A Method of Flow Stabilisation with High Pressure Recovery in Short, Conical Diffusers

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1. Introduction

The problem of obtaining proper flow spreading together with useful pressure recovery across rapidly expanding diffusers is of considerable practical importance. Many different approaches to this end have been reported in literature, e.g., vortex generators, screens or baffles, surface roughness, corrugations, etc., apart from the use of direct boundary-layer control. These methods have the common aim of preventing separation from the walls of the diffuser. With increasing expansion angle and area-ratio, however, the effectiveness of these methods either breaks down or is obtained at a high cost of pressure recovery.

This note describes a new method applicable to conical diffusers, originally developed for a particular configuration of 38° total angle and area-ratio 15. Steady exit flow with good uniformity of the velocity profiles was obtained by the use of radial splitters, with a pressure recovery coefficient \( C_p \) exceeding 0.6. Even higher pressure recovery performance was achieved with a diffuser of the same area ratio but having a reduced expansion angle (20°) of 25°, while the flow spreading action of the radial splitters was found to persist at least up to an expansion angle of 50°.

The present method is regarded as novel in that it does not seek to eliminate separation in the diffuser. Rather, it relies upon a steady separated flow to achieve the flow spreading action. The radial splitters divide the conical diffuser into a number of identical triangular expanding passages, each of which contains a separation bubble of large relative size. Some qualitative experiments have been carried out to explore the nature of this separated flow, and data is presented to guide the optimisation of the splitters for maximum pressure recovery in diffusers of different angles.

**Notation**

- \( A_2 \): Diffuser cross-sectional area in plane of splitter leading-edge.
- \( A_b \): Blockage area at splitter apex for trip area.
- \( l \): Splitter cut-off length (see Fig. 1).
- \( L \): Diffuser axial length.
- \( 0 \): Diffuser semi-cone angle.
- \( C_p \): Pressure recovery coefficient \( = p_{\text{d}}/p_{\text{i}} \) where
  - \( p_{\text{d}} \): Exit static pressure,
  - \( p_{\text{i}} \): Inlet static pressure,
  - \( q_{\text{i}} \): Inlet dynamic pressure.

2. Radial Splitters as Flow Spreaders

The use of splitters has been frequently attempted in various types of three-dimensional diffuser configurations, usually in cruciform or egg-box arrangement. However, these have been largely ad hoc experiments and the results in many cases have proved inconclusive. The usual approach has been to split the given diffuser into a parallel array of smaller diffusers each having a reduced effective angle, which the flow would presumably negotiate without separation. In practice, difficulties have arisen due to:

- Unequal capture of mass flow in the diffuser because of a non-uniform inlet profile.
- Excessive friction loss due to greater wetted surface.

The extension of this principle to conical diffusers requires the use of conical sleeves in a concentric manner to give a system of annular diffusers. This arrangement also subject to the above-mentioned drawbacks and is not a generally practical solution to the problem of complete separation in the inner cone.

It was reasoned that radial splitters would overcome the practical problems but also be more consistent with the entry flow uniformity: as long as the velocity profile was axi-symmetric, equal flow in the passages between the radial splitters would be maintained.

Furthermore, the known characteristics of the flow through triangular ducts suggested that a rapid but secondary flows along the inner corner of the passages (which has the narrowest included angle and imparts a natural tendency for flow spreading) would be sufficient to achieve an acceptable degree of complete separation in the inner cone. It was expected that in such an event the outer flow would still be essentially axi-symmetric with peaked velocity profile, which being unstable, mix in a more or less uniform flow a distance from the diffuser exit.

The radial splitter system adopted in this note was assembled of eight thin, flat vanes spaced at equal angles (45°), and running nominally the full length of the diffuser (Fig. 1). The choice of the number of vanes was a compromise between the desirability of a nanocombination (for promoting secondary flows) and the minimisation of wetted surface area. Initial tests with radial splitters were also carried out.

3. Summary of Preliminary Investigation

The initial experiments that lead to the confirmatory radial splitter concept have been reported. The main results of the preliminary work (for a conical diffuser of area ratio 15) summarised below serve as a background to the more detailed investigations which will be discussed in the later sections.

- With splitters having sharp (or well strutted) leading-edges, there was no flow spread to the extent of complete separation from the diffuser wall.
the flow consequently emerging as a steady, axisymmetric jet (Fig. 2a).

(ii) An entirely different flow pattern was found with splitters having blunt leading-edges (Fig. 2b). Separation now occurred in the inner corners at the apex of the splitters and extended over most of the splitter length. The flow was fully attached to the diffuser wall. An identical flow pattern, dominated by a separation bubble in the inner corner, was present in all the passages. The emerging flow was steady and practically uniform a short distance (i.e. 0-25 exit diameter) downstream of the exit plane. The pressure recovery, however, was very poor.

(iii) The corner-bubble flow, leading to successful flow spreading action, was also produced with sharp leading-edge splitters by placing a separation trip (namely a small bead) symmetrically over the apex. The trip evidently duplicated the function performed by the blunt apex in (ii). A minimum trip size was needed for this purpose, below which the flow reverted to the centre-jet type described in (i). Using a minimum trip, a significant pressure recovery across the diffuser was achieved,

(iv) Further gains in pressure recovery were obtained by cutting away a short initial length (l) of the splitters (as illustrated in Fig. 1). The minimum trip size needed to establish the bubble-vortex flow was somewhat bigger with the cut-away splitters.

These early results appeared sufficiently promising to warrant a more detailed investigation for exploring the pressure recovery potential of the splitters in conical diffusers of other angles, and also to elucidate the details of the flow mechanism. This was carried out with larger-scale diffuser models, as described in the following section.

4. Tests With Conical Diffusers

Three diffuser models were tested, of total conical angle 25°, 38° and 50°, all having an area ratio of 15 (the second diffuser was thus geometrically similar to the model used in the preliminary investigations, section 3). The inlet diameter in each case was 3 in (0-08 m) with a 3 in (0-08 m) inlet length of constant diameter incorporated. All models were constructed of fibre-glass reinforced plastic with smooth internal surfaces.

The splitters were assembled from 1/4 in (1-2 mm) thick aluminium or plywood vanes with sanded surfaces, bonded together accurately in a special jig. The leading-edges of the vanes were rounded off to an approximately elliptical shape, which was carried into the root (i.e. junction of the vanes) as far as possible. The separation trips were in the form of sharp-edged circular discs cut from thin plastic sheet, affixed concentrically on the splitter apex. The majority of the tests were carried out with eight-vane splitters; limited tests were also done with six-vane splitters in the 25° and 38° diffusers.

The airflow was supplied by means of a commercial centrifugal blower via a stilling chamber and an axisymmetric contraction, at a velocity of about 350 ft/sec (106-63 m/s) at the diffuser inlet. Reynolds number was based on the inlet diameter and air temperature at 60°C. The inlet turbulence level was about 0-5%. The diffusers discharged to atmosphere through a short tailpipe approximately half exit diameter in length, which also a total-pressure rake with the plane of measurement (i.e. approximately quarter exit diameter of the exit plane of the diffuser, Fig. 1). This distance was maintained to avoid misleading results due to the large flow inclinations that would inevitably occur (nearer the diffuser wall) in the exit plane when the flow was fully spread. By rotating the tailpipe with respect to the diffuser, the rake was positioned in the centre-plane of the different splitter passages in turn.

Accurate measurement of the exit velocity profile was rendered difficult because of the low velocities (about 20 ft/sec (6'1 m/s) when the exit was running full) and the high turbulence level. The uniformity of the exit flow was, therefore, checked visually on a multi-tube alcohol manometer connected to the total pressure rake. An additional check on the exit-flow behaviour was made in each case using a tuft probe.

Maw visualisation in the splitter passages was achieved by injecting a mixture of paraffin and titanium dioxide in the inner corners through a long hypodermic tube. When the corner bubble flow was present, the oil was carried along the corner by the reverse flow up to the apex and then swept downstream essentially along the bubble boundaries on the vane surfaces. This procedure allowed a rapid visualisation of the most interesting features of the flow (Fig. 3).

6. Results and Discussion

In the 25° and 38° diffusers, the eight-vane splitters were found to be effective without using a separation trip, for all values of cut-off length (l) from zero to the optimum (i.e. for maximum C.) The drop in C., caused by a small increment in l beyond the optimum was restored by applying a critical sized trip (Fig. 4).

In the 50° diffuser, however, the splitters were effective only with the application of a trip even for l=0. A critical trip size was determined to give maximum C, for each value.
Figure 3. Oil flow visualization of bubble vortex pattern.

Figure 4. Pressure recovery improvement with splitter cut-off.

of $I$, and these points only have been plotted in Fig. 4 for $2d=50^\circ$. The improvement in $C_p$ with increasing $I$, as shown in this figure levels off around $I/I_{critical}$ for all three diffusers. The limiting pressure recovery coefficients attained in the present tests were as follows:

- $2d = 25^\circ$: $C_p_{max} = 0.73$
- $38^\circ$: $C_p = 0.61$
- $50^\circ$: $C_p = 0.42$

(Note: For fully spread flow with no pressure losses, $C_p = 0.995$)

The exit flow was steady and uniform with the $25^\circ$ and $38^\circ$ diffusers. The $50^\circ$ diffuser exhibited a symmetric double-peak profile in the exit plane of measurement, with a central core of reversed flow. A tuft survey revealed that in this case the separation bubble did not terminate inside the splitter passages. A free-stagnation point was located on the axis about 4 in downstream of the diffuser exit plane. Tuft exploration indicated that downstream of the free-stagnation point the flow approached uniform conditions quite rapidly. However, the total axial distance to achieve this condition did not appear to be significantly less than for the $38^\circ$ diffuser.

Tests with six-vane splitters in the $25^\circ$ and $38^\circ$ diffusers showed these to be equally effective, although the exit flow was somewhat unsteady. Flow visualization suggested that the bubble inside the passage was less stable in this case. As seen in Fig. 4 the ultimate pressure recovery performance of the six-vane splitters was not superior to the eight-vane splitters.

Although a rather wide range of combinations of $I$ and $d/d_{exit}$ produced effective flow spreading and eight-vane splitters in the three diffusers, indicated that certain combinations were unfavourable for best pressure recovery in a given diffuser. The parameter appeared to be the trip blockage which includes the variations of both $I$ and $d$, and have been re-plotted as $C_p$ versus $A_{trip}/A_{exit}$ in Fig. 5. It contains the $C_p$ measurements for all trip sizes covering a wider range than Fig. 4. It also covers for the $25^\circ$ and $38^\circ$ diffusers where plotted, by taking the estimated blockage area of the passage (due to vane thickness) for $A_{trip}$. The plot shows a sufficient range to positively identify the $C_p$ for each diffuser, and provides a good indication of the fundamental role of the apex blockage.

To understand the manner in which, $A_{trip}/A_{exit}$ the pressure recovery characteristics, the influence of the bubble size and the exit profile were observed. The central core of the bubble was found to move downstream and away from the axis, as the size of the eddy in the inner corner of the passages. Correspondingly, the critical value of trip blockage had a small bulge in the profile which initially had a small bulge in the profile and then gradually straightened out, became nearly uniform at a developed a

Figure 5. Effect of splitter apex blockage on pressure recovery.

Figure 6. Effect of splitter apex blockage on pressure recovery.

EXIT VI DOTY PROF.

LEGEND

A A - $25^\circ$

C O - $38^\circ$

A - $50^\circ$

OPEN SYMBOLS - EVANES

CLOSSED SYMBOLS - CvANES

FLAGGED SYMBOLS - WITH CRITICAL TRIP

UNFLAGGED SYMBOLS - NO TRIP

A_{trip}/A_{exit} TICAL

UNIFORM EXIT PROFILE MAXIMUM

A_{trip}/A_{exit} TICAL

A_{trip}/A_{exit} TICAL

A_{trip}/A_{exit} TICAL
double-peaked shape (Fig. 6). A maximum in \( C_p \) was attained simultaneously with uniform exit flow.

The effect of inlet velocity profile was checked by placing a wire-gauze ring at a position 3 in (0.08 m) upstream of the diffuser inlet plane. With a symmetrical velocity profile, the effectiveness of the splitters was retained. When the gauze ring was placed eccentrically, however, the resulting asymmetric inlet velocity profile caused the corner-bubble flow to collapse in some of the splitter passages, leading to fluctuating exit flow. The radial vane splitter configuration is evidently sensitive to inlet asymmetry; it is, however, thought that some degree of tolerance in such a case may be achieved by locating the trip eccentrically to ensure corner-bubble flow in all splitter passages.

Supporting experiments with a triangular duct model, representing one of the passages of an eight-vane splitter in a 38° diffuser, to the same scale confirmed the qualitative aspects of the trip-induced corner-bubble flow. The changeover from the centre-jet to corner-bubble flow with increasing trip projection occurred suddenly at a particular value of trip blockage. Further increase of trip blockage was accompanied by changes in the exit profile similar to that observed with the conical diffuser. A small but distinct hysteresis was noted in the collapse of the corner-bubble with decreasing trip size, which occurred as suddenly but at a somewhat smaller value of the trip blockage than that which had produced the corner-bubble flow. At a trip setting close to this critical size, the flow alternated randomly between the centre-jet and corner-bubble patterns; such a switching could also be induced by a mechanical disturbance.

These characteristics are suggestive of a Coanda-type mechanism responsible for the flow attachment to the diffuser wall. If such a mechanism is operative in (he present instance, this would place a limit on the wall angle (i.e. diffuser semi-cone angle) for flow attachment and the existence of the bubble-vortex flow. According to the present results, however, such a limit would appear to lie beyond the minimum diffuser length for flow spreading through area-ratio 15. The practical advantage, if any, of a closer approach to the limiting expansion angle for smaller area-ratio diffusers remains to be investigated.

6. Concluding Remarks

The present experiments have fully confirmed the effectiveness of radial splitters in large area ratio conical diffusers of total expansion angles up to 50°. For area-ratio = 15, the optimum diffuser angle to achieve uniform exit flow in the shortest axial distance appears to be close to 40°, and with this arrangement a maximum pressure recovery coefficient of about 0.6 is possible. A higher \( C_p \) value (exceeding 0.7) for the same area-ratio can be attained with a reduced expansion angle of 25°.

Since the pressure recovery of the diffuser with splitters is essentially that of the individual passages, a comparison with conical diffuser performance is of interest. The effective expansion angle of the splitter passages in the 38° diffuser is 14°. Data on conical diffusers of area-ratio as large as 15 is scarce for the obvious reason of large-scale flow unsteadiness at exit. A 15° diffuser with area-ratio 7-55 was found to yield a pressure recovery coefficient between 0.55 and 0.57 (Ref. 2). It is evident that with the corner-bubble flow, the pressure recovery characteristics of triangular expanding ducts are superior and provide much better exit flow conditions than would be expected with an equivalent conical diffuser, particularly at the large area-ratio values considered here.

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References


Some Measured and Calculated Effects of Runway Unevenness on a Supersonic Transport Aircraft

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These studies led SNIAS* and RAE (working in conjunction with BAC) to make similar calculations for Concorde long before taxi trials began. As flight experience has been gained with this aircraft many further calculations have been made to help understand certain effects that were observed experimentally, and it is now possible to review the practical consequences of runway unevenness for one SST, and to indicate which of the undercarriage characteristics significantly affect vibration while taxiing, taking-off and landing. Discussions with companies working on other SST or supersonic bomber projects suggest that the experience of ground vibration on Concorde is likely to be typical of any aircraft having the geometry and mass and stiffness distributions of a configuration suitable for long range supersonic flight.

* Société Nationale Industrielle Aerospatiale.