FLOW FIELD FOR AN UNDEREXPANDED, SUPERSONIC NOZZLE

EXHAUSTING INTO AN EXPANSIVE LAUNCH TUBE

Robert R. Morris and John J. Bertin
The University of Texas at Austin

James L. Batson
U.S. Army Missile Command

SUMMARY

Static-pressure distributions along the launcher wall and pitot-pressure measurements from the annular region between the rocket and the launcher have been made as an underexpanded supersonic nozzle exhausted into an expansive launch tube. The flow remained supersonic along the entire length of the launcher for all nozzle locations studied.

INTRODUCTION

A variety of military rockets are launched from launch tubes (called non-tipoff launch tubes) having a constrictive change in cross section which allows the rocket to be constrained initially after ignition, while momentum is gained. During the time when the rocket exhausts directly into the small-diameter, aft-tube, the flow downstream of the nozzle exit is entirely supersonic and intersecting, weak shock waves occur. The weak shock wave which results when the exhaust flow impinges on the wall produces a streamwise increase in the pressure. Although some of the fluid in the shear layer cannot overcome the adverse pressure gradient due to the weak, impingement shock and is turned upstream into the annular region between the rocket and the launcher, i.e., becomes blow-by flow, the mass-flow rate of the blow-by flow is negligible. The resultant flow field is that for an underexpanded, supersonic jet exhausting into a constant-area tube having an inside diameter which is slightly larger than the nozzle exit (ref. 1).

Since the rocket has gained sufficient momentum by the time the nozzle-exit plane clears the aft tube, the rocket flies free of constraints in the forward tube. However, as the exhaust flow encounters the constrictive change in area, a considerable fraction of the exhaust flow may be turned upstream. The mass-flow rate of the blow-by flow depends on the characteristics of the flow impingement (and, therefore, on the Mach number and the pressure in the nozzle-exit plane, on γ of the exhaust gas, on the nozzle-half angle, and on the ratio forward-tube radius:nozzle-exit radius), on the distance from the nozzle-exit plane to the constriction, and on the constrictive geometry (i.e., the step geometry and the ratio aft-tube radius:forward-tube radius).

Significant blow-by flow was observed during a flight-test program (ref. 2) in which rockets were launched from non-tipoff launch tubes, for which the ratio $A_{aft}:A_{for}$ was 0.595. Because of the complexity of the flow in the launcher, additional data were needed to construct a realistic flow model. The necessary data were obtained in a test program (ref. 3) in the Rocket Exhaust Effects Facility at the University of Texas at Austin in which an underexpanded jet of unheated air was exhausted from a stationary nozzle into a constrictive launch tube. These cold-gas tests clearly showed that the exhaust flow was choked by the constriction so that the impingement shock was a normal shock wave. As a result, a significant fraction of the exhaust flow (approximately 14%) could not overcome the large adverse pressure gradient associated with the strong impingement shock.

Negligible blow-by flow was observed during a flight-test program (ref. 4) in which rockets were launched from a non-tipoff launch tube for which the ratio $A_{aft}:A_{for}$ was 0.717. However, in the supplementary cold-gas tests, the exhaust flow choked and significant blow-by flow was measured once the nozzle-exit plane had gone 15 r_{ne}, or more, into the forward tube of a launcher for which $A_{aft}:A_{for}$ was 0.735. The discrepancy between the flight-test data and the cold-gas data was attributed (ref. 5) to differences in the growth characteristics of the boundary layer for the two tests, in the nozzle half-angle, and in the geometry of the constriction.

The flow fields which result when the underexpanded, supersonic nozzle exhausts into a constrictive launch tube are qualitatively similar to the flows which are generated in second-throat ejector-diffuser systems (ref. 6). However, the generation of significant blow-by flow prohibits close correlations between the launcher flow fields and the ejector-diffuser flows.

Since the creation of possible unbalanced forces on the rocket by exhaust gases which are turned upstream as blow-by flow are of special concern, it is desirable to eliminate blow-by flow completely. Therefore, a series of tests were conducted in which unheated air was exhausted through an underexpanded, supersonic nozzle into an expansive launch tube. For this launch tube, the ratio $A_{aft}:A_{for}$ was 1.680. The pressure distributions along the launcher wall and the blow-by flow rates which were recorded when the nozzle exit plane was located from 0.00 r_{ne} to 5.86 r_{ne} into the small-diameter forward tube are discussed in the present paper.

SYMBOLS

p static wall pressure

p_{atm} atmospheric pressure

p_p pitot pressure

p_{t1} reservoir stagnation pressure

r_{ne} nozzle-exit radius

x axial coordinate relative to the change in cross section

x_{ne} axial location of the nozzle-exit plane

TEST PROGRAM

Static wall-pressure distributions and pitot pressures were measured as the underexpanded, supersonic jet exhausted into the expansive launcher.

Rocket Exhaust Effects Facility. - Unheated air, for which γ was 1.4, exhausted from a convergent:divergent nozzle. The throat radius was 0.95 cm. (0.38 in.), the nozzle-exit radius was 1.44 cm. (0.565 in.), and the half angle of the conical nozzle was 10°. Data were obtained for reservoir stagnation pressures from 1.66×10^6 N/m^2 (240 psia) to 6.90×10^6 N/m^2 (1000 psia). Thus, assuming isentropic flow in the nozzle, the theoretical value of the static pressure in the nozzle-exit plane for the lower reservoir pressure was only slightly greater than the atmospheric value.

The instrumented, variable-area launch tube could be moved axially to vary the location of the nozzle-exit plane relative to the constriction and, thereby, to simulate (in a quasi-steady manner) the flow fields which result when the rocket accelerates through the launcher. The assumption that the exhaust flow for the dynamic rocket launching was quasi-steady was based on the fact that the velocity of the exhaust gas was more than twenty times the velocity of the rocket as it left the launcher. As illustrated by the sketch of Fig. 1, the overall length of the launcher was approximately 84.6 cm. (33.3 in.). The large-diameter, aft tube, which was approximately 38.6 cm. (15.2 in.) long, was 4.45 cm. (1.75 in.) in diameter. The forward tube, which was approximately 46.0 cm. (18.1 in.), was 3.43 cm. (1.35 in.) in diameter. The change in cross section was accomplished by a rectangular step, which served as the origin for the dimensionless axial coordinate system. Thus, as indicated in Fig. 1, a negative value of the dimensionless, axial coordinate corresponds to a location in the small-diameter, forward tube of the launcher.

RESULTS AND DISCUSSION

A pitot probe was located in the annular region between the "rocket" nozzle and the launch tube at the forward end of the launcher (i.e., the left end of the launcher in Fig. 1) to record the possible existence of blow-by. The pitot pressure measured when the nozzle-exit plane was at the step (i.e., $x_{ne} = 0.0\ r_{ne}$) is presented in Fig. 2 as a function of the reservoir stagnation pressure. Over the entire range of stagnation pressure tested, the experimentally determined pitot pressure was less than the atmospheric pressure. Thus, the nozzle:expansive-launcher configuration acted as an ejector system and there was no blow-by flow. The increasing pitot pressure indicates that the entrained flow rate decreased as the reservoir stagnation pressure increased. As the reservoir stagnation pressure increased, the pressure in the nozzle-exit plane increased in direct proportion. As a result, the exhaust flow expanded through a greater angle as it left the nozzle and, therefore, had to be turned through a greater angle by the wall, increasing the pressure downstream of the impingement shock wave and reducing the entrained mass-flow rate.

The static wall-pressure distribution near the impingement of the exhaust flow is presented in Fig. 3 for $x_{ne} = 0.0\ r_{ne}$. A schlieren photograph of the flow exhausting into the atmosphere (which has been trimmed where the launcher wall would be) is included to illustrate the flow mechanisms which produce the pressure distribution. Shock waves which intersect at the nozzle axis indicate that the acceleration of the flow in the conical divergent section was not an isentropic process. However, measurements of the transverse pitot-pressure distributions indicate that these intersecting shock waves were relatively weak. (See ref. 7 for a discussion of the origin of these shocks.) The intercepting shock wave and the viscous shear layer at the jet boundary are evident farther from the axis. The oblique shock wave generated as the flow impinged on the wall produced a sudden increase in the static-wall pressure. Downstream of the impingement shock, the streamwise pressure decrease, due to the acceleration of the flow, was terminated abruptly as the shock generated within the nozzle and the intercepting shock wave intersected at the wall. These impinging shock waves produced a slight increase in pressure.

However, as indicated in the pressure distributions presented in Fig. 4, the flow remained supersonic throughout the launcher. This remained true as the nozzle was moved farther into the small-diameter, forward tube (refer to Fig. 1 for the nozzle exit positions for which pressures are presented in Fig. 4). Since the ratio of the radius of the forward tube to the radius of the nozzle-exit plane (r_{ne}) was only 1.195, the angle between the flow at the jet boundary and the wall was relatively large when the underexpanded nozzle exhausted into the forward tube. Thus, the impingement shock wave was stronger for the nozzle-exit locations of Figs. 4b and 4c. However, the supersonic flow downstream of the impingement shock accelerated through the change in area. As a result, there was no blow-by flow for any of the nozzle-exit positions.

CONCLUDING REMARKS

The static pressure distributions along the launcher wall and the pitot-pressure measurements from the annular region between the rocket and the launcher indicate that no blow-by occurred when the underexpanded, supersonic nozzle exhausted into an expansive launch tube. This was true for all values of the reservoir stagnation pressure and of the nozzle exit location.

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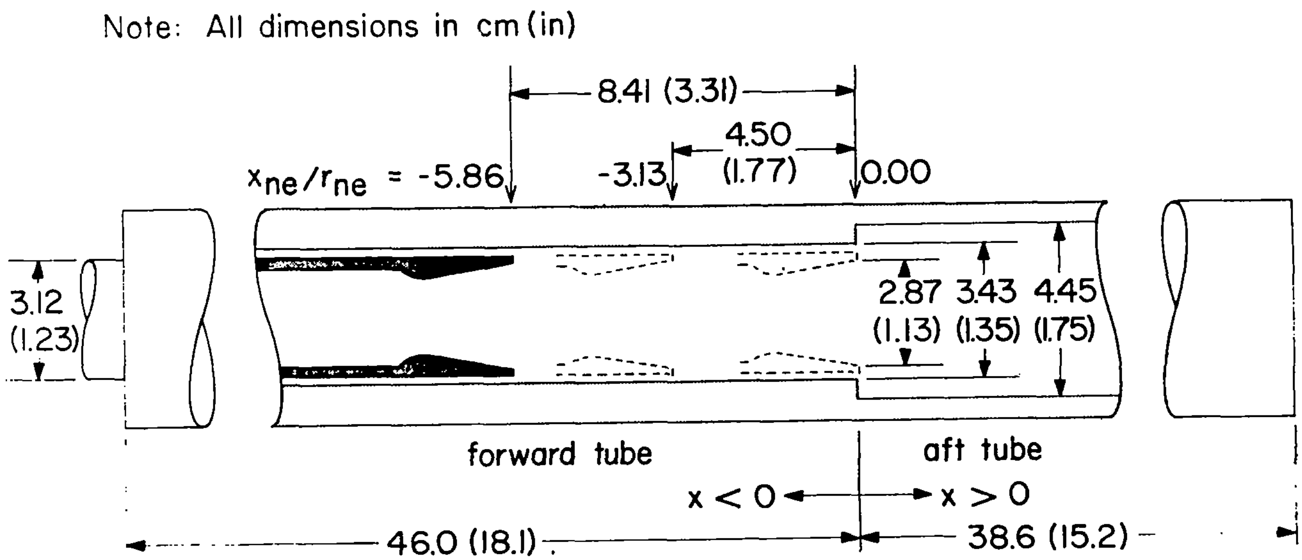

Figure 1. - Sketch of supersonic "rocket" nozzle in the expansive launch tube.

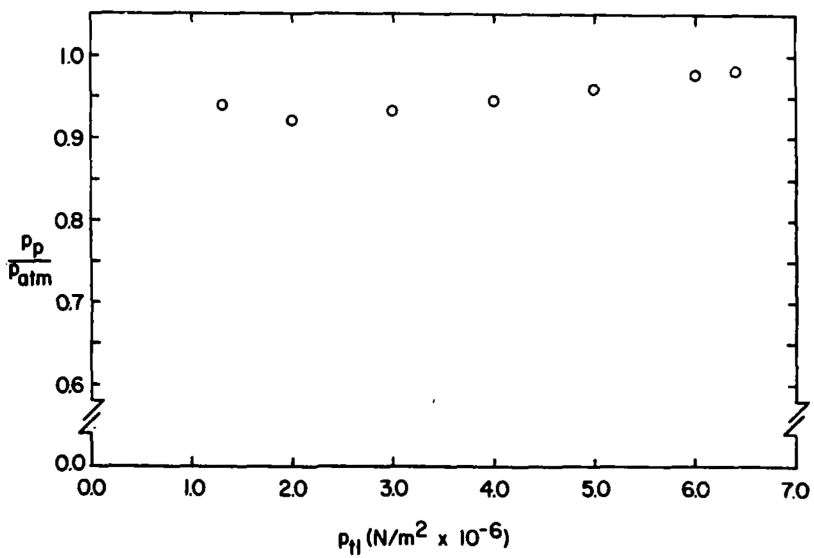

Figure 2. - Pitot-pressure measurements from the annular region between the rocket and the launcher as a function of the reservoir stagnation pressure.

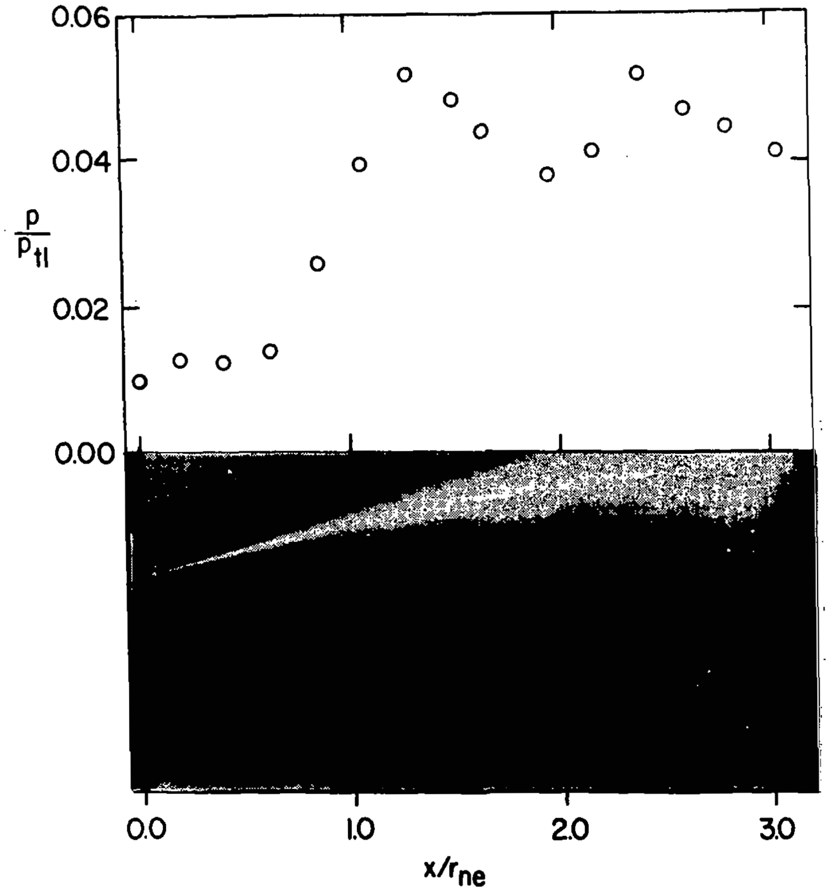

Figure 3. - Static-wall-pressure distribution near the impingement of the exhaust flow.
$p_{t1} \approx 6.4 \times 10^6$ N/m^2,
$x_{ne} = 0.0\ r_{ne}$.

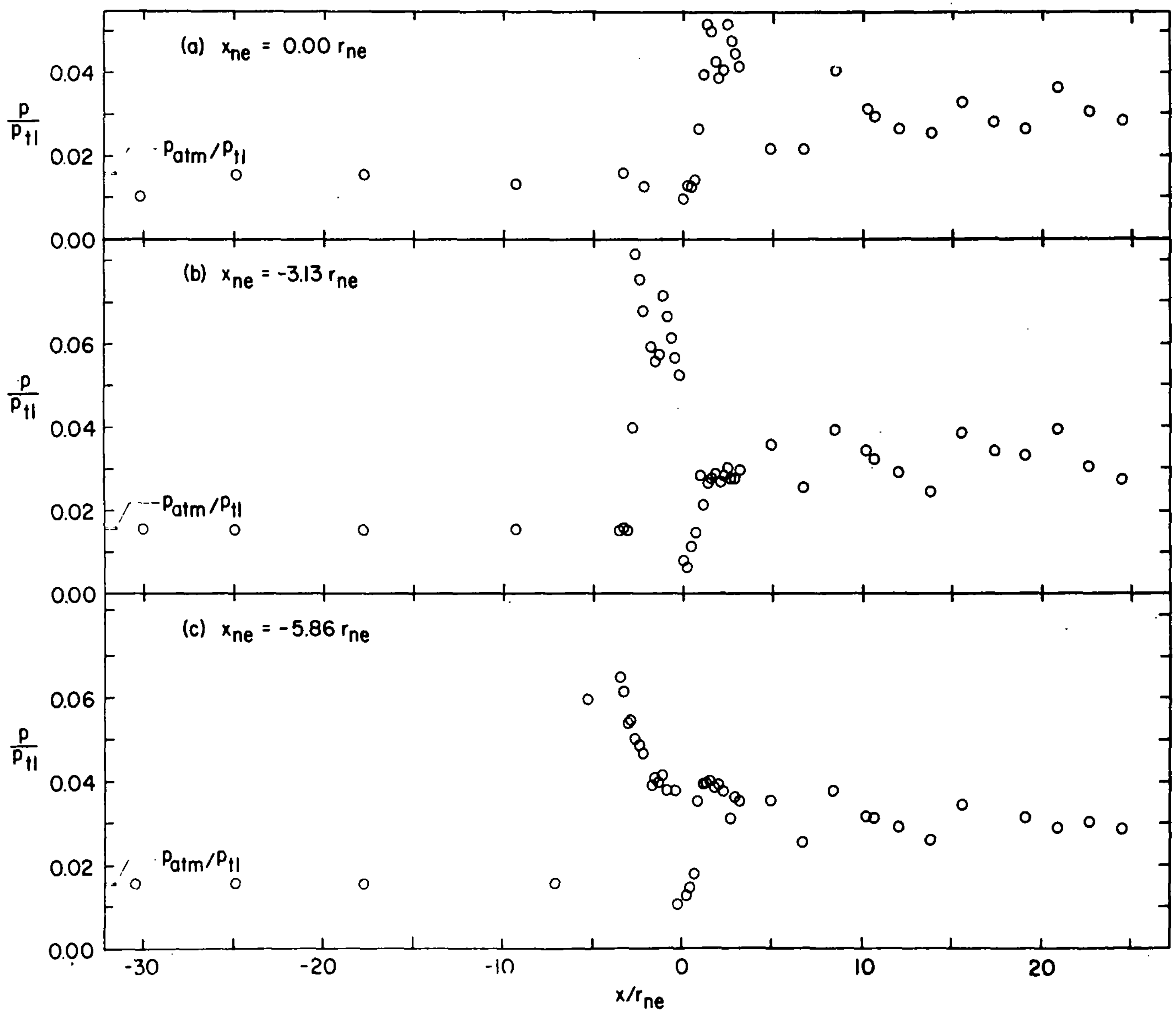

Figure 4. - The static wall-pressure distributions for the entire expansive launch tube for three nozzle-exit locations. $p_{t1} \approx 6.4 \times 10^6$ N/m^2.