Tests of Wall Suction and Blowing in Highly Offset Diffusers

W. H. Ball*
Boeing Military Airplane Company, Seattle, Washington

Tests were conducted in the Boeing Diffuser Test Facility to investigate the effect of centerline offset, wall suction, and blowing on diffuser performance. Effects of offset were studied using a family of two-dimensional diffusers. Effectiveness of wall suction and blowing in controlling the diffuser boundary layer was investigated initially with the highest offset two-dimensional diffuser. This was followed by a more detailed investigation of wall suction and blowing using a three-dimensional offset diffuser model. Configuration variables included centerline offset, hole area for distributed suction, and blowing slot height. Diffuser exit total pressure profiles and longitudinal wall static pressure distributions were measured to determine diffuser overall performance and obtain an indication of local flow behavior. Test results indicate that good performance can be achieved for diffusers with large offset by using small amounts of wall suction or blowing upstream of the separation point.

Nomenclature

A_δ^* = cross-sectional area occupied by boundary-layer displacement thickness
A_T = diffuser entrance (throat) area
H = height of exit for two-dimensional models
M_l = diffuser entrance (throat) Mach number
P/P_{T_0} = local static pressure ratio
P_T/P_{T_0} = local total pressure ratio
P_{T_2}/P_{T_0} = total pressure recovery at the diffuser exit
W_B/W_P = slot blowing airflow ratio to diffuser entrance airflow
W_s/W_p = wall suction airflow ratio to diffuser entrance airflow
Δ = diffuser centerline offset
$\Delta P_T/q$ = subsonic diffuser total pressure loss coefficient, $(P_{T_l}-P_{T_2})/q$

Introduction

AIR induction system designs for advanced aircraft concepts with integrated propulsion systems often require the use of subsonic diffusers with considerable centerline offset. When centerline offset is used, bends are required to turn the flow. Introducing bends into the process greatly complicates the task of designing a subsonic diffuser that can provide a smoothly varying, low-loss diverging passageway of proper area ratio that will deliver an adequate amount of uniform high-pressure airflow to the engine. Bends create centrifugal pressure gradients in the flow, induce secondary flows along the diffuser walls, and increase the probability of local boundary-layer separation. These factors make it difficult to achieve efficient diffusion.

The research study reported herein quantitatively investigated the relationship between diffuser performance and amount of centerline offset and, for a highly offset diffuser, determined the potential benefits of local wall suction and blowing in improving the diffuser performance.

The experimental investigation was accomplished in two parts. Part one was a preliminary evaluation of the effects of basic diffuser offset and wall suction and blowing on boundary-layer control using a low-cost two-dimensional (2-D) "workhorse" diffuser test apparatus. Part two was a more detailed investigation of boundary-layer control concepts using a three-dimensional (3-D) offset diffuser model with wall suction and slot blowing.

Model Description

During the first part of the investigation, a "workhorse" diffuser test apparatus was used to conduct two-dimensional diffuser offset studies. A photograph of the test apparatus is shown in Fig. 1. The test rig utilizes contour blocks cut from high-density styrofoam to form the top and bottom walls of the diffuser. The parallel sidewalls of the diffusers are formed by 1-in.-thick plexiglass panels. These transparent panels provide an opportunity to observe and photograph the flow phenomena in the diffuser during test runs by using tufts attached to the diffuser surfaces.

Three different diffuser offsets were tested using the workhorse diffuser test rig. The geometries of these diffusers are shown in Fig. 2. After testing of the three basic diffusers was completed, diffuser 3 was modified to incorporate provisions for wall suction and blowing on the lower surface. The area suction configuration utilized 12 full-width rows of 1/16-in.-diam holes, with approximately 42 holes/row. The holes were located approximately 5.5 in. downstream from the diffuser entrance. The full-width tangential blowing slot with a fixed height of 0.067 in. was sized to provide a blowing mass flow equal to 5% of the diffuser entrance airflow at a blowing plenum supply pressure of 40 psia.

All diffuser tests were run with a bellmouth upstream of the diffuser entrance. This bellmouth was a 2:1 area ratio lemniscate followed by a 3.5-in. constant-area section. This provided a thin entrance boundary layer.

Static and total pressure measurements provided the pressure data from which 2-D diffuser performance was determined. Twenty static pressure orifices were located along the upper and lower diffuser surfaces and a 40 probe total pressure rake was used to measure diffuser exit flow properties.

The geometry of the basic three-dimensional diffuser model is shown in Fig. 3. This model has the same area ratio ($A_e/A_t = 1.84$), length (20.4 in.), offset ($\Delta/H = 1.87$), area distribution, and entrance shape as diffuser 3 of the previous two-dimensional diffuser test.

Figure 4 is a photograph of the 3-D diffuser model installed in the Boeing Diffuser Test Facility. The forward lower portion of the model was designed with a removable plenum chamber insert that allows the quick change of suction and blowing insert plates. The suction and blowing plates used in the 3-D model are illustrated in Fig. 5. The suction configuration has an identical hole pattern to that used in the 2-D diffuser test. The full-width tangential blowing slot con-

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*Principal Engineer.

figuration for the 3-D model had an adjustable slot height that permits the gap height to be varied from 0.01 to 0.04 in. This adjustable gap height, plus the ability to vary blowing plenum chamber pressure, allows a wide range of blowing mass flows to be tested.

A round, four-arm, seven-probe/arm rotating rake assembly was used to measure the diffuser exit steady-state flow properties for the 3-D diffuser. Three rotating rake positions were used to provide 84 individual total pressure readings. A total of 29 static pressure measurements were taken along the internal diffuser surfaces.

The diffuser cross-sectional area distribution used for all of the 2-D and 3-D models is presented in Fig. 6. This area distribution was obtained using a computer program developed to aid in the design of subsonic diffusers of complex shapes.[1] The diffuser shapes selected for the study were obtained by an option to this method which defines a diffuser geometry that allows the flow to diffuse rapidly in regions of low wall curvature and less rapidly in regions of high wall curvature. Figure 6 also shows some of the more commonly used diffuser area distributions for comparison with the selected model area distribution.

Test Conditions and Procedure

The two-dimensional diffuser models were tested to evaluate the basic effects of offset and, for the highest offset diffuser, to obtain a preliminary evaluation of the general effects of wall suction and blowing. Diffuser primary airflow was controlled by a variable airflow control plug, and primary airflow was measured by an ASME flow-metering nozzle. The plexiglass sidewalls provided the opportunity to observe and photograph tuft patterns in the diffuser during testing. The test Reynolds number for the 2-D diffuser tests was approximately 5.5×10^6/ft.

The three-dimensional diffuser model provided a more precise evaluation of the effects of wall suction and blowing. It was equipped with more variations in suction and blowing configuration plates and designed to operate at higher primary plenum chamber and slot blowing chamber pressure. The basic operating procedure for the 3-D diffuser testing was the same as for the 2-D models. Upstream plenum pressure was set at the desired value, with the primary airflow plug partially open. The airflow control plug was then adjusted until throat static pressure measurements indicated a throat Mach number of 0.70 was obtained. The blowing or suction plenum pressure control valve was then adjusted to provide the desired blowing or suction plenum pressure. This valve position was then fixed while a series of data points were recorded at various primary airflow control plug positions. The test Reynolds number for the 3-D model test was approximately 6.9×10^6/ft.

Test Results

Two-Dimensional Diffuser Test

The results from testing the diffusers with various amounts of centerline offset are summarized in Fig. 7. Total pressure

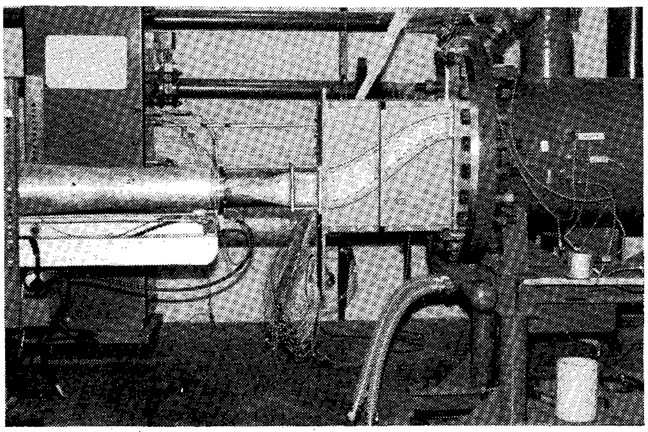

Fig. 1 Workhorse diffuser test apparatus.

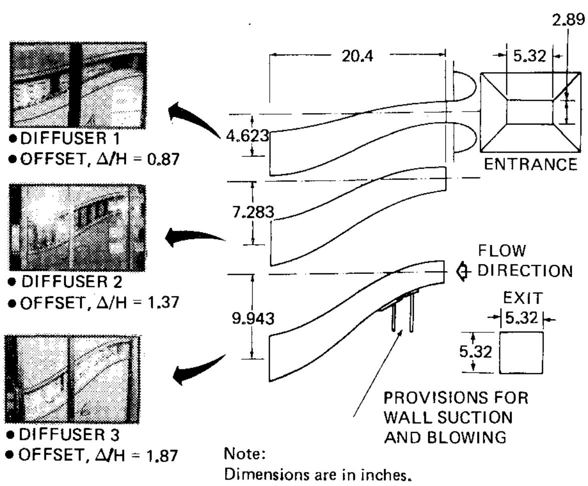

Fig. 2 Two-dimensional diffuser models.

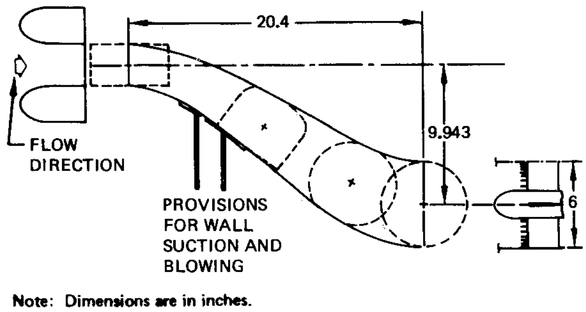

Fig. 3 Three-dimensional diffuser model.

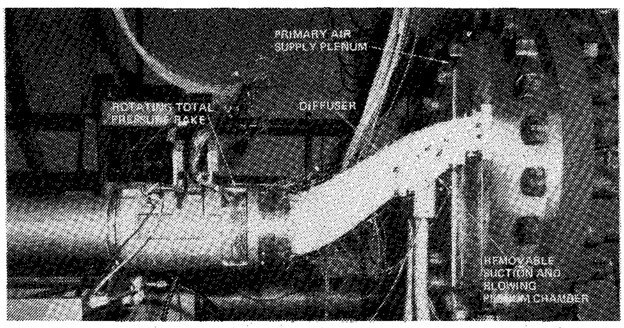

Fig. 4 Three-dimensional model installed in diffuser test facility.

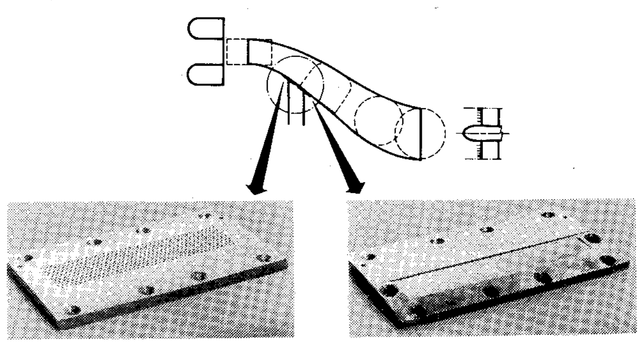

Fig. 5 Interchangeable suction and blowing inserts for three-dimensional diffuser model.

recovery, distortion, and duct loss coefficient are presented as a function of average throat (entrance) Mach number. The data show that increasing diffuser offset results in lower total pressure recovery, higher distortion, and a higher diffuser loss coefficient. Although the trends are consistent, the differences in performance between the three configurations are not large—0.3% in total pressure recovery (for example, at $M_l = 0.70$). It is likely that greater differences in performance between the three configurations would be observed if entrance conditions included the effects of a terminal normal shock, such as would be present in a supersonic inlet.

For the highest offset diffuser, the effectiveness of inner wall bleed and blowing are indicated by typical results (shown in Fig. 8) which show the effect of bleed and blowing on diffuser total pressure recovery and distortion. As shown by the data, either wall suction or blowing is very effective in improving the flow behavior through the diffuser. The results shown in Fig. 8 are for a suction mass flow ratio, $W_S/W_P = 0.04$, and a blowing mass flow ratio, $W_B/W_P = 0.05$.

The improvement in internal flow due to wall suction and blowing was also evident by the improved total pressure profiles measured at the centerline of the diffuser exit.

In addition to the measured pressure data which were obtained to calculate diffuser performance, tuft patterns were used to study the flow behavior through the diffusers. Examples of tuft patterns obtained in the diffuser are presented in Fig. 9. Blurred tufts indicate regions of unstable flow. Flow is generally stable in the forward half of the diffusers. For diffusers without suction or blowing, increasing turbulence is observed on the lower surface as distance increases aft along the diffuser, possibly indicating that a region of separated flow is present. Local wall upflow can also be observed by the upward-oriented angles of the tufts on the sidewall near the aft end of the diffusers.

The location of onset of lower surface instability observed by the tuft patterns in the diffuser with the greatest offset (diffuser 3; $\Delta/H = 1.87$) without boundary-layer control (BLC) correlates well with the measured static pressure distribution.

The measured diffuser exit total pressure contours for diffuser 3 without lower wall suction or blowing showed that a large low-pressure region is present at the lower portion of the diffuser. With either suction or blowing, however, the total pressure at the aft lower portion of the diffuser was significantly increased. An additional effect that was apparent was a shifting of some of the lower pressure air up around the sidewalls of the diffuser. The result of these changes was a moderate (< 1%) improvement in total pressure recovery and a significant reduction in distortion.

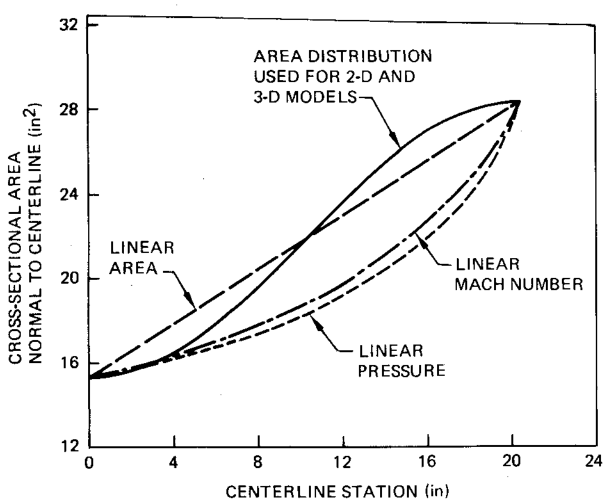

Fig. 6 Diffuser area distribution.

Three-Dimensional Diffuser Test

The initial test run of the 3-D diffuser was conducted without suction or blowing. This provided data for comparison with results from the 2-D model with similar offset, area ratio, and area distribution to validate the 2-D diffuser test concept. It also provided a set of baseline data for the remainder of the bleed and blowing tests.

Figure 10 compares the measured diffuser wall static pressure distributions from the 2-D and 3-D models without wall suction or blowing. It is evident from the nearly identical static pressures at the same measured airflow that total pressure recovery for the two diffusers is nearly identical. A comparison of the corresponding measured total pressure contours at the diffuser exits (Fig. 11) shows that the total pressure patterns are similar. It should be noted that in the case of the 2-D model, the total pressure rakes at the exit plane did not measure any total pressures within 0.53 in. of the sidewalls or 0.33 in. of the upper and lower surfaces. For the three-dimensional model, however, a four-arm, seven-

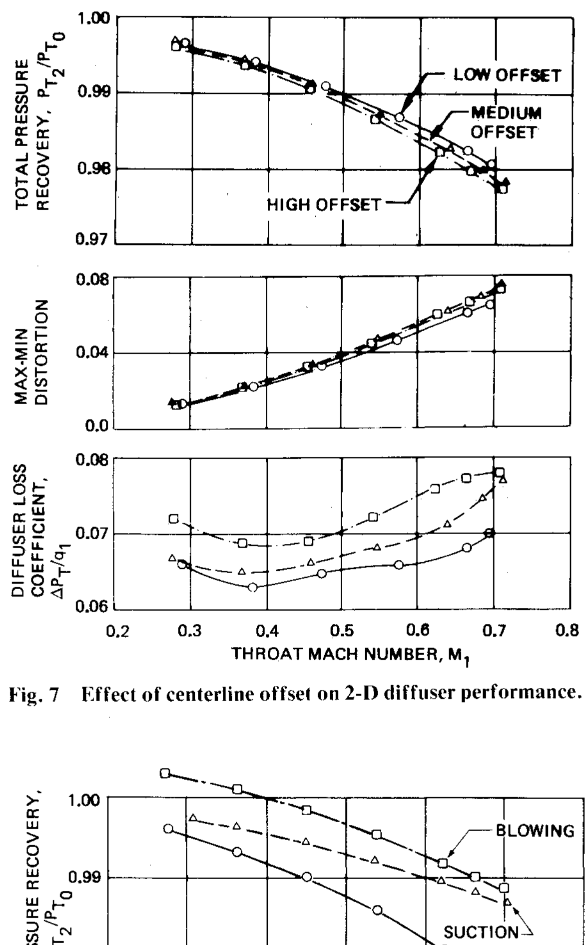

Fig. 7 Effect of centerline offset on 2-D diffuser performance.

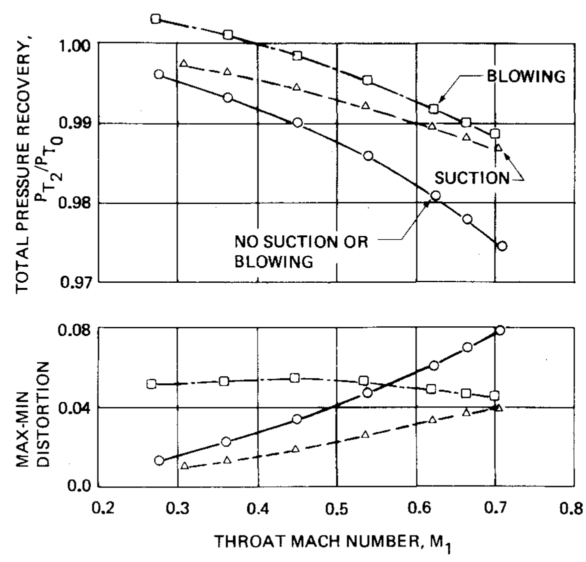

Fig. 8 Effects of suction and blowing on diffuser 3 performance.

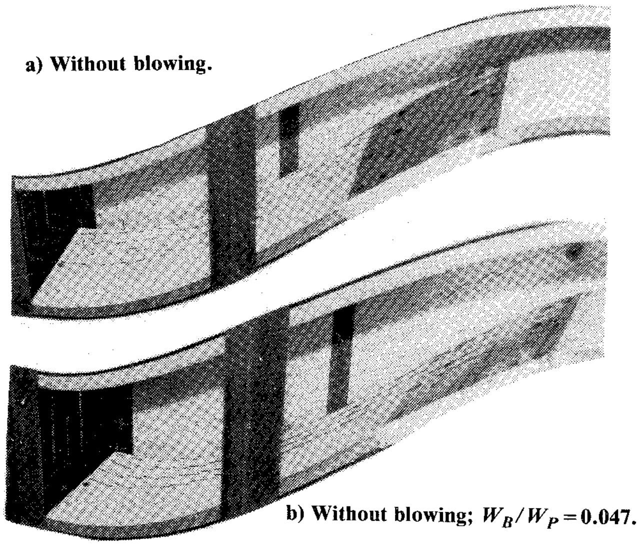

Fig. 9 Effect of wall blowing on tuft patterns, $M_I = 0.70$.

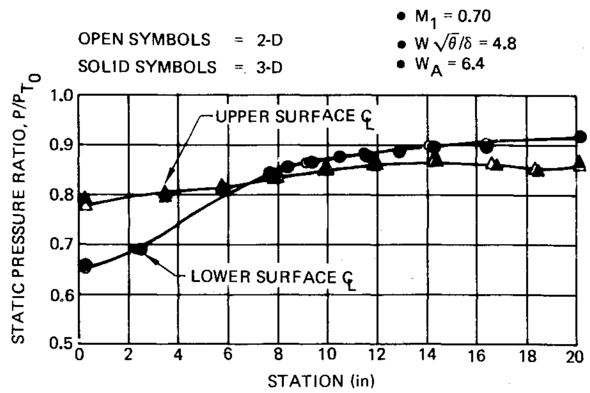

Fig. 10 Comparison of measured 2-D and 3-D static pressures.

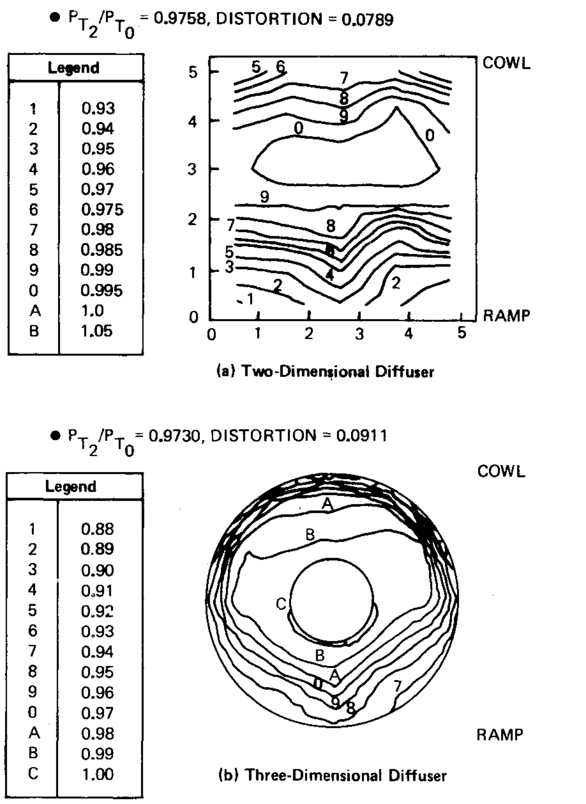

Fig. 11 Comparison of total pressure contours at exits of 2-D and 3-D diffusers; $M_I = 0.70$, no BLC.

probe/arm rotating rake was used at the diffuser exit. This rake extended to within 0.10 in. of the wall. Also, three rotating rake angular positions were used to provide a precise measurement of the exit properties. Because probes were located closer to the wall, the rotating rake measured more of the low total pressures within the boundary-layer region than the rake used on the 2-D models. While this results in a more precise definition of the exit flow properties, it also results in a lower indicated average total pressure recovery and a higher max-minus-min distortion $[P_{T_{max}} - P_{T_{min}}/P_{T_{avg}}]$ for the 3-D diffuser, compared to the 2-D diffuser. This can be observed in the performance data presented in Fig. 12.

Figure 13 presents measured performance data for the 3-D diffuser with and without wall suction and blowing. Data shown are for a suction and blowing mass flow ratio, $W_S/W_P = W_B/W_P = 0.022$; blowing slot height is 0.02 in. The 3-D data show a result similar to the results obtained using the 2-D workhorse diffuser model: either wall suction or blowing provide significantly improved total pressure recovery and reduced diffuser loss coefficient. Distortion is relatively insensitive to the effects of suction and blowing.

Figure 14 presents data showing the effect of varying wall suction mass flow on diffuser performance for an entrance Mach number of 0.70. From these data it can be seen that most of the benefits in terms of improved total pressure recovery and reduced distortion are obtained at a suction mass flow ratio of 0.02.

The effect of variations in blowing slot mass flow ratio on diffuser performance for several gap heights is shown by the plotted data in Fig. 15. The data shown are for a diffuser entrance Mach number of 0.70. The data show that a 0.02-in. gap height is more effective in improving total pressure recovery (for the same blowing mass flow) than the 0.04-in. gap height. The range of blowing mass flows tested with the 0.01-in. gap height was not effective in improving recovery and distortion. Similar to the results from the wall suction test, most of the benefits from slot blowing are obtained at blowing mass flow ratios of 0.02. Distortion appears to be relatively insensitive to the effects of blowing mass flow ratio for each slot opening except for the highest mass flows, where the high-pressure air being injected tends to severely distort the total pressure profile. This distortion is shown by the plotted diffuser exit centerline profiles in Fig. 16, measured with various amounts of slot blowing mass flow. A blowing mass flow ratio of 0.016 is adequate to provide full boundary-layer profiles on the lower surface. Use of $W_B/W_p = 0.022$ results in over-pressurizing the lower portion of the boundary-layer profile, creating increased distortion and recovery.

The corresponding exit profiles for the case of wall suction (Fig. 17) show a trend toward increasingly full total pressure profiles as suction mass flow ratio is increased. The profiles show that nearly all the benefit is obtained at a suction mass flow ratio of 0.023. Further increasing the suction mass flow ratio to 0.047 brought only a negligible additional improvement. Typical diffuser exit total pressure contours for the 3-D diffuser with and without suction and blowing are compared in Fig. 18 for an entrance Mach number of 0.70. These contours show the improved region of flow at the bottom of the diffuser that results from the effects of wall suction and blowing.

A theoretical analysis was performed to calculate the boundary-layer development on the lower surface of the model. This was done to aid in the design and location of the wall suction and slot blowing configurations. This analysis was performed using the local wall pressure distribution obtained by a three-dimensional potential flow program[2] as input to a two-dimensional boundary-layer program.[3] This program provides a finite difference solution of the boun-

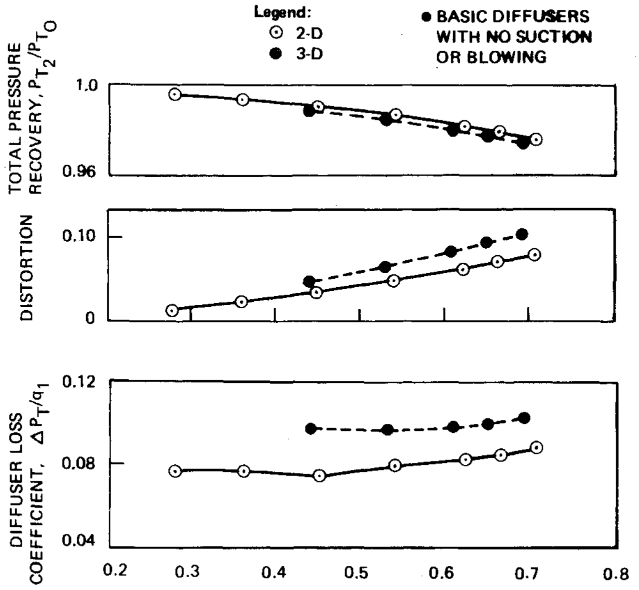

Fig. 12 Comparison of measured performance data for 2-D and 3-D diffusers.

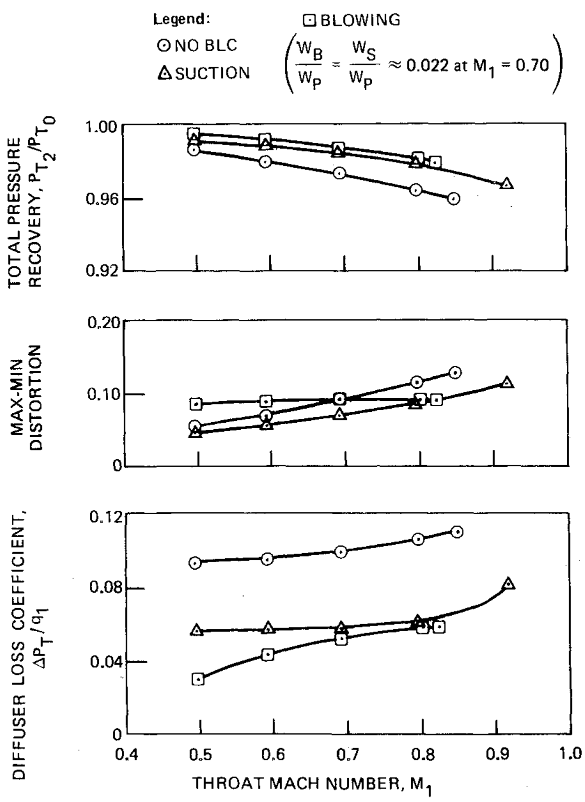

Fig. 13 Effect of throat Mach number on 3-D diffuser performance.

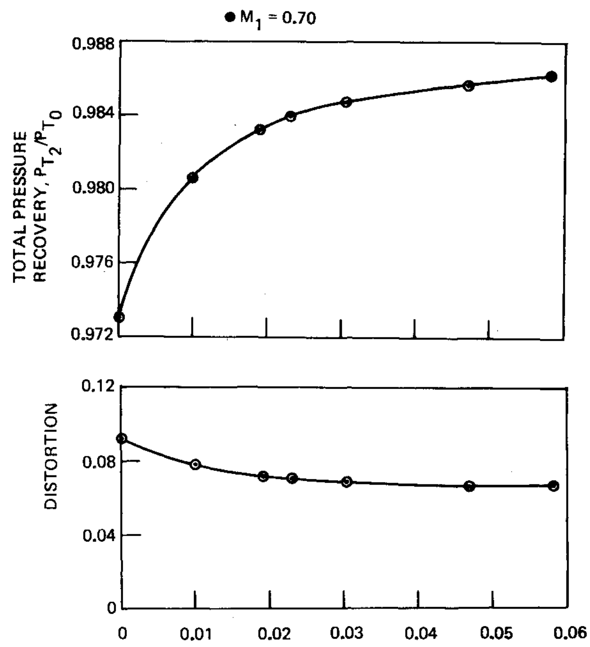

Fig. 14 Effect of suction on 3-D diffuser performance.

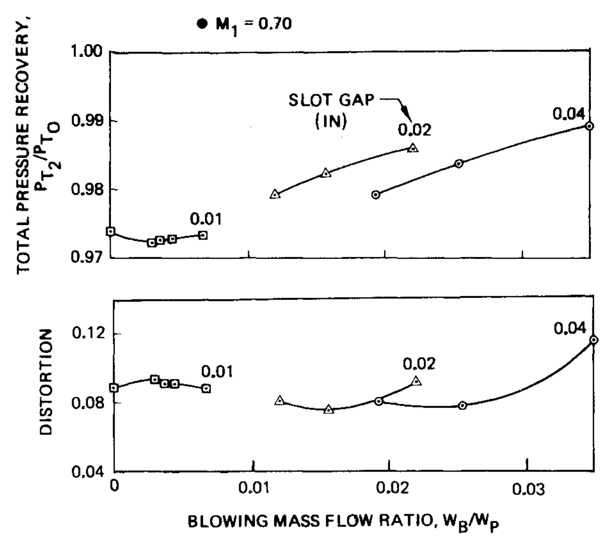

Fig. 15 Effect of slot blowing on 3-D diffuser performance.

dary-layer equations. It computes laminar and turbulent boundary-layer development on two-dimensional or axisymmetric surfaces with or without heat transfer. It will also compute regions of bleed.

The results of the boundary-layer analysis are presented in Fig. 19, which shows predicted skin-friction coefficient and boundary-layer thickness as a function of model station. Results are shown for several different wall suction mass flow ratios, and for the basic diffuser without wall suction.

The theoretical skin-friction coefficient for the basic diffuser without wall suction approaches zero near model station 7.0, indicating possible separation. The predicted separation point moves farther downstream with increasing amounts of wall suction mass flow until, at a wall suction mass flow ratio of 0.022, the boundary layer remains attached to the end of the diffuser. The measured diffuser static pressures (in Fig. 20) correlate well with the predicted boundary-layer behavior. Without wall suction, the measured static pressures start to deviate noticeably from the theoretical inviscid static pressure distribution near model station 7.0, the theoretically predicted separation point. As wall suction mass flow is progressively increased, the measured pressures increase, approaching the inviscid pressures over an increasingly greater portion of the diffuser length. Although the measured static pressures are somewhat lower than the predicted inviscid pressures, good general agreement with the shape and level of the inviscid pressures was obtained at suction mass flow ratios above 0.02. This suggests that boundary-layer separation has been eliminated. The remaining pressure difference is attributed to the blockage effects of the remaining attached boundary layer on the diffuser walls.

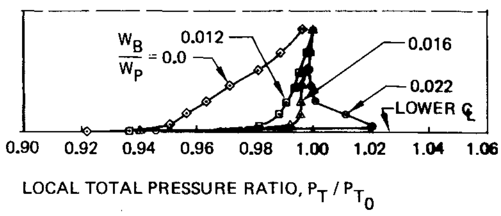

Fig. 16 Effect of slot blowing on exit total pressure profiles for 3-D diffuser at $M_I = 0.70$.

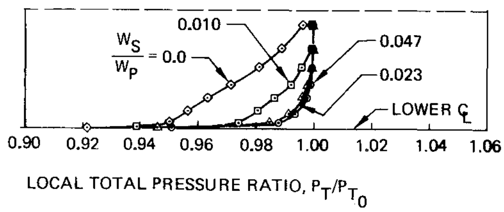

Fig. 17 Effect of area suction on exit total pressure profiles for 3-D diffuser at $M_I = 0.70$.

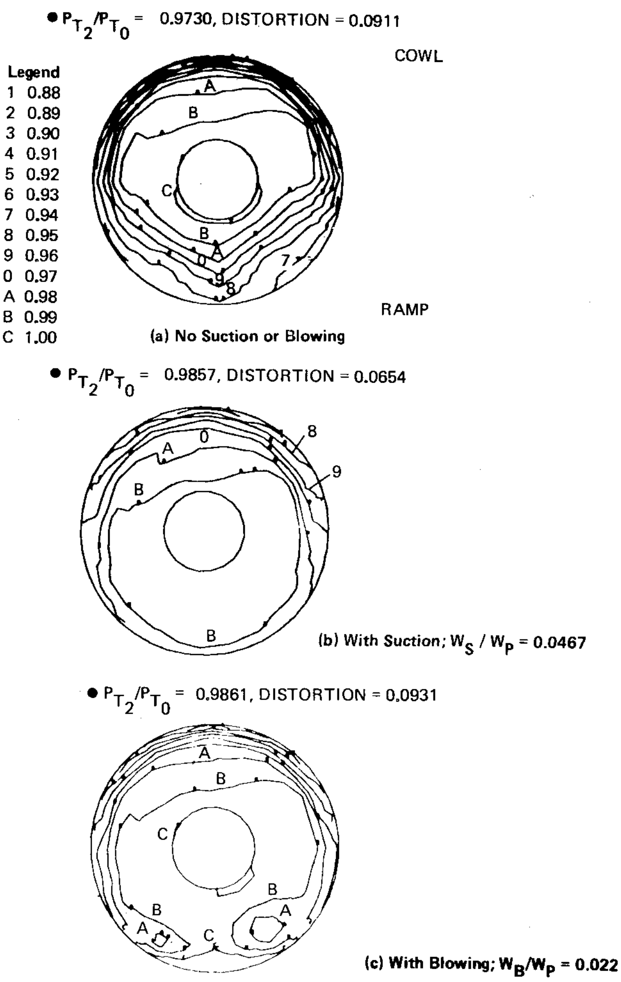

Fig. 18 Diffuser exit contours for 3-D diffuser; $M_I = 0.70$.

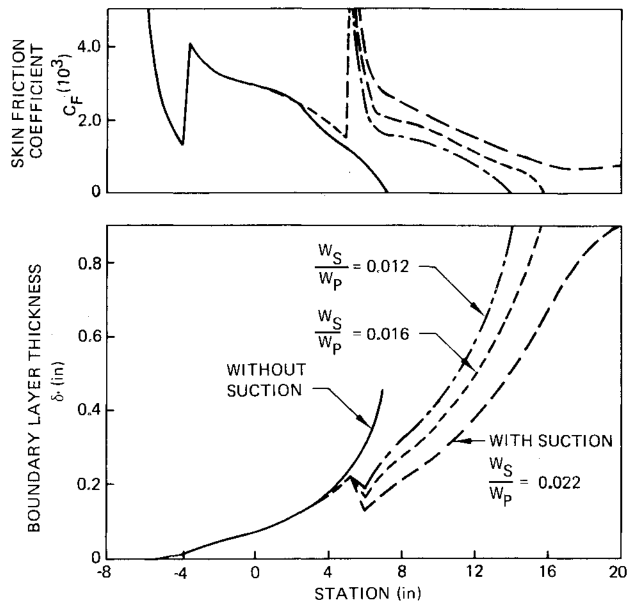

Fig. 19 Calculated boundary-layer growth on diffuser lower surface.

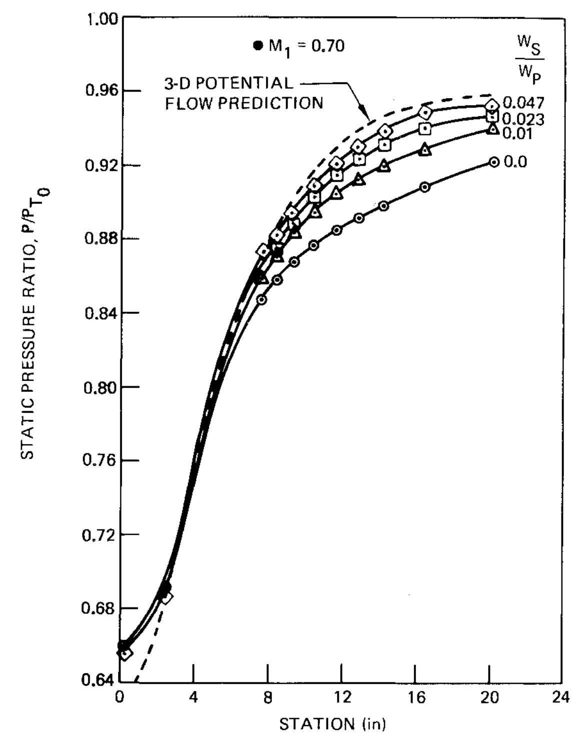

Fig. 20 Effect of suction on 3-D diffuser lower surface static pressure distribution.

The measured lower surface longitudinal static pressures obtained with and without various amounts of slot blowing are compared with theoretical inviscid static pressures in Fig. 21. Blowing has little effect on the static pressures forward of station 8.5, a distance 3 in. downstream from the slot location; measured pressures are only slightly higher than those measured without blowing. Aft of station 8.5, however, the wall static pressures increase rapidly along the diffuser at a rate of increase that is related to the amount of blowing mass flow. Larger blowing mass flow ratios produce greater increases in wall static pressures. At a blowing mass flow equal to 2.2% of primary throat flow, the wall static pressures agree within 1% of the inviscid pressure over most of the diffuser length aft of station 12.0. Another phenomenon that is evident is the tendency for the pressure distributions with blowing to flatten out or even decrease slightly near the aft end of the diffuser as blowing mass flow ratio is increased. This phenomena was not observed when wall suction was utilized. The pressure distribution phenomena measured when blowing is utilized are related to the internal flow interactions created by the combined effects of mixing between high- and low-velocity streams, diffusion, turning, and secondary

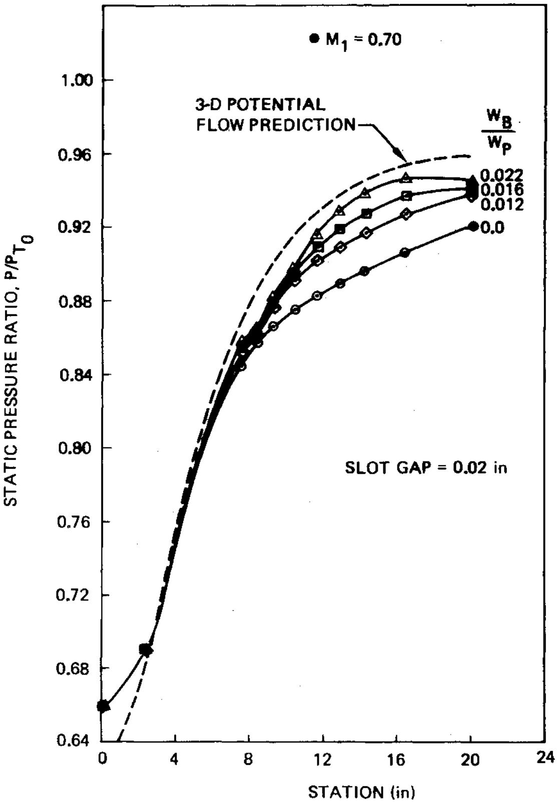

Fig. 21 Effect of slot blowing on 3-D diffuser lower surface static pressure distribution.

flows. The complex flowfield that is obtained at the diffuser exit when blowing is used is illustrated in Fig. 18c. Additional wall static pressure measurements and traversing total pressure rake surveys at several longitudinal diffuser stations would be useful in gaining a more complete understanding of offset diffuser flows with wall blowing.

Conclusions

It has been demonstrated experimentally that a novel "workhorse" diffuser test apparatus can be utilized to economically and quickly test a family of two-dimensional diffusers. The data obtained using this apparatus provided good general agreement with data from a three-dimensional model with the same offset and area ratio.

The effects of diffuser centerline offset on measured two-dimensional diffuser performance were found to be small for a range of centerline offsets (Δ/H) between 0.87 and 1.87, when uniform subsonic entrance conditions are provided with a thin boundary layer.

Effective boundary-layer control was achieved in a highly offset diffuser with wall suction or slot blowing mass flow of approximately 2% of primary entrance flow. It is reasonable to believe that further significant reductions in the amount of mass flow required for boundary-layer control by blowing can be achieved by refinements of the blowing configuration concepts.

Experimental results showed that more effective boundary-layer control was achieved by using a blowing slot height of 0.02 in., compared to either larger (0.04) or smaller (0.01) height blowing slots.

Experimentally measured diffuser longitudinal static pressure distributions both with and without wall suction correlate well with the flow behavior inferred from theoretical boundary-layer calculations and tuft photographs.

References

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[2]Forester, C. K., "Body-Fitted 3-D Full-Potential Flow Analysis of Complex Ducts and Inlets," AIAA Paper 81-0002, St. Louis, Mo., Jan. 1981.

[3]Reyhner, T. A. and Hickcox, T. E., "Combined Viscous-Inviscid Analysis of Supersonic Inlet Flowfields," *Journal of Aircraft*, Vol. 9, Aug. 1972, pp. 589-595.