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Some Techniques for Improving the Performance of Short Conical Diffusers

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SUMMARY An experimental investigation has been carried out to assess the performance of short conical diffusers and attention has been focussed on assessing the merits of two different techniques for improving their performance.

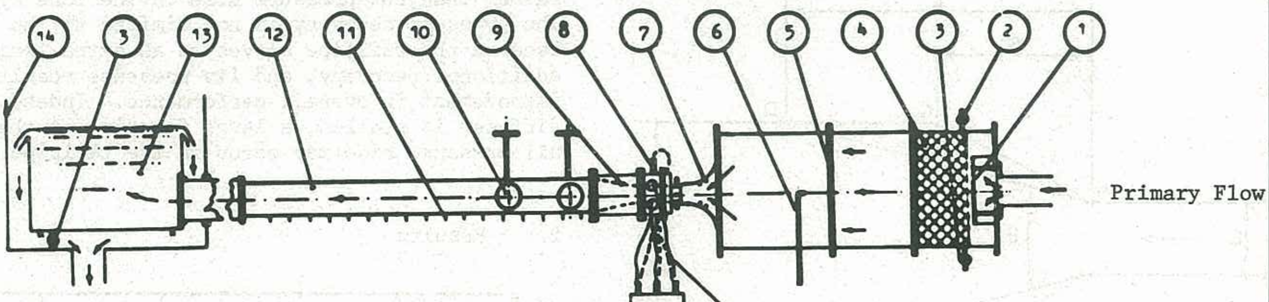
The first technique was to truncate the cone and, in all cases considered, it was found that this caused a reduced pressure recovery, typically 4 per cent for a 50 per cent truncation. Accordingly truncation is not recommended when a complete cone of the optimum angle can be accommodated, but it is recommended in preference to an untruncated, wider angle diffuser when there is a limitation on length.

In the second part of the investigation, the aim was to study the possible benefits to be gained from injecting a secondary supply of fluid into the diffuser through an annular slot at the inlet. The results show that injection has a very favourable effect on both the pressure recovery and the uniformity of the discharging flow.

1 INTRODUCTION

In some situations, the axial length of a diffuser must be short, dictating the use of higher cone angles than that required for maximum effectiveness or the use of truncation of an optimum angled cone at a sudden enlargement. The objective of the current programme of research has been to assess the merits of truncation and of boundary layer injection through an annular slot at the inlet to a wide-angled diffuser.

The same basic test installation was used for both investigations and this is depicted in Fig. 1. The size of the measured pressure recovery obviously depends on the location of the upstream and downstream pressure tappings (stations 1 and 2). Station 1 is located sufficiently far upstream of the cone ($2D_1$) for the measured pressure to be unaffected by streamline curvature at the entrance. The location of Station 2 will be discussed later.



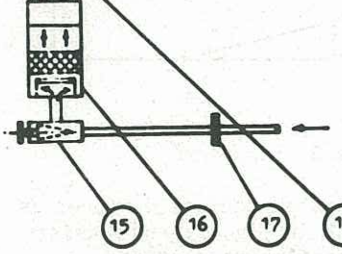


Figure 1

KEY 1. Baffle plate and gauze. 2. Air bleed valve 3. Drainage valve. 4. Honeycomb flow straightener. 5. Gauzes. 6. Pitot on axis of pressure chamber. 7. Bellmouth incorporating two wire trip rings to provoke boundary layer transition, ($\delta_1^* \simeq 0.005\ D_1$ at diffuser entrance). 8. Six ports discharging the secondary flow into an annular reservoir and then through the injection slot. 9. Conical test diffuser. 10. Potot traverse gear. 11. Static pressure tappings. 12. Tailpipe. 13. Constant head tank. 14. Overflow tank. 15. Needle-type control valve. 16. Secondary pressure tank. 17. Orifice place. 18. Flexible tubes

For the truncation investigation, the cone angle was 10° and the diffuser comprised a number of mating cones, enabling AR to be varied from 1.97 to 9.80. For the injection work, D_2 = 85.7 mm, AR = 3.265 and the cone angle could be set at 20° or 30°. The slot width was progressively increased by machining the outer surface.

NOTATION

P	static pressure
U	mean velocity
$\dot{m}$	mass flow rate
ρ	density
ν	kinematic viscosity
D	diameter (D_1 at the diffuser entry and D_2 in the tailpipe)
AR	overall area ratio $(D_2/D_1)^2$
θ	total angle of divergence of the cone
R_e	Reynolds number (U_1D_1/ν)
δ^*	boundary layer displacement thickness (axisymmetric definition)
L	length of the untruncated diffuser measured from the cone entrance
S	axial distance downstream of the cone entrance to the truncation section
S/L	truncation ratio
k	velocity ratio (U_s/U_1)
w	slot width
c	slot area as a fraction of the cone entry area
η	effectiveness (defined later)
C_p	pressure recovery coefficient (defined later)

Subscripts

1	primary flow condition at the cone entrance
2	downstream flow condition (defined later)
s	secondary flow condition at the annular injection slot

2 INVESTIGATION OF TRUNCATED CONICAL DIFFUSERS

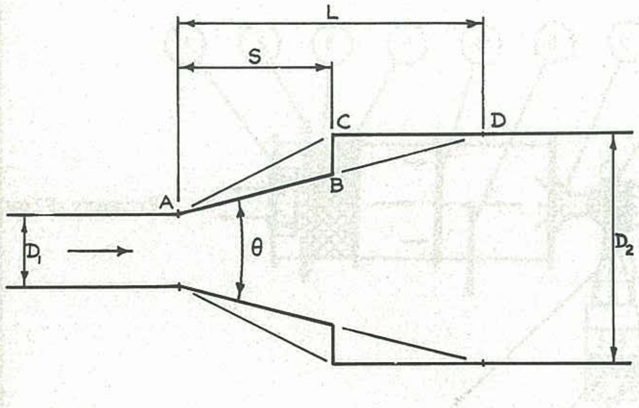


Figure 2

The configuration of a truncated conical diffuser is shown by the heavy line ABCD in Fig. 2, and consists of a simple cone discharging through a sudden enlargement into a long parallel tailpipe. Such a configuration was examined in the first investigation, the aim having been to study the following aspects of performance:-

a) the magnitude of the overall pressure recovery;

b) the axial length in which this recovery occurs;

c) the unsteadiness, asymmetry and non-uniformity of the tailpipe flow.

Regarding the overall pressure recovery, one might expect this to be only slightly affected by a moderate truncation since the flow velocity is relatively low at the truncation section. The effect, it might be supposed, would be particularly small in cases where flow separation occurred in the untruncated cone.

One might further expect truncation to yield a more rapid diffusion due to the shortening of the cone, in which case the overall rise in pressure would be achieved in a shorter length. This would be important in instances where the axial length available for diffusion is limited to such an extent that a continuous cone of the optimum angle of divergence cannot be accommodated.

Finally, one might expect truncation to give a steadier and more symmetrical flow in the tailpipe by provoking an axi-symmetric annular separation of the stream at a fixed axial position. This would contrast with the type of separation normally encountered in an untruncated diffuser where the stream separates from the wall at one angular position but not at another, and where the separation point may move both axially and circumferentially over a period of time.

Accordingly the aim of the investigation was to test these conjectures and hence to permit a comparison to be made between the merits of:

a) a conical diffuser (ABD) and having the optimum angle of divergence (≃ 10°),

b) a moderately truncated diffuser (ABCD) of the same angle, and

c) a wider-angle, untruncated diffuser (ACD) having the same length as (b).

In the truncation investigation, Station 2 was taken to be the point of maximum pressure in the tailpipe because our concern in this case was with the total recovery in the diffuser and tailpipe together rather than the pressure rise in the cone by itself. The pressure recovery is not limited to the cone because the tailpipe serves as an extra length for additional recovery, and its presence results in an improvement in overall performance. Indeed, if the diffuser is stalled, a large fraction of the overall pressure rise may occur in the tailpipe.

2.1 Results

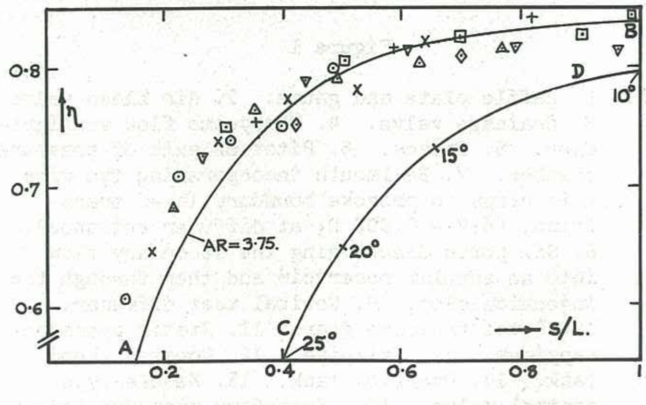


Figure 3 Effects of truncation and area ratio on effectiveness.

Fig. 3 shows a selection of effectiveness results and the symbols relate to different area ratios as follows:-
⊙ 9.80, x 6.75, ▲ 5.45, ▽ 4.26,
⊡ 3.75, + 3.24 and ◇ 2.79.

It is clear that the area ratio has a small effect and the experimental data fall almost onto a single line, the slight deviation from which appears to be due as much to scatter as to an AR effect. The pressure recovery is always reduced by truncation and, in a typical case, truncation of the cone by 50% incurred a 4% drop in η. The magnitude of the reduction in pressure recovery is approximately equal to the loss incurred by a sudden enlargement which has the same area change. The curve AB is a theoretical one which has been calculated on this basis.

Curve CD in Fig. 3 indicates experimental data presented by Gibson for untruncated wide-angled diffusers of the same length as the present truncated ones (ACD in Fig. 2). The area ratio was 4 and the boundary layer at the diffuser entrance was thicker than in the present work. Comparison of CD with the present data reveals that the 10° truncated diffuser is markedly superior to its untruncated counterpart by a margin which increases progressively with reduction in cone length. On the other hand, the true margin is exaggerated somewhat by the differences in boundary layer thickness.

It may be concluded that, when maximum pressure recovery is the sole performance criterion, truncation is recommended only when there is a limitation on length such that an untruncated cone of the optimum angle cannot be accommodated. On the other hand, when there is such a limitation, a truncated diffuser having the optimum angle is recommended in preference to a wider-angle untruncated diffuser of the same length.

3 INVESTIGATION OF SLOT INJECTION AT THE CONE ENTRANCE

The second investigation has been to study the possible benefits to be gained from injecting a secondary supply of fluid into the diffuser through an annular slot at the inlet, re-energising the boundary layer.

One might expect the major benefit from injection to be gained in cases where flow separation occurs in the diffuser in the absence of artificial flow control but where separation is prevented when injection is applied. In this event one would expect similar benefits to those discussed in Section 2. An additional benefit from the use of injection could be expected if the diffuser were carrying hot gases because in such cases the injected fluid could serve the dual purpose of re-energising the boundary layer and cooling the wall. In contrast, the use of suction or splitter vanes, etc. would have the adverse effect of increasing the heat transfer to the wall.

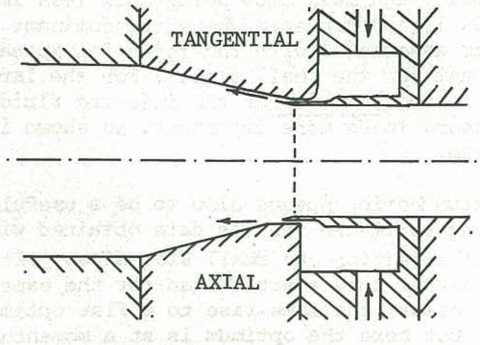


Figure 4 Configurations for slot injection.

The rig was designed so that the secondary fluid could be injected in either an axial direction or a tangential direction as shown in Fig. 4, an advantage of axial injection being that the assembly is then structurally less complex. Therefore, an assessment of the relative merits of tangential and axial injection has been possible and this comprises one aspect of the work to be described. Another important feature of the injection geometry is that the slot is located as near to the cone entrance as is structurally possible.

Other major aspects of the investigation have been to assess the relative importance of Reynolds number, injection rate and the various geometrical parameters. Two cones were available, of 20° and 30° total angle, and for each one the slot width could be progressively increased by machining the outer surface. Most of the work has been carried out with a thin, turbulent boundary layer at the diffuser entrance and with an overall area ratio of 3.265.

3.1 Experimental Results

In the injection investigation, the dimensionless parameter with which the pressure recovery has been quantified is the pressure recovery coefficient C_p defined as follows, so as to take account of the kinetic energy and pressure energy of the injected fluid:-

$$C_p = \frac{(\dot{m}_s + \dot{m}_1)(P_2 - P_1)}{\dot{m}_1 . \frac{1}{2}\rho U_1^2 + \dot{m}_s . \frac{1}{2}\rho U_s^2}$$

where U_1, U_s, and $\dot{m}_1$, $\dot{m}_s$ are respectively the velocities and mass flows of the primary and secondary streams. Attention is drawn to the fact that the parameter represents the dimensionless pressure rise up to the cone exit plane in this case because it is at this plane that the effects of injection are most pronounced, particularly with regard to the quality of the discharging flow.

In the above expression, no account is taken of any flow non-uniformity which might be present in the primary and injected streams, and the secondary fluid is presumed to be injected at the pressure P_1. Also of interest is the fact that when there is no injection the expression simplifies to the more usual form:-

$$C_p = (P_2 - P_1)/\frac{1}{2}\rho U_1^2$$

Turning to suitable dimensionless parameters to describe the injection rate, three different ones will be employed, viz the velocity ratio $k (= U_s/U_1)$, the mass flow ratio $\dot{m}_s/\dot{m}_1$, and the momentum ratio $\dot{m}_s U_s/\dot{m}_1 U_1$. The general expression for C_p can now be simplified to the form

$$C_p = \frac{(P_2 - P_1)(1 + ck)}{\frac{1}{2}\rho U_1^2 \quad (1 + ck^3)}$$

where c is the slot area expressed as a fraction of the cone entry area.

Initially a pilot study was made to determine the direction which should be taken later and it is desirable to summarise the results, which were obtained using large axial slots (1.05 mm < w < 3.18 mm). They were as follows:

(1) For a particular width of slot (w = 1.05 mm), the improvement in pressure recovery (i.e. maximum pressure rise across the diffuser with injection minus the rise without injection) was more than 20% greater in a 30° diffuser than in a 20° one. Also the maximum value of C_p for the 30° cone was almost as high as for 20°. Therefore it appeared that there was little to be gained by reducing the cone angle to below 30° because the implied increase in axial length would probably not be compensated adequately by the associated improvement in maximum C_p.

(2) For the large slots considered, it was found that the optimum injection rate occurred at a velocity ratio k in the range 1.0 to 1.2. For a slot of width 1.05 mm, this represented a secondary flow rate in the range 10 to 12 per cent of the primary one and, for a width of 3.18 mm, the corresponding range was 30 to 36 per cent. When the slot was widened there was a progressive increase in maximum C_p and hence it was concluded that the width should be as large as possible consistent with secondary supply availability. (On the other hand it was recognised that in the majority of diffuser applications, a large supply would not readily be available for this purpose.)

(3) Regarding the quality of the flow discharging from the cone, the degree of non-uniformity was greatly reduced by injection, typically the velocity variation across the duct being lessened by optimum injection to about one third of the value for zero injection. Furthermore the flow remained attached to the diffuser walls, in contrast to the case for k = 0. Unfortunately the velocity profiles also showed that the beneficial effects were partially offset by a deterioration in flow symmetry, but it was uncertain whether this was a genuine feature of the flow or whether it was caused by a possible lack of concentricity of the annular slot.

(4) The effects of Reynolds Number on performance were found to be small and similar in magnitude to those previously observed in diffusers which were used without injection. For $R_e > 2 \times 10^5$, viscosity effects were negligible.

As stated previously, the pilot study indicated the direction required to be taken in the subsequent investigation and the areas likely to be of greatest interest. For example, it revealed that it would be appropriate to concentrate on a 30° cone angle and to employ a single primary flowrate having a magnitude in the regime where performance was independent of Reynold's Number. Also, following the discovery that the secondary velocity was required to be somewhat greater than the primary one for the injection to be optimized, the major part of the later work was confined to small slots. A maximum mass ratio $\dot{m}_s/\dot{m}_1$ of about 0.2 was employed with a value of about 0.1 envisaged as the limit for useful design application.

It was conjectured that the reduction of slot size might cause a deterioration in flow symmetry, similar to that mentioned above, and one of the objectives of the present programme of work has been to clarify this. Other objectives have been to extend the previous study by studying injection phenomena in greater detail and to compare the relative merits of tangential and axial secondary flows.

Some pressure recovery results, for axial injection and a 30° cone angle, are given in Fig. 5 and show the effects of k and c on C_p. The same set of data is presented in three different ways viz with respect to k in the top diagram, $\dot{m}_s/\dot{m}_1$ in the centre and momentum ratio $\dot{m}_s U_s/\dot{m}_1 U_1$ at the bottom.

Referring first to the top diagram, this confirms that large increases in pressure recovery can result from the use of secondary injection and a maximum C_p of about 0.75 is obtained for all the slots which were tested (except the smallest). This may be compared with a value of about 0.28 for zero injection. In contrast a small amount of injection has an adverse effect and causes C_p to fall below 0.28, probably due to inadequate energizing of the boundary layer and a consequent worsening of the overall velocity distribution. However, when the injection rate is increased above $k \simeq 0.4$, there is a progressive increase in pressure recovery until the maximum is attained.

The optimum value of k at which it occurs is shown to be dependent on the size of the slot and, in this respect, the results differ from the previous ones for larger slots where the optimum k lay in the range 1.0 to 1.2 in each case. For the present range of smaller slots, the optimum k increases with decreasing slot size, and for the smallest width (c = 0.032) has a value of about 2.0.

Clearly, this indicates that a large secondary velocity is needed, but the requirement is more than compensated by the smallness of the slot itself, and the optimum mass flowrate is found to be less than for the larger slots. This is shown in the centre diagram of Fig. 5, the sequence of the family of curves having been reversed from that in the previous diagram. Also of interest is the fact that if the mass fraction is to be limited to 0.1, c must not exceed 0.07, corresponding to a slot width of 0.75 mm in the present rig.

The same data have been presented in terms of momentum ratio in the bottom diagram and when this is done, the previous families of curves now collapse approximately to a single line. After an initial fall at low rates of injection, the line rises to a fairly flat peak at a momentum ratio of about 0.14, the maximum C_p being about 0.75 as mentioned earlier. Incidentally, the figure of 0.14 may be used for design purposes to estimate the appropriate size of slot for a given secondary supply, the required empirical expression being $0.14c = (\dot{m}_s/\dot{m}_1)^2$. Also, it may be concluded from the collapse that for the present range of small slots the diffuser performance is governed primarily by the momentum of the injected fluid, the corresponding velocity and mass flow being much less important. This is another area where the dominant mechanisms associated with the injection appear to be different for the small slots. For the large ones, it is the velocity of the injected fluid which appears to be more important, as shown in the top diagram.

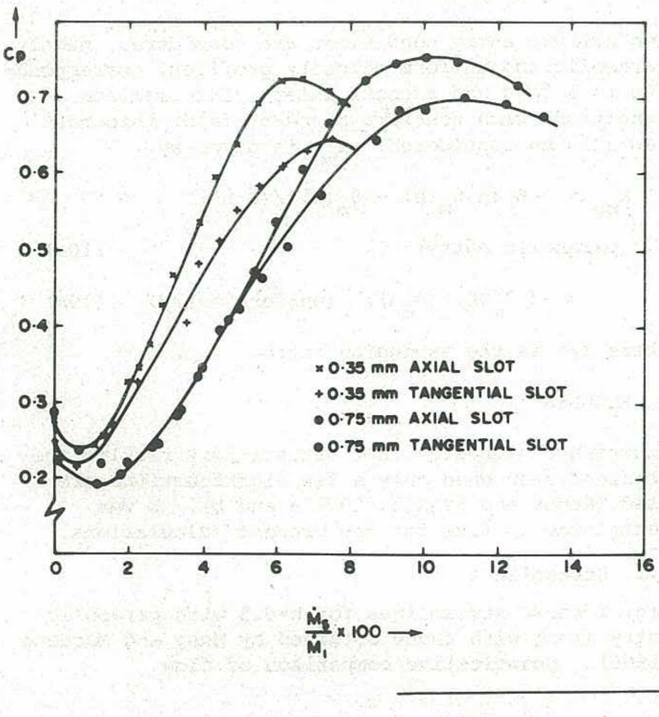
The momentum ratio appears also to be a useful correlating parameter for the data obtained with tangential injection and small slot sizes. Although there is rather more scatter than for the same axial injection cases, the same rise to a flat optimum is apparent, but here the optimum is at a momentum ratio of approximately 0.16. Further results are given in Figure 6 to show a comparison between exial and tangential injection for two sizes of slot. The diffusers which have axial injection clearly have a much better performance, the peak C_p being higher and occurring at a lower rate of injection. With the 0.35 mm slot, the peak C_p is about 0.08 higher, and with the 0.75 mm slot it is about 0.05. With no injection, the performance with the tangential slot is again worse than with the axial one possibly due to the small downstream-facing step present in the tangential slot geometry, as shown in Figure 4. One effect of the step is to shorten the diffuser slightly but a more important consequence is thought to be that it encourages flow separation and counteracts the benefits due to injection. In most other respects (e.g. regarding the effects of slot size) the axial and tangential modes of injection produce similar behaviour.

Further data relating to the discharging flow were obtained from velocity measurements for axial and tangential injection and for differenct values of k. For the axial slot, an improvement in velocity profile occurs with increasing injection and the recirculation region which is present initially becomes smaller and ultimately disappears when k is about 2, a similar value to the optimum for maximum pressure recovery. The profiles do not reveal any deteriorating symmetry due to injection and so the results for the axial slot do not support the tentative conclusion to teh contrary ehich was drawn in the preliminary work with large slot.

Turning to the velocity profiles for tangential injection, these reveal that the flow is now less stable than for axial injection and there is a tendency for any asymmetry already present to be am amplified by the injection. The present profiles for small tangential slots are in fact similar to those for large axial ones form which the above tentative conclusion was made.

Figure 5 Effects of injection rate and slot size on Pressure Recovery Coefficient (Axial injection and 30° cone angle)

Figure 6 Comparison of axial and tangential injection for two sizes of slot.



It may be concluded from the comparison between the axial and tangential modes of injection that in every aspect that has been examined the axial mode is better. The slot geometry is less complex, the pressure recovery is greater and is achieved with less injection, and the discharging flow is more stable and symmetrical.

Regarding the general merits of secondary injection, it is concluded that, by causing the flow to remain attached to the conical wall, injection yields considerable improvements in both the quality of the discharging flow and the magnitude of the pressure recovery. C_p is more than doubled by optimum injection in spite of the fact that C_p is defined so as to take account of the additional kinetic energy and pressure energy of the injected fluid. The slot width should be as large as possible, consistent with there being an appropriate secondary supply available, and for design purposes it is recommended that the size should be estimated from the empirical expression

$$0.14c = (\dot{m}_s/\dot{m}_1)^2.$$

Reduction of the cone angle from 30° to 20° offers a small improvement in the maximum C_p at the expense of an increase of over 50% in the cone length.

4 ACKNOWLEDGEMENTS

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