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TECHNICAL NOTE

No. 1607

EFFECT OF SIZE AND NUMBER OF OUTLET PIPES ON DESIGN OF COLLECTORS FOR RATING AND TESTING AXIAL-FLOW COMPRESSORS

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SUMMARY

An experimental investigation to determine the effect of design factors on the performance of collectors for axial-flow compressors consisted of air-flow studies of an experimental collector on which six different outlet configurations were used. By using outlet pipes with different diameters and by using either one or two pipes, the ratio of outlet-pipe cross-sectional area to the collector-inlet cross-sectional area was varied from 0.52 to 3.12. The effects of the size and number of outlet pipes on the static-pressure distribution at the collector inlet, the flow limitation, and the total-pressure losses downstream of the collector inlet were studied.

The size and number of outlet pipes apparently had little effect on the static-pressure distribution at the collector inlet. In a collector with a sudden expansion at the inlet, the ratio of cross-sectional outlet-pipe area to cross-sectional collector-inlet area had to be greater than 2.0 to prevent choking in the outlet pipes. When two different outlet configurations of the same total flow area were used, the total-pressure-loss factor was smaller with one outlet pipe than with two. With the exception of the smallest outlet configuration investigated, the principal total-pressure losses occurred at the collector inlet because of the sudden expansion in flow area.

INTRODUCTION

In the design of collectors for rating and testing axial-flow compressors, the static-pressure variation around the collector inlet must be less than 5 percent of the mean velocity pressure and the collector and ducting losses must be low enough to permit the desired operating range of pressure ratios and flows (reference 1). Another factor in the design of these collectors that may limit the size and the configuration of the collector and outlet piping is the availability of space. When the standards for rating axial-flow compressors were established, little was known of the effect of design factors on collector performance. A research investigation was therefore started to determine the effect of size and number of outlet pipes on the performance of an experimental collector.

Air-flow studies of an experimental collector on which six different outlet configurations were used are reported herein. Each outlet configuration was composed of either one or two outlet pipes and the ratio of the outlet-pipe area to the collector-inlet area was varied from 0.52 to 3.12 by varying the pipe diameter. The effects of the size and number of outlet pipes on (1) the static-pressure distribution at the collector inlet, (2) the total-pressure losses through the collector, and (3) the limitation of the flow are presented.

SYMBOLS

Any consistent set of units may be used for the following symbols, which are used in this report:

A flow area

g acceleration of gravity

M Mach number, $\sqrt{\frac{2}{\gamma-1}\left[\left(\frac{P}{p}\right)^{\frac{\gamma-1}{\gamma}}-1\right]}$

P mean total pressure

p mean static pressure

Δp deviation from mean static pressure at station 2 (fig. 1)

R gas constant for normal air

ΔS increase in entropy

T total temperature

W	weight flow of air
$\frac{P_r - P_x}{P_r - p_r}$	total-pressure-loss factor between two stations
γ	ratio of specific heats for normal air

Subscripts:

2	station 2, collector inlet (fig. 1)
5	outlet-pipe measuring station 6 diameters downstream of collector outlets (fig. 1)
n	any station downstream of station 2 (fig. 1)
r	reference station
x	station immediately downstream of reference station

APPARATUS AND INSTRUMENTATION

Apparatus

A schematic diagram of the research unit used for this investigation is shown in figure 1. Flow through the rig was produced by the pressure difference between the laboratory altitude exhaust system and the room air. By controlling the pressure in the altitude exhaust system and hence the pressure ratio across the unit, a range of air flows could be obtained. The minimum total pressure in the exhaust system varied from test to test, which gave pressure ratios varying from 0.23 to 0.33 across the unit between the altitude exhaust system and station 2.

Air flowed through an orifice tank, a section of concentric cylinders representing the outer and inner walls of the flow passage of an axial-flow compressor, a collector equipped with a cylindrical baffle, and into either one or two outlet pipes. The outlet pipes were connected to the altitude exhaust system through diffuser sections having a total angle of 7°, 12-inch-diameter piping, and about 45 feet of 16-inch-diameter piping, as shown by figure 2. The orifice tank was equipped with a 20-inch-diameter sharp-edge orifice plate (fig. 1). A screen having 8 wires per inch was located 32 inches upstream of the concentric cylinders and a wooden nozzle was placed at the outlet of the orifice tank to obtain smooth flow at the annulus inlet.

Cross-sectional flow area at the collector inlet (station 2) was 0.385 square foot; the collector-inlet annulus had an outer diameter of 14.00 inches and an inner diameter of 11.20 inches. The experimental collector had an outer diameter of 35.00 inches, an inner diameter of 7.22 inches, and a length of 12.50 inches. A 24-inch-diameter cylindrical baffle with 55-percent open area was used inside the collector to minimize the effect of outlet pipes on static-pressure variation at the collector inlet.

870

Instrumentation

Temperature- and pressure-measuring stations were located in the positions indicated by figure 1. Station 1 is 18 inches in front of the orifice plate; station 2 is 2.75 inches upstream of the inside face of the front plate; stations 3 and 4 are 2.5 inches upstream and downstream of the baffle, respectively; and station 5 is approximately 6 pipe diameters downstream of the collector.

Temperatures were measured with iron-constantan thermocouples and a self-balancing potentiometer. Static pressures were obtained with 0.040-inch-diameter wall taps and total pressures with standard 0.040-inch-diameter total-pressure tubes. Pressures were taken visually and photographically from manometers and the atmospheric pressure was measured on a microbarograph. Weight flow was determined from temperature measurements at station 1 and the pressure drop across the calibrated orifice was measured with an NACA micromanometer in inches of alcohol.

At station 2, 15 static-pressure taps were placed circumferentially around the inner cylinder and 15 around the outside casing. These static-pressure taps were connected to a manometer board in opposition to a reference pressure that was one of the 30 static pressures; thus accurate readings in inches of water above or below the reference pressure were obtained. The reference pressure was obtained separately on a mercury manometer. In addition, fixed total-pressure tubes were located in four circumferential positions 90° apart in the same plane as the static-pressure taps. The total-pressure tubes were placed in the stream at a position one-third of the passage width from the inside wall of the casing to obtain an approximate average total pressure. These total pressures, as well as the pressures at stations 3, 4, and 5, were measured on a manometer board in inches of mercury. A total of 16 static-pressure taps were installed in the collector to determine the pressure drop across the baffle: eight taps were placed in each end plate; four were equally spaced a short distance upstream of the baffle (station 3), and four were equally spaced a short distance downstream of the baffle (station 4). The static-pressure taps in the rear plate were displaced 45° from those in the front plate to obtain an average static-pressure distribution around the collector. Measurements in the two outlet pipes (station 5) consisted of static and total pressures and temperatures that were taken according to the recommendations of reference 2.

The precision of the temperature and pressure measurements is estimated to be within the following limits:

Temperature, °F . . . . ±1
Static pressures at station 2, in. water . . . . ±0.10
Other pressures, in. Hg . . . . ±0.10

PROCEDURE AND CALCULATIONS

The following outlet configurations were investigated:

Outlet configuration	Outlet-pipe diameter (in.)	Number of pipes	Total cross-sectional area (sq ft)	Ratio of outlet-pipe area to collector-inlet area
A	6.06	1	0.20	0.52
B	6.06	2	.40	1.04
C	8.58	1	.40	1.04
D	8.58	2	.80	2.08
E	10.50	1	.60	1.56
F	10.50	2	1.20	3.12

For each of these outlet configurations, data were taken over a range of Mach numbers at station 2 varying from a minimum of approximately 0.19 to the maximum value that was obtainable with the available pressure ratio.

The circumferential variation of static pressure at the collector inlet was obtained by subtracting a mean static pressure from each of the 30 individual static pressures and dividing this difference Δp by a mean impact pressure $P_2 - p_2$.

Two methods of representing the losses for the various outlet configurations were used. The first method employs a nondimensional total-pressure-loss factor defined as the difference between the average of the four total pressures P_r at reference station 2 and the average total pressure P_x at a given measuring station divided by the average impact pressure $P_r - p_r$ at station 2. Because this method does not directly show the total-pressure ratio, which is an important variable for compressible flow at high Mach numbers, another method was used in which the ratio of total pressure at a given measuring station to the total pressure at the reference station is directly expressed. The relation of total-pressure-loss factor, total-pressure ratio, and Mach number is given in the following equation

$$\frac{P_r - P_x}{P_r - p_r} = \frac{1 - P_x/P_r}{1 - \dfrac{1}{\left(1 + \frac{\gamma-1}{2} M_r^2\right)^{\frac{\gamma}{\gamma-1}}}} \qquad (1)$$

and is shown in figure 3 for normal air $(\gamma = 1.3947)$. For each Mach number there is a maximum total-pressure-loss factor corresponding to a total-pressure ratio of zero. For example, for a Mach number of 1.0 the maximum total-pressure-loss factor is 2.12. Because the increase in entropy is given by

$$\Delta S = -RT \log P_x/P_r \qquad (2)$$

and the loss of available energy by $T\,\Delta S$ (where T is assumed constant and equal to the temperature of the surroundings) a total-pressure ratio of zero represents an infinite loss in available energy.

RESULTS AND DISCUSSION

Static-Pressure Variation at Collector Inlet

A typical variation of static pressure with angular position at the collector inlet (station 2) is shown in figure 4. The angular position referred to as 0° is the top point on the vertical center line of the unit. All other angular positions are designated in a counter-clockwise direction from this reference point looking downstream. Although these curves are for outlet configuration D at one Mach number, they are representative of all the configurations investigated. The curves for the inner and outer cylinders are not in perfect agreement but both curves follow the same general trend.

Data points at angular positions of 0° on the inner cylinder and 144° on the outer cylinder were omitted because of faulty static-pressure taps. All these variations in static pressure are small and are within ±2.5 percent of the mean impact pressure; except for a few isolated points with deviations ranging from ±2.65 to ±3.63 percent of the mean impact pressure, the static-pressure variation stayed within these limits for all configurations studied.

In order to give a complete picture of the static-pressure variation at station 2 over a range of Mach numbers for all outlet configurations, composite curves of the mean deviation of p_2/P_2-p_2 are shown in figure 5. Individual points on these curves were determined from the arithmetical average of the absolute values of the deviation from the average static pressure p divided by the mean impact pressure at a particular Mach number. Changing the size and number of outlet pipes apparently had little effect on the static-pressure deviation at station 2. The spread of the pressure deviation for the various outlet configurations is only approximately 0.4 percent of the mean impact pressure and the deviations are only slightly greater with one outlet than with two.

Flow Limitations and Over-all Total-Pressure Losses

The absolute limitation on the flow will be reached when choking occurs at some point in the system. Because the maximum possible flow in a compressor at a given speed is obtained when choking occurs in the compressor, the operating range will be limited if choking occurs at some point in the downstream system before it occurs in the compressor. In order to prevent choking downstream of the collector inlet before it occurs at the collector inlet, the downstream cross-sectional area must be larger than the cross-sectional area at the collector inlet, as indicated by simple one-dimensional analysis based on uniform flow. From the continuity and energy equations the following relation is obtained

$$PA = W\sqrt{\frac{RT}{\gamma g}}\,\frac{\left(1+\frac{\gamma-1}{2}M^2\right)^{\frac{\gamma+1}{2(\gamma-1)}}}{M} \qquad (3)$$

where W, R, T, and g are considered constant along the flow path if no heat transfer occurs. The minimum possible value of the right-hand side of the equation occurs when M is equal to 1.0.

In order to prevent choking, the product PA must be greater than this minimum value. Because the total pressure P decreases from station to station downstream of the collector inlet owing to losses, the cross-sectional area A must be correspondingly increased. At maximum flow, the loss in total pressure may be quite large and hence the required increase in area may also be quite large.

The Mach numbers calculated from the total- and static-pressure measurements in the outlet pipes at the maximum-flow points are shown in table I:

TABLE I

Outlet configuration	Number of pipes	$\frac{A_5}{A_2}$	Mach number at station 5
A	1	0.52	0.85
B	2	1.04	.84
C	1	1.04	.82
D	2	2.08	.76
E	1	1.56	.84
F	2	3.12	.42

When two outlet pipes were used, the Mach number was the average of the Mach numbers in the two pipes. Except for configuration F, choking conditions were closely approached or actually encountered. For uniform flow, choking should occur at a Mach number of 1.0 but for nonuniform flow choking may occur at mean Mach numbers less than 1.0. Although the evidence is inconclusive that choking actually occurred in the outlet pipes at the maximum-flow points, the mean Mach numbers of the flow in the outlet pipes considerably exceeded the mean Mach number of the flow at the collector inlet except for configurations D and F. The Mach number of the flow in the outlet pipes for configuration D was approximately equal to the Mach number of the flow at the collector inlet. Although choking may not have been encountered in the outlet pipes for configuration D, choking would still be expected to occur first in the outlet pipes because of the more rapid increase in Mach number at the downstream stations, as indicated by equation (3).

The Mach number of the flow in the outlet pipes for configuration F was only 0.42, which shows that the flow was not limited by the outlet pipes but by either the available pressure difference or by choking at some other point in the system. Choking probably occurred at the collector inlet inasmuch as the Mach number calculated from average static- and total-pressure measurements was 0.8. The foregoing observations indicate that the ratio of cross-sectional outlet-pipe area to cross-sectional collector-inlet area A_5/A_2 has to be greater than 2.0 to prevent choking in the downstream ducting.

Losses in the collector and the outlet pipes are especially important in experimental investigations because of the effect of these losses in limiting the range of operation of the compressor. These losses are important not only in connection with choking but also in limiting the flow in many practical cases where the available pressure ratio is insufficiently small to produce choking. Two methods of presenting the total-pressure losses are shown in figure 6. In the first method (fig. 6(a)), a nondimensional total-pressure-loss factor between the collector inlet (station 2) and the outlet-pipe measuring station (station 5) is plotted against the Mach number at the collector inlet. In general, the total-pressure-loss factor increases with an increase in Mach number. As the area ratio increases, the maximum Mach number at the collector inlet also increases and, because the maximum Mach number at the collector inlet for configuration F was the highest, it is evident that choking did not occur at the collector inlet for the other configurations. As expected, for a given number of outlet pipes and a given attainable Mach number the total-pressure-loss factor decreased as the area ratio increased.

A comparison of outlet configurations B and C of the same area ratio showed that a smaller total-pressure-loss factor was obtained with one large outlet pipe than with two smaller ones. For configurations D and E, the total-pressure-loss factor at low Mach numbers is higher with two outlet pipes than with one although the area ratio is greater for the two outlet pipes. At higher Mach numbers, however, the effect of the area ratio appears to overshadow the effect of the number of outlet pipes on the total-pressure-loss factor. A probable explanation of the greater losses for the two small outlet pipes is that the losses due to sudden contraction of the flow would be larger because of the greater change in area between the collector and the outlet pipes. The losses due to sudden contraction of the flow would consequently be greater for the small outlets.

The direct total-pressure losses between the collector inlet (station 2) and the outlet-pipe measuring station (station 5) are shown in figure 6(b), in which the ratio of the average total pressure at the outlet-pipe measuring station to the average total pressure at the collector inlet is plotted against the Mach number of the flow at the collector inlet. A comparison of the pressure ratios for the maximum-flow point on each of the curves shows that lower pressure ratios, and hence higher losses, were obtained as the outlet-pipe area was increased. The increase in losses with increased outlet area is due to the predominant effect of increased Mach number at the collector inlet over the effect of decreasing total-pressure-loss factor. For example, for configurations A and B, the actual losses at the maximum-flow point increased between configurations A and B as evidenced by the decrease in total-pressure ratio in spite of the large decrease in total-pressure-loss factor (fig. 6(a)). Inasmuch as the total-pressure ratio across the entire unit including the ducting downstream of the outlet-pipe measuring station remained substantially constant at the maximum-flow point throughout the entire investigation, the over-all total-pressure loss would have to be approximately the same for all configurations. At the maximum-flow point, the losses downstream of the outlet-pipe measuring station were therefore the largest when the losses upstream of the outlet-pipe measuring station were the smallest. If the flow were entirely subsonic, the reverse of the results shown for all but configurations D and F would occur. For all the configurations except D and F, the Mach numbers at the outlet-pipe measuring station are nearly the same as shown in table I. The smallest outlet pipes that allowed the largest area expansion into the downstream ducting would therefore produce the lowest velocities and losses in the downstream ducting. If choking occurred at the outlet-pipe measuring station, however, and supersonic velocities were present in the expansion section, the observed results could be readily explained because the larger area expansion would permit higher supersonic velocities and greater losses. Under choking conditions in the outlet pipe, the downstream pressure may be varied over a wide range without affecting the Mach number at the collector inlet or the outlet-pipe measuring station.

The curves of figure 6(b) indicate that choking did not occur at the collector inlet with any of the configurations except possibly F. Although the exhaust facilities were inadequate for determining whether choking actually occurred at the collector inlet for configuration F at the maximum-flow point, if a sufficient pressure difference were available, choking would probably first occur at the collector inlet because the maximum attainable Mach number in the outlet pipes was considerably less than the Mach number at the collector inlet.

Distribution of Losses through Collector

The distribution of the total-pressure loss from the collector inlet to the outlet-pipe measuring station for all outlet configurations at a Mach number of approximately 0.19 at the collector inlet is presented in figure 7. The general relation is typical for all Mach numbers investigated even though the position of the curves changes slightly with Mach number. Because of the chaotic flow conditions in the collector proper, the static pressures at stations 3 and 4 were used in calculating the total-pressure-loss factors. The static pressures should be representative of the total pressures inasmuch as practically the entire velocity pressure would be lost because of the large abrupt change in flow area between the collector inlet and the collector proper. When two outlet pipes were used, the total-pressure-loss factor was calculated from the arithmetical average of the total pressures in the two outlet pipes. For all outlet configurations, the total-pressure-loss factor between the collector inlet and the baffle (stations 2 and 3) is nearly the same. Also, the total-pressure-loss factor across the baffle is almost constant, which indicates that changes in the outlet configuration had little effect on the flow up to and across the baffle. Between station 4 and the outlet-pipe measuring station, there was an extremely large increase in total-pressure-loss factor for outlet configuration A. When the area ratio was increased to 1.04 (outlet configurations B and C), a considerable decrease in total-pressure-loss factor between the last two stations from that of outlet configuration A was produced. Further decreases in total-pressure-loss factor were produced in succession with configurations D, E, and F but a point of diminishing returns was rapidly being approached. For all configurations except A, the principal total-pressure loss resulted from the sudden expansion at the collector inlet. The greatest reduction in losses should therefore be obtained by using an efficient diffuser at the collector inlet.

Even though the reduction in total-pressure-loss factor with an increase in outlet-pipe area appears small, it nevertheless makes possible the attainment of higher Mach numbers at the collector inlet before choking occurs in the outlet pipes. If the large losses in the collector could be reduced by efficient diffusion, the size of the outlet pipes required to prevent choking would be reduced.

SUMMARY OF RESULTS

Air-flow studies were made on a simple experimental collector for axial-flow compressors, which had a sudden expansion at the inlet and a cylindrical baffle. The results of these studies in which the ratio of outlet-pipe area to collector-inlet area was varied from 0.52 to 3.12 by using six different outlet configurations are as follows: 870

1. The spread of the static-pressure deviation at the collector inlet caused by changing the size and number of outlet pipes was only 0.4 percent of the mean impact pressure and the deviations were only slightly greater with one outlet than with two.

2. The ratio of cross-sectional outlet-pipe area to collector-inlet cross-sectional area had to be greater than 2.0 to prevent choking in the outlet pipes.

3. When two different outlet configurations having the same total flow area were used, a smaller total-pressure-loss factor was obtained with one outlet pipe than with two.

4. With the exception of the smallest outlet configuration investigated, the principal losses occurred at the collector inlet because of the sudden expansion in flow area.

Flight Propulsion Research Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, December 9, 1947.

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2. Ellerbrock, Herman H., Jr., and Goldstein, Arthur W.: Principles and Methods of Rating and Testing Centrifugal Superchargers. NACA ARR, Feb. 1942.

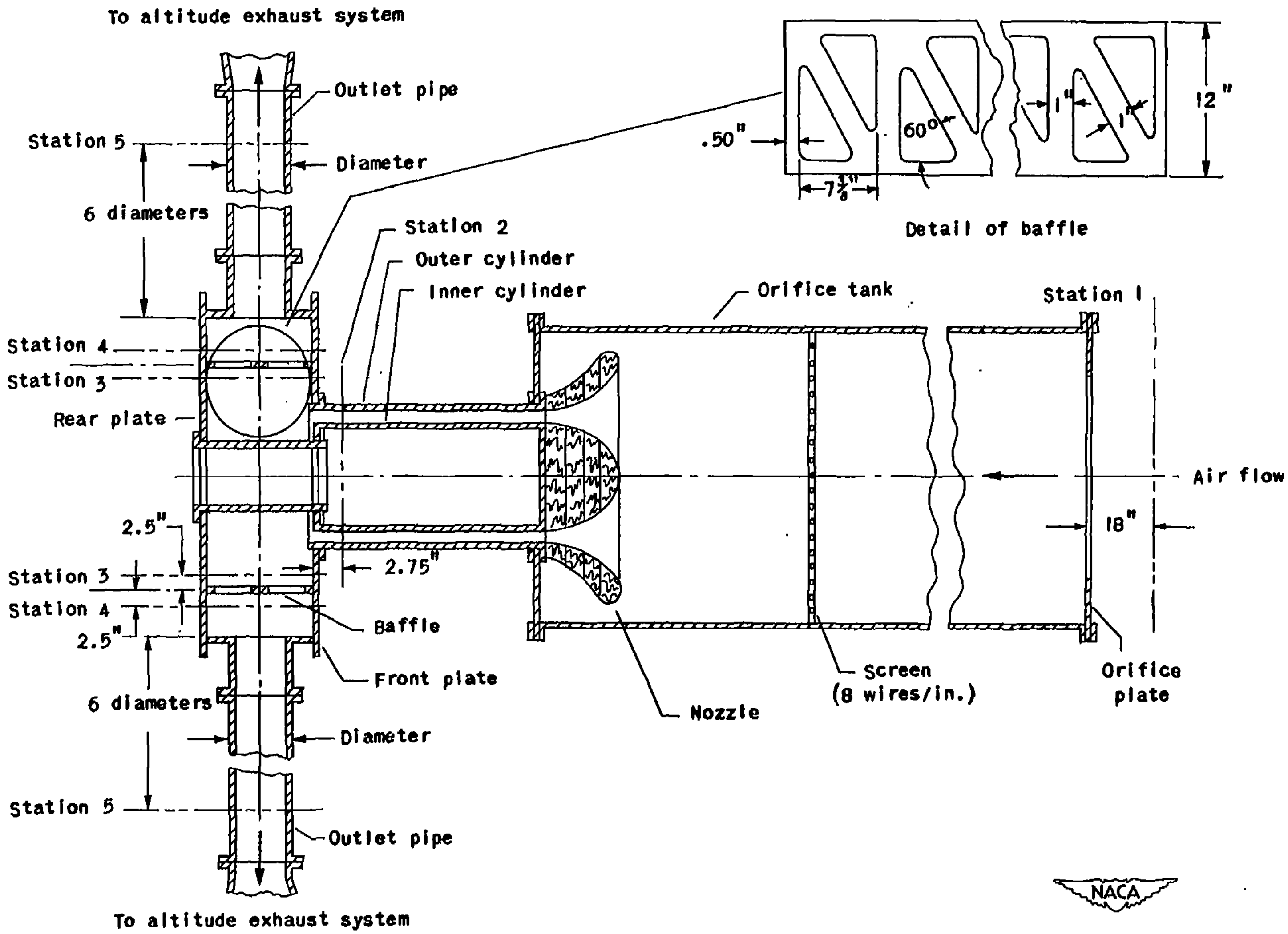


Figure 1. - Schematic diagram of research unit for axial-flow compressor collector showing location of measuring stations.

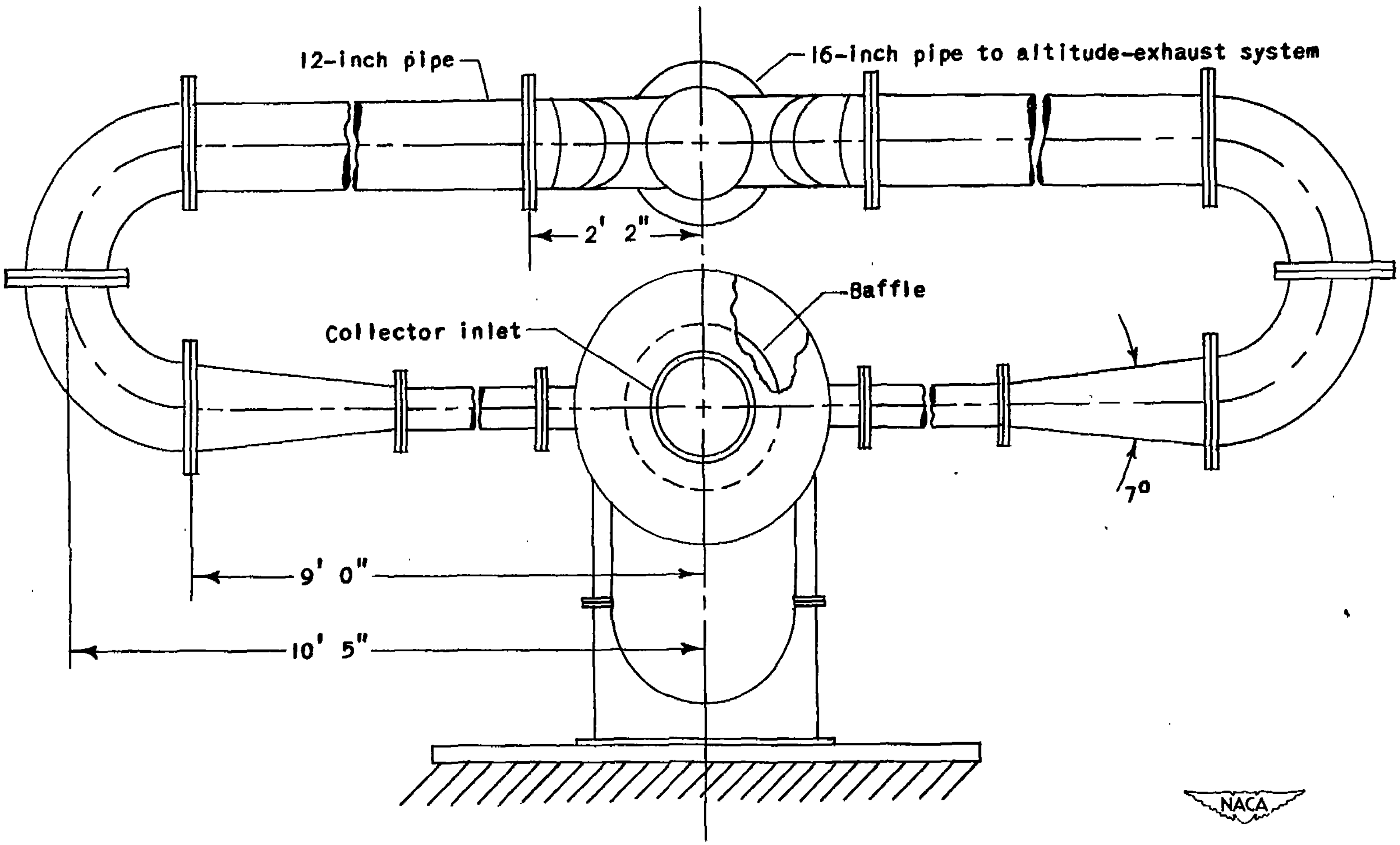


Figure 2. - Schematic diagram of ducting downstream of collector outlets.

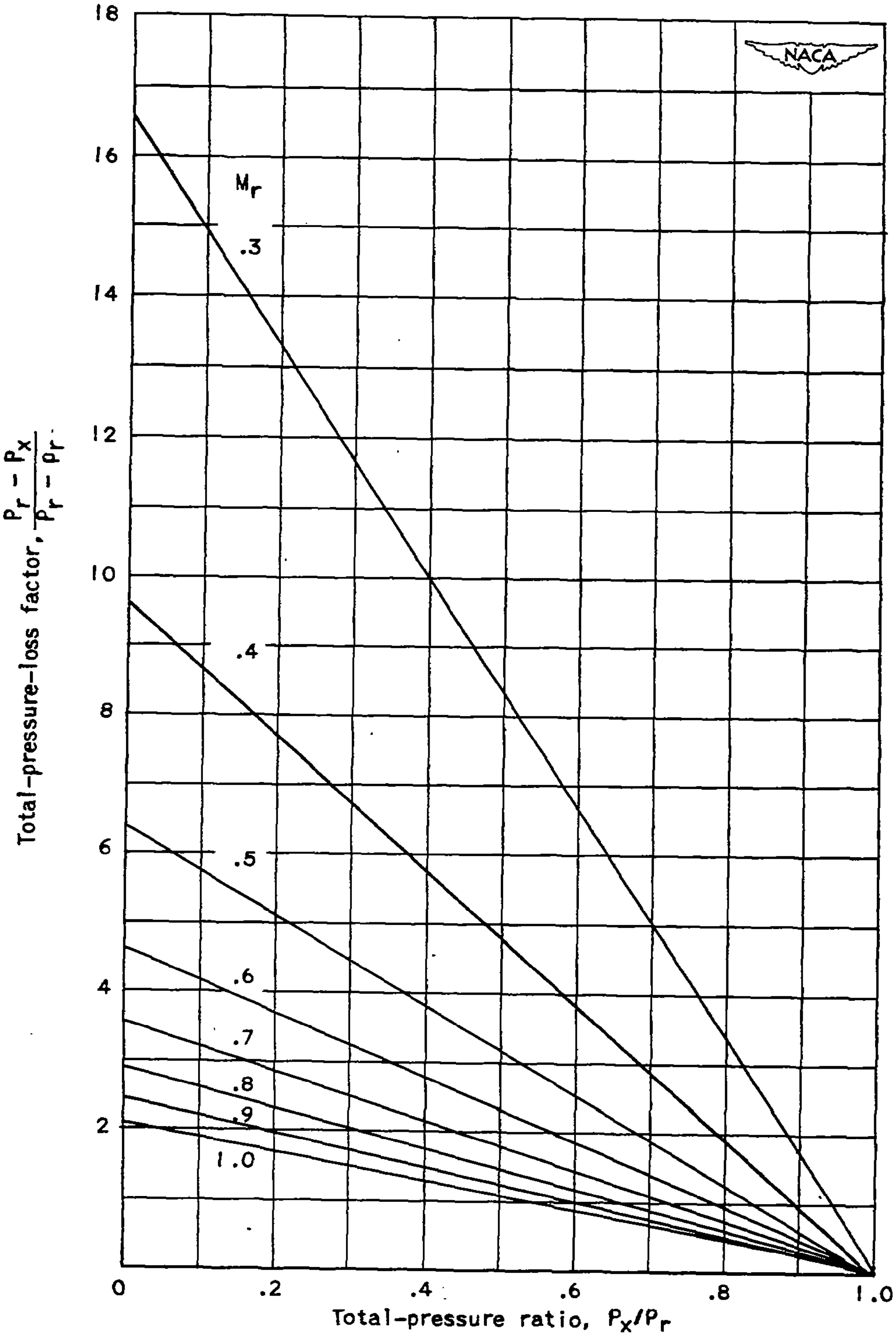


Figure 3. - Relation of total-pressure-loss factor, total-pressure ratio, and Mach number for normal air ($\gamma = 1.3947$).

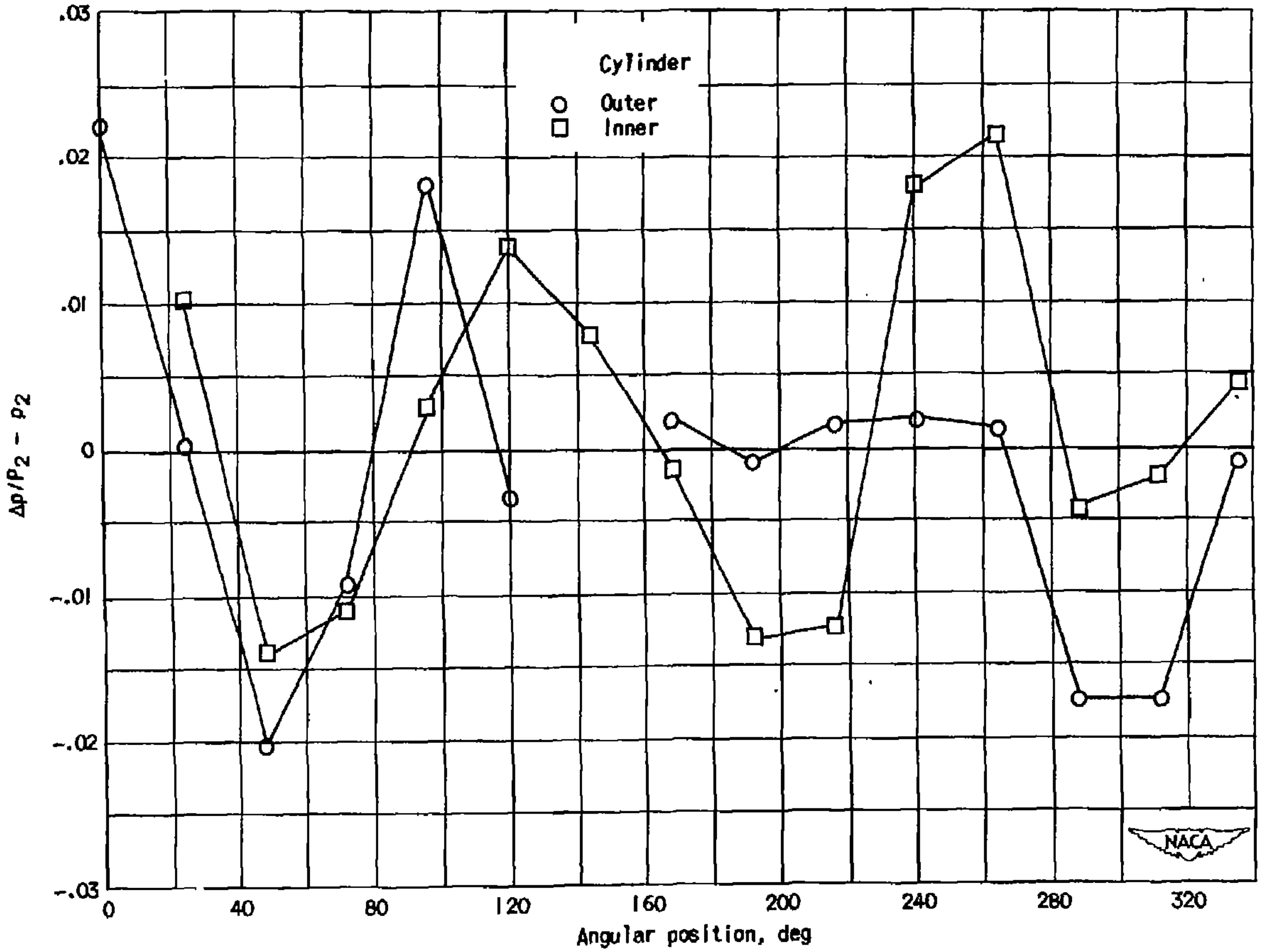


Figure 4. - Typical static-pressure variation at inlet to collector, station 2.

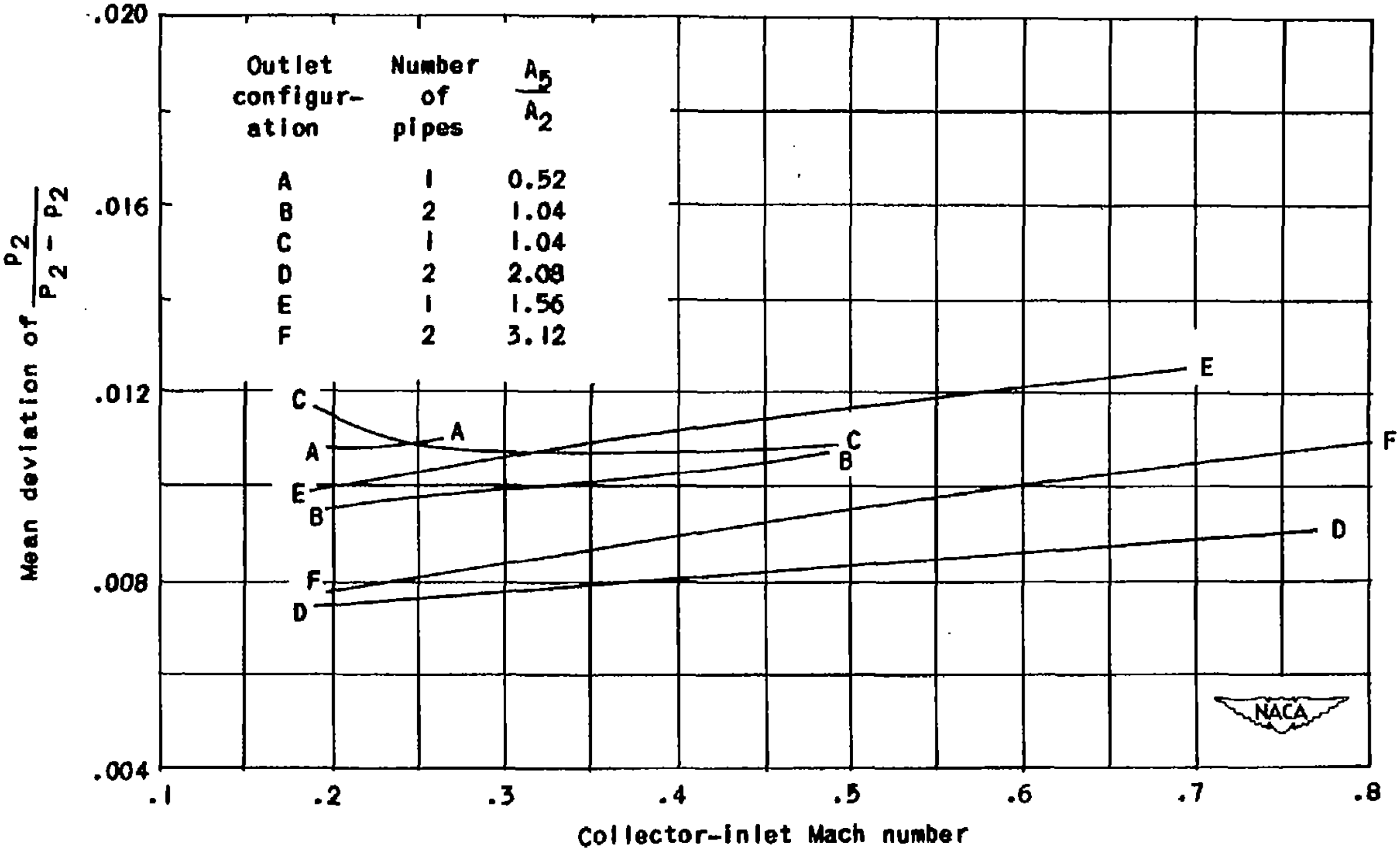
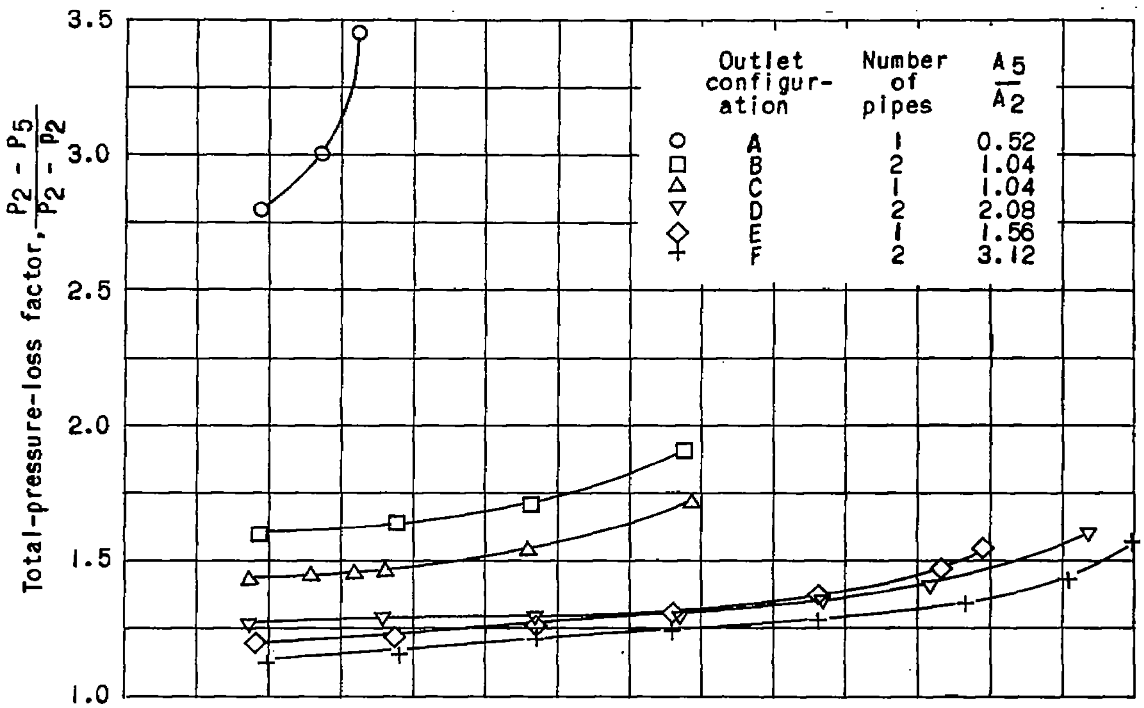
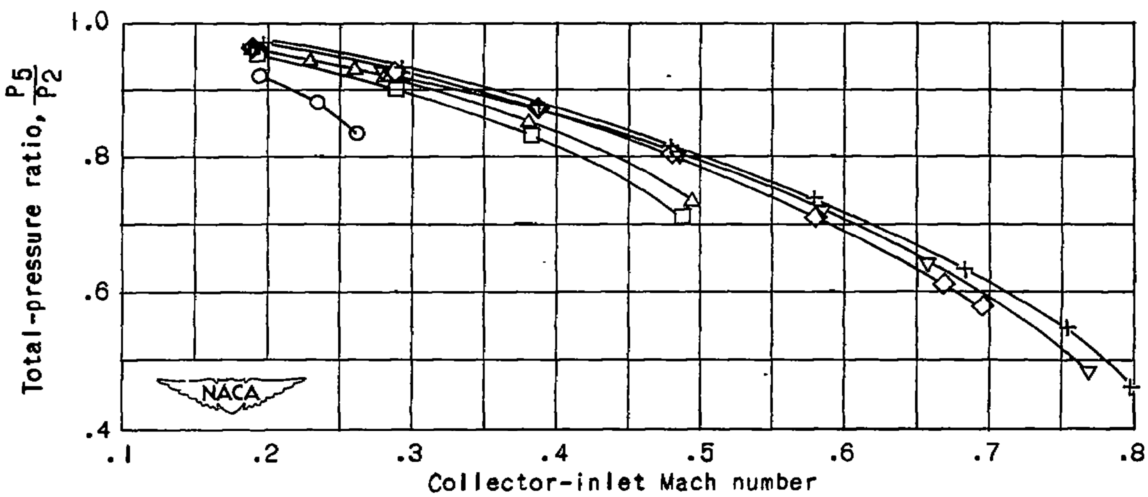


Figure 5. – Comparison of mean deviation of $p_2/(P_2 - p_2)$ for all outlet configurations investigated.



(a) Variation in total-pressure-loss factor.



(b) Variation in total-pressure ratio.

Figure 6. - Variation of total-pressure-loss factor and total-pressure ratio with Mach number for all outlet configurations investigated.

870

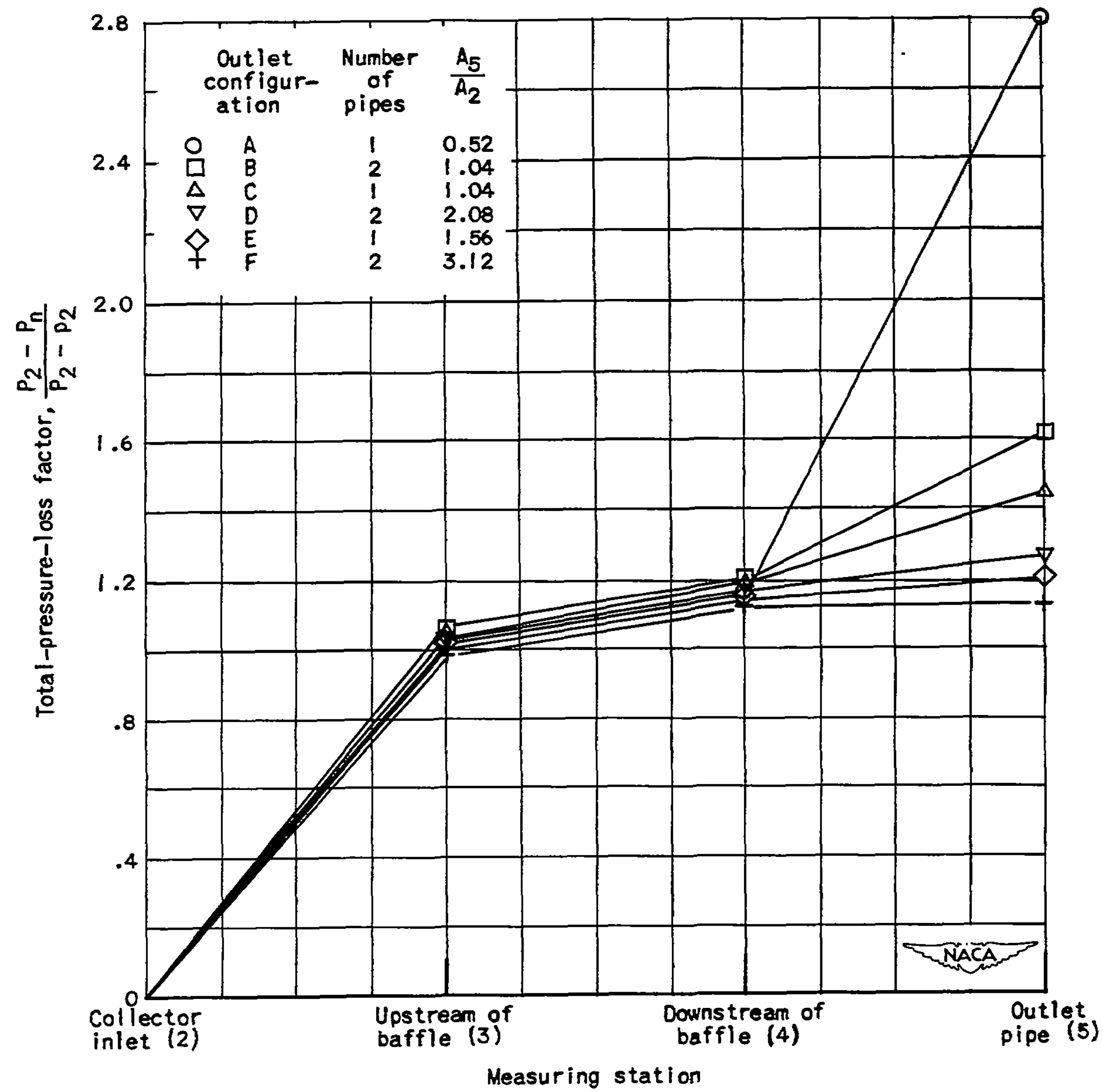


Figure 7. - Distribution of total-pressure losses between collector inlet and outlet-pipe measuring station at collector-inlet Mach number of 0.19 for all outlet configurations investigated.