about 2, while the conical diffuser discharge varies from one with intermittent separated regions at \(N/D_i = 5\) to one containing a fixed separated zone at \(N/D_i = 2\) \[7\].

## Conclusions

Suction pressures for suction rates greater than critical and critical suction rates have been determined for a wide range in suction gap geometry, and these variables have been found common to diameter expansion ratios greater than 1.3 and inlet lengths to the step greater than 5 to 6 pipe diameters. These results pertain to Reynolds numbers large enough to produce a turbulent boundary layer ahead of the step expansion. Together with information previously obtained for a thin inlet boundary layer \[1\], the new results allow estimates of suction requirements for most inlet flows likely to be encountered in practice. Critical suction rates were not grossly different from values obtained for the thin inlet boundary layer, while suction pressure-differentials were considerably lower than values for the thin inlet boundary layer.

The present device appears to be a competitive alternative to a conical diffuser whenever certain upper limits on axial length are imposed; i.e., it is primarily useful as a short diffuser. In particular, for an area expansion ratio of 3.72 and a Reynolds number near 10\(^6\), the suction diffuser gives higher effective pressure recoveries than conical diffusers whenever length ratios \(N/D_i\) are less than about 8, a clear advantage being evident for length ratios equal to 5 or less. These conclusions are based on recovery from inlet to a plenum receiving the flow at diffuser exit and pertain to either of two inlet flows, the fully developed turbulent flow considered in this investigation, or the flow with thin boundary layer investigated in a previous paper \[1\].

## APPENDIX

### Effects of Truncating Expanded Pipe for Basic Step-Flow

Experiments described briefly in this section were prompted by an afterthought to interpret some of the pressure distributions obtained. The apparatus used for the investigation had been dismantled and partly disposed of so that an ad hoc system had to be assembled. Basically, the experimental objective was to determine effects of the length of expanded pipe on the pressure distribution downstream of the step, including final pressure recovery. While such effects were primarily sought for cases with suction at the step, facilities were not available to accomplish this at the time, and the undoubtedly related basic step-flow was investigated instead.

An outline of the primary (axisymmetric) flow boundaries employed is included in Fig. 15. Air enters a nozzle with elliptic profile from a large plenum fed by a fan, traverses a short distance of straight pipe, then enters an expanded pipe section (tailpipe) which is terminated a distance \(N\) downstream of the step where the air is discharged to the laboratory.

The first measurements were made with a tailpipe of length \(N = 3.98D_i\). This pipe had wall pressure taps at regular axial intervals. Axial distribution of static pressure and the laboratory pressure were measured relative to inlet static pressure, then converted to distribution of \(C_p\) and to \(C_{pr}\), respectively, where \(C_{pr}\) now represents pressure recovery from inlet to the plenum (laboratory) receiving the flow. Next, a downstream section of the tailpipe was sawed off and measurements repeated. This process was repeated several times, the last measurement being made for zero tailpipe length.

Fig. 15 presents the results. Variations of \(C_p\) with distance downstream of step, \(x/D_i\), for several relative lengths, \(N/D_i\), are represented by open symbols, while variations of \(C_{pr}\) with \(N/D_i\) are represented by solid symbols.

First consider \(C_p\) distributions. In general, the pressure at the wall of the tailpipe is fairly insensitive to tailpipe length, except for regions close to the exit for tailpipes shorter than about \(2D_i\), where pressures are slightly increased relative to values for long tailpipes. The reattachment point for a long tailpipe is estimated \(6\) to be near \(x/D_i = 2\), and therefore the increase in pressure near exit (relative to the pressure at the same downstream location for long tailpipes) is probably associated with separated flow.

Next consider variations of pressure recovery with tailpipe length. For lengths \(N/D_i\) presumed to extend beyond the reattachment point, \(N/D_i > 2\), the pressure recovery at given \(N/D_i\) practically coincides with the value of \(C_p\) at \(x/D_i = N/D_i\) for long tailpipes. This behavior is consistent with the insensitivity of \(C_p\) to tailpipe length noted above and with the expectation that exit pressure equals laboratory pressure for the attached exit flows assumed to prevail for these tailpipe lengths. However, for \(N/D_i < 2\), cases where the exit flow is assumed to separate from the pipe wall (actually verified by tuft explorations), the pressure recovery at given \(N/D_i\) is greater than the value of \(C_p\) at \(x/D_i = N/D_i\) for long tailpipes. This is a result in accord with the increase in \(C_p\) toward tailpipe exit (relative to the value for long tailpipes at the same \(x/D_i\) noted in the preceding paragraph for these cases.

## References


## DISCUSSION

James M. Robertson

This paper presents a welcome extension of the author's earlier study of the edge-suction effect for a relatively thin approach boundary layer. The relation between the two studies is well characterized by the relative momentum thickness \(\theta/D_i\) of the approach conduit flow. As noted in the paper, the thin layer corresponds to \(\theta/D_i = 0.005\), while the fully developed flow in the present paper was \(\theta/D_i = 0.05\). The third, less extensively studied case, produced by the pipe \(L/D_i = 5.5\) length corresponds to a \(\theta/D_i\) of about 0.015 (calculated from author's statement that boundary layer thickness was about 30 percent of radius, then \(\theta/D_i = 0.30/2 \times 10\)). This value is just three times the small and about one-third the larger thickness. As apparent from the upper plots of Figs. 3 and 4 (as well as, in part, Fig. 5) the results are essentially the same for the two thicker layers with the pressure recovery appreciably less than found with the thin layer, at least for \(L/D_i\) values less than about 0.04. The effect of approach layer thickness on the edge-suction effect seems

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\[6\] Based on generalized treatment of reattaching flows by Roskko and Lau \[8\].

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less than one might have expected, thus suggesting that the basic flow occurrence is not simply one of boundary-layer removal.

Despite the author’s extensive study of many factors affecting this edge-suction effect in axisymmetric flow expansions, it seems desirable to search for good understanding (if not theory) of the flow behavior so that one might be able to predict the pressure regain in as yet untested configurations. For some reason the additional experimental results do not seem to clarify the basic flow mechanisms. As this writer sees it, the edge-suction effect must result from either of two occurrences in the flow or (more likely) a combination thereof. These are: boundary-layer suction, the removal of low-velocity fluid near the wall which is incapable of surmounting the downstream pressure rise, or production of a strong pressure gradient across the flow near the corner thus turning the flow into or toward the corner and spreading the flow out into the larger conduit. The study reported by Tillman and Sisto involved analysis—via ideal-fluid theory—of the jet deflection and yielded rather-good agreement with experiment, although there seems to have been some arbitrariness in fixing of some of the constants of the analytical transformations. In view of the agreement found between prediction and measurement of jet deflection, they concluded that boundary-layer removal was only of secondary effect. From this evidence and that presented earlier by the author it would seem that the strong transverse pressure gradient produced near the convex corner is the cause of the improvement in pressure recovery. But how is this pressure gradient related to the suction pressure and flow? The writer has looked into the boundary-layer suction concept a bit further and, as will be noted, finds that it also indicates the general nature of the occurrences. One is thus forced to conclude that some joint interaction of the two occurrences is involved and must be considered in any proper analysis.

On the boundary-layer suction basis, one assumes that enough of the near-wall, low-speed, flow is sucked off so that the approach velocity of the streamline separating the main flow from that sucked off has enough energy to expand into the downstream pressure. Thus, if we denote by \( u_i \) the velocity found in the approach flow at radial distance \( r_i \) of the streamline dividing \( Q_o \), then one expects that

\[
C_p = 1 - \left( \frac{u_i}{u_o} \right)^3
\]

The resulting prediction has been evaluated for the author’s study of the fully developed pipe flow (thickest boundary layer) using an empirical velocity profile relation—logarithmic wall-law relation—near the wall and a centerline velocity of 1.2 \( u_i \). For various values of \( Q_o \), the location of the wall distance defining \( u_i \) was found via integration of the velocity profile. Typical \( C_p \) values thus found via the above equation are listed in the accompanying table. The author’s measured results—from Table 1 and Fig. 9 for optimum conditions in terms of gap size—are also tabulated for comparison. Moderately good agreement appears, especially for the higher suction flows. At low suction flows the predicted pressure regain falls below that of the sudden expansion without suction (\( C_p = 0.40 \)) when \( Q_o/Q_m < 0.006 \). This result is due to the effects of turbulence mixing in the receding flow downstream of the sudden enlargement. That mixing is presumably smaller for the higher suction, as is suggested by the pressure distributions presented in Figs. 11 and 12 of the paper. The above rough analysis would suggest that the boundary-layer suction concept does have some relevance to the edge-suction effect.

Study of the author’s results, especially those presented in Fig. 5 for the critical suction rates, suggests that the least suction

would be needed for \( \alpha = 0 \), i.e., for the suction slot along the side of the approach pipe just ahead of the corner. Thus, for a rather-thin slot of \( a/D_i \) about 0.02, extrapolation of the results to zero angle suggests \( C_p \) values of 0.11 and 0.16 and thus \( Q_o/Q_m \) values of 0.0088 and 0.0128 for the thick and thin approach layers. Similar extrapolation of the \( C_p \) data of Table 2 for the thick layer suggests an effective pressure recovery of 0.54, only some 0.05 below the maximum found for finite angles at the same suction ratio. Of course the gain above the zero suction \( C_p \) value of about 0.40 is relatively smaller at zero slot angle.

It would seem to this writer that what we need to acquire for an adequate understanding of the edge-suction effect is a more detailed picture of the flow field especially near and downstream of the suction slot clear into the separation in the concave corner of the expansion. Information—and its correlation with the suction flow and slot geometry—on the wall pressure variation on the back face of the expansion would be most suggestive and useful. If available it would permit one to simply predict the pressure regain via a momentum-integral control-volume analysis. Does the author have any indication on how the pressure varies on this back face, between the \( C_p = 0 \) value just ahead of the slot to the appreciable corner values indicated by Figs. 11 and 12? In the corresponding analysis for the flow without suction (Borda loss prediction) it is assumed, with some justification, that this face pressure is constant.

### Authors’ Closure

The author is grateful to Professor Robertson for his continued interest in, and contributions toward, an understanding of the edge suction concept. His discussion is directed toward a qualitative prediction of the flow behavior. In the past the author has made a number of similar attempts, but, unfortunately, to little avail.

The model suggested in the discussion evidently involves the view that the separation pressure on the face of the step corresponds to the stagnation pressure in the undisturbed upstream flow at the radius of the streamline dividing the suction flow from the interior flow. Thus the predicted separation pressure, which the discussers for simplicity considers roughly equivalent to the downstream pressure recovery, becomes purely a function of suction rate, as shown in Table 3. Table 1 and Fig. 9 indicate a rather significant dependence on gap size and inclination angle so this prediction method is at best very approximate.

At one time the author attempted to predict the base pressure of a long cylindrical body which was aligned with the approach flow, truncated at the full cross section in the rear, and equipped with a suction slot around the entire trailing perimeter. It was assumed that the base pressure would be equal to the separation pressure, which in turn was guessed similar (in normalized form) to that measured in the pipe. The predicted base pressure had a substantial positive value which would propel the body into the approach flow if the nose of the body were properly streamlined, a totally unacceptable prediction. The method suggested in the discussion would have given a similar result. In the present view of the author, the separation pressure is intimately tied to the entire flow field and depends on the geometry of the suction gap.

In response to Professor Robertson’s call for details on the flow...
near the suction gap, the author is happy to furnish some pressure distributions measured in the vicinity of a large suction gap provided on a downstream-facing plane step in a wind tunnel, Fig. 16. As indicated in the figure, the approach height to the step is 32 in. and the discharge height is 40 in., the step then being 8 in. high. The approach boundary layer was turbulent and 1 to 1/2 in. thick. Pressures were measured along the lower wall at mid-span of the step. As for the experiments reported in the paper, the suction slot was formed by two 30-deg included-angle wedges (Fig. 1); for the data in Fig. 16, the gap projection was 0.95 in. and the inclination angle was 45 deg. The critical suction rate coefficient for this gap was \( C_{qr} = 0.40 \).

The upper graph in Fig. 16 shows the static pressure coefficient as function of distance along the wall, s, upstream and downstream of the convex corner and for a suction rate well above critical. The pressure coefficient is positive at the first measurement point beyond the lip of the lower wedge (s = 1.01 in., lip at s = 0.95 in.), drops slightly, then climbs toward a value near 0.6.

Fig. 16 Static pressure distribution near suction gap in plane step

Over the next inch along the face of the step where the flow probably separates. Along the remainder of the step there is a slow decrease toward the concave corner, then a slow increase toward reattachment on the bottom wall and a subsequent adjustment to the downstream pressure which must correspond to a value less than \( C_p = 0.36 \), the value for potential flow through the step.

The lower graph in Fig. 16 shows pressures within approximately one gap width of the suction gap on an expanded s-scale. Results for additional suction rates are included. At the critical rate, \( C_q = C_{qr} = 0.40 \), the pressure hardly varies in the s-interval plotted here, possibly because the flow separates even before the first measuring station is reached. Below the critical suction rate, \( C_q = 0.35 \), pressures become negative toward the suction gap; the gap now functions as an orifice fed from a reservoir having a pressure somewhat greater than that in the upstream flow.

These additional data hopefully will contribute to further clarification of the flow, but the author still cannot offer a satisfactory explanation which accounts for effects of the suction gap geometry and the boundaries of the main flow.