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PRESSURE LOSSES IN DUMP COMBUSTORS

LEWIS P. BARCLAY, CAPT., USAF

TECHNICAL REPORT AFAPL-TR-72-57

OCTOBER 1972

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PRESSURE LOSSES IN DUMP COMBUSTORS

LEWIS P. BARCLAY, CAPT., USAF

FOREWORD

This report covers work done during the period 1 April 1970 to 30 May 1971 under Task 301212 by the Experimental Group of the Ramjet Engine Division, Air Force Aero Propulsion Laboratory.

This report has been reviewed and is approved.

Edward T Curran

E. T. CURRAN
Chief, Ramjet Technology Branch
Ramjet Engine Division, AFAPL

ABSTRACT

Volume limited missiles require a particularly exacting form of component integration. One possibly useful concept is the integral rocket ramjet (IRR). In the IRR system the propellant, for the solid rocket booster, is cast directly into the same volume that is used for the ramjet combustor. The size of this ramjet combustor is fixed more by the booster requirements than those of the ramjet. Typically, this results in a ramjet combustor of the sudden expansion or dump combustor type in which one or more relatively small inlet ducts dump the air into a large combustor volume. While the dump combustor is not new, it is less developed than the conventional combustor.

The thrust of this study is directed to a better understanding of the pressure losses in dump combustors. Attendant to this study was an effort to simplify methods of predicting compressible flow losses. Application of the incompressible pressure loss factors and equations to compressible problems can lead to serious errors at Mach numbers above 0.3. During this study an equation was derived to predict compressible pressure losses. This equation expresses the pressure loss as a function of the Mach number and a pressure loss factor which is independent of Mach number. Subsequently it was found that the compressible pressure loss factor, called N_D the dissipation number, was numerically equal to the incompressible pressure loss factor, K_t, for any given fluid system. The incompressible parameter is basically a function of geometry and Reynolds number and there exists a wealth of data relating to it.

Because of their possible use in missile propulsion two basic dump combustor designs were selected for testing. The first was a coaxial circular inlet model, the second, a dual side-mounted rectangular inlet model. The measured dissipation numbers were compared to the predicted incompressible parameters and found to be encouragingly similar. The results of this study show, on a preliminary basis, that it may be possible to use the existing incompressible data to predict compressible pressure losses. Additional work is required in this area to establish the limits of this concept.

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LIST OF SYMBOLS

A	area
d	diameter
G	mass flux
K_t	incompressible pressure loss parameter
M	Mach number
N_D	compressible pressure loss parameter
P_t	total pressure
q	dynamic pressure
Re	Reynolds number
V	velocity
β	inlet angle, first or symmetric branches
δ	inlet angle, second branch
γ	ratio of specific heats
Δ	change in/of some parameter
ρ	density

Subscripts and Superscripts

1	inlet or upstream condition
2	combustor, downstream condition
w	wall condition
*	nozzle throat

SECTION I

DISCUSSION

1. Pressure Loss Equations

Generally, pressure losses in fluid systems are specified by:

$$\Delta P_{loss} = P_{t_1} - P_{t_2} \tag{1}$$

The pressure loss is considered some fraction of the incoming dynamic pressure. The fraction is usually given the symbol K_t (Reference 1). Equation 1 becomes for incompressible flow

$$P_{t_1} - P_{t_2} = K_t \frac{1}{2} \rho_1 V_1^2 \tag{2}$$

For practical purposes, K_t is a function of the geometry of the flow process and the Reynolds number. Reference 1 contains a fairly comprehensive collection of data from many sources, giving values of K_t for various systems.

In using the published values of K_t in processes involving compressible fluids, it has been found that up to Mach number ≈0.3, Equation 2 predicts the pressure loss accurately. Beyond this Mach number, the measured pressure losses deviate increasingly with Mach number from those predicted by Equation 2. Compressible flow has long been recognized for Mach number dependence. The isentropic relations and many others are well-known compressible flow Mach number functions. Because of this experience with Mach number and compressible flow, it has been heretofore assumed that a compressible analog to K_t would be a function of Mach number as well as geometry and Reynolds number. The nature of the Mach number dependence of K_t has been elusive and essentially impossible to document.

In 1969, Dr. P. J. Ortwerth of the Air Force Aero Propulsion Laboratory approached the problem of compressible losses from considerations of turbulent energy dissipation. Basically, he solved the conservation equation in three dimensions. Equation 2 is essentially the result of a one-dimensional treatment. Dr. Ortwerth assumed that the total energy dissipated could be treated as a fraction of the dynamic pressure and he defined that fraction as N_D, the dissipation number. The complete derivation of his equation may be found in Reference 3 The equation, which expresses the pressure ratio, is given below.

$$\frac{P_{t_2}}{P_{t_1}} = e^{-N_D \frac{\gamma}{2} M_1{}^2} \tag{3}$$

With a few substitutions, Equations 2 and 3 become strikingly similar. An exponential series expansion has the form

$$e^X = 1 + X + \frac{X^2}{2!} + \frac{X^3}{3!} + \cdots \frac{X^n}{n!} \tag{4}$$

Applying this series, Equation 3 becomes:

$$\frac{P_{t_2}}{P_{t_1}} = 1 - N_D \frac{\gamma}{2} M_1{}^2 + \frac{(N_D \frac{\gamma}{2} M_1{}^2)^2}{2} - \frac{(N_D \frac{\gamma}{2} M_1{}^2)^3}{6} + \ldots \tag{5}$$

Manipulating Equation 2 to the pressure ratio form gives:

$$\frac{P_{t_2}}{P_{t_1}} = 1 - K_t \frac{1}{2} \rho_1 V_1{}^2 \frac{1}{P_{t_1}} \tag{6}$$

Substituting the perfect gas law, the sonic velocity equation and the isentropic pressure relation, Equation 6, becomes:

$$\frac{P_{t_2}}{P_{t_1}} = 1 - K_t \frac{\gamma}{2} M_1^2 \left(1 + \frac{\gamma-1}{2} M_1^2\right)^{\frac{\gamma}{1-\gamma}} \tag{7}$$

Eliminating the higher order terms for low M_1's in Equations 5 and 7 gives:

$$\frac{P_{t_2}}{P_{t_1}} = 1 - N_D \frac{\gamma}{2} M_1^2 \tag{8}$$

and

$$\frac{P_{t_2}}{P_{t_1}} = 1 - K_t \frac{\gamma}{2} M_1^2 \tag{9}$$

From Equations 8 and 9, it can be said that

$$N_D = K_t \tag{10}$$

Figure 1 shows a comparison of Equations 3 and 7 for $\gamma = 1.4$ and identical values of K_t and N_D. As can be seen, for $M_1 < 0.1$ pressure losses are insignificantly affected by which equation is used. Up to $M_1 = 0.3$ the difference is less than 1/4%, which is less than instrumentation accuracy. However, beyond $M_1 = 0.3$ the curves diverge significantly.

The value of the above is determined by which equation more accurately predicts the actual pressure losses. To answer this question the test rig, shown schematically in Figure 2, was used to measure pressure losses. The inlet and exit orifices were made from one-inch thick plastic. The approach profile to the throat was a circular arc

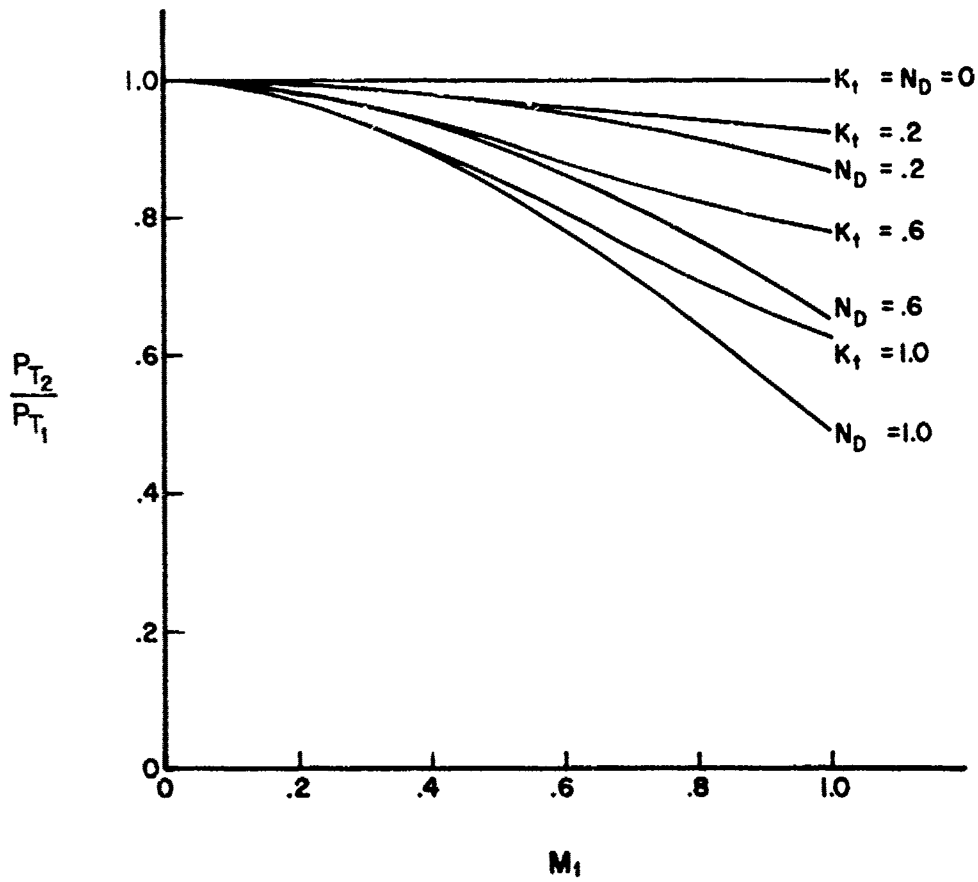


Figure 1. Comparison of Compressible and Incompressible Pressure Loss Equations

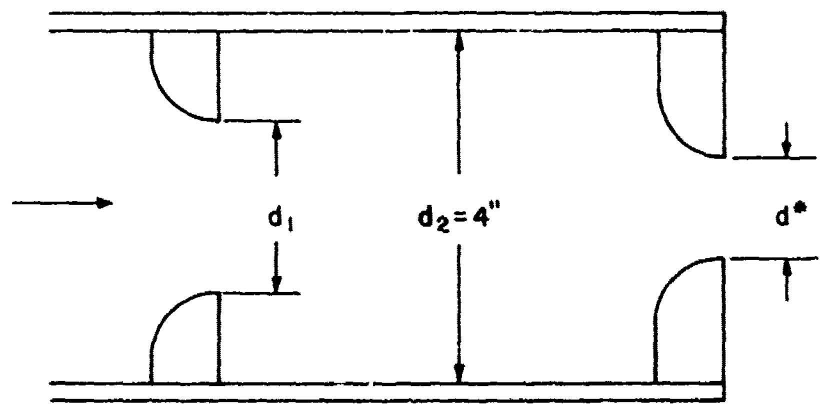


Figure 2. Coaxial inlet Model Sketch

with a radius of one inch. The system could be run at internal pressures between atmospheric and 100 psia. With the exit nozzle choked, the Mach number field in the system was fixed, although the Reynolds number could still be varied with pressure and temperature. The Reynolds number, based on inlet diameter, was kept constant at 5.0 x 10^5 during these tests.

An inlet area ratio, $A_1/A_2 = 0.25$, was arbitrarily chosen and a small exit nozzle, d* = 1.0 inch, used to obtain a low inlet Mach number. The system was then run at several pressure levels, all with a choked exit. The inlet Mach number was 0.12, well into the incompressible region, for all cases. From the pressure data, N_D and K_t were calculated from Equations 3 and 7, respectively. Both calculated to be 0.8. A plot of Equations 3 and 7 was made for these for Mach numbers between 0 and 0.6. Then the exit nozzle diameter was changed several times to vary the inlet Mach number and the data plotted on the above graph. These are presented as Figure 3.

There are three significant features to Figure 3. First, the data follow the compressible rather than the incompressible prediction. Second, in following closely a single value N_D curve, the data demonstrate that N_D is independent of Mach number. Third, the data indicate that experimentally determined K_t values, such as found in existing literature, can be substituted for N_D in the compressible equation with a reasonable degree of confidence.

2. Reynolds Number Effects

A review of the literature on K_t's shows a strong Reynolds number effect usually in the range $10^5 \leq Re \leq 10^6$. To allow observation of

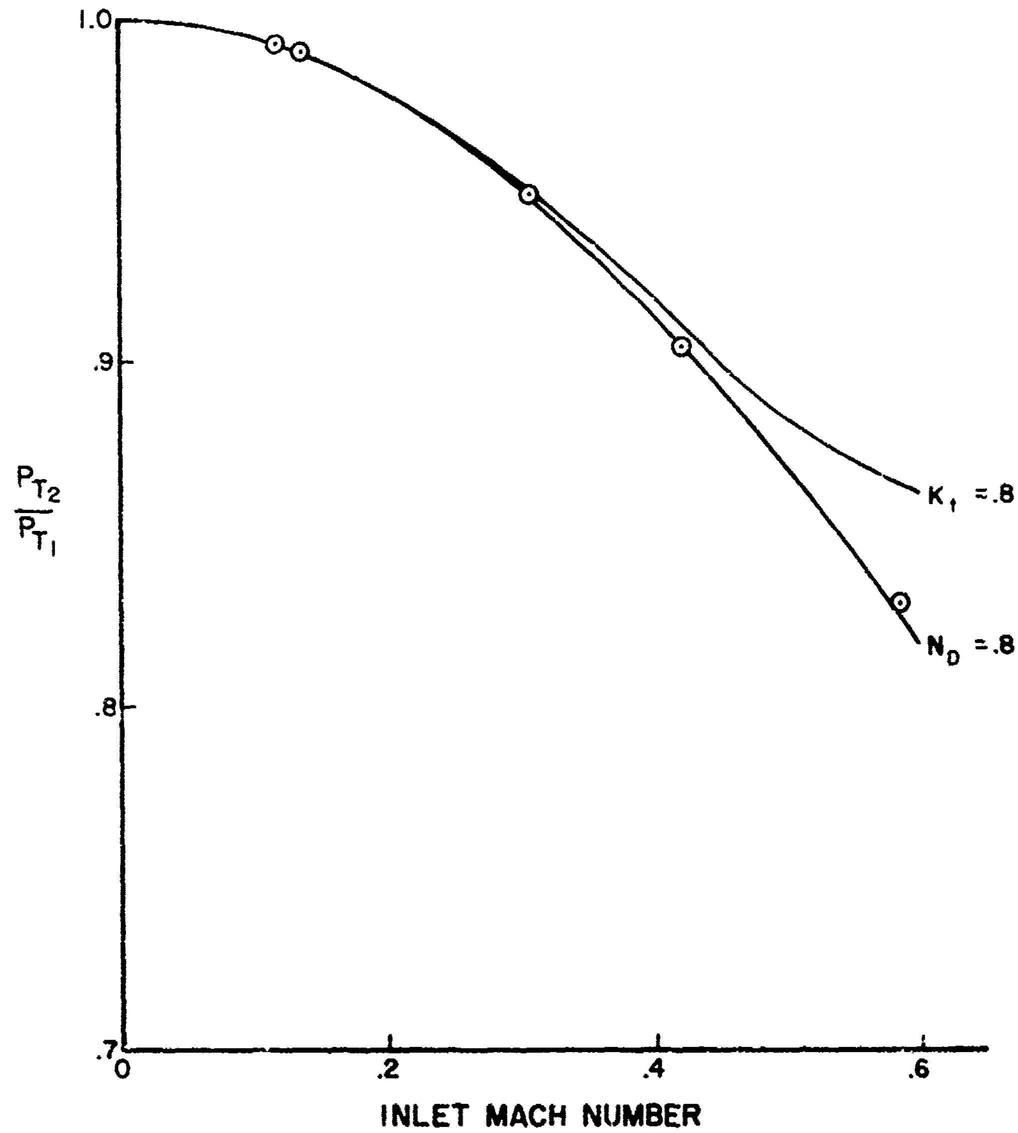


Figure 3. Compressible and Incompressible Predictions with Data

this effect, a series of tests was performed with the same rig as shown in Figure 2. A single inlet area ratio, $A_1/A_2 = 0.391$, and a single inlet Mach number, $M_1 = 0.34$, were used. The inlet Reynolds number was varied by changes in inlet pressure and temperature. The results are shown in Figure 4. As can be seen, the Reynolds number effect can be quite large. The exact Reynolds number range for the above effect is a function of many factors and Figure 4 should not be applied to other geometries. Much data may be found in Reference 1 that describes the Reynolds number effects for other systems.

It is important to note that there are, mixed with experimental K_t values in the open literature, a number of analytic and semi-analytic expressions for K_t. Because of various simplifying assumptions, these expressions usually contain some error even for incompressible processes. The most serious of these assumptions, and one rarely mentioned, is that there is no Reynolds number dependence. Experimental work invariably shows the Reynolds number dependence, particularly in the range mentioned where K_t may change by an order of magnitude.

The next two sections will cover experience with analytic and semi-analytic expressions, respectively. There will also be some data on the effect of slight deviation from the geometric configuration for which the expression applies. The two geometries selected represent possible configurations for dump combustors.

3. Coaxial Sudden Expansion

The simplest dump combustor is one that uses a circular coaxial inlet generically similar to the test rig shown, in Figure 2.

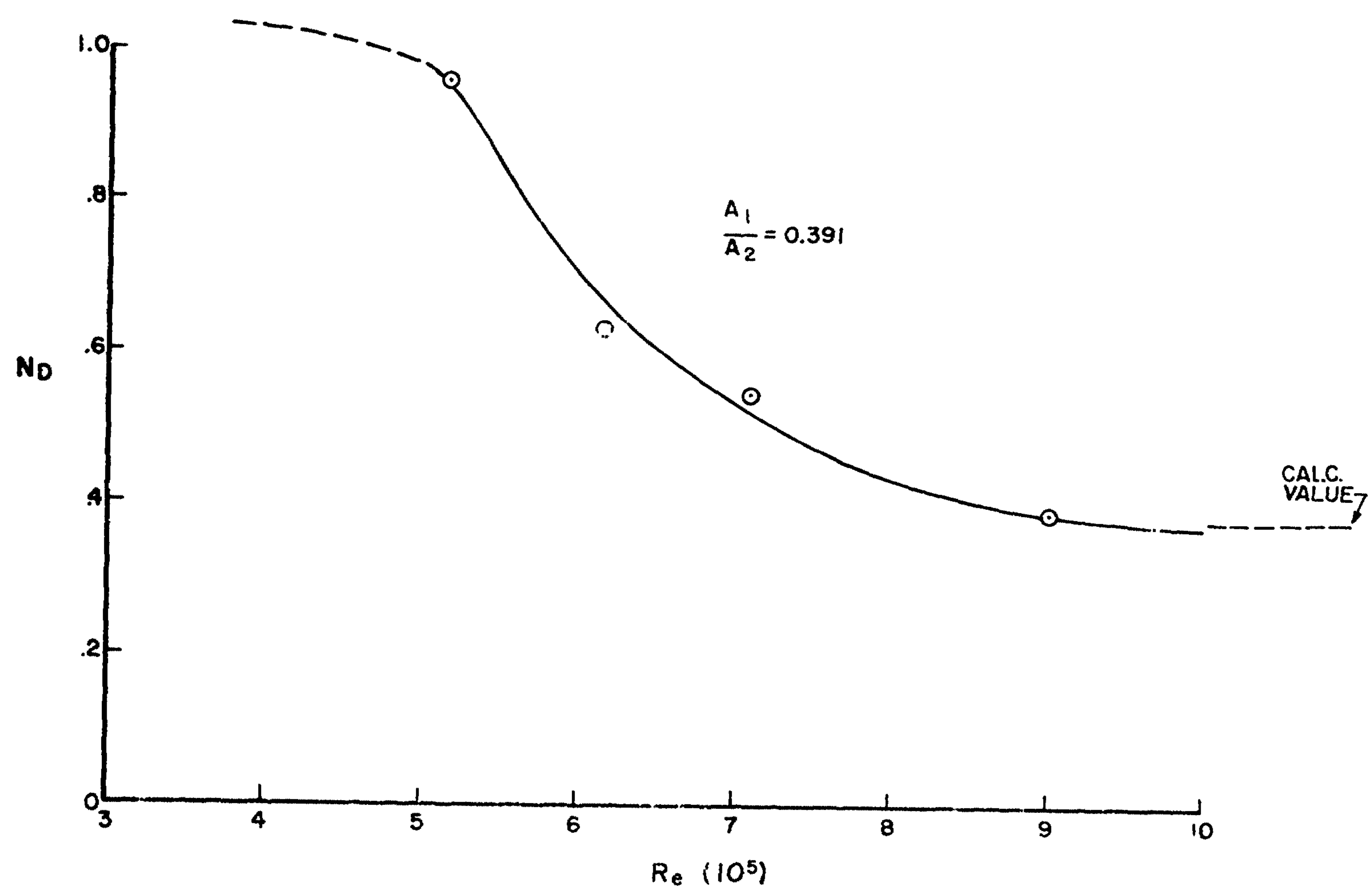


Figure 4. Effect of Reynolds Number on Pressure Loss Factor

Reference 1 contains an analytic expression of K_t for this system.

$$K_t = (1 - \frac{A_1}{A_2})^2 \tag{11}$$

The basic assumption in the derivation is that the pressure on the sudden expansion wall, P_W, is equal to the static pressure of the inlet fluid, P_1. There is no stated assumption regarding the Reynolds number nor does it appear in the derivation. As shown in the previous section, Reynolds number effects can be significant.

A series of tests was made in which the inlet area ratio was varied by changes of the inlet area only. The inlet Mach number was varied by changing the exit nozzle several times for each inlet area. The Reynolds number was not controlled but always fell in the range 5×10^5 to 9×10^5. Equation 3 was used to calculate N_D's from the pressure data and average values were plotted along with the predictions of Equation 11. These are presented as Figure 5. The separate points at each area ratio show approximately the effect of Reynolds number and to some extent measuring precision. Strictly the area ratio should include a discharge coefficient for the inlet area. For this class of orifice and value of Reynolds number the discharge coefficient is from 0.97 to 1.0.

The divergence between the data and the predicted curve is notable. A review of the data showed that the initial assumption regarding the expansion wall pressure is not valid. This might be intuitively expected but the significance might be elusive. Figure 6 shows the ratio of the wall and inlet pressures as a function of inlet area ratio. The data follows an empirical equation of simple form.

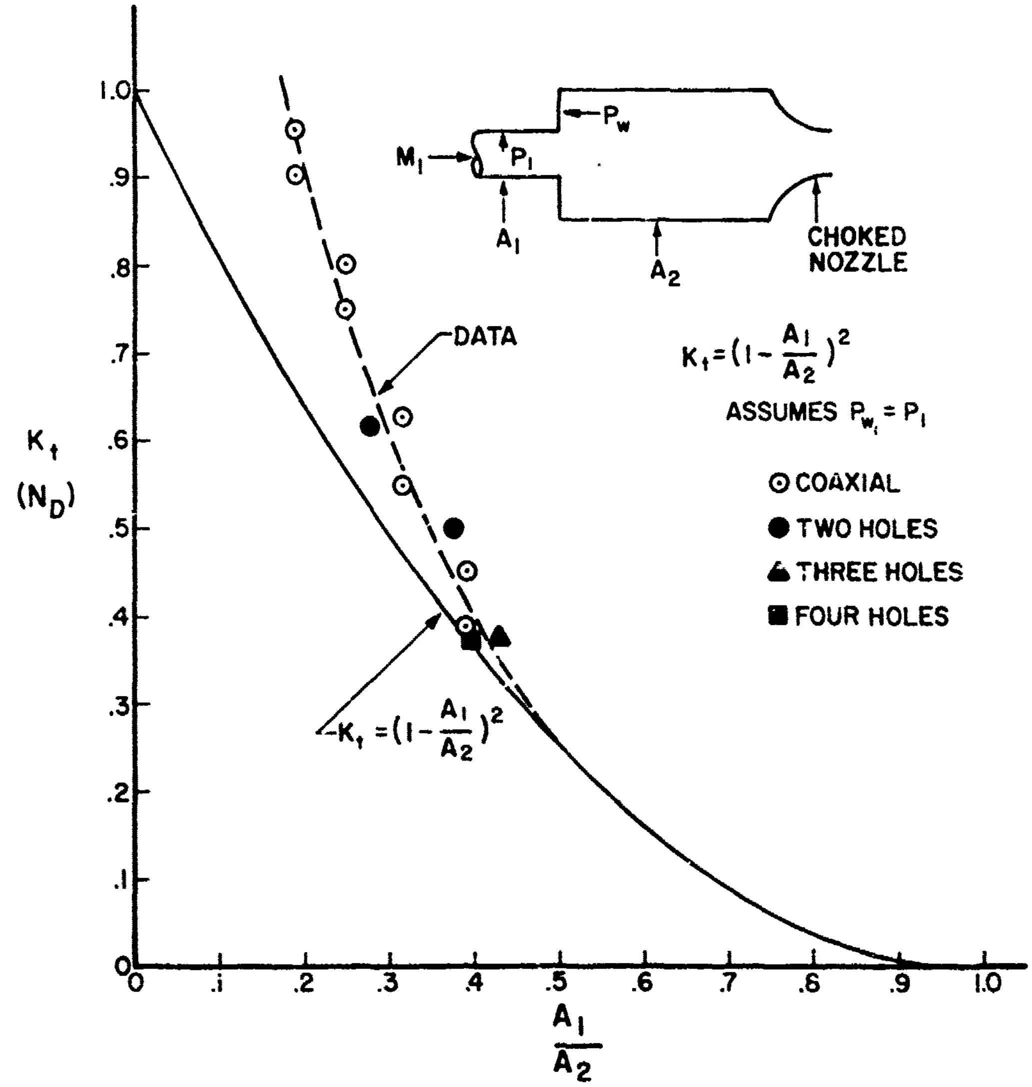


Figure 5. Pressure Loss Factors for Coaxial Sudden Expansion

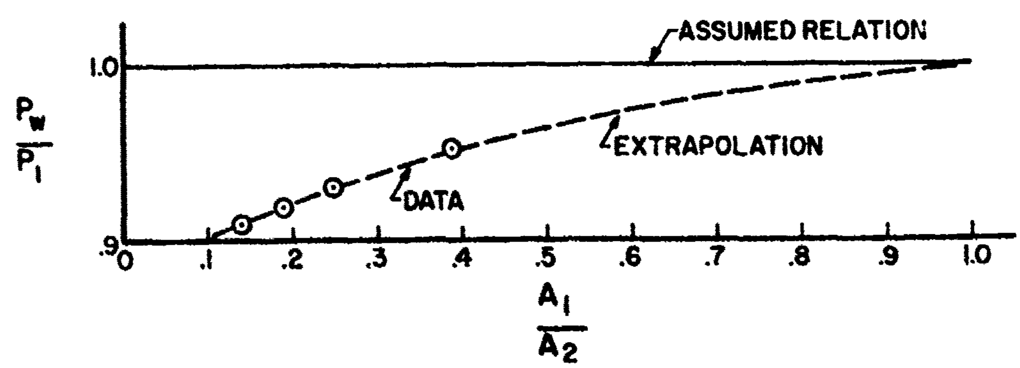


Figure 6. Effect of Area Ratio on Pressure Ratio for a Coaxial Sudden Expansion

$$\frac{P_w}{P_1} = (\frac{A_1}{A_2})^{0.05225} \qquad (12)$$

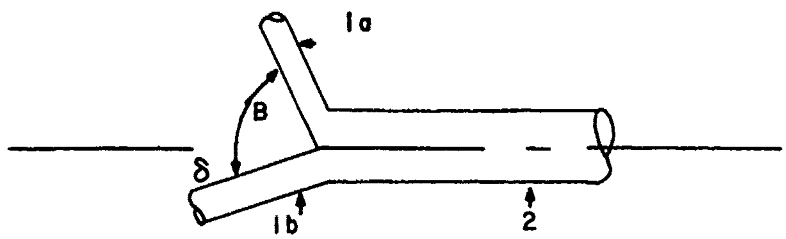
While the data in Figure 6 cannot be said to explain the divergence noted in Figure 5, the relationship is apparent.

An attempt was made to incorporate Equation 12 into an analytic derivation of a more precise expression for K_t, however, a closed form solution was not possible. It was hoped that the expression would more closely approximate the data in Figure 5.

A variation of the coaxial sudden expansion involves multiple inlets symmetrically located about and parallel to the axis of the combustor. A series of tests were made to see whether the number of inlet ports affected the pressure loss for this case. Inlet plates with two, three, and four holes were used. The holes in each case were tangent to each other to group them as close as possible. Tests and data reduction were as for the single inlets. The N_D's were plotted on Figure 5 and are sufficiently close to the coaxial data curve as to show no appreciable difference.

4. Dual Inlets

As just shown, a very special case of dual inlets behaves essentially the same as a single inlet. More commonly, however, dual inlet systems include one or more entry angles and a choice of entry position as design variables. Reference 1 contains a semi-analytic expression for K_t as a function of separate entry angles and area ratios for each of two branches flowing into a single line as shown in the following sketch



$$_aK_{t_2} = \lambda + \left(\frac{G_2}{G_a}\right)^2 - 2\,\frac{A_{1a}}{A_2}\cos\beta' - \left(\frac{G_b}{G_a}\right)^2\left(2\,\frac{A_{1b}}{A_2}\cos\delta'\right) \qquad (13)$$

$_aK_{t_2}$ = loss coefficient from 1a to 2 based on q_1 where λ is a function of β.

β' and δ' are monotonic functions of β and δ, respectively.

G is the mass flux in the subscripted section.

The reference contains plots of λ and $2\,\frac{A_{1a}}{A_2}\cos\beta'$ as functions of β and $\frac{A_{1a}}{A_2}$, respectively.

The Reynolds number, which is absent from Equation 13, appears in the derivation in component form rather than as the familiar group. While the Reynolds number affects the value of K_t, this effect is not apparent from the form of the equation.

Equation 13 applies specifically to systems having circular cross sections and coplanar axes. During this study all test hardware was coplanar although in the future non-coplanar systems might be of interest. Most of the tests for this section had rectangular inlets, however, some models with circular inlets were tested to investigate the effects of cross section shape. Finally, the test hardware included both combustor dome and side entry models while Equation 13 is for dome entry only.

For a dual inlet combustor the entry angles β and δ are equal as are the inlet areas and mass fluxes. Equation 13 then reduces to:

$$K_t = \lambda + \left(\frac{A_1}{A_2}\right)^2 - 2\,\frac{A_1}{A_2}\cos\varepsilon' \qquad (14)$$

where A_1 is the total inlet area = $A_{1_a} + A_{1_b}$.

Two general plots were made from Equation 14, one of K_t vs $\frac{A_1}{A_2}$ for different values of β, Figure 7, and one of K_t vs. β for different values of $\frac{A_1}{A_2}$, Figure 8. The multiple crossovers on Figures 7 and 8 make it difficult to generalize about the effects of β or $\frac{A_1}{A_2}$. One would have to pick combinations of β and $\frac{A_1}{A_2}$ for some system design for reasons other than are obvious from the plots. In a dump combustor, for instance, the inlet Mach number is affected by $\frac{A_1}{A_2}$ so that $K_t\,M_1^2$ must be treated as a combination rather than separately. Similarly the choice of β might be made for its effect on internal and external vehicle configuration requirements rather than for its effect on K_t.

It is interesting to note that the $\beta = 0$ curve in Figure 7 is somewhat lower than the coaxial sudden expansion curve. The difference is probably related more to the semi-empirical origin of Figure 7 versus the analytic origin of the coaxial curve rather than the geometric differences themselves.

Figure 9 shows sketches of the configurations tested. The closest to the configuration of Reference 1 was Figure 9a, although the model has a flat dome whereas the reference configuration has no dome. The rectangular inlets were chosen because they are commonly found on side-mounted inlet combustors. Usually the inlet transitions to circular cross section and then turns to enter the vehicle body. This

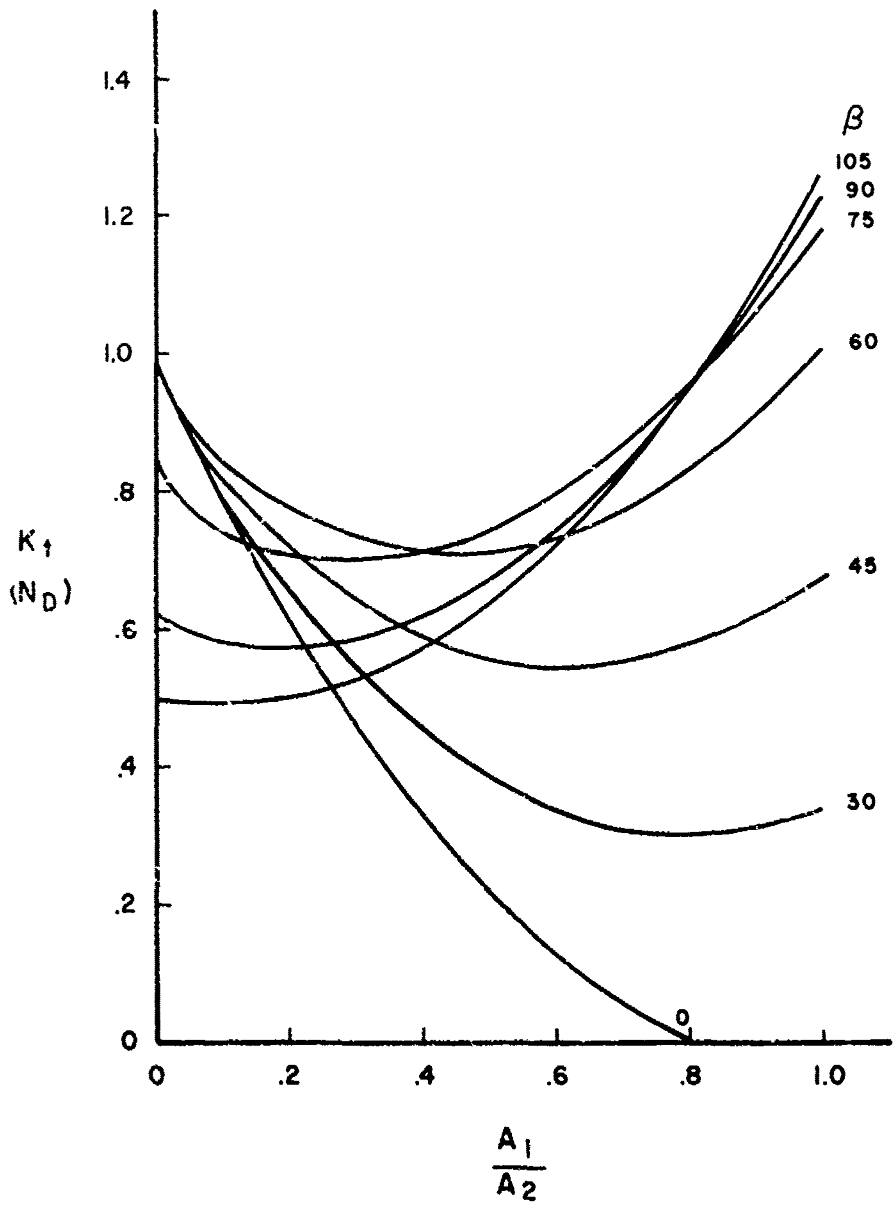


Figure 7. Pressure Loss Factor for Dual Inlets for Various Inlet Angles

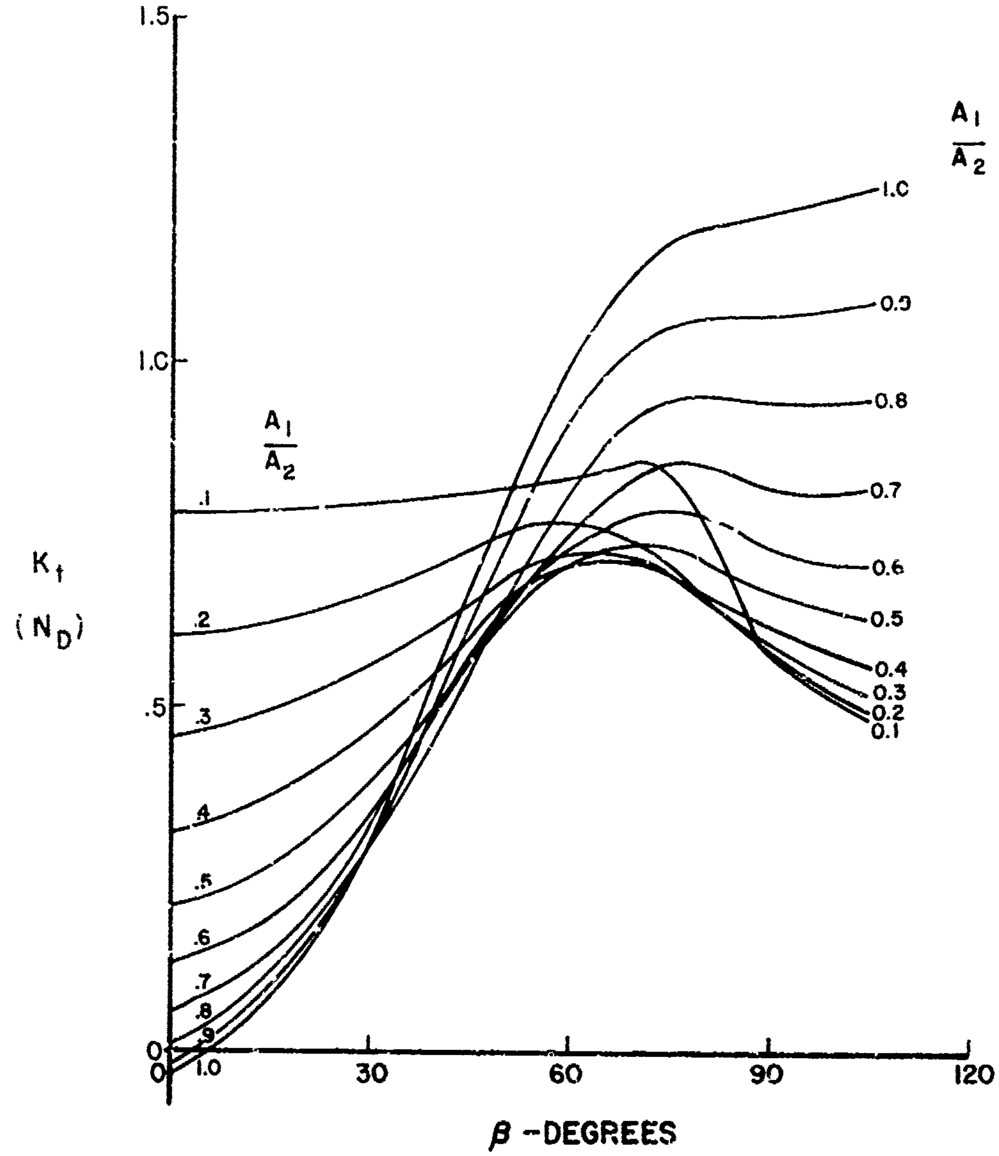


Figure 8. Pressure Loss Factor for Dual Inlets for Various Area Ratios

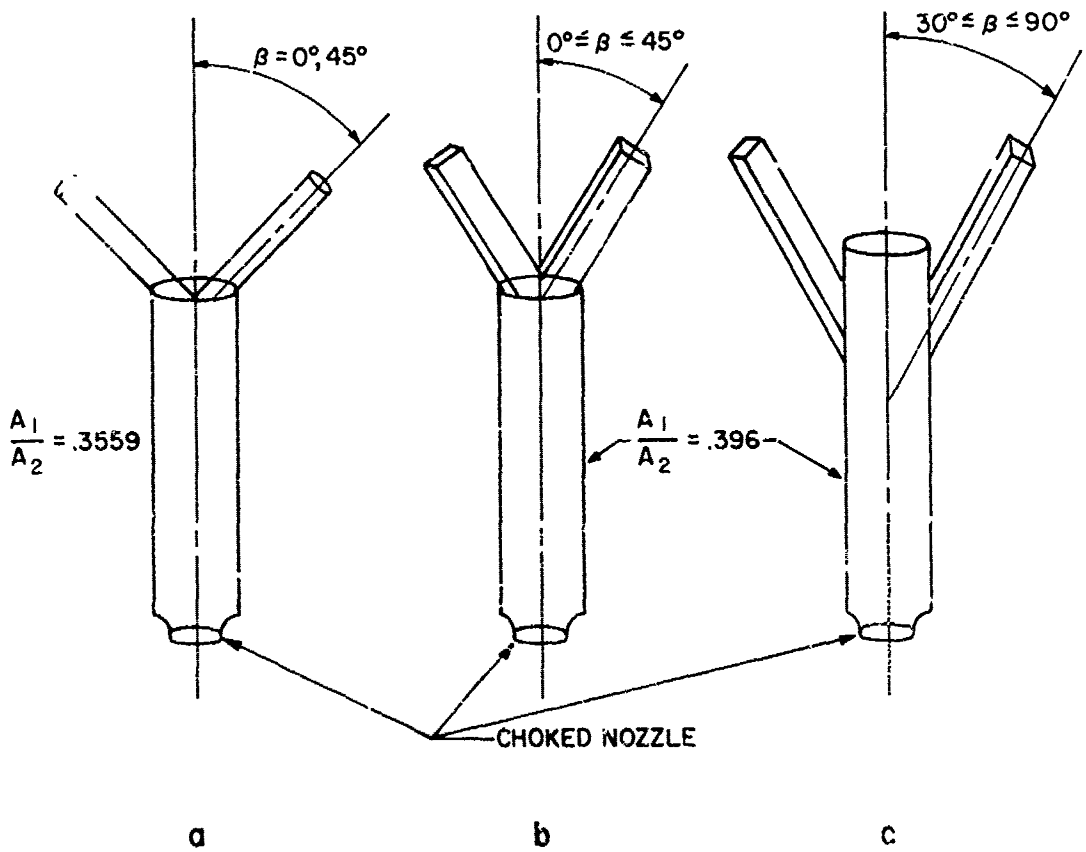


Figure 9. Dual Inlet Model Sketches

is the origin of the angular combustor entry. It was considered interesting to determine if the losses for a rectangular turn and dump would be lower than for transition, turn, and dump. Loss factors for turns in circular ducts and rectangular ducts exist in Reference 1, the latter form being lower in most cases. This left values of the dump loss factors to be determined. An aspect ratio of 1.4 was arbitrarily chosen for the rectangular inlets. All tests were conducted at a Reynolds number of 5.45×10^5 and with an exit nozzle diameter of 2.25 inches.

Figure 10 includes both the predicted K_t curves from Equation 14 and the N_D's calculated from Equation 3 with the test data. All three data curves follow the shape of the predicted curves rather well. The significant features of the figure are threefold. First, the difference between dome and sidewall inlets is small, the dome inlets being lower. Second, the difference between circular and rectangular inlets is similarly small, the circular being lower. Third, what is probably a Reynolds number effect is the most significant, the predicted curve being lower. Presumably the data used in the reference analysis was obtained at a Reynolds number greater than 10^6 where the effect is negligible. The test Reynolds number is more typical of dump combustors and is in the region where Reynolds number effect can be significant.

A point that merits some special attention is the data $\beta = 90°$, which is about 30% higher than expected. In tests with $\beta \geq 60°$, a flow rotation was noted downstream of the dump. The magnitude and direction of the rotation were random with only general trends noticeable. The

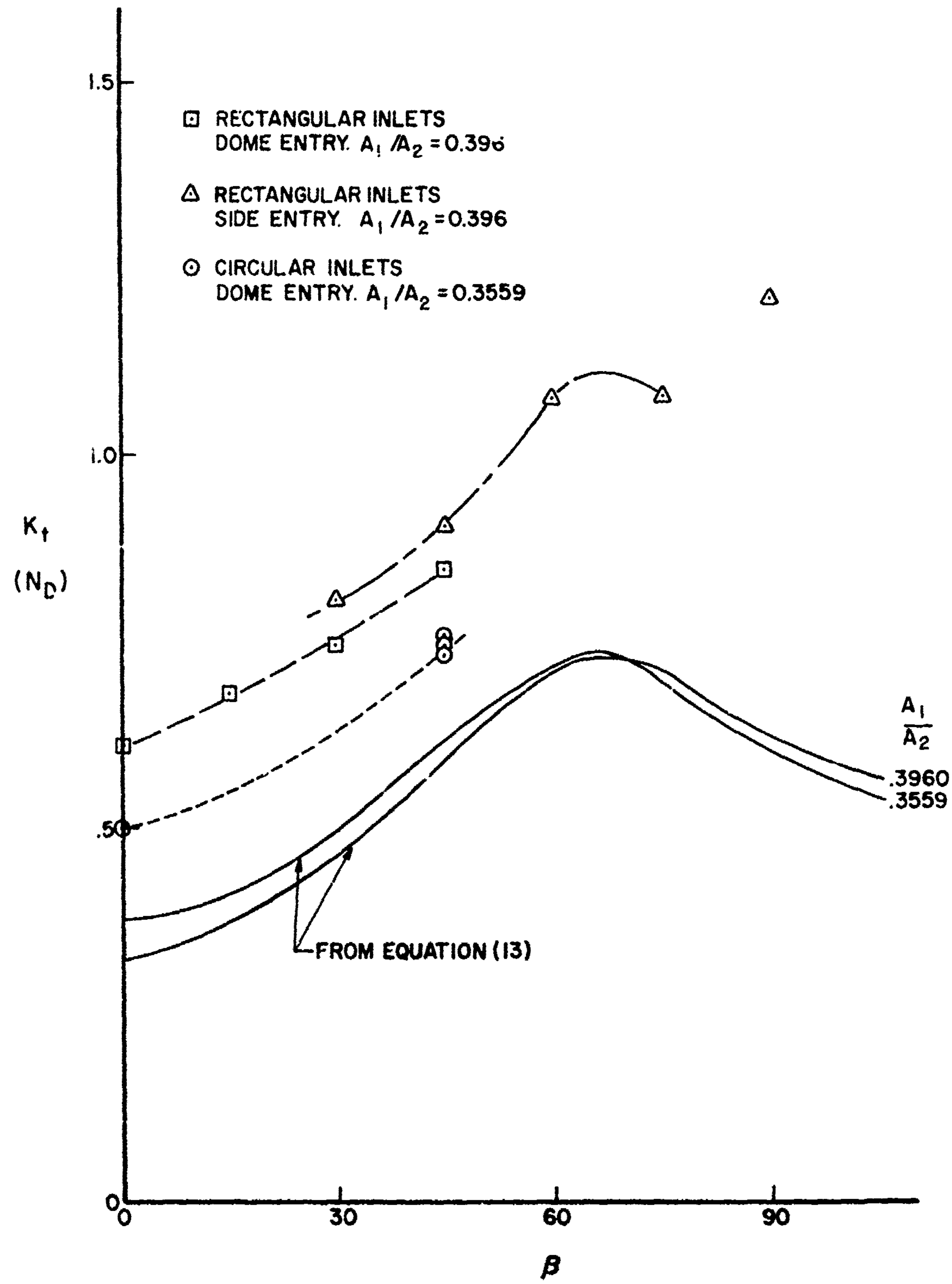


Figure 10. Pressure Loss Factors for Various Dual Inlet Configurations

rotational speed, on the average, increased with the entry angle. The direction was for the most part counterclockwise looking downstream; however, with no external stimulus observable, the rotation was seen to slow and reverse. The rotation was not noticeably affected by the plugging and unplugging of one or the other inlet during a test. Rotational velocity measurements were attempted with a vane in the stream and a strobelight. The rotational speed was rarely constant long enough for a valid measurement. The highest speed observed by strobelight was 2340 rpm at β = 90°. Reference 2 includes some data on a similar phenomenon in pipe bends. Of particular interest is the data on the frequency of rotation direction switching.

Measurements in the dome revealed $P_W \approx 0.99\ P_1$ with no significant angle effect, indicating that the assumption $P_W = P_1$ as in the coaxial analysis would be fairly good in a similar analysis of the dual side-wall inlet system at lower area ratios. Figure 11 shows the pressure profile on the inlet and combustor walls through the dump point.

CONCLUSIONS AND RECOMMENDATIONS

1. Further work is required to improve confidence in the use of the compressible equation; however, it is evident from the data in this report that the compressible equation is quantitatively and qualitatively superior to the incompressible equation in predicting compressible pressure losses.
2. The use of existing incompressible pressure loss parameters in the compressible equation appears valid providing the loss factors are derived from experimental data at comparable Reynolds numbers.

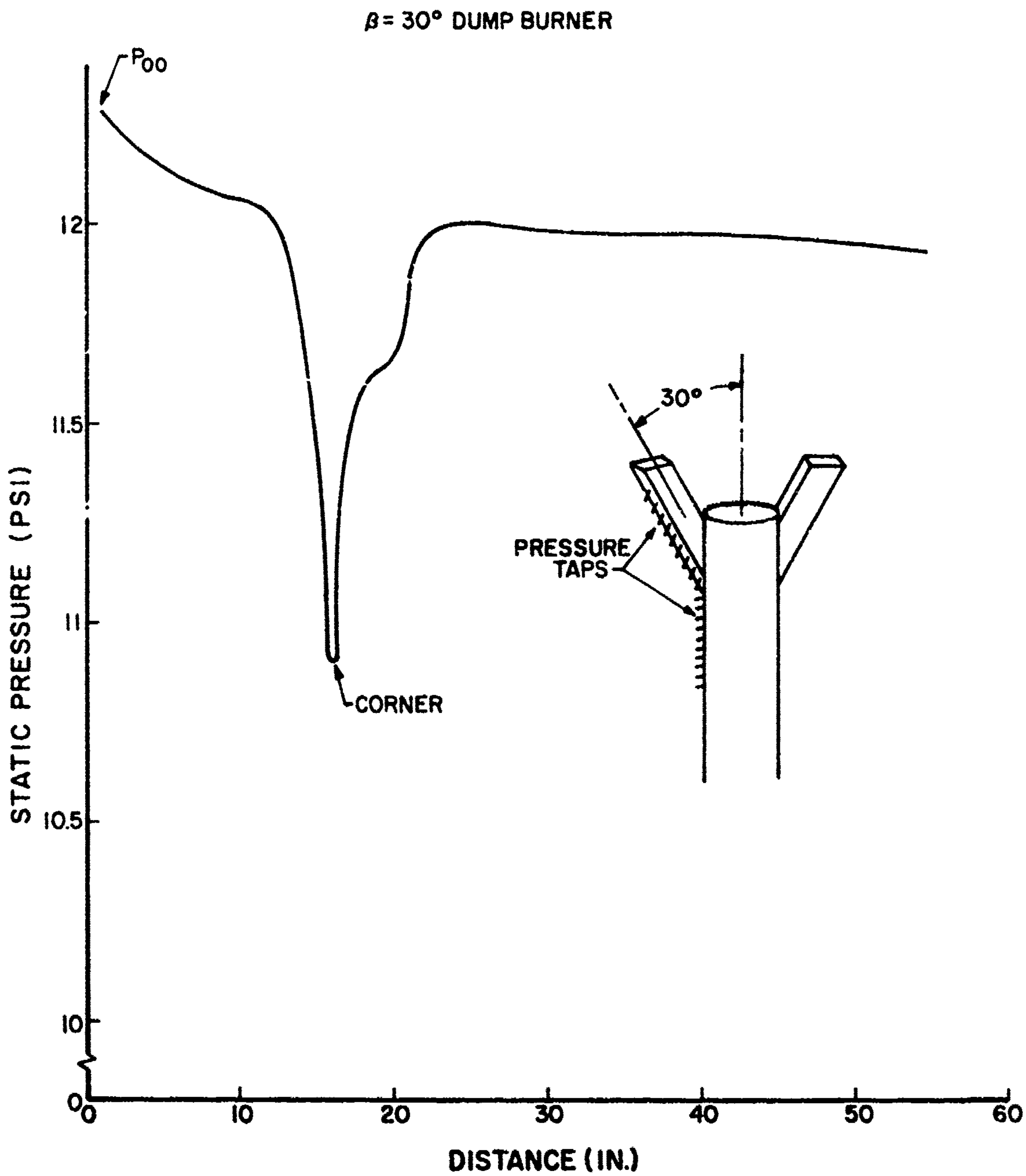


Figure 11. Static Pressure Profile in a 30° Dual Inlet Dump Combustor

3. Pressure loss factors derived analytically or only partly based on experimental data should be applied with care and due consideration for the configurations and assumptions used in their derivation. Exact duplication of geometry and/or supplemental testing for Reynolds effects may be necessary.

4. Additional study of the flow rotation noted in the dual inlet model should be undertaken. Establishment of a stable recirculation zone for flameholding may, under this condition, be difficult or impossible.

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13. ABSTRACT

Volume limited missiles require a particularly exacting form of component integration. One possibly useful concept is the integral rocket ramjet (IRR). In the IRR system the propellant, for the solid rocket booster, is cast directly into the same volume that is used for the ramjet combustor. The size of this ramjet combustor is fixed more by the booster requirements than those of the ramjet. Typically, this results in a ramjet combustor of the sudden expansion or dump combustor type in which one or more relatively small inlet ducts dump the air into a large combustor volume. While the dump combustor is not new, it is less developed than the conventional combustor.

The thrust of this study is directed to a better understanding of the pressure losses in dump combustors. Attendant to this study was an effort to simplify methods of predicting compressible flow losses. Application of the incompressible pressure loss factors and equations to compressible problems can lead to serious errors at Mach numbers above 0.3. During this study an equation was derived to predict compressible pressure losses. This equation expresses the pressure loss as a function of the Mach number and a pressure loss factor which is independent of Mach number. Subsequently it was found that the compressible pressure loss factor, called N_D the dissipation number, was numerically equal to the incompressible pressure loss factor, K_t, for any given fluid system. The incompressible parameter is basically a function of geometry and Reynolds number and there exists a wealth of data relating to it.

Two basic dump combustor designs were selected for testing because of their possible use in missile propulsion. The first was a coaxial circular inlet model, the second,

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a dual side-mounted rectangular inlet model. The measured dissipation numbers were compared to the predicted incompressible parameters and found to be encouragingly similar. The results of this study show, on a preliminary basis, that it may be possible to use the existing incompressible data to predict compressible pressure losses. Additional work is required in this area to establish the limits of this concept.

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