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Thrust Augmenting Ejectors for High Pressure Ratio Propulsive Jets

S.A. FISHER
Senior Research Scientist, Aeronautical Research Laboratories, Melbourne

SUMMARY Some results are presented of a continuing investigation designed to demonstrate the feasibility of using simple ejector augmentation, without afterburning, to increase the static thrust of a rocket motor. The investigation is based on experiments using high pressure air as a primary fluid, supported by static rocket firings with selected augmentor geometries. The results suggest that a significant thrust improvement is available.

1. INTRODUCTION

In its simplest form, air augmentation of a propulsive jet involves no afterburning or other form of net energy addition to the flow. The object is to increase the mass flow and reduce the jet velocity by such means that the resultant gain in propulsive efficiency outweighs all of the penalties due to application of the augmentor. The potential for increasing net thrust in this way is greatest at static or low speed conditions, when the momentum drag of the induced secondary flow is small.

Possible techniques for air augmentation range from ejector entrainment to the use of turbomachinery to transfer energy from the primary to the secondary streams. Despite the losses inherent in the turbulent mixing process, ejectors have strong appeal on the grounds of simplicity and lightness, and have already found application in V/STOL aircraft propulsion systems. Of present interest is the possibility of using ejector augmentors to improve the performance of rockets in very low speed flight; here the very poor propulsive efficiency of the high velocity unaugmented jet provides added incentive to exploit the principle.

An investigation is under way to determine the increase in static rocket thrust which can be achieved by air augmentation with ejectors of practical size.

2. NOTATION

A	Duct or flow area
D	Diameter
L_e	Ejector length measured from inlet throat
M	Mach number
P	Static pressure
P_o	Total pressure
T_o	Total temperature
θ	Diffuser half-angle
μ	Ratio of secondary to primary mass flows
ν_d	Diffuser area ratio A_3/A_2
ν_e	Ejector area ratio A_1/A_1'
τ	1 + (augmentor thrust)/(primary thrust)

Subscripts

a	Relating to ambient conditions
1, 2, 3	Relating to stations 1, 2 and 3 in Figure 1

Superscripts

$'$	Relating to primary flow only
$''$	Relating to secondary flow only

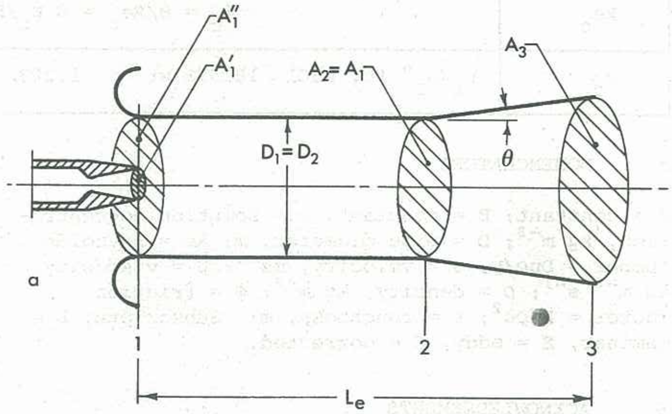

Figure 1 Definition of ejector geometry

3. BACKGROUND

Ejectors for augmenting the thrust of relatively low pressure ratio jets have been fairly thoroughly explored (e.g. Quinn, 1973, Reid, 1962, Viets, 1975, Whitley, 1974). Much of this work has been aimed at V/STOL aircraft applications, with severe constraints on ejector size and shape but relative freedom in respect of primary nozzle configurations. Highly complex nozzle arrangements have been developed (Viets, 1975) to maximise the rate of mixing between the primary and entrained gas streams, and useful levels of thrust augmentation have been demonstrated with extremely compact ejectors.

Recorded investigations of non-afterburning thrust augmentors having jet pressures and temperatures appropriate to rocket motors (Simonson and Schmeer, 1962) are much scarcer, and the existing data is insufficient to allow confident prediction of either the performance which can be reasonably achieved or the appropriate ejector configurations. Moreover, the nature of a rocket efflux prohibits the use of most of the enhanced mixing devices developed for other applications, further limiting the technology base available for approaching the present task.

4. THEORETICAL ASPECTS

Compressible flow theory based on principles of conservation of mass, momentum and energy can be applied to the flow in a thrust augmenting ejector if complete mixing of the primary and secondary streams is assumed to have occurred within the length of a mixing tube having either constant area or constant internal static pressure with respect to its length, or for incomplete mixing if certain assumptions are made regarding

TABLE I

OUTLINE OF THE CALCULATION OF THE Re-ϕ CORRELATION FOR ELECTROLYTE SOLUTIONS

Calculation	Data	Result
Re	NaCl 10.37% wt; Dia = 0.02926 m; u = 1.1514 m s^{-1}; ρ_{20} = 1.073 kg m^{-3}; μ_{20} = 1.205 x 10^{-3} kg $m^{-1}s^{-1}$	Re = 3 x 10^4
ϕ	Moody Plot or more simply $\phi = 0.04015\ Re^{-\frac{1}{4}}$	ϕ = 0.00305
ϕ_L	Hagen-Poiseuille equation $\phi_L = 8/Re$	ϕ_L = 0.000267
Re_L	Hagen-Poiseuille equation $\phi = 8/Re_L = 0.00305$	Re_L = 2623
Re_E	$Re_E \simeq Re_L$ $\phi_E \simeq \phi$	Re_E = 2623 ϕ_E = 0.00305, within - 0.38%
μ_E	$\mu_E = D\ u\ \rho/Re_E$	μ_E = 13.782 x 10^{-3} kg $m^{-1}s^{-1}$
ϕ_c Re_c	Hagen-Poiseuille equation $\phi_c = 8/Re_c = 8\ \mu_c/D\ u\rho$	ϕ_c = 0.00367 Re_c = 2180
μ_c	μ_L/μ_L° for NaCl 10.37% wt = 1.203, $\mu_c = 1.203\ \mu_E$	μ_c = 16.583 x 10^{-3} kg $m^{-1}s^{-1}$

5 NOMENCLATURE

A = constant; B = constant; c = solution concentration, kg m^{-3}; D = pipe diameter, m; Re = Reynolds Number = $Du\rho/\mu$; u = velocity, ms^{-1}; μ = viscosity, kg m^{-1} s^{-1}; ρ = density, kg m^{-3}; ϕ = friction factor = $R/\rho u^2$; ε = roughness, m: Subscripts, L = laminar, E = eddy, C = corrected.

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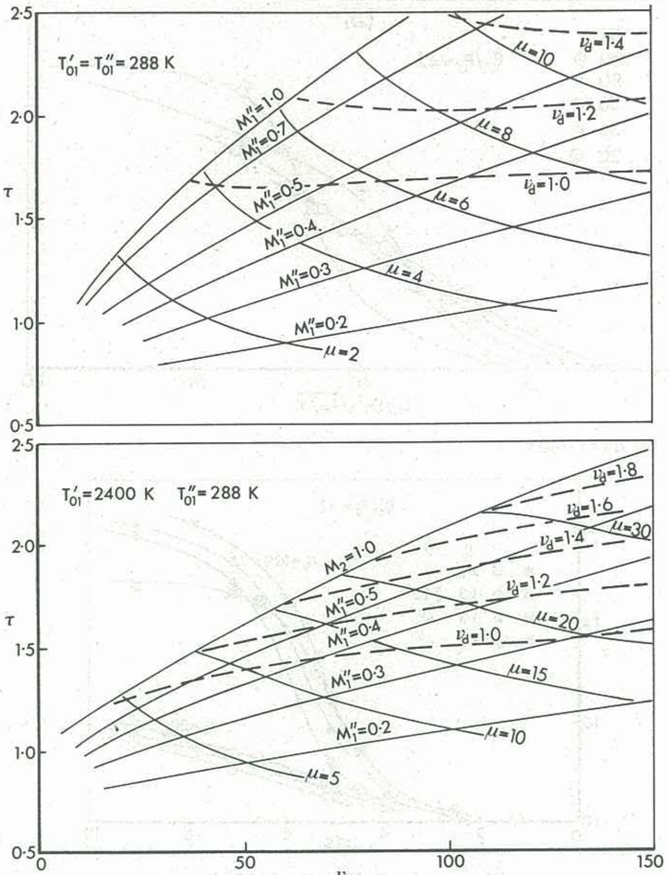

Figure 2 Theoretical performance for $P'_{01}/P_a = 50$

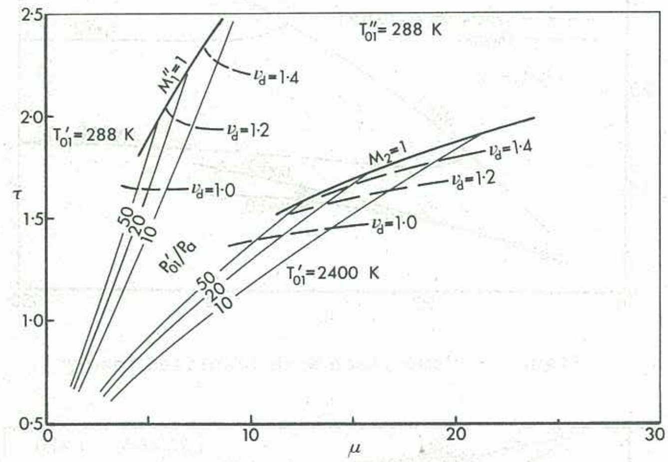

Figure 3 Effect of pressure and temperature at $\nu_e = 50$

temperature distributions. An early step in the present investigation was to analyse a wide range of idealised axisymmetric ejectors of the form shown in Figure 1, to identify the configurations which were likely to be of most interest. All had constant area mixing followed by diffusion, with one-dimensional (fully mixed) flow at the end of the mixing tube and no friction losses. Figure 2 shows how thrust augmentation ratio, secondary flow inlet Mach number and mass flow ratio vary with ejector geometry, for a primary pressure ratio of 50 and for two different values of primary jet temperature. Figure 3 shows the effect of varying both the primary pressure and temperature, with an ejector area ratio of 50. The properties of air are assumed to apply for both primary and secondary streams, and in all cases the primary nozzle is correctly expanded relative to ambient pressure, which means that the nozzle geometry varies with primary pressure ratio.

The theoretical treatment is currently being refined to include the effects of flow non-uniformity at both upstream and downstream ends of the ejector, internal friction, different primary gas properties and primary nozzle expansion ratio.

A most important parameter missing from Figures 2 and 3 is ejector length, which can be addressed theoretically only with an understanding of the mixing process within the ejector. At the high primary pressure ratios of present interest compressibility effects are dominant, and the flow in the mixing region is characterised by trains of shock waves which are often unsteady. The problem is compounded further when complex shaped nozzles are used to accelerate the mixing. In this situation, heavy reliance must be placed on experiments for determining the effect of length on augmentor performance.

5. EXPERIMENTS

5.1 General Approach

For the bulk of the experimental programme, unheated high pressure air has been used in place of a rocket jet, since this greatly eases the task of investigating the necessary range of variables. To maintain a link between the "cold" test results and the rocket situation, these experiments are supported by static rocket firings in conjunction with selected augmentor geometries.

5.2 Cold Tests

5.2.1 Apparatus

The test rig is illustrated schematically in Figure 4. The axisymmetric ejector model consists of a bellmouth inlet, interchangeable sections of parallel mixing tube, interchangeable diffusers and an instrumentation ring for pressure measurement. The model is mounted horizontally, with provision for measurement of the axial thrust on the ejector.

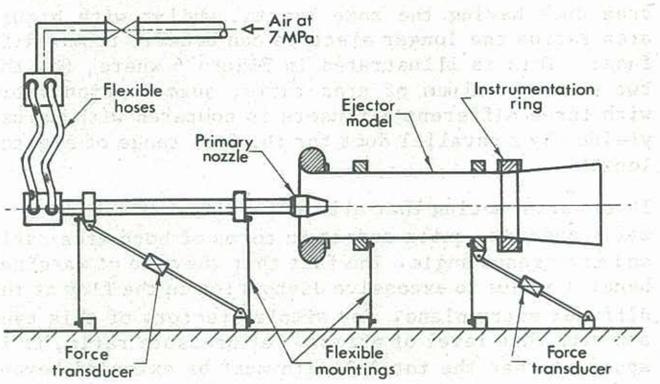

Figure 4 Rig for cold tests

The primary air comes from storage vessels at a pressure of up to 7MPa and at room temperature, and the jet is formed by one of a range of interchangeable nozzles. All of the nozzles employed sofar are convergent-divergent types with an expansion ratio of 4.03; they include a family of differently sized conical nozzles by means of which the ejector area ratio is varied, in addition to some having more complex configurations which are described in Section 5.2.4 below. The nozzles are mounted independently from the ejector model, again with provision for axial thrust measurement.

5.2.2 Effect of ejector geometry

A summary of thrust performance of the experimental range of augmentors which use the simple, axisymmetric nozzles is presented here for a primary pressure ratio $P'_{01}/P_a = 42$, this being a pressure which is convenient and representative of chamber pressures which may be encountered in solid fuel rockets. For present purposes, the calculated values of thrust augmentation

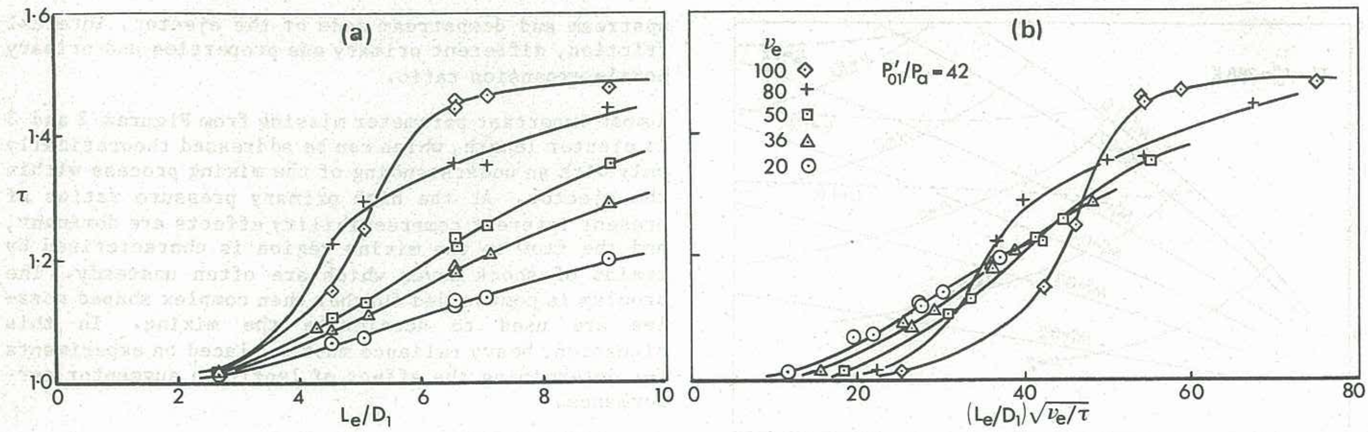

Figure 5 Ejector performance with no diffuser

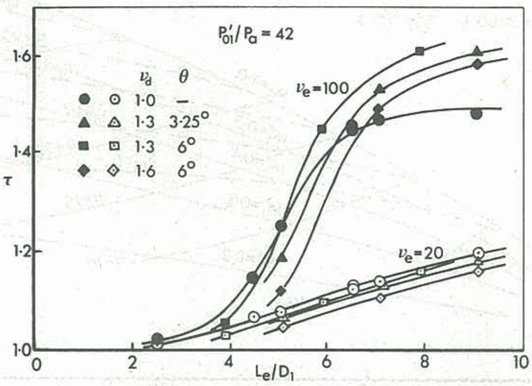

Figure 6 Effect of diffuser

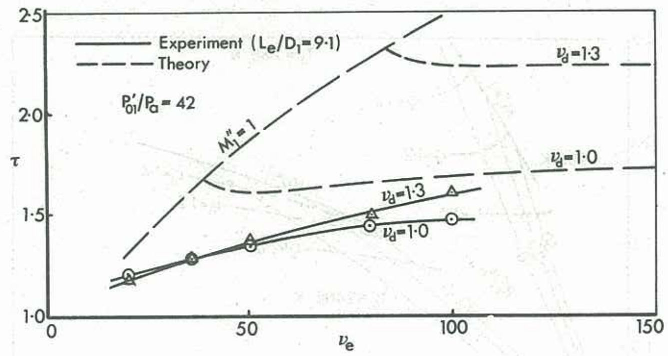

Figure 7 Comparison with idealised theory

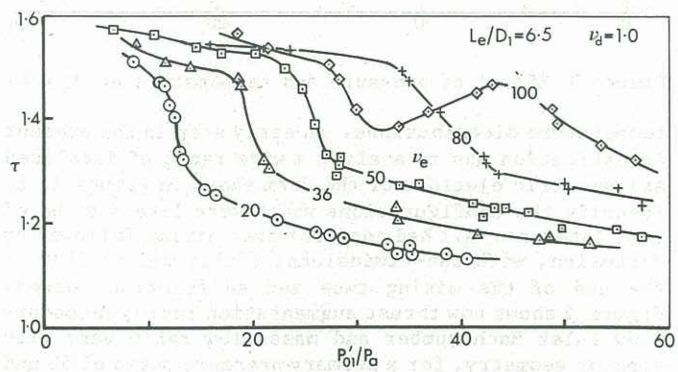

Figure 8 Effect of primary pressure ratio

ratio are based on measured ejector forces coupled with theoretical isentropic thrust figures for the different primary nozzles used.

Thrust augmentation ratio for ejectors with no diffusers is shown plotted in Figure 5(a) against ejector length/diameter ratio, and in Figure 5(b) against a parameter which expresses ejector length as a multiple of primary nozzle exit diameter for a constant level of total thrust, and which gives a measure of absolute ejector size. The latter graph is included to show how the optimum ejector area ratio changes with length. Over the range of geometries tested, thrust performance generally increases with length although, as Figure 5 shows, the rate of increase tends to diminish with longer ejectors as frictional losses begin to counteract the beneficial effects of more complete mixing between the primary and entrained flows.

The effect of a diffuser depends on both ejector area ratio and length. At the smaller area ratios covered by the present experiments the performance of an ejector with a diffuser is always inferior to that of a constant area duct having the same length, whilst with higher area ratios the longer ejectors can benefit from a diffuser. This is illustrated in Figure 6 where, for the two extreme values of area ratio, augmentation ratio with three different diffusers is compared with values yielded by a parallel duct for the full range of ejector length.

It is worth noting that all three diffusers are, by normal standards, quite modest in terms of both area ratio and divergence angle. The fact that they are of marginal benefit is due to excessive distortion in the flow at the diffuser entry plane. For simple ejectors of this type and with this level of primary jet pressure ratio, it is apparent that the total length must be extended beyond the range of present interest for a diffuser to perform effectively.

In Figure 7 the performance levels of two ejectors having the maximum length included in the present experiments, one with no diffuser and the other with a diffuser area ratio of 1.3, are compared with the corresponding theoretical curves for ideal ejectors. This further emphasises the shortfall in diffuser performance, particularly with low values of ejector area ratio where the effect of incomplete mixing is greatest.

5.2.3 Effect of primary pressure ratio

In Figure 8 the thrust augmentation ratio of a typical family of ejector geometries is plotted against primary pressure ratio. The thrust variations which occur with changing blowing pressure are not predicted by idealised theory, being evidently associated with changes in the turbulent mixing mechanism within the duct. In fact it is generally apparent that the nature of the flow in a typical ejector undergoes some gross changes with variations in blowing pressure; changes which are reflected not only in thrust variations but also in measured mean velocity profiles, and in acoustic tones which suggest phases of unsteadiness in the flow. There is evidence to suggest that at least some of these changes are associated with instability in the shock system originating at the primary nozzle exit, which varies in strength with the degree of under- or over-expansion of the nozzle. The positive effect on entrainment of unsteadiness in a jet is well established (Viets, 1975).

5.2.4 Effect of enhanced mixing devices

In addition to the range of conical primary nozzles which provided the results already discussed, two further nozzles designed to accelerate the mixing between the primary and entrained flows have been tested at one value of ejector area ratio. The first of these is basically conical, but has a set of vanes distributed around its inner periphery immediately upstream of the exit plane, designed to generate a system of streamwise vortices at the boundary of the primary jet. The second has an internal shape providing transition from a circular throat to a three-lobed cross section at its exit. Both have a throat size and nominal expansion ratio equal to the conical nozzle for which $\nu_e = 36$, and their basic thrust levels have been measured as being insignificantly different from that of the simple nozzle.

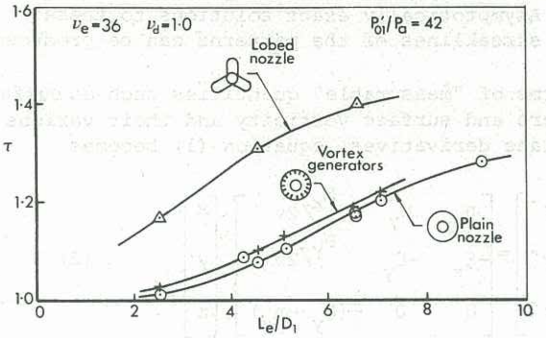

Figure 9 Effect of enhanced mixing devices

Figure 9 shows the performance of parallel duct ejectors tested in combination with these nozzles with a primary pressure ratio of 42, compared with the corresponding curve for the simple conical nozzle. The vortex generators give a small though consistent improvement in performance, whilst the lobed nozzle yields much greater levels of ejector thrust. The latter arrangement is clearly worthy of more detailed investigation, which must include the practicality of applying the lobed shape to rocket nozzles.

5.3 Rocket Firings

The basic form of the experimental rig being used for ejector tests in conjunction with rocket motors is illustrated in Figure 10. Some thrust results are shown in Figure 11, together with corresponding performance curves for comparable ejector geometries in combination with the cold air jet.

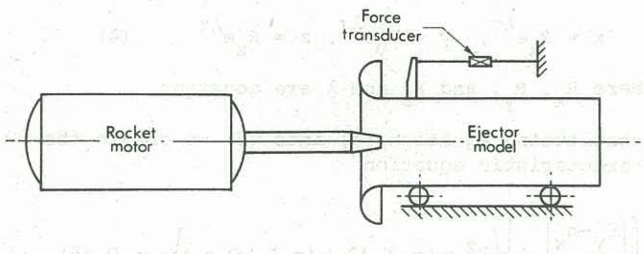

Figure 10 Rig for rocket tests

At least for this limited range of configurations, the augmentation ratios are generally higher with the rocket jet, a trend which is contrary to that which the idealised theory would predict on the basis of temperature effects alone (Figure 3). Although there are other differences between the properties of the rocket efflux and those of air which are not taken into account by the present theory, and which may influence the comparison, the difference suggests that the rate of mixing between the rocket jet and the secondary flow is somewhat higher than for the corresponding cold air jet. (It will be recalled that the theoretical treatment does not address the mixing process.) This effect could be explained in terms of both increased gas viscosity due to the higher temperature (Quinn, 1976) and the relatively high turbulence level in the rocket jet.

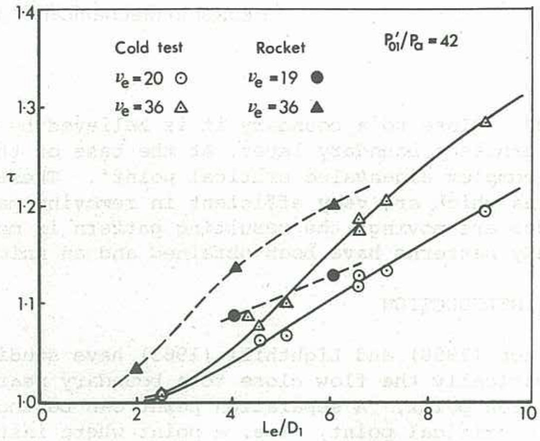

Figure 11 Comparison of rocket and cold test results

6. CONCLUSIONS

The results of experiments with a range of ejector augmentors having unheated high pressure air as a primary fluid, confirmed to some extent by rocket firings with certain ejector geometries, suggest that significant improvement may be gained in the static thrust of a rocket using an augmentor of reasonable size.

Future developments which promise further improvements in performance include the optimisation of primary nozzle shape to maximise the rate of mixing in the ejector. Measures will also be taken to gain a better understanding of changes in the mixing mechanism which apparently occur with variations in ejector geometry and primary pressure ratio.

7. ACKNOWLEDGEMENT

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