Scale Model Testing of 90° Supersonic Turn Ejector Systems for Altitude Simulation

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An experimental investigation was conducted to determine the operational and heat-transfer characteristics of rocket engine altitude-simulation ejector systems with 90° supersonic turns. Both constant-area and second-throat types, of varying geometries, were tested. Both types, with 90° turns required higher engine chamber pressures to obtain an ejector system start than geometrically similar straight systems. This chamber pressure required to start was reduced by 20 atm with the use of a secondary ejector that will enable a 58:1 expansion ratio nozzle to flow full at an engine chamber pressure of 120 psia. Heat-transfer measurements in sharp 90° turns yielded maximum values of heat-transfer coefficient 40 times those predicted by the Bartz equation. The maximum heat-transfer coefficient was reduced to 6 times that predicted by Bartz's equation by in creasing the radius of curvature of the 90° turn.

Nomenclature

A = cross-sectional area
B = length of straight section preceding turn
D = internal diameter
h = heat-transfer coefficient
K = thermal conductivity
L = centerline length
M = Mach number
P = static pressure
P_r = Prandtl number
R = radius
R_e = Reynolds number
T = temperature
ψ = contraction ratio, A_{D1}/A_{D2}

Subscripts

a = ambient or air
c = chamber
℄ = ejector centerline
d = primary duct
e = nozzle exit
f = film
p = primary ejector duct conditions or primary fluid
s = secondary ejector duct conditions or secondary fluid
sc = secondary ejector chamber
v = environmental cell (engine compartment) conditions

Superscripts

$*$ = nozzle throat, sonic conditions

Introduction

UPPER-stage rocket engines with large area ratio nozzles must be tested under simulated altitude conditions at some stage in their development. Goethert[1] reviewed the facility development problems associated with altitude testing of rockets and the use of straight ejector systems for such testing. However, it is also desirable to test these engines in a vertical downward firing position to simulate gravity effects, in which case the exhaust gases must be turned 90° to provide adequate disposal. Use of a straight vertical ejector system and a flame deflector leads to a large facility height and the possibility of inadequate disposal. An alternate method is a 90° turn ejector system, which can also serve to duct toxic flammable exhaust gases some distance from the test stand. However, very little data have been published on turn ejectors.

The experimental investigation reported in this paper was concerned with the operational and heat-transfer characteristics of 90° supersonic turn ejector systems.[2–4] Reference 5 reports a similar investigation carried out with 90° subsonic turn ejector systems. Tests were conducted with and without secondary ejectors, which provide reduced environmental pressures during the start and shutdown of the engine and provide a reduced primary ejector back pressure that results in a lower starting chamber pressure. Large area ratio nozzles can flow full at low engine chamber pressures when a secondary ejector is used in conjunction with the primary ejector.

Apparatus and Test Method

The scale-model ejector system, shown in Fig. 1, consisted of the engine compartment (environmental cell), the primary ejector, and the secondary ejector. These scale model tests used contoured $\frac{40}{1}$ area ratio nozzles with 0.3- to 0.8-in.-diam throats. The working fluid was nitrogen that could be preheated to 1600°R. Pressures and wall temperatures were recorded by means of a sampling switch and reduced to obtain pressure profiles and temperature histories of the duct wall. The wall temperature histories were used to estimate local heating conditions and required insulation of the ejector during the test. Two main types of 90° supersonic turn primary ejector systems were tested. The first type, shown in Fig. 1, is called a second throat ejector. Removal of the convergence where D_1 now equals D_2 resulted in the second type of ejector tested, the constant area ejector.

Two types of secondary ejectors were tested, each of which had an annular or peripheral nozzle rather than the common centerbody type in order that heat-transfer problems in the area could be minimized. The first type of secondary ejector allowed a constant-area ejector to be maintained from the second throat of the primary ejector to the end of the ejector system by using angular injection of the secondary fluid. The second type of secondary ejector tested, which introduced the gases parallel to the primary stream, had an increased duct diameter aft of the secondary nozzle. Nitrogen was used as the working fluid in all cases.

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Test Results and Discussion

In this paper, the performance of an ejector system is defined as the dependence of the engine compartment pressure P_v and nozzle exit pressure P_e on the nozzle chamber pressure. Figure 2 shows a typical primary ejector performance curve where at low chamber pressures the nozzle exit pressure is somewhat lower than the compartment pressure, indicating separated flow in the nozzle. As chamber pressure is increased, both the compartment and nozzle exit pressures decrease until a minimum is reached. This is the starting pressure of the ejector system where the nozzle and ejector flow full, and both pressures become proportional to the nozzle chamber pressure. As the chamber pressure is decreased, a point is reached where the low compartment pressure cannot be sustained, and a rapid increase in pressure occurs, accompanied by separated flow in the nozzle; this will be called the minimum operating pressure for the ejector.

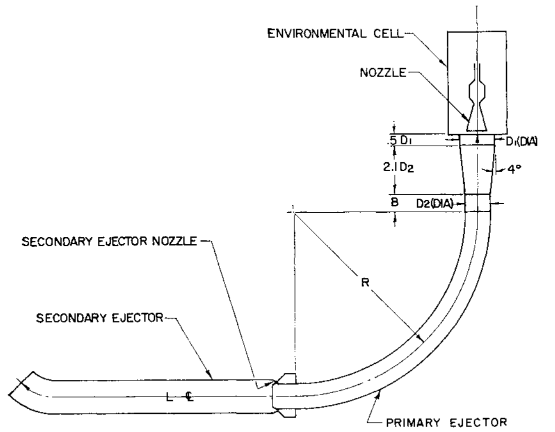


Fig. 1 A 90° supersonic turn ejector system.

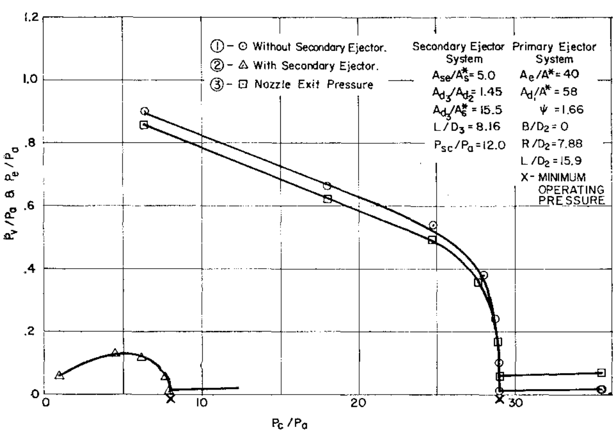


Fig. 2 Typical performance of an ejector system.

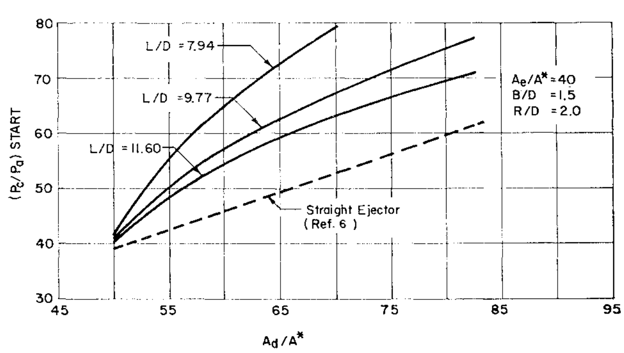


Fig. 3 Starting pressure ratio vs duct to nozzle throat area ratio (constant-area ejectors).

Previous investigations of straight ejector systems[6,7] have shown that the starting pressure of a primary ejector system is a function of the ejector area ratio (A_{D_2}/A^*), contraction ratio (A_{D_1}/A_{D_2}), and length to diameter ratio (L/D). For a 90° turn ejector system, these variables influence the ejector performance in much the same manner.

Constant-Area Primary Ejectors

The effect of ejector inlet to nozzle throat area ratio, on "starting" chamber pressure for selected values of over-all length, is shown in Fig. 3. Experimental results obtained with straight ejectors[6] are shown for comparison. With both straight and curved ejectors, it is apparent that, for increasing ejector inlet area ratio, the chamber pressure required for starting also increases. It should be noted that constant-area ejectors with a 90° bend started at a higher chamber pressure than the straight ejector, and the increase in $P_{c_{start}}$ is greater for larger A_{D_1}/A^* values. The performance of 90° turn ejectors with a given over-all length and a turning radius of 2 diam is improved by increasing the initial straight section of the ejector from 0 to 3.3 diam, thereby optimizing the height for a specific constant area ejector.

The influence of over-all length on ejector performance is also shown in Fig. 3, which illustrates that (for the same A_D/A^*) the greater the length for the range tested, the lower the chamber pressure required for starting. Reference 6 data indicate a basic difference between curved and straight ejectors in that an $L/D > 6$ does not influence the performance of a straight ejector.

An over-all view of Fig. 3 indicates that the starting chamber pressure ratio $(P_c/P_a)_{start}$ decreases primarily with decreasing A_D/A^* and secondarily with increasing ejector L/D for the ejectors tested in which $L/D \leq 11.60$.

Second-Throat Primary Ejectors

For a given ejector-inlet to nozzle-throat area ratio, A_{D_1}/A^*, the starting pressure can be reduced as shown in Fig. 4 by the use of a second throat. The maximum second-throat contraction ratio for starting, as a function of ejector-inlet Mach number, is given in Ref. 7, which was developed from straight-ejector tests. All, except three, of the second-throat ejectors tested during this program had a contraction ratio of 1.66, which is greater than one-dimensional theory allows. Similar results were reported in Refs. 1 and 7. The ejector that had a contraction ratio of 2.07 showed some difficulty in starting; it would not start when the engine-chamber pressure was increased rapidly from zero to steady-state operating conditions. When a slow engine starting transient was used, the ejector started with no apparent difficulty. When 2.22 was used as

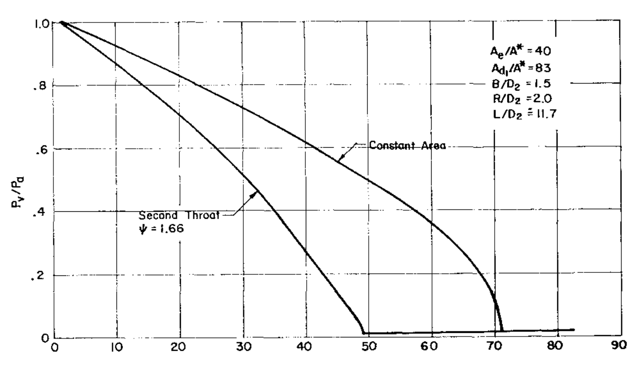


Fig. 4 Performance comparison of constant-area and second-throat ejectors.

the contraction ratio, a start condition could not be obtained.

The effect of ejector inlet area ratio on the starting chamber pressure for selected values of second-throat length, L/D_2, is shown in Fig. 5. These results show that, as with constant-area ejectors, the primary variable that influences performance of second-throat ejectors is A_{D_1}/A^*. The larger the ejector inlet area ratio, the larger the P_c required for starting. When comparing Figs. 3 and 5, it should be noted that the effect of increasing A_{D_1}/A^* does not have as pronounced an effect on second-throat ejectors as it does on constant-area ejectors.

Figure 5 also shows the influence of L/D_2 on ejector performance; the larger the L/D_2 for the range tested, the lower the starting chamber pressure. Again, in comparison with Fig. 3, the effect of changing L/D_2 is not as pronounced in second-throat ejectors as it is in constant-area ejectors.

Tests were made to determine the effect of a straight cylindrical section upstream of the second throat contraction. No significant effect upon performance was noticed.

Figure 6 shows the effect on starting chamber pressure of the initial straight section length prior to the 90° turn. It

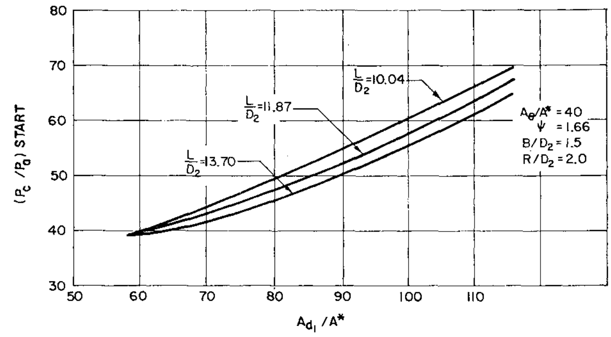


Fig. 5 Starting pressure ratio vs duct to nozzle throat area ratio (second-throat ejectors).

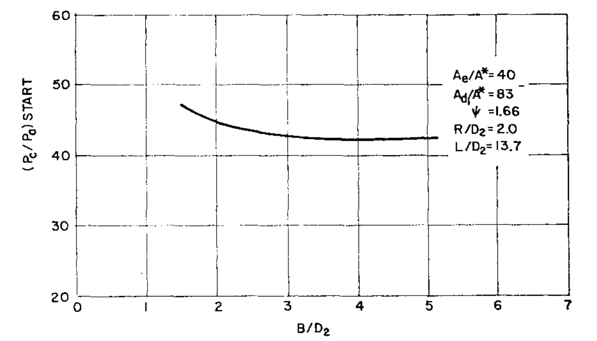


Fig. 6 Effects of B/D on performance of second-throat ejectors.

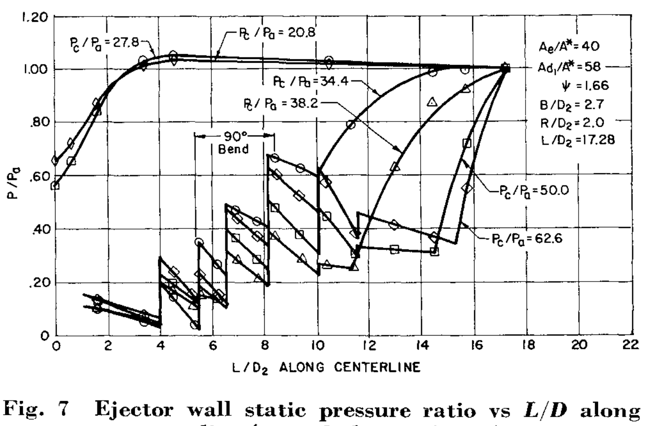


Fig. 7 Ejector wall static pressure ratio vs L/D along centerline (second-throat ejector).

should be pointed out, however, that this is a specific curve, valid only for a turning radius of 2.0 duct diam. Similar results were obtained for constant-area ejectors. As the turning radius is increased, the straight section prior to turning can be decreased without decreasing performance.

The 90° turning radius was increased from a radius of 2 to a radius of 7.88 duct diam. The major influence upon performance of increasing the turning radius was in the hysteresis effect. This hysteresis effect is the difference between the chamber pressure required to start the ejector system during engine-chamber pressure increase and the minimum operating point during decrease of engine-chamber pressure. Hysteresis is inherent in second-throat straight ejectors and was found also in second-throat ejectors with small turning radii (2 duct diam). When the turning radius was increased to 7.88 duct diam, this hysteresis effect disappeared, and the chamber pressure required to start the ejector was decreased about 10% and coincided with the minimum operating pressure. Optimization of test stand height for second-throat ejectors depends more on system requirements than do constant-area ejectors. Figure 5 shows the lowest $(P_c/P_a)_{start}$ occurring at a B/D_2 of 4, which, when combined with the elbow of R/D_2 equal to 2, gives an over-all height (see Fig. 1) of 9.2 D_2. A 10% increase in performance can, however, be obtained by decreasing the B/D_2 to 0 and increasing the R/D_2 to 8 and hence the over-all height to 11.2. Economics will be an important governing factor in selecting a height for any test facility.

Static wall pressure distribution for a second-throat ejector is shown in Fig. 7. The static pressure is increased to ambient by a turbulent mixing process before the ejector has started (P_c/P_a = 20.8 and 27.7). For all chamber pressures sufficient to start the ejector, this rise in static pressure is first accomplished by a series of oblique shocks and then by turbulent mixing. Figure 7 also shows that there is a growing shock structure in the ejector; i.e., as chamber pressure is increased, the existing ejector shock structure is increased in length.

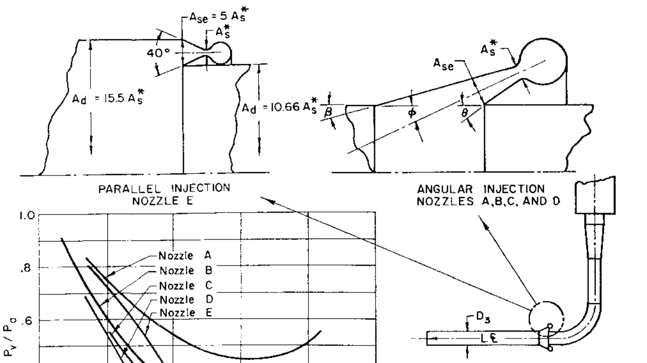
The engine was gimbaled up to 3° for certain tests, and no effect upon performance was noted. The nozzle exit area ratio, A_e/A^*, was 40, and the ejector inlet area ratio, A_{D_1}/A^*, was 58 for all gimbal tests.

Secondary Ejector Systems

It has been shown that for a specific ejector system (including a given nozzle and specific heat ratio) the ratio of P_c/P_a required to start will remain constant. Therefore, the actual chamber pressure P_c required for starting is a function of the ejector exit back pressure P_a. Reduction of atmospheric or essentially the back pressure that the primary ejector sees is the task of the secondary ejector and will enable the primary ejector to start at a lower value of P_c.

The first series of tests was made with a constant-area secondary ejector with angular injectors of the type shown in Fig. 8 to determine cell evacuation capabilities in the absence of primary flow. Performance improved as the injection angle φ was decreased (curves A through D in Fig. 8), but a start condition (P_v/P_{sc} remaining constant after minimum P_v is obtained) was not obtained until φ was decreased to 12.5° (curve D in Fig. 8). When angles greater than 12.5° were used, the impingement of the jet boundaries in the center of the duct caused flow reversal of a portion of the fluid, which prevented the ejector from starting. Tests were then made to determine the pumping capabilities of the 12.5° model. In all cases, the introduction of a primary flow caused the cell pressure to increase; engine-chamber pressure was varied throughout its normal range, but no start condition was obtained.

For the next series of tests, the secondary ejector gases were introduced parallel to the centerline of the ejector in the configuration illustrated in Figs. 1 and 8. All the ejectors tested operated satisfactorily and pumped the environmental compartment down to a low pressure (P_v/P_a = 0 05, curve E in



SECONDARY EJECTOR NOZZLE	A_{d_2}/A_s^*	A_{se}/A_s^*	β	θ	ϕ
A	13.15	3.82	24	46	35
B	10.35	2.34	14	46	30
C	10.15	1.87	14	25	19.5
D	10.66	2.62	5	20	12.5

Fig. 8 Performance of secondary ejectors.

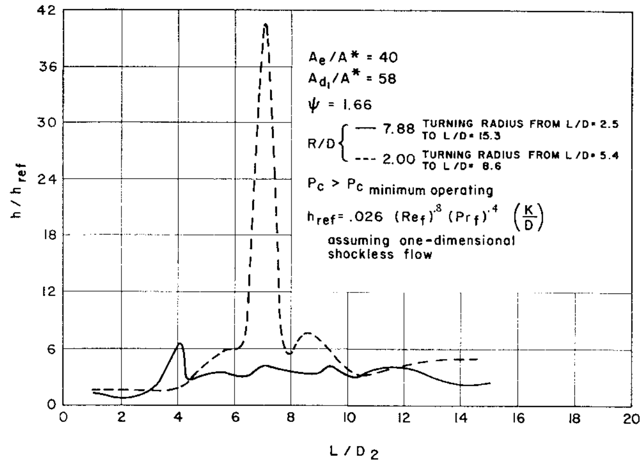


Fig. 9 Effects of turning radius on heat-transfer coefficient distribution.

Fig. 8). The curve in the lower left corner of Fig. 2 shows the effectiveness of the secondary ejector operating with the primary ejector; the starting P_c/P_a was reduced from 29 to 8. This means that contoured nozzles with area ratios up to 58 and with chamber pressures as low as 120 psia could be tested at simulated altitudes up to 100,000 ft.

It should be mentioned that more recent work in the field of secondary ejectors[8] has shown that, even though a system similar to the latter one just mentioned was used, in some cases ejector system start conditions could not be obtained. This was the result of changing the primary fluid (fluid being pumped) from nitrogen to hydrogen while maintaining nitrogen as the secondary fluid (pumping fluid). Ejector start conditions were not effected by the change in primary fluids when the secondary system was not in operation. It was not until the molecular weight of the secondary fluid was reduced that a start condition could be obtained. A definite relationship between the velocities and momentums of the primary and secondary fluids and the ability of the secondary ejector to enable the primary system to start at low values of engine pressure was found. Reference 8 should be consulted for a detailed discussion and analysis.

Heat-Transfer Considerations

The performance of an ejector system may be only slightly affected by the different methods of turning the flow through 90°, but the local heat-transfer coefficients on the outside wall of the turning section increase rapidly as the turning radius is reduced to 2 duct diam. Thus, ejector heat transfer could play a major role in the designing of a 90° turn ejector.

Data obtained from pressure measurements, spark shadowgraph, and water table hydraulic analogy tests indicate that the high heat-transfer rates in the sharp bend ejector are in part caused by the shock structure in the elbow. The sharp bend ejectors appear to have flow separation in the elbow and a resulting strong curved shock near and parallel to the wall at the point of highest heat flux. This results in an extremely nonuniform flow distribution. The large radius ejectors have a complex but fairly uniform shock system throughout their length which allows a more uniform distribution of flow and therefore less severe and more uniform heat flux distribution.

The heat-transfer coefficient distribution, showing the effect of turning radius, is presented in Fig. 9. The reference heat-transfer coefficient h_{ref} is the calculated value based on Bartz's equation and the assumptions of shockless, one-dimensional flow. The maximum heat-transfer coefficient for the sharp bend ($R = 2D$) ejector is 40 times that obtained from Bartz's equation and the forementioned assumptions and 6 times that for the large radius ejector ($R = 7.88D$) as shown in Fig. 9.

A more detailed evaluation of the heat-transfer test results of 90° supersonic turn ejector systems is presented in Refs. 3 and 4. Heat-transfer rates of 90° subsonic turn ejector systems have also been investigated and are presented in Ref. 5.

Concluding Remarks

1) The results of this program indicated sufficient differences between straight and 90° turn ejector systems so that facilities that plan to incorporate a 90° turn in the ejector system should not rely on data for straight ejector systems for design. Both second-throat and constant-area ejectors show higher engine chamber pressures required to start the ejector system than those required by straight ejectors.

2) A properly designed secondary ejector (auxiliary pumping system) will allow large area ratio nozzles to flow full at low chamber pressures. An ejector system (including secondary ejector) was tested which would allow contoured nozzles with area ratios up to 58 to be tested at simulated altitudes up to 100,000 ft with chamber pressures as low as 120 psia.

3) Other differences between straight and 90° turn ejector systems were noted throughout the program, but perhaps the most significant is the effect of turning radius upon heat transfer in the ejector system. A turning radius of 2 duct diam resulted in a heat-transfer coefficient at the 45° point in the elbow 40 times greater than predicted by the Bartz equation. Increasing the turning radius to 7.88 duct diam resulted in a maximum heat-transfer coefficient of 6 times that predicted by Bartz.

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