NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3793

EXPLORATORY INVESTIGATION OF THE USE OF AREA SUCTION TO ELIMINATE AIR-FLOW SEPARATION IN DIFFUSERS HAVING LARGE EXPANSION ANGLES

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SUMMARY

An exploratory investigation has been made with area suction used for boundary-layer control in conical diffusers with expansion angles of 30° and 50° and with an area ratio of 2. These tests, made at a mean inlet Mach number of about 0.2, indicated that the air-flow separation was eliminated by the use of area suction, and the resulting total-pressure and static-pressure losses were less than those for a 10° diffuser without boundary-layer control. The air-flow separation was eliminated in the 30° and 50° diffusers with suction mass flows of 3 and 4 percent of the inlet mass flows, respectively.

INTRODUCTION

The results of experimental investigations have shown that separation of the boundary layer occurs in diffusers that have total expansion angles greater than about 15°. This air-flow separation results in total-pressure and static-pressure losses, and in nonuniform velocity profiles at the exit of the diffuser (refs. 1 to 4). In order to improve these characteristics investigations have been conducted where the boundary layer in the diffuser has been re-energized with vortex generators or blowing through slots, or the boundary layer in the diffuser has been removed by suction through slots (refs. 5 to 11). The results of some of these tests showed that large improvements were made; however, air-flow separation did not appear to be eliminated in the conical diffusers with total expansion angles greater than about 30°.

Since area suction (suction applied over a distributed area) was effective in eliminating air-flow separation on a wing at high angles of attack (ref. 12), exploratory tests were initiated to determine whether area suction would eliminate air-flow separation in diffusers with large expansion angles. These exploratory tests were conducted using a 30°

and a 50° conical diffuser with various extents of porous area. For comparative purposes, a 10° conical diffuser with no porous surface was also tested. Due to the exploratory nature of these tests, the tests were performed with only one inlet boundary-layer condition and for a mean inlet Mach number of about 0.2.

NOTATION

a	speed of sound, ft/sec
A	cross-sectional area, sq ft
g	acceleration of gravity, ft/sec^2
H	local total pressure, lb/sq ft
$\overline{H}$	arithmetic average total pressure, lb/sq ft
K	ratio of average total-pressure loss to theoretical incompressible value for an abrupt expansion, $\frac{(\overline{H}_1 - \overline{H}_2)/\overline{q}_1}{[1 - (A_1/A_2)]^2}$
l	length of diffuser, measured along center line, in.
m	mass flow of air, $\frac{W}{g}$, $\frac{\text{lb/sec}}{\text{ft/sec}^2}$
$\overline{M}$	average Mach number, $\frac{\overline{U}}{a}$
p	local static pressure, lb/sq ft
$\overline{p}$	arithmetic average static pressure, lb/sq ft
P	static-pressure coefficient, $\frac{p - \overline{p}_1}{\overline{q}_1}$
q	dynamic pressure, $H - p$, lb/sq ft
r	radial distance, in.
R	radius, in.
u	local velocity, ft/sec
U	velocity outside of the boundary layer, ft/sec

$\overline{U}$ average velocity at a given cross section, ft/sec

W weight rate of flow, lb/sec

x longitudinal distance along center line of diffuser, measured from beginning of diffuser, in.

y distance from wall of diffuser, in.

$\frac{\delta^*}{R_1}$ ratio of boundary-layer displacement thickness to inlet radius

$\frac{\theta}{R_1}$ ratio of boundary-layer momentum thickness to inlet radius

η ratio of average static-pressure rise to theoretical incompressible value, $\frac{(\overline{p}_2 - \overline{p}_1)/\overline{q}_1}{1 - (A_1/A_2)^2}$

2θ diffuser expansion angle, deg

Subscripts

1 inlet, 2 inches upstream of beginning of diffuser

2 exit

p plenum chamber

s suction

MODEL AND APPARATUS

The test apparatus and different diffuser sections are shown in figure 1. The three conical diffusers tested had expansion angles of 10°, 30°, and 50°, and they had exit area to inlet area ratios of 2 to 1. The 10° diffuser was constructed from wood and finished with Fiberglas. The 30° and 50° diffusers were constructed from commercially produced porous sintered stainless steel with a thickness of about 1/16 inch. The flow characteristics of this porous material were such that 6 cubic feet per second per square foot would pass through the material when a pressure difference of 60 pounds per square foot was applied across the material. The extent of porous area was controlled by covering a portion of the porous area with a nonporous tape about 0.003 inch thick. For some of the tests, the porous stainless steel was completely covered with this nonporous tape to simulate a diffuser without boundary-layer control.

The main air flow was sucked through the test apparatus by a constant-speed-motor and centrifugal-pump combination. The air-flow rate was controlled by throttling the exit of the pump. A static-pressure orifice at station 1 and a total-pressure tube in the 32-inch-diameter bellmouth (fig. 1) were used as a reference dynamic pressure. The average dynamic pressure at station 1 was determined from a survey made with a probe inserted at station 1. For the suction tests, the air was sucked through the porous steel by a centrifugal pump driven by a variable-speed motor. The quantity of air removed by this suction pump was measured by a standard ASME orifice meter.

The pressures at the exit of the diffusers (station 2) were measured with a fixed rake spanning the cross section of the diffuser. This rake consisted of 26 total-pressure and 8 static-pressure tubes. Twenty of the total-pressure tubes were arranged so as to be centered in regions of equal area, and they were connected to an integrating board so that an area-weighted average of the total pressures could be obtained. Static-pressure orifices were located in the wall of the diffuser so that the longitudinal distribution of the static pressure could be measured. The boundary-layer profiles at station 1, two inches forward of the inlet of the diffuser, were measured with a probe consisting of a total-pressure and a static-pressure tube. This probe was in the duct only when measurements of the inlet boundary-layer profile were desired.

TESTS

Tests were made of the 30° and 50° diffusers with various extents and locations of porous area. These tests were made at an inlet Mach number of about 0.2, and they were performed with various suction mass flows. Tests were also made with the porous area of the 30° and 50° diffusers sealed and with the 10° diffuser in order to obtain data which could be compared with previously reported data for similar conical diffusers.

RESULTS AND DISCUSSION

Total-Pressure and Static-Pressure Losses

The total-pressure and static-pressure loss factors, K and $1 - \eta$, for the 30° and 50° diffusers with area suction and for conical diffusers without boundary-layer control are compared in figure 2. These factors are used to express the performance of a diffuser in terms which tend to be independent of the area ratio. The parameters K and η have also been referred to as the diffuser loss factor and the diffuser effectiveness, respectively. It can be seen that area suction greatly reduced the loss factors; in fact, the values were less than those measured for the 10° diffuser of the present test. The data for the diffusers without boundary-layer control were obtained from references 1, 2, 3, 4, and 10, and they are presented as bands of data because of the differences in values reported. Values for the 30° and 50° diffusers with the porous areas sealed could not be accurately measured with the apparatus used because of the unsteady flow resulting from the separation of the boundary layer. However, the approximate values of loss factors measured for these diffusers were within the bands of data shown in figure 2. With suction applied, the flow in the diffuser was very steady.

The effect of area suction on the total-pressure, static-pressure, and velocity distributions at the exit of the 30° and 50° diffusers (station 2) is shown in figure 3. These data for the 30° and 50° diffusers with suction are compared with those for the 10° diffuser without suction in figure 4. This figure shows that area suction reduced the total-pressure losses to values less than those of the 10° diffuser, indicating that the air-flow separation normally attendant with wide-angle diffusers was eliminated by the use of area suction. In figure 4, it is also seen that the static-pressure distribution at the exit of the diffuser with suction became less uniform as the diffuser angle was increased from 10° to 30° to 50°. This type of pressure gradient would be expected in potential flow in a wide-angle diffuser (see ref. 13).

It should be pointed out that a comparison of the velocity profiles at the exit of the diffusers (fig. 4) does not provide a comparison of the boundary-layer profiles because of the previously noted nonuniform static-pressure distribution. However, the boundary-layer thickness at the exit of the diffuser can be determined from the total-pressure distributions presented in figure 4. A comparison of these distributions shows that the boundary-layer thicknesses at the exit of the 30° and 50° diffusers with suction were less than that of the 10° diffuser. Further, the shape of the total-pressure distributions (fig. 4) indicates that the boundary layer in the diffusers with suction is at least as stable as that in the 10° diffuser. Since there is little or no separation at the exit of the 10° diffuser, it can be concluded that area suction has eliminated the air-flow separation that existed in the 30° and 50° diffusers without boundary-layer control. A typical inlet boundary-layer profile measured in these tests is shown in figure 5. These measurements show that a thin, stable, turbulent boundary layer existed at the inlet of the diffusers.

The longitudinal distributions of static-pressure coefficient along the wall of the 30° and 50° diffusers presented in figure 6 show that area suction increased the static-pressure recovery along the entire length of the diffusers. The longitudinal distributions of static-pressure coefficient for the 30° and 50° diffusers with suction are compared with that for the 10° diffuser in figure 7. The data of this figure indicate that area suction permits equivalent static-pressure recovery to be obtained with a diffuser only a fraction of the length of the 10° diffuser.

Suction Requirements

The effect of suction mass flow on the total-pressure recovery of the 30° and 50° diffusers is shown in figure 8 for several lengths of porous area. It can be seen that a large increase in total-pressure recovery is obtained with small suction flow ratios. It can be ascertained from the data presented in previous figures that air-flow separation has been eliminated in the diffuser when the suction flow ratio is sufficient to insure essentially complete total-pressure recovery. It can also be seen in this figure that it is not necessary, or even desirable from a suction flow standpoint, to apply area suction down the entire length of the diffuser. The suction mass-flow ratios and the pumping pressure coefficients required for the 30° and 50° diffusers at the lowest suction mass-flow ratio where separation was indicated to be eliminated are summarized in the following table:

2θ	x/l	m_s/m_1	P_p
30°	0.16	0.030	-0.7
50°	.15	.042	-1.9

The relatively large pumping pressure coefficients required for the 50° diffuser resulted because sufficient inflow velocities could be obtained through the dense porous stainless steel only by providing a large pressure differential. It would be expected that these pumping pressure coefficients could be reduced by the use of a porous material that had a greater porosity near the beginning of the diffuser. Based on other applications of area suction (e.g., ref. 12) it would be expected that the use of a material with a tapered porosity could also reduce the suction mass-flow ratios required to eliminate separation.

CONCLUSIONS

Exploratory tests were made with area suction applied to conical diffusers with expansion angles of 30° and 50°. These tests, made at a mean inlet Mach number of approximately 0.2, indicated that the air-flow separation was eliminated by use of area suction, and that the resulting total-pressure and static-pressure losses were less than those for a 10°

diffuser without boundary-layer control. The air-flow separation was eliminated in the 30° and 50° diffusers with suction mass flows of 3 and 4 percent of the inlet mass flows, respectively.

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REFERENCES

1. Gibson, A. H.: On the Resistance to Flow of Water Through Pipes or Passages Having Divergent Boundaries. Royal Society of Edinburgh Trans., vol. 48, pt. 1, 1911-1912, pp. 97-116.

2. Gibson, A. H.: Hydraulics and Its Application. Fourth ed., D. Van Nostrand Co., 1930, pp. 92-93.

3. Peters, H.: Conversion of Energy in Cross Sectional Divergences Under Different Conditions of Inflow. NACA TM 737, 1934.

4. Little, B. H., Jr., and Wilbur, Stafford W.: Performance and Boundary-Layer Data From 12° and 23° Conical Diffusers of Area Ratio 2.0 at Mach Numbers Up to Choking and Reynolds Numbers Up to 7.5×10^6. NACA Rep. 1201, 1954.

5. Valentine, E. Floyd, and Carroll, Raymond B.: Effects of Several Arrangements of Rectangular Vortex Generators on the Static-Pressure Rise Through a Short 2:1 Diffuser. NACA RM L50L04, 1951.

6. Wood, Charles C.: Preliminary Investigation of the Effects of Rectangular Vortex Generators on the Performance of a Short 1.9:1 Straight-Wall Annular Diffuser. NACA RM L51G09, 1951.

7. Henry, John R., and Wilbur, Stafford W.: Preliminary Investigation of the Flow in an Annular-Diffuser-Tailpipe Combination With an Abrupt Area Expansion and Suction, Injection, and Vortex-Generator Flow Controls. NACA RM L53K30, 1954.

8. Ackeret, J.: Removing Boundary Layer by Suction. NACA TM 395, 1926.

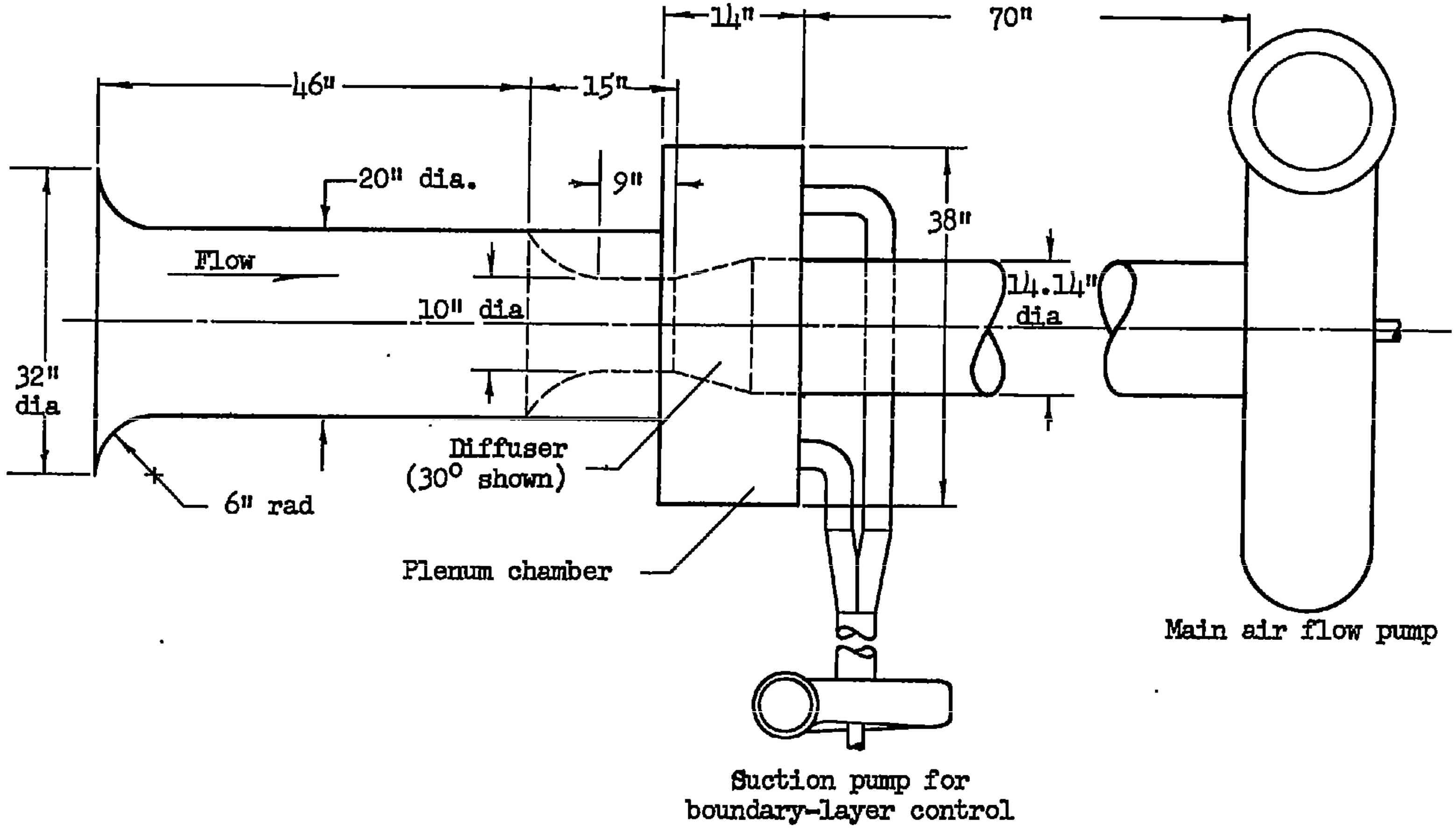
9. Biebel, William J.: Low-Pressure Boundary-Layer Control in Diffusers and Bends. NACA WR L-84, 1945. (Formerly NACA ARR L5C24)

10. Gratzer, L. B., and Smith, R. H.: Boundary Layer Control for Wide Angle Diffusers. Aero. Lab. Rep. 300, Univ. of Washington, Nov. 22, 1948.

11. Manoni, L. R.: Wide Angle Diffusers Employing Boundary Layer Control. Rep. R-95460-12, Research Dept., United Aircraft Corp., Mar. 19, 1952.

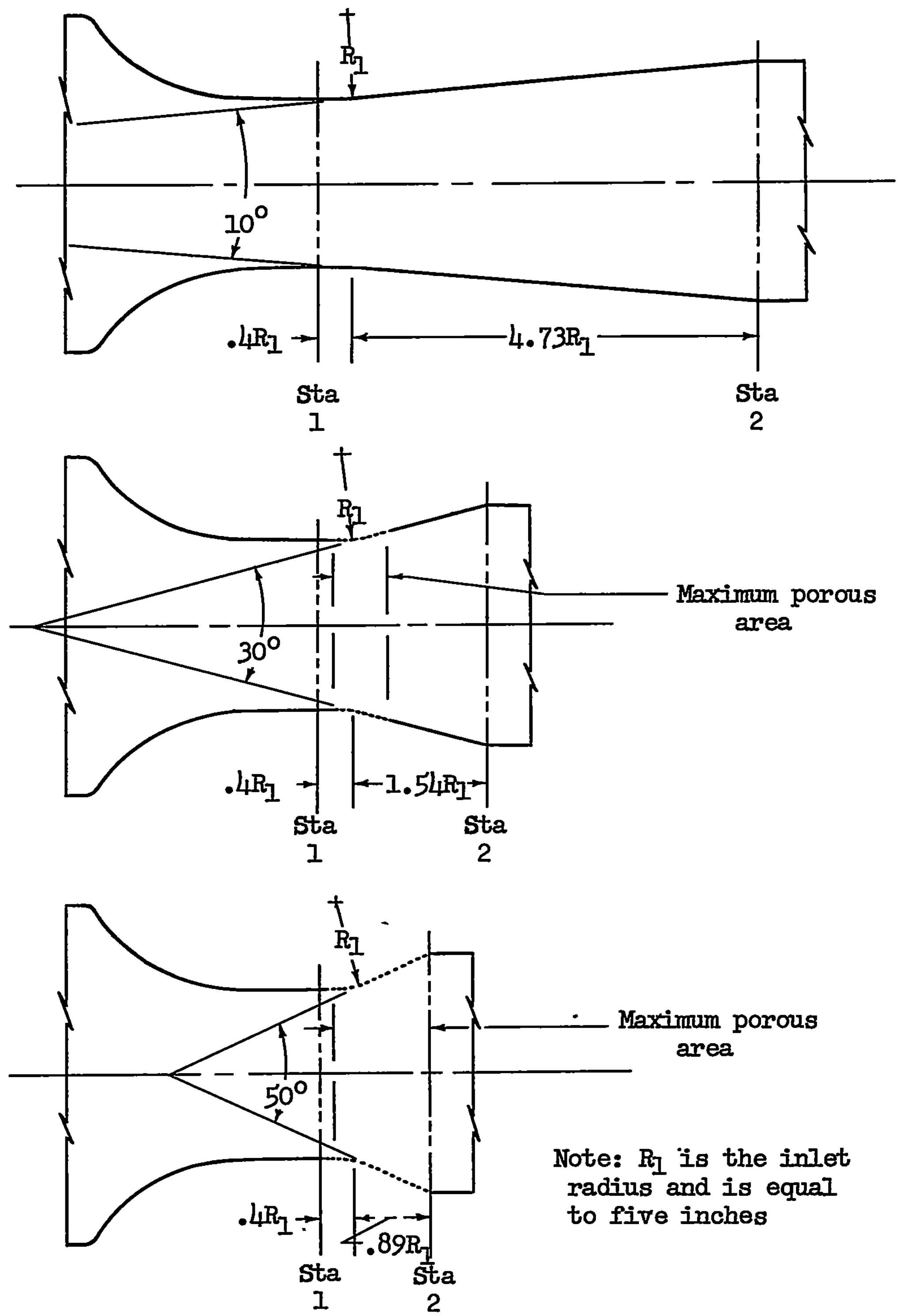
12. Holzhauser, Curt A., and Martin, Robert K.: The Use of Leading-Edge Area Suction to Increase the Maximum Lift Coefficient of a 35° Swept-Back Wing. NACA RM A52G17, 1952.

13. Rouse, Hunter: Elementary Mechanics of Fluids, Chapter II. John Wiley and Sons, Inc., 1946.



(a) Over-all setup.

Figure 1.- Dimensional characteristics of test apparatus.



(b) Diffuser details.

Figure 1.- Concluded.

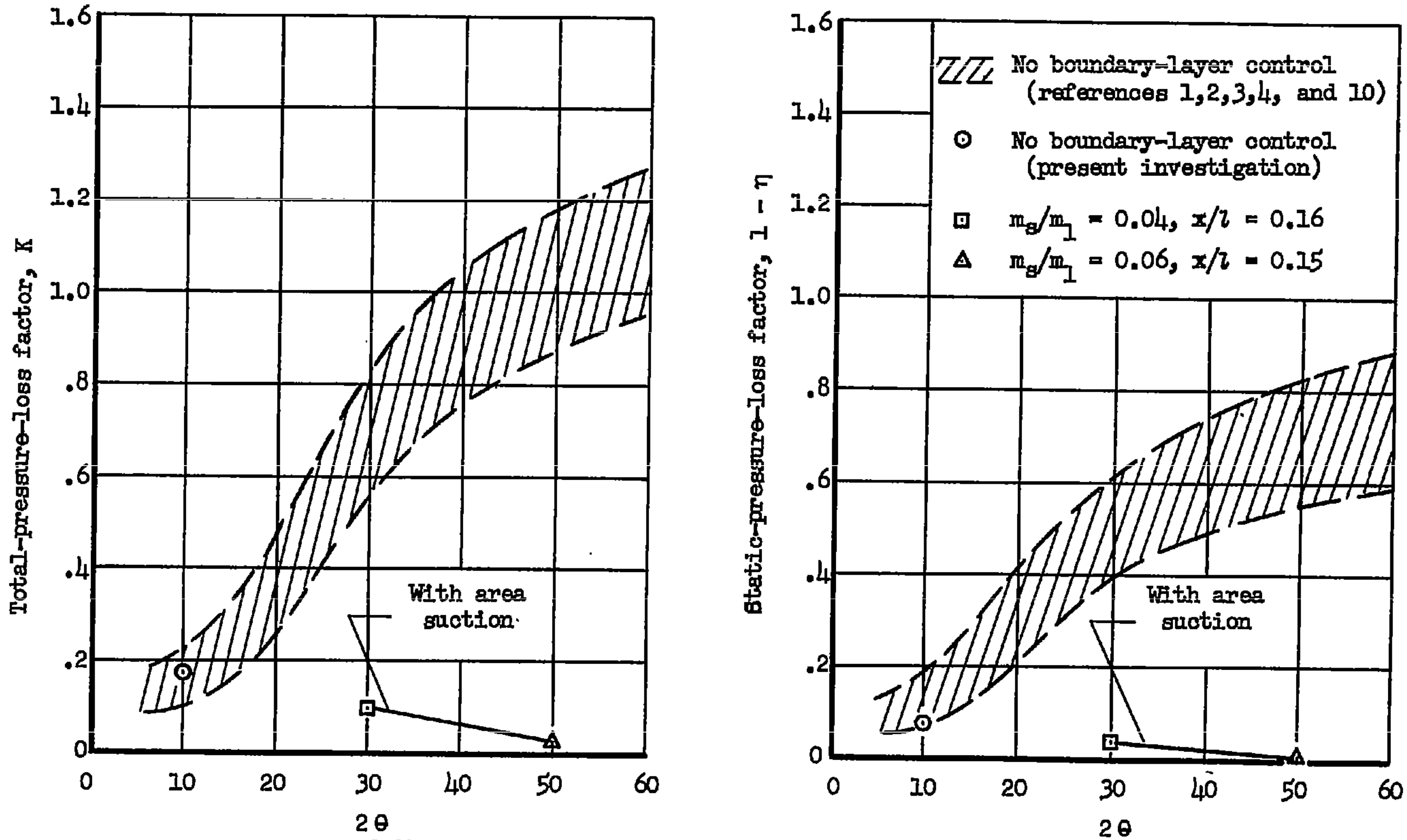
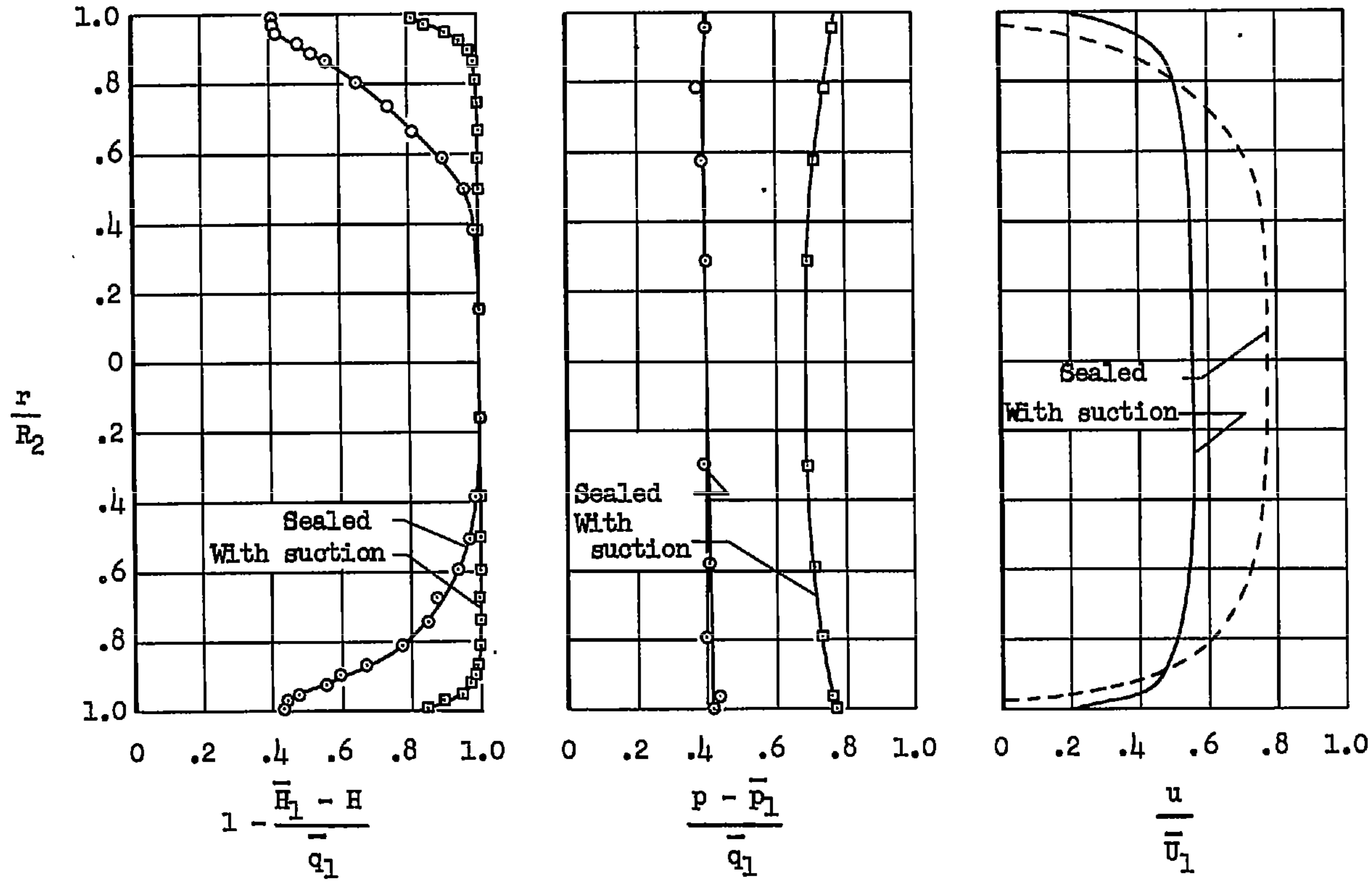
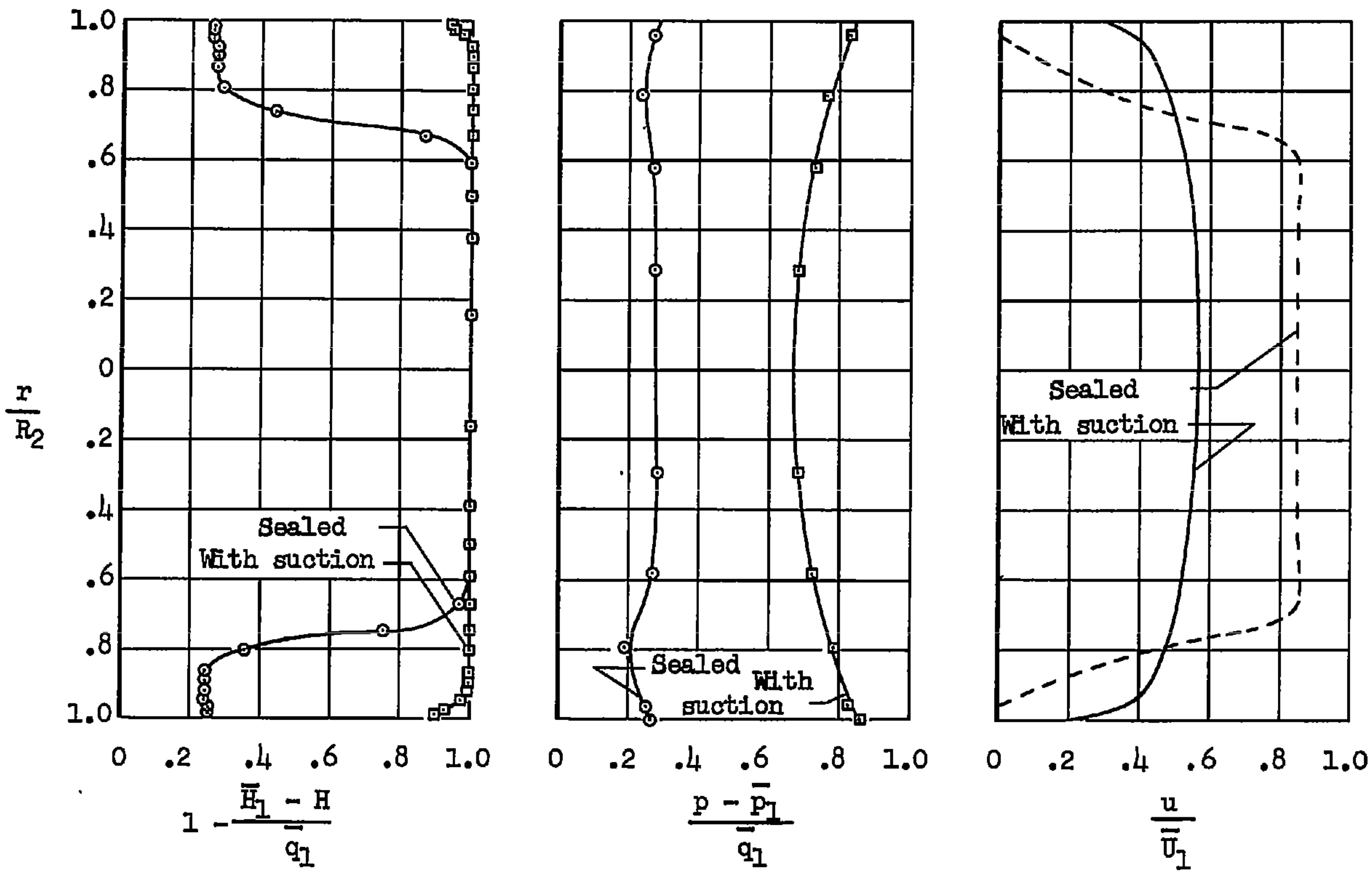


Figure 2.- Variations of diffuser total-pressure and static-pressure loss factors with expansion angle for conical diffusers with and without area suction; $\overline{M}_1 = 0.2$, $A_2/A_1 = 2$.



(a) $2\theta = 30^{\circ}$, sealed and with suction ($m_s/m_1 = 0.04$, $x/l = 0.16$).

Figure 3.- Effect of area suction on the total-pressure, static-pressure, and velocity profiles at the exit of the diffuser; $\overline{M}_1 = 0.2$, $A_2/A_1 = 2$.



(b) $2\theta = 50^{\circ}$, sealed and with suction ($m_s/m_1 = 0.06$, $x/l = 0.15$).

Figure 3.- Concluded.

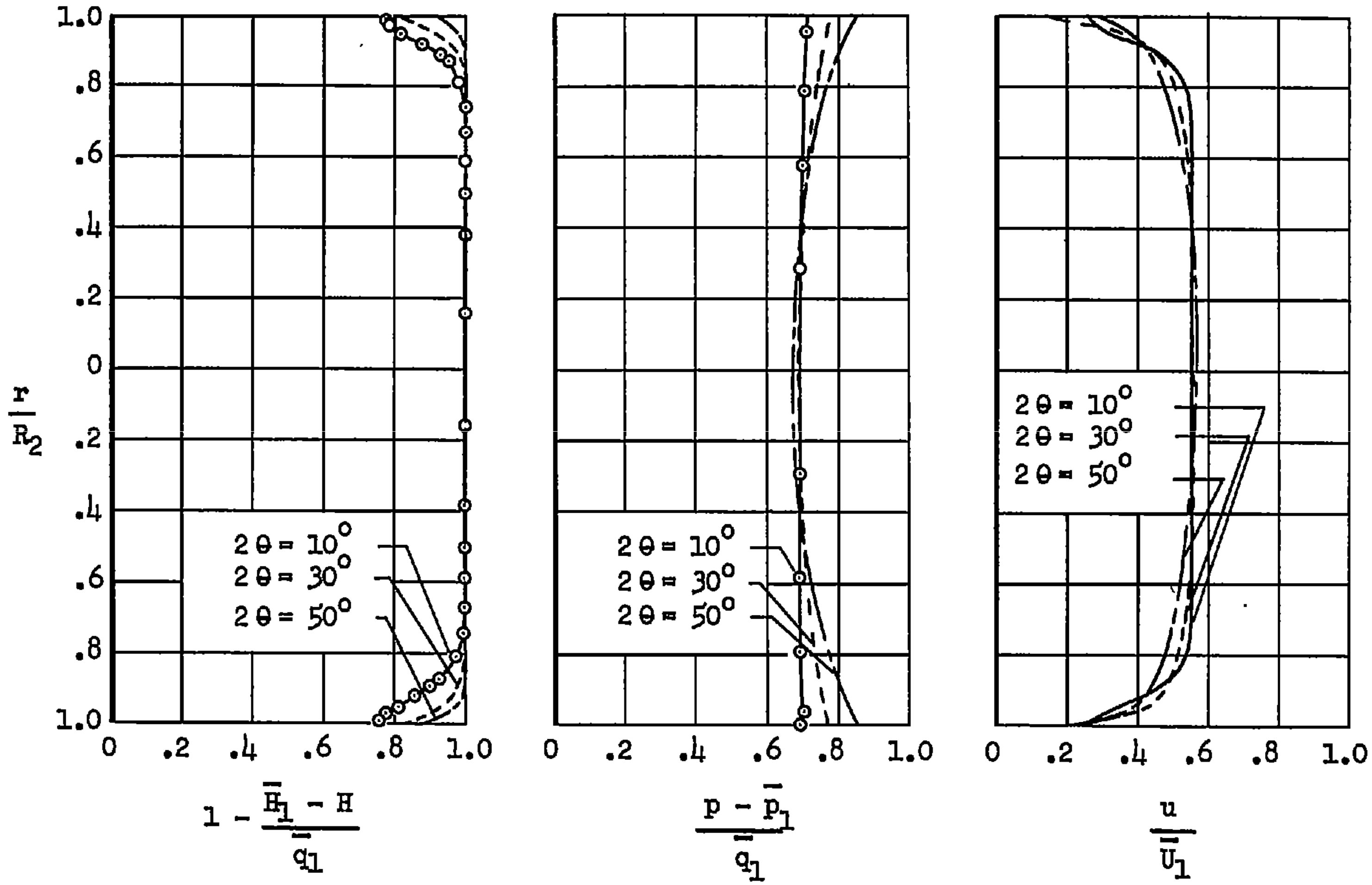


Figure 4.- Comparison of total-pressure, static-pressure, and velocity distributions at exit of 10° diffuser with those of 30° and 50° diffusers with area suction, $m_s/m_1 = 0.04$ and 0.06, respectively; $\bar{M}_1 = 0.2$, $A_2/A_1 = 2$.

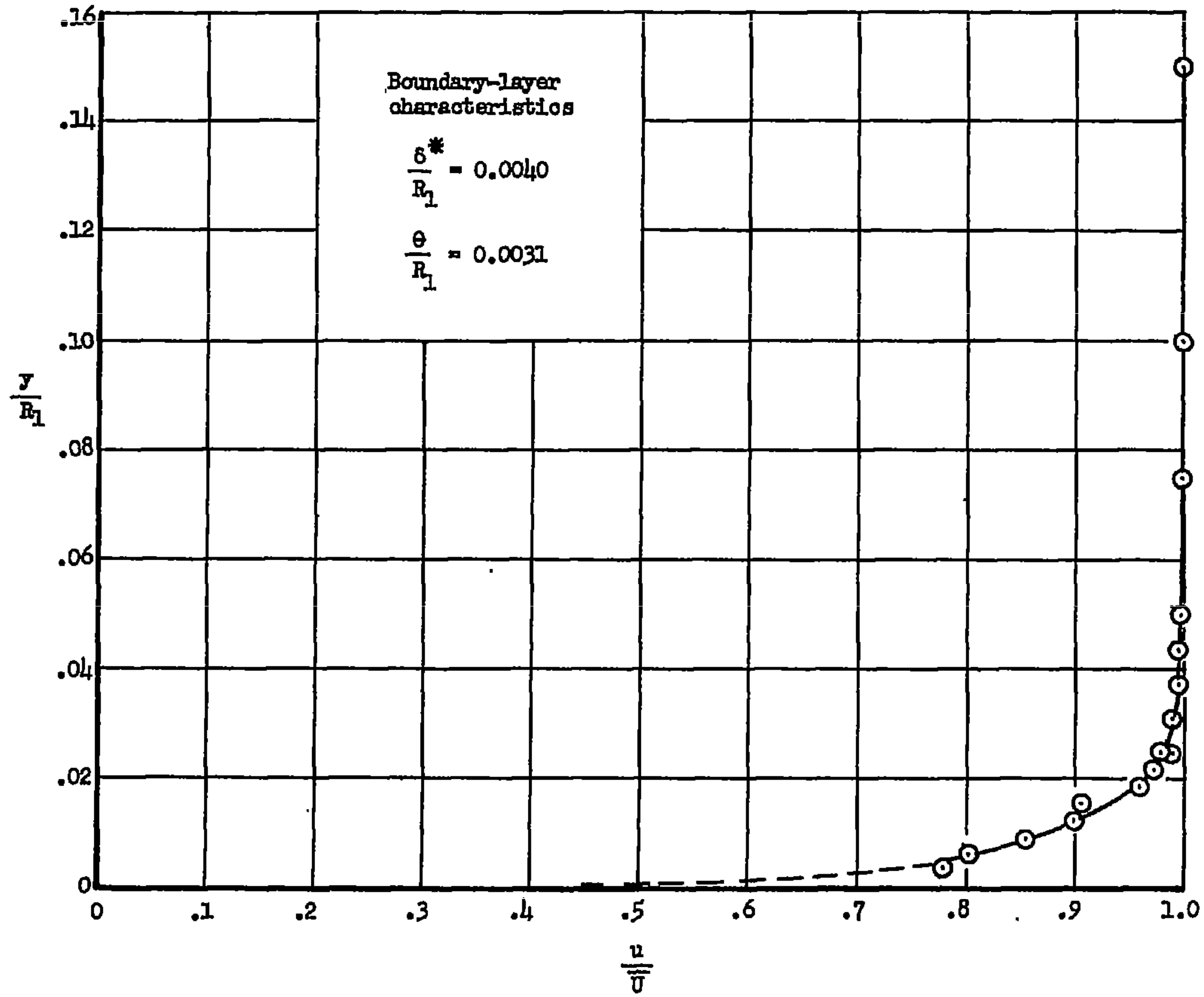
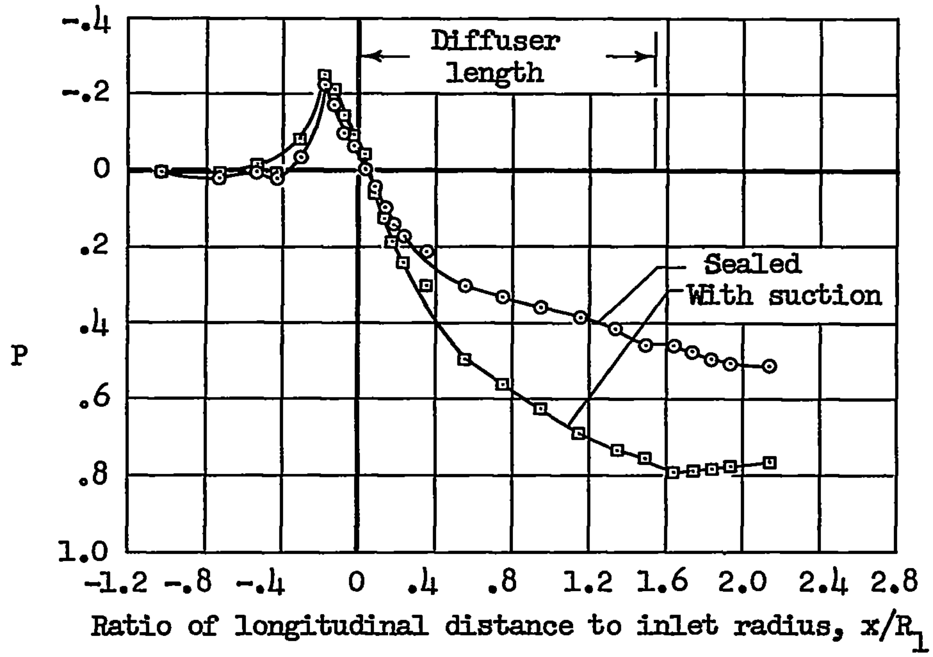
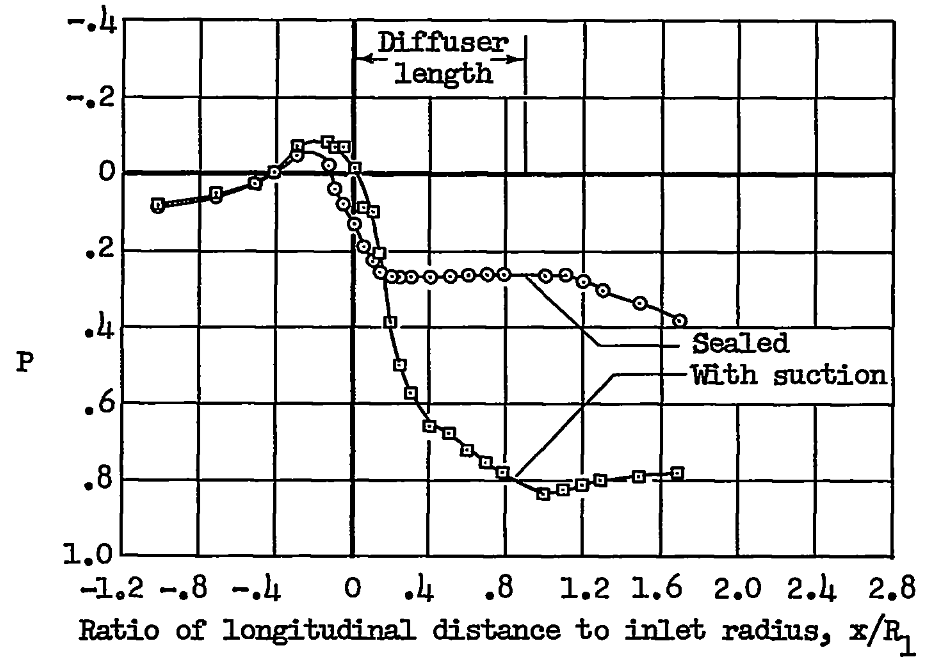


Figure 5.- Inlet boundary-layer profile for 10° diffuser; $\bar{M}_1 = 0.2$, $A_2/A_1 = 2$.



(a) $2\theta = 30^{\circ}$, sealed and with suction ($m_s/m_1 = 0.04$, $x/l = 0.16$).



(b) $2\theta = 50^{\circ}$, sealed and with suction ($m_s/m_1 = 0.06$, $x/l = 0.15$).

Figure 6.- Effect of area suction on the longitudinal static-pressure coefficients along the wall of the diffuser; $\overline{M}_1 = 0.2$, $A_2/A_1 = 2$.

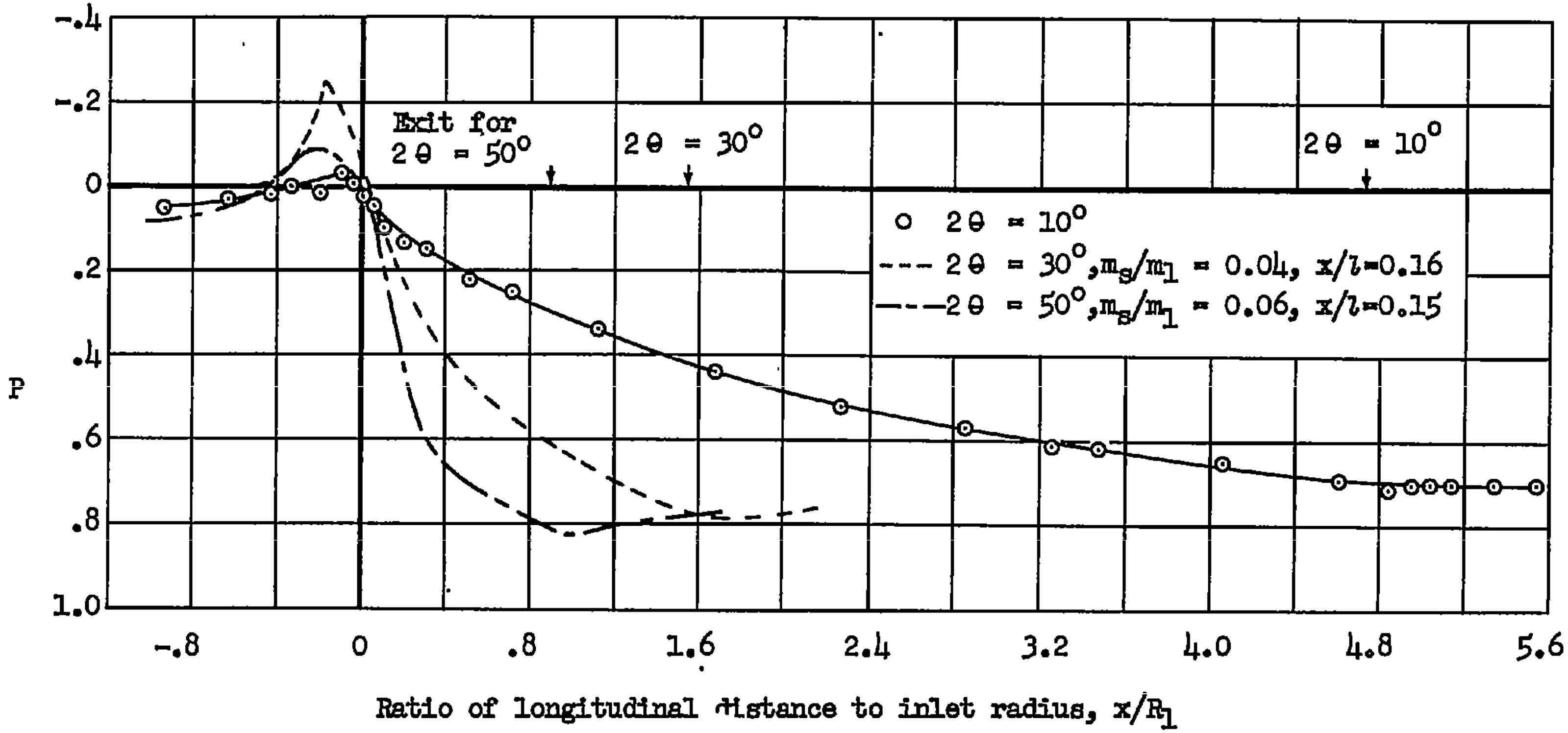
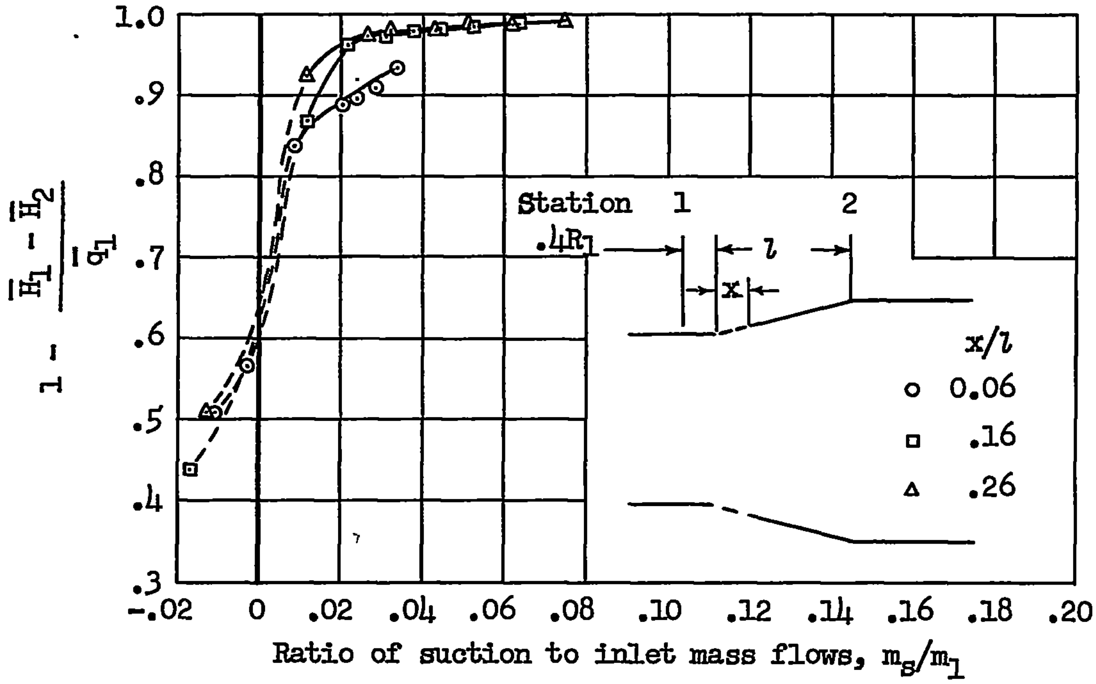
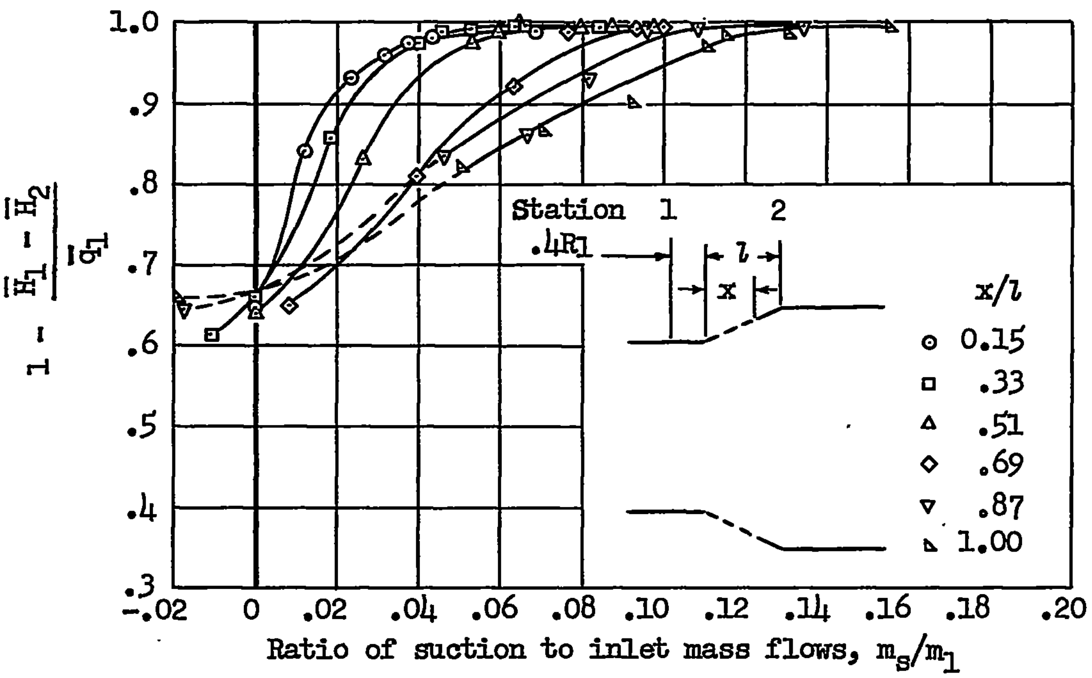


Figure 7.- Comparison of the longitudinal distributions of static-pressure coefficients along the 10° diffuser, 30° diffuser with suction, and the 50° diffuser with suction; $\overline{M}_1 = 0.2$, $A_2/A_1 = 2$.



(a) $2\theta = 30^\circ$



(b) $2\theta = 50^\circ$

Figure 8.- Variation of total-pressure recovery with suction mass flow for several extents of porous area; $\bar{M}_1 = 0.2$, $A_2/A_1 = 2$.