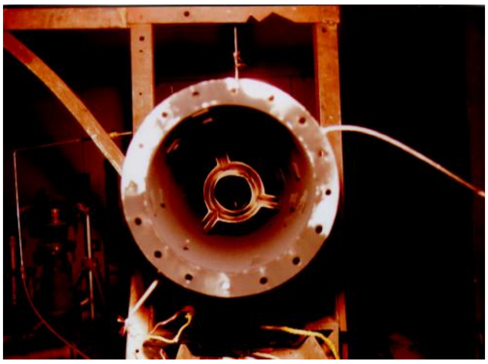

Fig.4. View of bellmouth intake, primary supersonic nozzle

Fig.5. Ring V-gutter flame stabiliser

The afterburner consisted of a diffuser (area ratio 2.2) and a constant area duct (diameter 232 mm) provided with an integral fuel injector/flame stabiliser. The fuel injector types used were channel anvil and plain opposed. The flame stabiliser was a conventional V gutter ring (Fig.5), and its dimensions were chosen to minimise the adverse effect of the primary jet induced skewed velocity profile. The afterburner nozzles employed were either of the conical type (area ratio 0.51) (Fig.3) or plug type (Fig.6) (area ratio 0.3, 0.5, 0.7) which had an axial movement provision for varying the area ratio. Kerosene fuel was used both in the primary combustor and afterburner. The afterburner was ignited by hot streaks. Smooth combustion was achieved (Fig. 6,7), once the afterburner was properly configured.

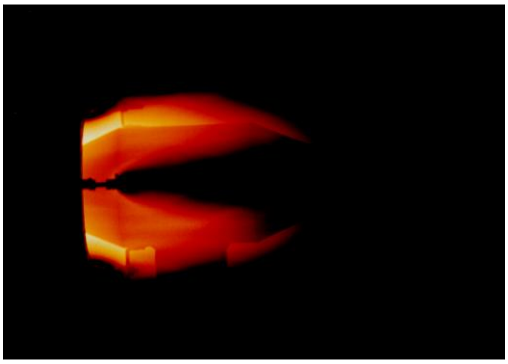

Fig. 6. Kerosene flame issuing from plug nozzle

Fig. 7. Kerosene flame issuing from conical nozzle

Results and discussion

Initially, the basic thrusts of the primary nozzles (Mach 2.73, exit dia 86mm; tubes dia 53, 81, 105 mm) were determined for variations in primary pressures and temperatures (Fig.8).

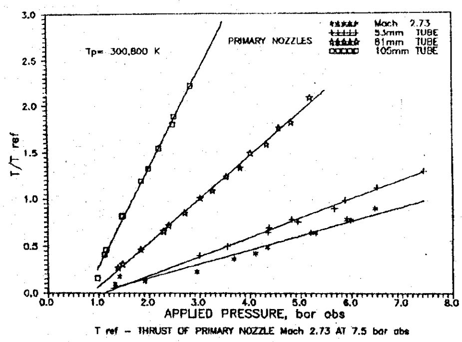

Fig. 8. Primary nozzle thrust - effect of primary pressure, temperarure

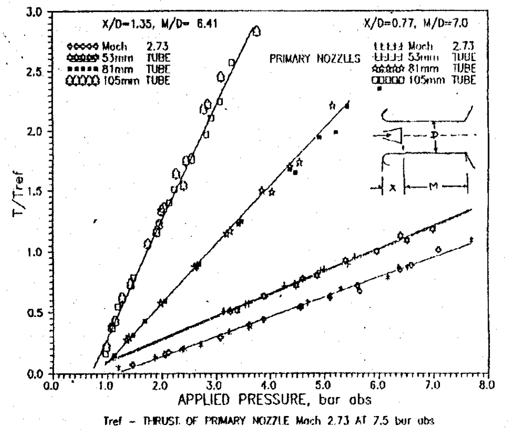

Fig.9. Ejector thrust - effect of primary pressure, temperature (no difuser, afterburner)

The primary thrust was found to vary linearly with the applied pressure and was independent of air temperature (300K, 800 K), as expected from theory. A constant area shroud (without diffuser) was then fitted around the primary nozzle and the ejector thrust determined (Fig.9). It was seen that the thrust again varied linearly with the applied pressure and was independent of the primary gas temperature. These trials were for a fixed mixing tube diameter and for different insertion depths of the primary nozzle within the bellmouth/mixer and mixer lengths. It is known that increasing the primary temperature has little effect on the performance of short ejectors (Ref.10). The thrust variations which occur with a change in applied primary pressure cannot be predicted by idealised theory as they are evidently associated with changes in the mixing mechanism within the duct (Ref.3). Fig. 10 shows the improvement of thrust with the inclusion of a diffuser (area ratio 2.2) for the case of a Mach 2.73 conical primary nozzle. Again, it is seen that the thrust varies linearly with the applied pressure and is independent of primary temperature (300K & 800K).

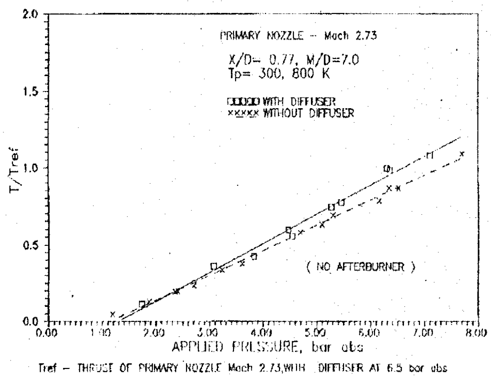

Fig 10. Ejector thrust - effect of primary pressure and temperature, diffuser

The variation of the thrust augmentation ratio (ϕ) with applied pressure for different primary nozzles within a constant diameter shroud, which does not terminate with a diffuser, is shown in Fig.11. The thrust augmentation ratio was defined as the ratio of the ejector thrust to the primary thrust at the same applied primary pressure.

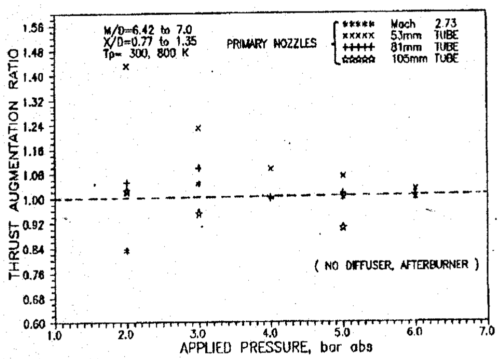

Fig.11.Thrust augmentation ratio - effect of pimary pressure and temperature, nozzle mixing length and insertion depth

It is seen that for similar test conditions, the ejector with a supersonic nozzle maintained a thrust augmentation ratio (ϕ) roughly around one whereas the 105 mm tube nozzle showed a definite deterioration of (ϕ) below one. The smallest nozzle tube (53 mm dia) gave augmentation ratios upto nearly 1.4. This however, decreased as the applied pressure increased, possibly due to a change in the mixing pattern. Clearly there is an adverse effect of increase in primary nozzle size relative to the shroud diameter. Friction could have a bearing in the range tested. The mixing tube length, depth of insertion of the primary nozzle within the bellmouth as well as the primary air temperature do not show any significant effect on the thrust augmentation ratio in the range tested.

The variation of thrust augmentation ratio (ϕ) with applied pressure for an ejector provided with a supersonic prmary nozzle, with and without a diffuser, is shown in Fig.12. The definite advantage of using a diffuser is evident. The primary temperature was found to have no appreciable effect. ϕ was found to fall below one for applied pressures below 3 bar. At very low pressures, the nozzle would not have run full, once the Summerfield limit was crossed.

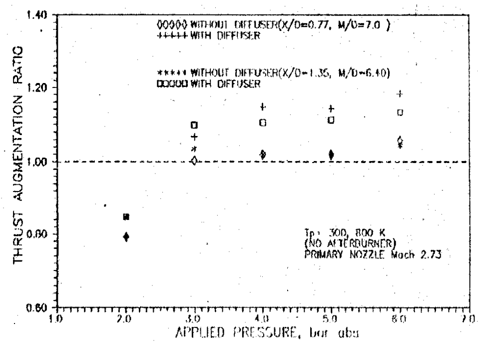

Fig. 12. Thrust augmentation ratio - effect of diffuser, primary pressure and temperature

An afterburner together with an exit nozzle (area ratio 0.51) were added to the ejector, which had a supersonic primary nozzle, and the trials conducted, with and without combustion. Fig. 13 clearly illustrates the definite need for an afterburner. ϕ > 1 could be achieved for a certain applied pressure range. ϕ is seen to be nearly 0.7. when the afterburner is off. The necessity of a careful design of the afterburner in order to decrease internal losses due to the fuel injector/stabiliser and nozzle needs to be stressed. The standard channel/anvil fuel injector was found to be slightly inferior to a plain opposed injector. In both cases, ϕ was found to decrease with an increase in applied pressure. The fall in thrust augmentation ratio is due to a thermal throttling effect.

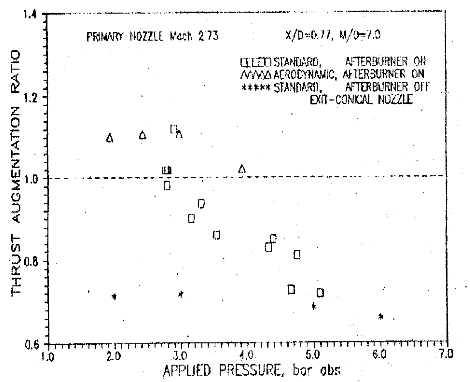

Fig. 13. Ejector ramjet thrust augmentation ratio - effect of primary pressure, afterburner

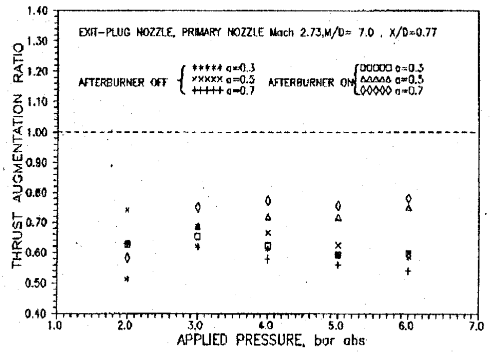

Fig. 14. Ejector ramjet thrust augmentation ratio - effect of primary pressure, afterburner

Heat addition and afterburner nozzle opening should be coordinated or else there will be a fall in thrust. Heat release should be carefully controlled and, in the extreme, may even lead to an intake unstart. In the case of the plug nozzle, ϕ was seen to be far below one, with and without combustion. It was seen to improve with combustion (Fig.14). For all the above trials with the afterburner, a typical operating condition set was that the temperature of the primary stream and the exit temperature of the afterburner were made roughly equal, for ambient temperatures of the secondary flow.

Concluding Remarks

A proof-of-concept experiment was devised to demonstrate the feasibility of a kerosene fuelled ejector ramjet. Thrust augmentation ratios greater than one were achieved in a subscale kerosene fuelled ejector ramjet at simulated takeoff. The performance of the subscale ejector ramjet was found to critically depend on the engine configuration selected and the flow parameters chosen.

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