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Experiments on Flow Through One to Four Inlets of the Orifice and Borda Type

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ABSTRACT

Choke flow rate and pressure profile data were taken on sequential axially aligned inlets of the orifices and Borda type. The configuration consisted of from two to four inlets at two nominal separation distances of 0.7 and 30 diameters.

At the nominal 30 diameter spacing, the reduced flow rate follows a simple empirical relation based on the reduced flow rate for a single inlet.

At the nominal 0.7 diameter spacing, fluid jetting was prevalent at low temperatures and flow rates were the same as for a single inlet.

INTRODUCTION

Fluid machinery components and heat transfer devices contain contoured inlet configurations, most of which are sequential. Compressors, pin-finned heat exchangers, labyrinth seals and step seals, for example, consist of two or more sequential inlets. The details of heat transfer and flow dynamics in these configurations are not well understood in many cases.

In order to understand some flow phenomena in the seals of high performance turbomachines, ref. 1, a series of choked fluid flow tests with single and multiple sharp-edge orifice and Borda type inlets were conducted, refs. 2-8. Borda inlets were studied so as to examine the effects of a protrusion into the "reservoir region" whereas the orifice inlets were studied to determine how the flow responded to a sharp-edge configuration; both of these basic types of geometries are found in the seal configuration, ref. 1.

Flow jetting in single inlets, refs. 2, 3, 4, 6, occurred over a wide range of fluid state conditions and was found to be inhibited by increasing: i) the inlet stagnation temperature, ii) the length to diameter ratio (L/D) and iii) tube roughness. These tests established that the jetting phenomena could occur in a single orifice or Borda inlet passage to over 105 L/D.

Jetting was further investigated in multiple inlet configurations, refs. 5, 7, 8, where four sequential inlets were studied. At the nominal separation distance of 30 diameters, the flow was found to be nearly independent of the upstream reservoirs and inlets; whereas at a separation distance of nominally 0.7 diameters, jetting occurred at the lower inlet stagnation temperatures. Separation distances between these two were investigated in a water table flow visualization study, which demonstrated flow instabilities for a range of $1<L/D<10$ for these sequential inlets, refs. 5, 7.

Previous studies have been done with sequential inlets, refs. 9-13, but the working fluid states were either incompressible liquid or gas and a range of fluid conditions, encountered in high performance turbomachines, many of which flow cryogens, are not considered.

Consequently, the purpose of this paper is to compare the nature of flow rates and pressure distributions in N-sequential inlets of the orifice and Borda types at nominal separation distances of 30 and 0.7 diameters over a wide range of reduced fluid state conditions. A comparison will also be drawn between applicable theoretical results and these N-sequential orifice and Borda inlet configurations.

SYMBOLS

b	slope
Cf	flow coefficient
D	diameter of the inlet
f	friction factor
G	mass flow rate
G^*	flow normalizing parameter, 6010 g/cm^2-s for nitrogen, $\sqrt{(P_c \rho_c)/Z_c}$
H	enthalpy
l	length of inlet
L	length of separation distance
m	slope
N	number of inlets
n	slope
P	pressure
S	entropy
T	temperature
V	specific volume
Z	compressibility
$\rho = 1/V$	density

Subscripts:

c	thermodynamic critical
e	exit
I	isentropic
i	i-th sequential inlet
o	stagnation, or reference
r	reduced by normalizing parameter
1	case for N = 1, the single inlet, or unit equivalent tube

APPARATUS AND INSTRUMENTATION

The blowdown type flow facility was basically that described in ref. 14, but modified to accommodate the various sequential orifice and Borda inlet configurations, refs. 5, 7, 15, 16. A close-up photograph of the Borda inlet is given as fig. 1a and the orifice inlet as fig. 1b. The working fluid was nitrogen.

The Borda type inlets with l/D of 1.9 were designed to be similar to those used in ref. 2, with spacers of 15.24 cm (6.0") and 1.03 cm (.407"). This provided two fixed spacings of 30 and 0.8 diameters respectively. A schematic of the N-sequential Borda geometry at the 0.8 separation distance is presented in fig. 2a, which also gives inlet geometry and pressure tap locations.

The orifice type inlets with l/D of 0.5, similar to those of ref. 3, were designed with spacers of 15.24 cm (6.0") and 0.32 cm (0.125"). These provided two fixed spacings of 32 and 0.66 diameters respectively. The schematic showing the pressure tap locations and inlet geometry of the N-sequential orifice at 0.66 diameters is presented as fig. 2b.

Figure 2c provides a schematic of the N-sequential orifice (or Borda) inlet configuration with the 15.24 cm (6.0") spacers. This figure also gives pressure tap locations on the 15.24 cm (6.0") spacers.

These sequential inlet configurations were fitted between inlet and outlet flange adaptors to accommodate the multiple lengths. The multiple surfaces were satisfactorily sealed by mylar gaskets between flat faces. Pressure and flow data were recorded as described in refs. 5, 14. The working fluid is nitrogen and the reduced temperature ranges from $0.68<T_r<2.5$ (liquid to gas) with the reduced pressure to $P_r<2.5$.

ANALYSIS

The treatment of the simplest set of sequential inlets is quite complicated. In a thermodynamic treatment, where only the end state conditions are considered, the ith-sequential inlet may be assumed to expand isentropically, followed by an isobaric recovery in the "mixing chamber" or spacer to the adiabatic locus, with choking at the Nth inlet, ref. 5.

The governing equations, as described in ref. 5, may be written:

$$(G/Cf)_i^2 = 2\rho^2 \, (H_o - H_i) \tag{1}$$

where the constraints are:

Isentropic

$$S_o(P_o,T_o)_i = S(P_e,T_e)_i \tag{2}$$

Isobaric

$$P_{e,i} = P_{o,i+1} \tag{3}$$

Critical Flow (choked)

$$[G_m^2(dV/dP)e]_{(i=N)} = -1 \tag{4}$$

where

$$G_m^2 = (2/V^2)\int_P^{P_o} VdP_{(i=N)} \tag{5}$$

which upon convergence, $(G/Cf) \rightarrow G_m$.

To determine a solution, each inlet must be assumed independent of the previous inlet, such as was assumed for the nominal 30 diameter spacing. We must then assume i) a value for the pressure ratio across the first inlet, ii) that the choking condition applies to the last inlet, iii) that the iteration will converge to a solution, and iv) a flow coefficient for each inlet. A constant flow coefficient of 0.75 was selected to account for entrance losses in each inlet with low carryover. Fluid properties were calculated using GASP, ref. 17

At the nominal 0.7 diameter spacing, it is assumed that the flow recognizes the N-sequential inlets spaced at this separation distance as one inlet; the flow jetting condition is dominant. This assumption is based on previous experimental results and flow visualization studies, which were limited to four sequential inlets, refs. 5, 7.

The flow rates in sequential inlets can also be analyzed by the extrapolation of the flow rate through a single inlet with the appropriate constraints. Using a modified Bernoulli equation and constant area ducts, one obtains from ref. 16,

$$Gr/Gr_1 = N^{-n} \tag{6}$$

where n = 1/2.

Thus knowing the mass flow rate for one inlet, the flow rate through any number of N-inlets can be determined. This relation, which assumes that the N-inlets act independent of each other and the losses per stage are the same for each sequential inlet, provides one with an elementary first order result.

Another elementary result can be obtained from relating friction factors of N-tubes and flow coefficients of N-inlets. Using ref. 18 and the assumption that the total friction factor loss is the sum of the individual "tube" friction factor losses, and the losses per "tube" are the same, one obtains:

$$Gr/Gr_I \; \alpha \; N^{-m}(4fL/D)^{-m} \tag{7}$$

From the plots of ref. 2, 13, 15, 16 it is apparent that:

$$Gr/Gr_1 \; \alpha \; N^{-m} \tag{8}$$

Thus, if $Gr_1 = Gr_I \; Cf$, then it follows from ref. 16 that:

$$(4fL/D)^{-m} = Cf \tag{9}$$

This provides an elementary first order relationship between N-tubes and N-inlets. Thus, the sequential inlets can be thought to act as a sequence of connected tubes with various amounts of friction present. At large values of (4fL/D), n→m. Further analysis can be found in ref. 5, 16.

RESULTS

Experimental Results

The experimental results covering a wide range of inlet stagnation temperatures and pressures are now presented in two sections, i) Flow rates and ii) Pressure profiles. Experimental data may be found in ref. 5, 7, 15, 16.

Flow Rates

Figs. 3a,b,c,d present reduced flow rate as a function of reduced inlet stagnation pressure for various isotherms. The reduced flow rate is given by:

$$Gr = G/G^* \tag{10}$$

where G^* is determined by the extended corresponding states theory, ref. 5, 19, 20.

As an example of the N-sequential inlets, the flow rates for the three sequential Borda and orifice inlets for the nominal 30 diameter spacing, are given in fig. 3a,c respectively. They are very similar, with the Borda flow rates being slightly higher.

At the nominal 0.7 diameter spacing, the N-sequential Borda and orifice, as exemplified by N = 3, are again form similar, fig. 3b,d. They are significantly higher than the flows for the nominal 30 diameter spacing, but are very similar to that of a single Borda or orifice inlet, ref. 2,3. The N-sequential inlets, with the data limited up to N = 4, all show these similar trends, ref. 15, 16.

Pressure Profiles

Fig. 4a,b,c,d give a perspective of the variation of pressure profile with reduced inlet stagnation temperature. There is a significant change between the nominal spacing of 0.7 and 30 diameters.

At the nominal 30 diameter spacing for the N-sequential Borda and orifice, the pressure profiles exhibit a sharp drop at the entrance of each inlet, followed by some recovery within that inlet, fig. 4a,c, where N = 3 is shown. The recovery within the Borda inlet is concave downward whereas the recovery in the orifice inlet is concave upwards. This may indicate a fuller recovery for the Borda inlet. The two through four sequential Borda and orifice inlets exhibit similar trends, ref. 15, 16. At the last inlet, i = N, jetting was found to occur, as indicated by the flat pressure profile at the lower inlet stagnation temperatures for both the orifice and Borda case. The pressure profile varies the most at this last sequential inlet. The profile is flat at the lower inlet stagnation temperatures whereas at the higher inlet stagnation temperatures, the profile is arched. The sequential Borda exhibit a greater variation and a larger arched profile than the sequential orifice, but both inlet configurations are form similar.

The pressure profiles for the N-sequential orifice and Borda inlets spaced at the nominal 0.7 diameter spacing at the lower inlet stagnation temperatures resemble that of a free jet, again N = 3 is used for explanatory purposes. The fluid seems to flow unimpeded even though they are separated at a nominal distance of 0.7 diameters. At the higher inlet stagnation temperatures, the recovery is somewhere between that of a free jet and of sequential independent inlets, such as those spaced at nominally 30 diameters.

Further comparisons and experimental data can be found in ref. 1, 2, 3, 5, 7, 8, 15, 16, including some of the effects of backpressure.

Analytic Comparisons

At the nominal 30 diameter spacing, we expect the sequential inlets to act independent of one another. The constant flow coefficient for each inlet used to predict the flow rates causes some problems, as well as attempting to calculate the flows near the thermodynamic critical region.

The calculated flow rates for liquid and gas are given on figs. 3a,c for the N = 3 case. These approximate the experimental curves fairly well. The experimental flow rates for the sequential Borda inlets fit the calculated flow rates somewhat better than the sequential orifice inlets. This may indicate a tendency for the Borda inlets to align or direct the flow, with less losses than the orifice case, and that the assumed flow coefficient of 0.75 better represents the Borda case; whereas a flow coefficient of 0.7 may better represent the orifice case.

The results of the experimental flow rates with the calculated flow rates for the N-sequential inlets at the 30 diameter nominal spacing are given in figs. 5, 6. The experimental and calculated flow rates seem to follow an empirical power law relation:

$$Gr \propto N^{-b} \tag{11}$$

where N is the number of sequential inlets and (b) is the undetermined function of inlet temperature and pressure.

From the experimental results and theoretical calculations, it appears that (b) $\approx$ 0.4. The elementary relation, equation 6, predicts a value of (b) = 0.5, but (b) $\approx$ 0.4 appears valid over a wide range of inlet pressure and temperatures, to the first order and excluding the thermodynamic critical region.

The reduced mass flux empirical relation can be further normalized by flow through a single inlet, thus:

$$Gr/Gr_1 = N^{-b} \tag{12}$$

Hence, if Gr_1 and (b) are known, the mass flux for N well separated, herein taken as nominally 30 diameters for this configuration, but is in general cavity and Reynolds number dependent, similar sequential inlets can be determined directly from knowing the mass flux through a single inlet. The flow through this single inlet is governed by the inlet stagnation conditions.

The experimental and calculated magnitude of the exponent (b) as a function of reduced inlet stagnation temperature is given as fig. 7 for various reduced pressures. The exponent (b) seems to exhibit a variational or "sine" type behavior within the critical region. For a reduced inlet pressure above the critical region, the amplitude of the variation of the exponent (b) seems to be less than for reduced inlet pressures below the critical region. These experimental and calculated flow rates both exhibit this tendency of variation. The behavior of the exponent (b) in the critical region is unknown.

The exponent (b), as plotted in fig. 7, seems to be of a lesser magnitude for the Borda inlet case as compared to the orifice inlet case. An exponent (b) of a greater magnitude indicates a lower flow rate and flow coefficient. Hence, the orifice inlet should have a slightly overall lower flow coefficient than the Borda inlet, as a possible consequence of the alignment of the flow by the Borda inlet. This was previously encountered in ref. 5, 7, 8.

The calculated and theoretical flows for both the orifice and Borda case, have very similar trends, as exemplified by the exponent (b). The experimental flow rates generally lie below the theoretical, and losses are not accounted for in the theoretical treatment, but both the calculated and experimental exponents (b) are form similar with respect to inlet temperature. The flow rate and (b) are presently an undetermined function of temperature and fig. 7 can be used as a guide. Further analytic comparisons can be found in ref. 16.

SUMMARY

Choked flow rate and pressure profile data were taken and studied for a configuration consisting of up to four sequential orifice and Borda inlets for nominal spacings of 30 and 0.7 diameters as an indicator of fluid flow through N-sequential inlets.

At a nominal spacing of 30 diameters, the pressure profiles exhibit a sharp drop at the leading edge of each inlet followed by some recovery within that inlet and little further recovery in the spacer chamber. At the lower inlet stagnation temperatures, fluid jetting can occur in the last of the sequential inlets. The Borda and orifice inlets both showed this tendency. These sequential inlet configurations appear to function independently with control or choking occurring at the last of the sequential inlets, $i = N$.

At a nominal separation distance of 0.7 diameters at the lower inlet stagnation temperatures, fluid jetting was prevalent throughout all of the sequential inlets in both the Borda and orifice case. The flow rates were the same as for a single inlet and appeared to be controlled or choked at the first inlet, ($i = 1$), independent of the downstream sequential inlet configuration.

Analytic modeling is complex, but a simplistic model of the nominal 30 diameter spacing appears to give good correlation with the experimental data outside of the thermodynamic critical region. The data seem to follow a simple empirical relation:

$$\dot{G}r/\dot{G}r_1 = N^{-b}$$

where b is a non-linear function of temperature and is weakly dependent on pressure. Outside the critical region, (b) was found to be nominally 0.4. The principal feature of these results are that if one knows the mass flux for a single inlet, then one knows, to a first order, the mass flux for N-sequential well separated inlets, which is approximately 30 inlet diameters for this configuration. Further, the mass flux is governed by the stagnation pressure and temperature conditions upstream of the first inlet.

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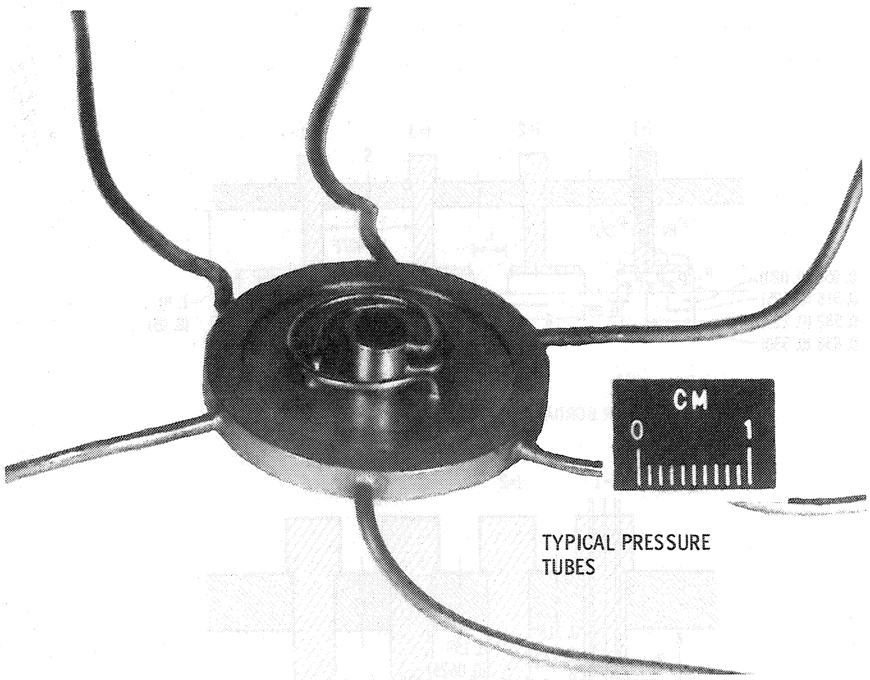
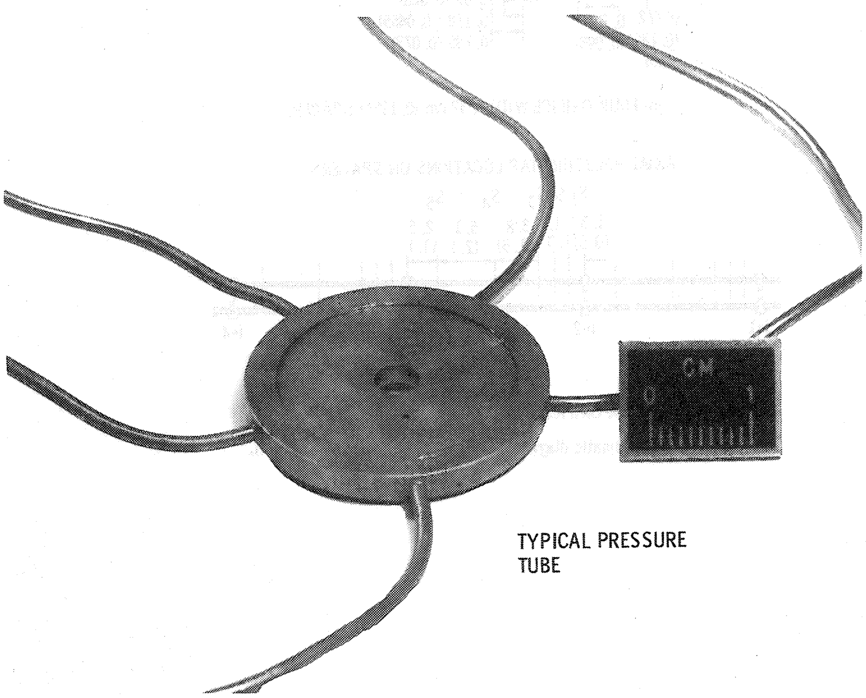
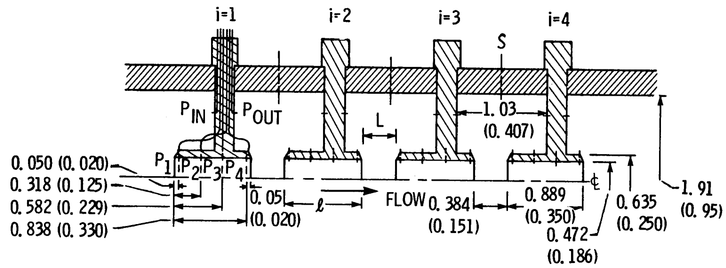


(a) BORDA.

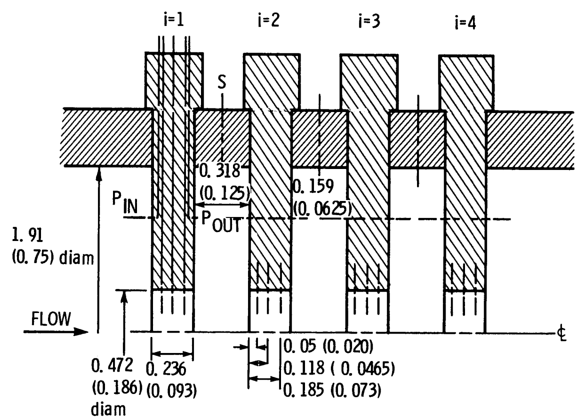


(b) ORIFICE.

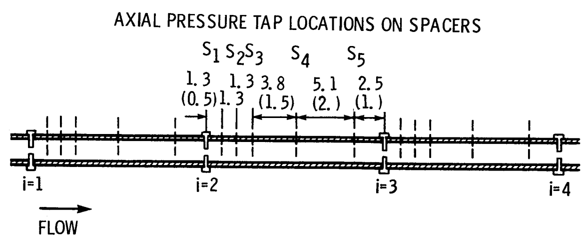
Figure 1. - Photograph of the inlet configuration.



(a) FOUR BORDA WITH 1.03 cm (0.407") SPACER.



(b) FOUR ORIFICE WITH 0.32 cm (0.125") SPACER.



(c) FOUR ORIFICE WITH 15.24 cm (6") SPACER.

Figure 2. - Schematic diagram of N-sequential inlet test section.

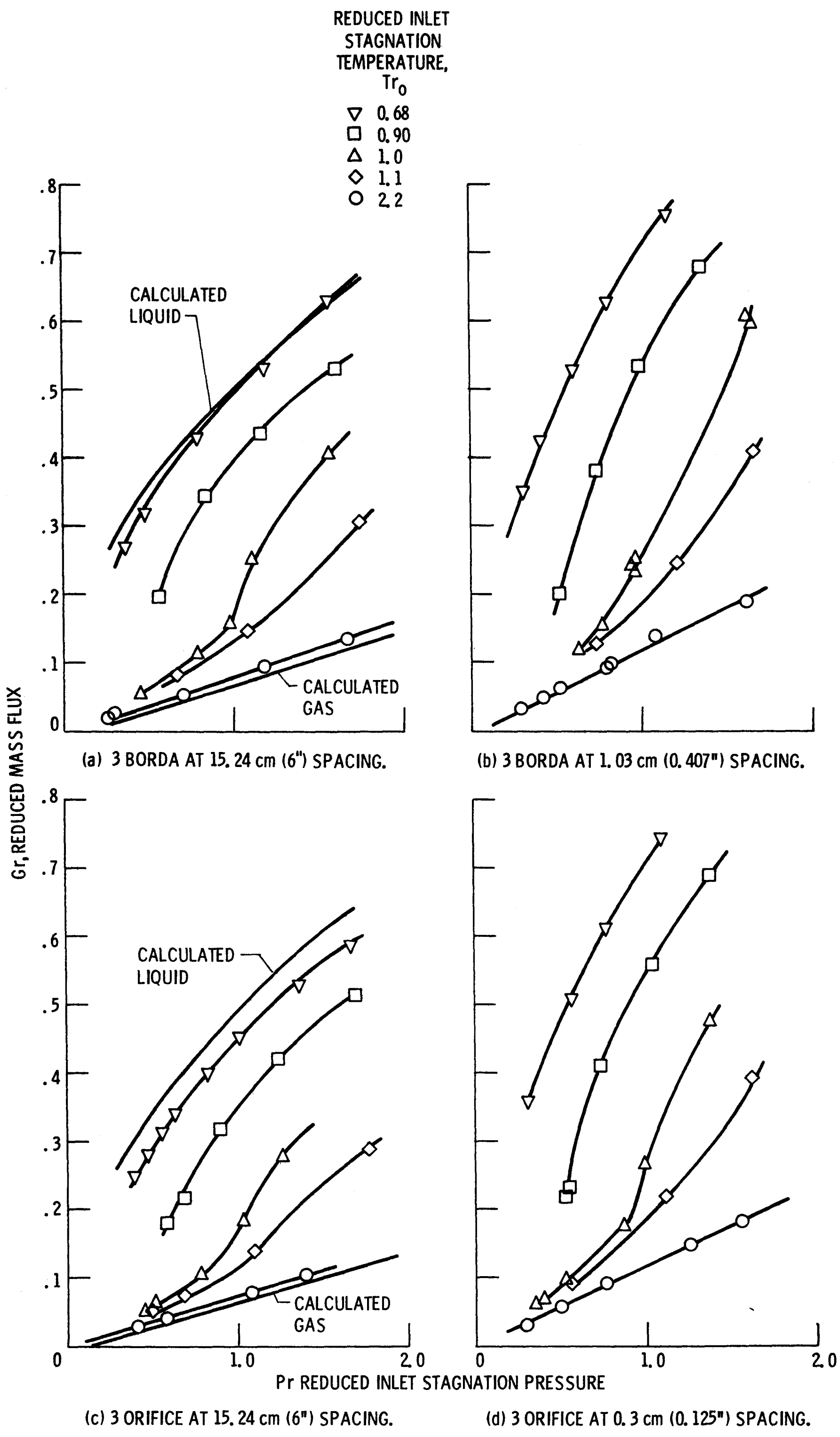


Figure 3. - Reduced mass flux as a function as reduced inlet stagnation pressure for selected reduced inlet stagnation temperatures.

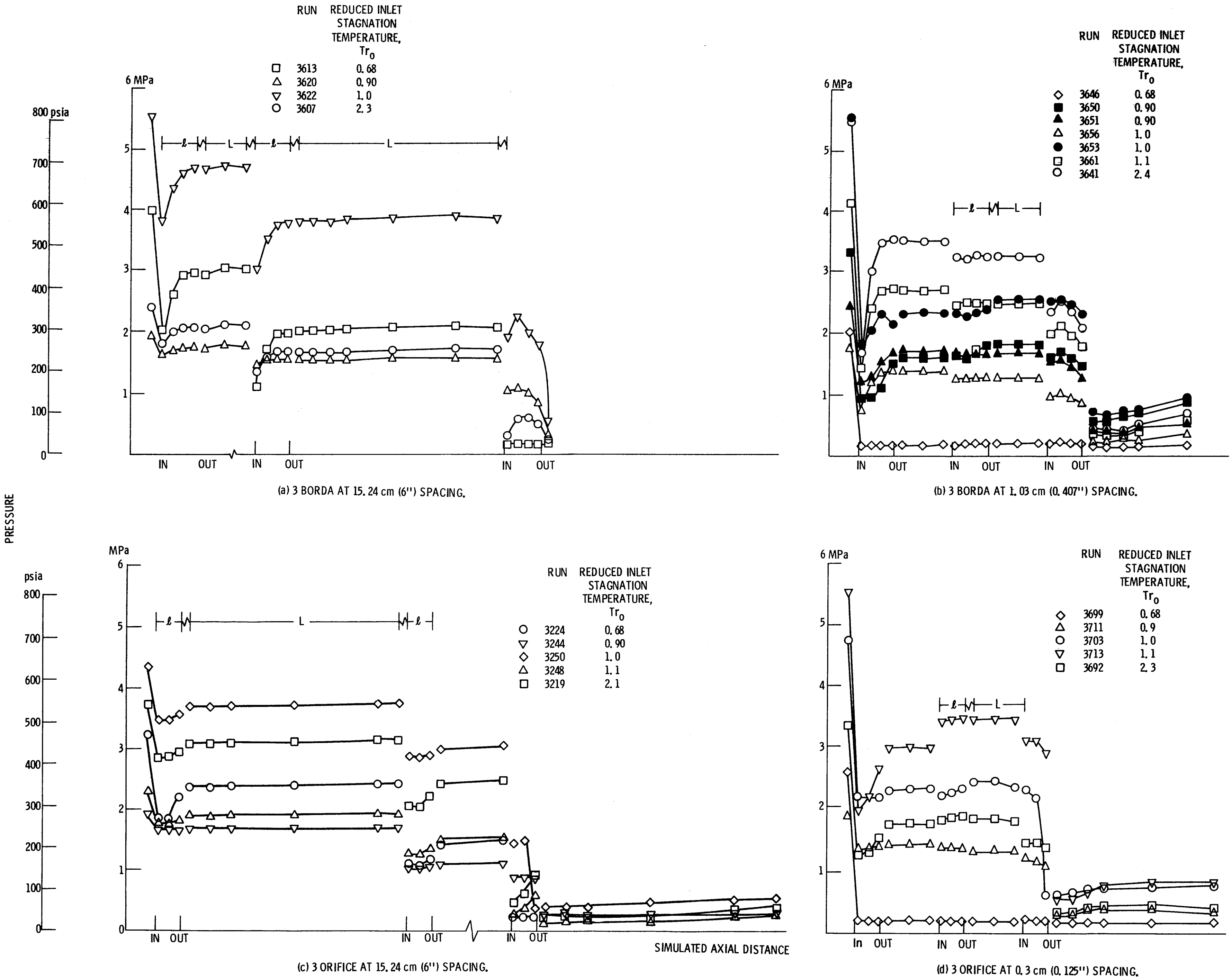
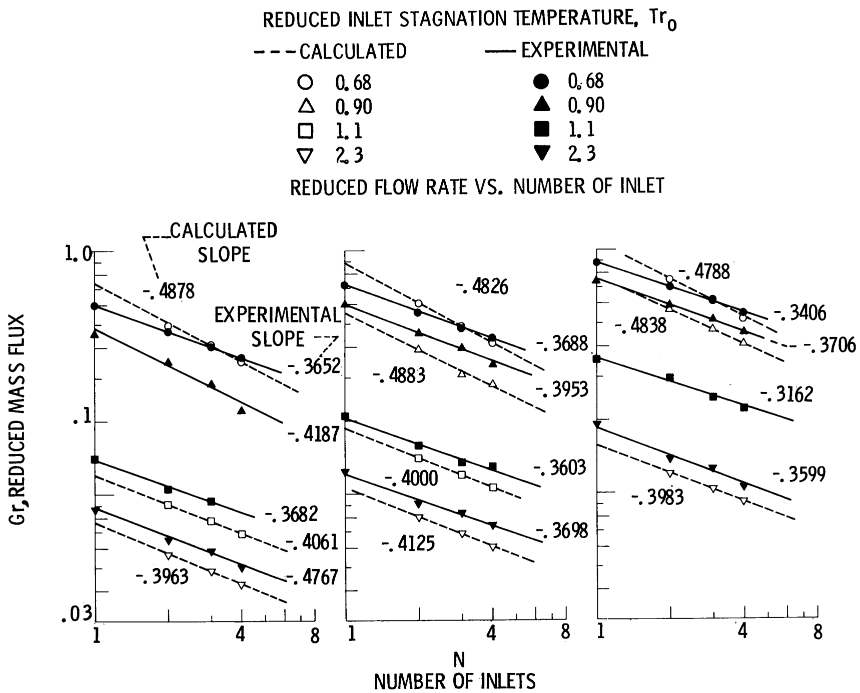
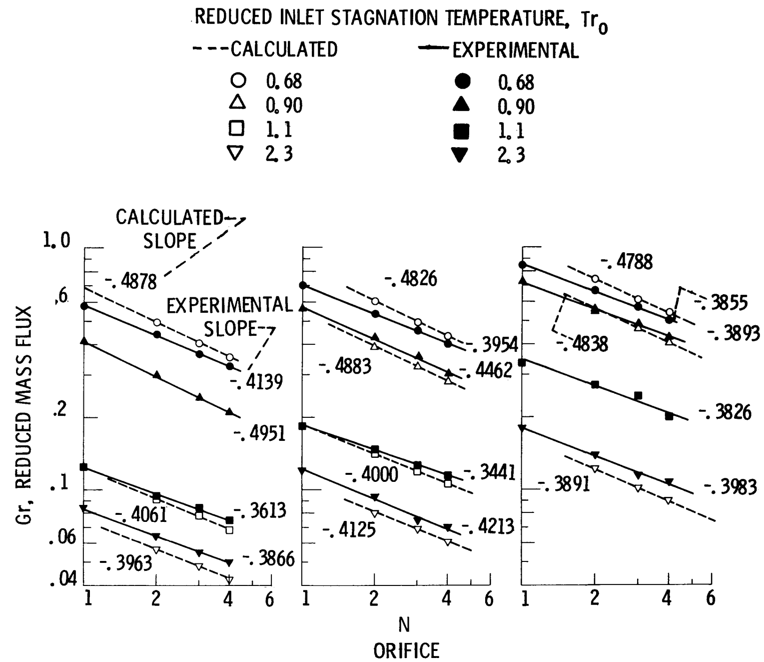


Figure 4. - Pressure profiles at selected inlet stagnation temperatures.



(a) REDUCED INLET PRESSURE $Pr_0 = 0.7$. (b) REDUCED INLET PRESSURE $Pr_0 = 1.0$. (c) REDUCED INLET PRESSURE $Pr_0 = 1.5$.

Figure 5. - Reduced mass flow rate at a function of N for the Borda inlet at selected reduced inlet stagnation temperatures.



(a) REDUCED INLET PRESSURE $Pr_0 = 0.7$. (b) REDUCED INLET PRESSURE $Pr_0 = 1.0$. (c) REDUCED INLET PRESSURE $Pr_0 = 1.5$.

Figure 6. - Reduced mass flow rate as a function of N for the orifice inlet at selected reduced inlet stagnation temperatures.

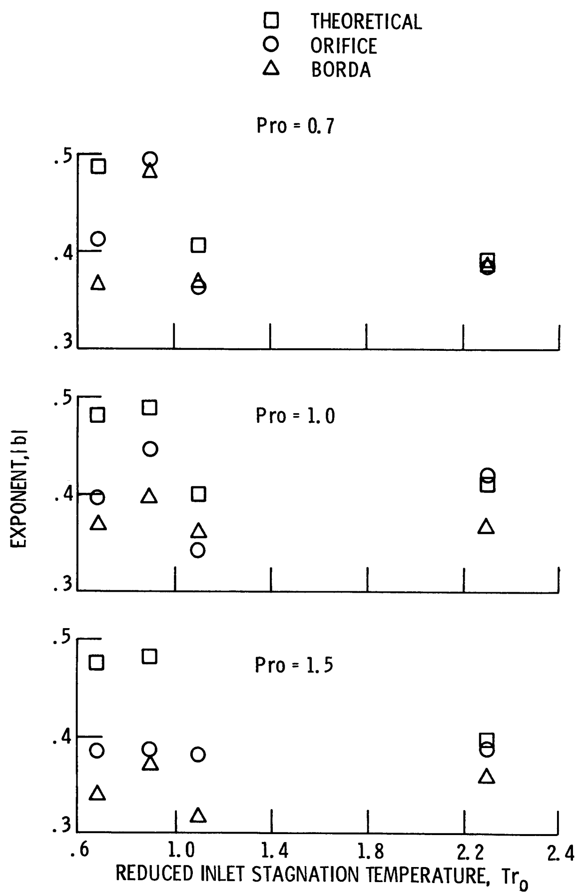


Figure 7. - The N^{th} inlet exponent, (b), as a function of reduced inlet stagnation temperature for selected reduced inlet stagnation pressures.

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16. Abstract

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