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Performance improvement of axial diffusers for incompressible flow

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PERFORMANCE IMPROVEMENT OF AXIAL DIFFUSERS FOR INCOMPRESSIBLE FLOW

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PERFORMANCE IMPROVEMENT OF AXIAL DIFFUSERS FOR INCOMPRESSIBLE FLOW

1. NOTATION AND UNITS

		Units	
		SI	British
A	cross-sectional area of duct	m ²	ft ²
A_b	cross-sectional area of bluff body	m ²	ft ²
A_E	effective flow area, $(w_1 - 2\delta^*)(b - 2\delta^*)$ for rectangular diffuser	m ²	ft ²
A_s	cross-sectional area of injection slot	m ²	ft ²
A_2^*	cross-sectional area at exit of a C_{pr}^* diffuser	m ²	ft ²
a	spacing for rectangular vanes	m	ft
a_r	rib depth	m	ft
B	blockage parameter, $\frac{A - A_E}{A}$	—	—
b	width of rectangular diffuser (between parallel walls for single-plane expansion), see Sketch 2.2	m	ft
b_r	rib cavity width	m	ft
b_v	vortex generator height	m	ft
C_{pr}	static-pressure recovery coefficient, see Section 2.2.1	—	—
$C_{pr,c}$	static-pressure recovery coefficient for controlled diffuser	—	—
C_{pr}^*	optimum value of C_{pr} for given length ratio (L/R_1 , L/w_1 and L/h_1 for conical, plane-walled with single-plane expansion and annular diffusers, respectively)	—	—
C_{prI}	value of C_{pr} for an ideal diffusion process, $1 - 1/(A_2/A_1)^2$	—	—
C_{prI}^*	ideal static-pressure recovery coefficient for a C_{pr}^* diffuser, $1 - 1/(A_2^*/A_1)^2$, see Section 2.3	—	—
c	slot area ratio, A_s/A_1	—	—
c_v	vortex generator chord	m	ft
D	diameter of circular section	m	ft
D_h	hydraulic diameter, $4A/\text{perimeter}$	m	ft
d	diameter of annulus centre body	m	ft

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d_c	diameter of cylindrical insert	m	ft
h	annulus width, $R_o - R_i$	m	ft
h_1	radial distance of inlet vane from diffuser wall	m	ft
h_2	radial distance of inlet vane from diffuser axis	m	ft
K_r	screen pressure drop coefficient	—	—
K_t	total-pressure loss coefficient, see Section 2.2.2	—	—
$K_{t,c}$	total-pressure loss coefficient for controlled diffuser	—	—
L	axial length of diffuser	m	ft
l	vane length	m	ft
m	total mass flow rate through section	kg/s	slug/s
m_s	mass flow rate of injected stream	kg/s	slug/s
N	total number of vanes	—	—
n	vane identification number	—	—
p	static pressure	N/m ²	lbf/ft ²
p_t	total pressure	N/m ²	lbf/ft ²
R	radius of circular duct	m	ft
Re	Reynolds number ($\bar{V}_1 D_1 / \nu_1$, $\bar{V}_1 w_1 / \nu_1$ and $\bar{V}_1 h_1 / \nu_1$ for conical, plane-walled with single-plane expansion and annular diffusers, respectively)	—	—
r_n	radius of n th vane at inlet	m	ft
s	vortex generator spacing	m	ft
t	rib thickness	m	ft
$\bar{V}$	area-averaged mean axial velocity, $m/\rho A$	m/s	ft/s
V_c	centre-line velocity	m/s	ft/s
V_s	velocity of injected stream	m/s	ft/s
v	local velocity	m/s	ft/s
w	width of rectangular duct (between diverging walls for single-plane expansion), see Sketch 2.2	m	ft
x	axial fence gap	m	ft
x_c	distance from diffuser inlet to cylindrical insert	m	ft
x_s	screen spacing	m	ft

x_v	distance of leading edge of radial splitters from diffuser inlet	m	ft
x_ϵ	distance from diffuser inlet at which roughness commences	m	ft
Y	radial fence gap	m	ft
α	vane angle	degree	degree
α_v	angle of attack of vortex generator	degree	degree
β	screen porosity (ratio of open area to total area of screen)	–	–
δ^*	two-dimensional boundary-layer displacement thickness, $(D_1/4)(1 - \bar{V}/V_c)$ for conical diffusers ⁶⁸ and $(D_h/8)(1 - \bar{V}/V_c)$ for rectangular and annular diffusers	m	ft
ϵ	average particle size for surface roughness	m	ft
ν	kinematic viscosity of fluid	m ² /s	ft ² /s
ρ	density of fluid	kg/m ³	slug/ft ³
ϕ	angle between diffuser wall and diffuser axis (total divergence angle = 2ϕ for symmetrical diffusers)	degree	degree

Additional subscripts

i	denotes inner wall of annular duct
o	denotes outer wall of annular duct
opt	denotes optimum conditions
1	denotes inlet plane of diffuser
2	denotes exit plane of diffuser

2. INTRODUCTION

This Data Item presents design recommendations for improving the performance of axial diffusers for incompressible flow. Sections 4 to 11 give, where possible, design recommendations and guidance on optimum performance improvement by various techniques in addition to general consideration of the methods. The information given is based on data from a limited range of tests for each method and any extrapolation must be applied with caution. A tentative basis for interpolation or extrapolation is given in Section 2.3. Table 2.1 provides information that will assist in the selection of suitable control methods for various circumstances.

For optimum performance a modest wall angle ($\phi \leq 5^\circ$) is required. Therefore the first consideration when designing a diffuser is to utilise all the available length in order to minimise the wall angle. The effect of wall angle on diffuser performance is discussed in Section 3. Restrictions on length may result in a wide-angle diffuser, some examples of which are:

- (i) gas turbine pre-combustor diffusers,
- (ii) wind tunnel diffuser sections,
- (iii) inlet channels of glycol injection heat exchangers,
- (iv) electro-static precipitator pre-entry diffusers.

Inlet flow conditions also affect diffuser performance. For optimum performance a uniform (one-dimensional) inlet velocity profile is required. In practice conditions at inlet will not be uniform, resulting in less than optimum performance. The effects of non-uniform inlet conditions at entry are discussed in ESDU 76027.

A comprehensive study of diffusers in incompressible flow is given in the following Data Items.

ESDU 76027, Introduction to design and performance data for diffusers.

ESDU 73024, Performance of conical diffusers in incompressible flow.

ESDU 74015, Performance in incompressible flow of plane-walled diffusers with single-plane expansion.

ESDU 75026, Performance of circular annular diffusers in incompressible flow.

TABLE 2.1 Summary of Improvement Methods

Section	Control method	Description of method	Improvement in static-pressure recovery	Exit velocity profile	Installation	Comments
4	Vanes and splitters	Inlet, guide vanes, divider plates and splitters.	****	May be peaked.	Fixing may be a problem. No auxiliary power requirements.	Performance impaired by asymmetric inlet flows. Vibration may be a problem.
5	Screens and perforated plates	Act as flow spreaders.	*	Very good.	Simple to install. No auxiliary power requirements. Regular maintenance required.	Should be used where exit velocity profile is of paramount importance. Static-pressure recovery and total-pressure loss will be impaired.
6.1	Surface roughness	Roughness applied to diffuser walls.	**	Fair.	Simple to install.	Effective only for diffuser geometries that lie in the flow regime boundary between the transitory separation and jet flow. Acoustic resonance may be a problem.
6.2	Ribs	Transverse grooves cut in diffuser walls.	***	Fair.		
7.1	Vortex generators	Small aero-foils placed around circumference of diffuser inlet.	**	May be peaked.	Simple and cheap to install. No auxiliary power requirements.	Sensitive to inlet boundary layer thickness. Limited to wall angles $\leq 15^\circ$.
7.2	Hybrid diffuser	Fence at inlet creates a bound ring vortex.	****	Good.	Requires complicated fences and auxiliary power.	Can be used without bleed although not very efficient. Not suitable for rectangular diffusers.
8	Truncation	Diffuser truncated to give a sudden enlargement resulting in controlled separation.	**	Fair.	Simple to install.	Effective only for diffuser geometries that lie in the transitory separation region.
9	Injection	High velocity stream injected into boundary layer.	****	May be peaked.	Requires slot and auxiliary power.	Performance impaired by asymmetric inlet flows.
10	Boundary layer removal	Boundary layer removed through walls by suction.	****	Good.	Requires slot and auxiliary power.	Can overcome poor inlet flow conditions.
11.1 to 11.3	Curved walls	Boundary layer growth controlled by curving walls.	***	Good.	Wall profiles are complicated to construct. Additional control devices may also be required.	Optimum design is difficult to achieve.
11.4	Inserts	Star-shaped inserts spread flow and create turbulence.	**	Fair.	Support of inserts may be a problem.	Optimum design is difficult to achieve.

**** $C_{pr,c}/C_{pr} > 2.4$;

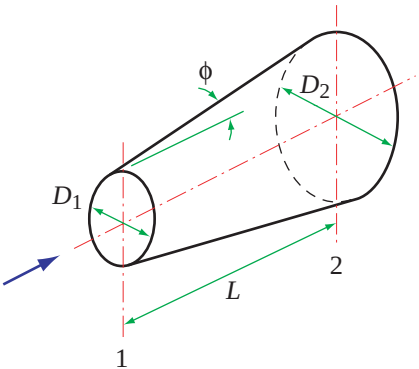
*** $C_{pr,c}/C_{pr} = 1.5$ to 2.4 ;

** $C_{pr,c}/C_{pr} = 1.0$ to 1.5 ;

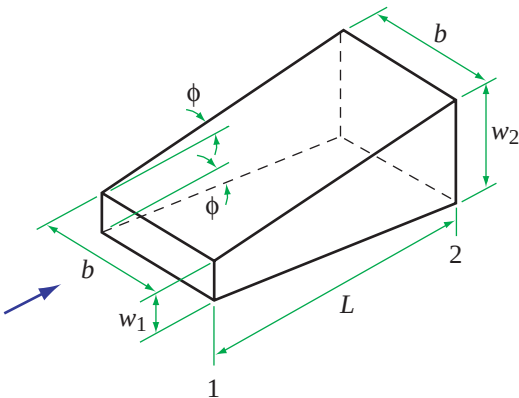
* No improvement.

2.1 Diffuser Geometry

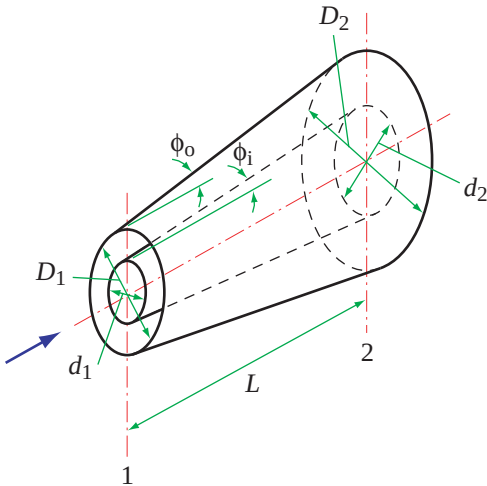
The data presented in this Item apply to the diffuser geometries illustrated in Sketches 2.1 to 2.4.



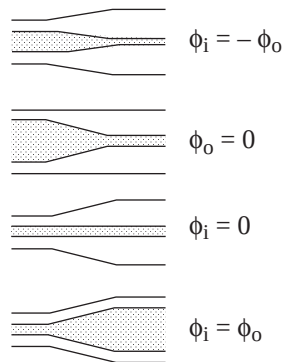
Sketch 2.1 Conical diffuser



Sketch 2.2 Plane-walled, single-plane expansion diffuser



Sketch 2.3 Annular diffuser



Sketch 2.4 Some special annular types

2.2 Diffuser Performance Parameters

This section covers the more commonly used diffuser performance parameters. A more detailed study of these parameters is given in ESDU 76027.

The following performance parameters are based on the assumption that velocity, static pressure and total pressure at inlet and outlet are uniform across the section (one-dimensional flow). More precise evaluations can be obtained from weighted mean values, see, for example, Reference 1. The use of weighted mean values takes account of flow non-uniformities but requires detailed cross-sectional surveys of pressure and velocity which may not be available.

2.2.1 Static-pressure rise; one-dimensional, incompressible flow

The static-pressure rise can be defined in terms of a non-dimensional recovery coefficient, C_{pr} , where

$$C_{pr} = \frac{p_2 - p_1}{\frac{1}{2}\rho \bar{V}_1^2} \quad (2.1)$$

In Equation (2.1), $(p_2 - p_1)$ is the static-pressure rise between stations 1 (inlet) and 2 (exit) and the product $\frac{1}{2}\rho \bar{V}_1^2$ is the mean inlet kinetic pressure. Values of C_{pr} normally range from zero to one and are dependent on diffuser geometry and inlet flow conditions.

2.2.2 Total-pressure loss; one-dimensional, incompressible flow

The total-pressure loss can be similarly defined using a non-dimensional coefficient, K_t , where

$$K_t = \frac{p_{t1} - p_{t2}}{\frac{1}{2}\rho \bar{V}_1^2} \quad (2.2)$$

Alternatively, K_t can be related to C_{pr} by

$$K_t = C_{prI} - C_{pr} \quad (2.3)$$

where C_{prI} is the ideal static-pressure recovery coefficient given by

$$C_{prI} = 1 - 1/(A_2/A_1)^2 \quad (2.4)$$

2.2.3 Outlet flow specification

The information on outlet flow is usually restricted to general comments on flow stability and uniformity. These comments can be correlated to give a series of flow regimes that describe the flow for any given diffuser geometry. The effects of diffuser geometry on the flow regime are discussed in Section 3.2.

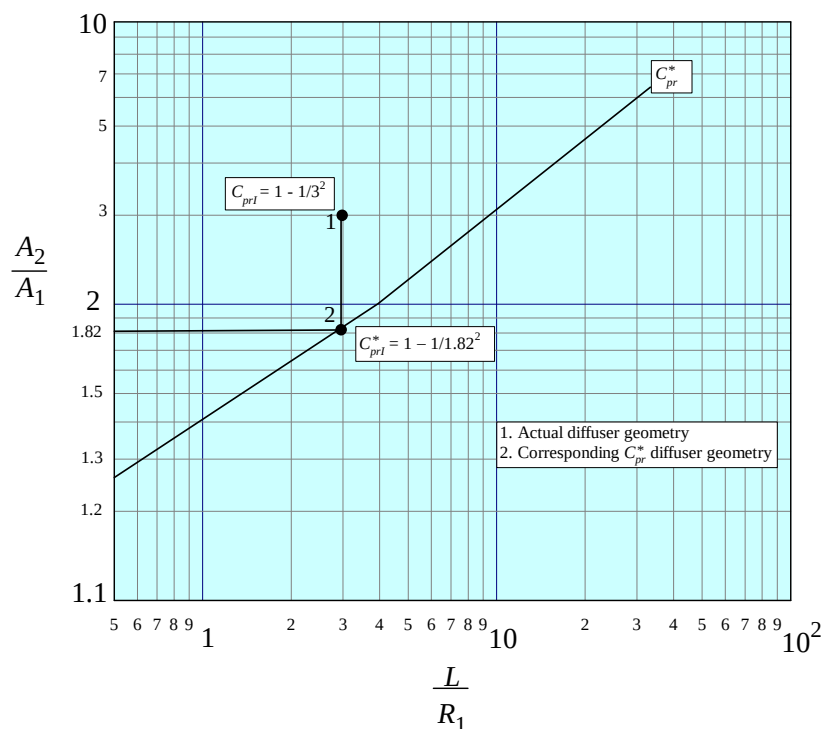
2.3 Interpolation and Extrapolation of the Data

Since the available data are restricted to isolated diffuser geometries, a definitive and comprehensive guide to performance improvement cannot be given. However, the following tentative approach for interpolation or extrapolation of the available data to other geometries is proposed.

The potential for improvement in diffuser performance can be characterised by the extent to which the performance falls short of an optimum. In the present case, where generally length is a limiting parameter, the appropriate optimum is taken to be an optimum diffuser of the same length ratio as the actual diffuser, *i.e.* a C_{pr}^* diffuser.

Since variations in operating conditions make it difficult to define C_{pr}^* precisely, ideal values are used. Thus, as an approximation, the actual diffuser performance in relation to its optimum can be characterised by the ratio C_{prI}/C_{prI}^* .

The area ratio, A_2^*/A_1 , to give a C_{pr}^* diffuser can be obtained from the appropriate performance chart, an example of which is shown in Sketch 2.5.



Sketch 2.5 Performance chart for conical diffusers showing C_{pr}^* line, from ESDU 73024

For conical diffusers the C_{pr}^* line is independent of inlet entry length and, assuming no tailpipe, Figure 3 of ESDU 73024 should be used.

For rectangular diffusers the position of the C_{pr}^* line is dependent on the inlet blockage parameter, B_1 . The value of B_1 can be calculated from the following equations:

$$B_1 = (A_1 - A_E)/A_1, \quad (2.5)$$

where $A_1 = bw_1$

$$\text{and } A_E = (w_1 - 2\delta_1^*)(b - 2\delta_1^*). \quad (2.6)$$

The inlet boundary layer displacement thickness, δ_1^* , can be calculated from

$$\delta_1^* = (D_h/8)(1 - \bar{V}_1/V_c). \quad (2.7)$$

The appropriate performance charts for rectangular diffusers with various inlet blockage parameters are Figures 4 to 7 of ESDU 74015. Although the aspect ratio, b/w_1 , may change the actual value of C_{pr} , the position of the C_{pr}^* line will be unaltered and can therefore be used for any aspect ratio.

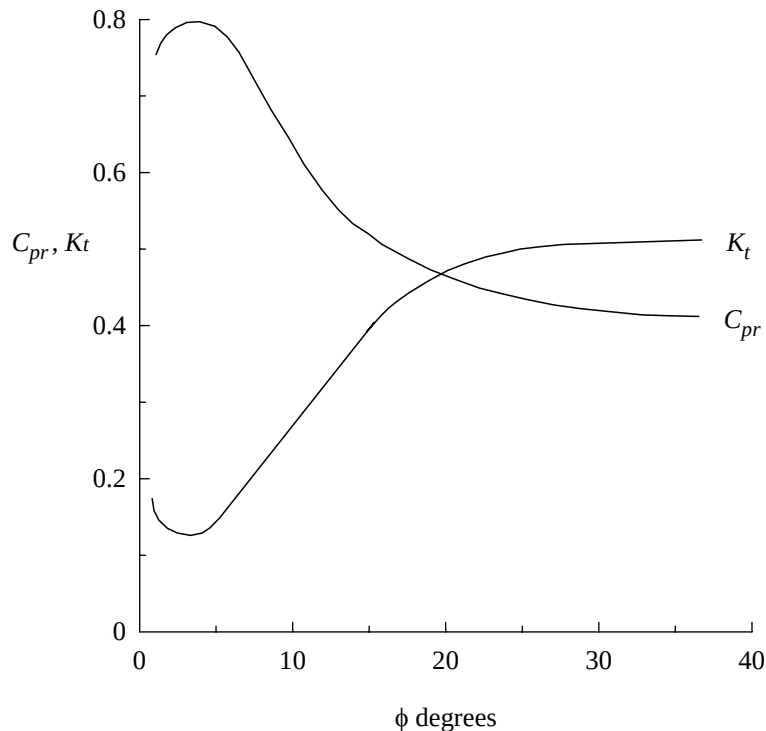
For annular diffusers the position of the C_{pr}^* line is dependent on the annular configuration as defined in ESDU 75026.

3. EFFECTS OF WALL ANGLE ON PERFORMANCE

This section is confined to the effects of wall angle, ϕ (see Sketches 2.1 to 2.4), on the performance of diffusers. For a discussion of the effect of other geometric parameters on performance see ESDU 76027.

3.1 Static- and Total-pressure Coefficients

Data for a conical diffuser of area ratio 3, from ESDU 73024, are presented in Sketch 3.1 in order to illustrate the effect of increasing wall angle on the static- and total-pressure coefficients.

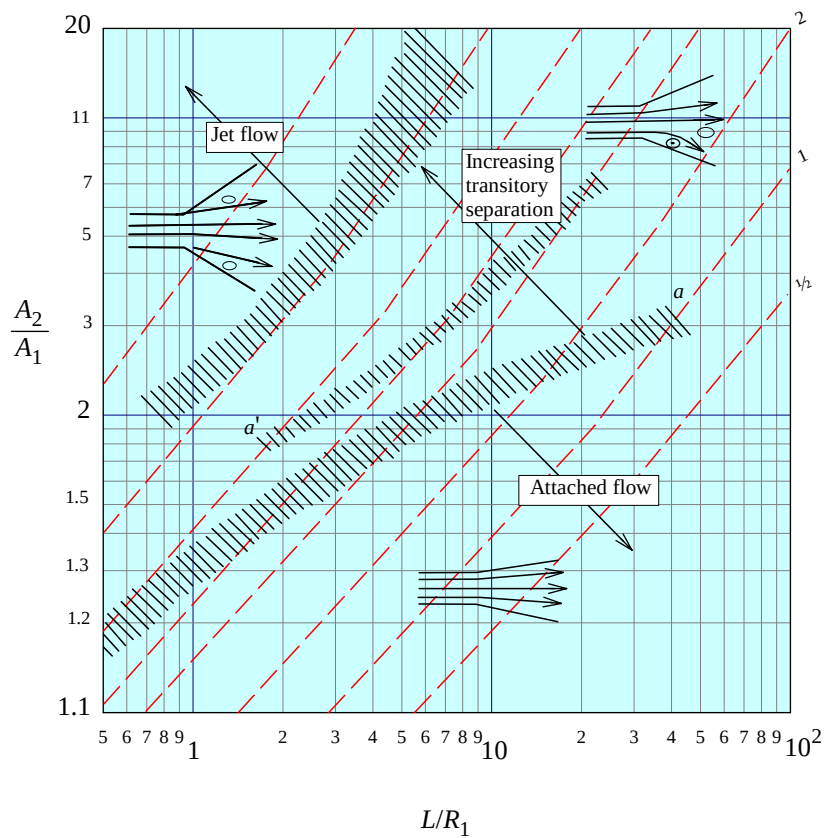


Sketch 3.1 C_{pr} and K_t against wall angle for a conical diffuser of area ratio 3

Sketch 3.1 indicates that a wall angle of approximately 4° gives optimum performance although an impractically long diffuser may result. At wall angles greater than 4° performance is impaired by boundary layer growth and eventual separation.

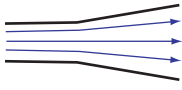
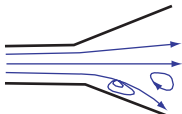
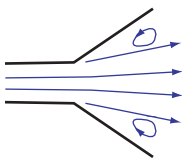
3.2 Outlet Flow Specification

The effects of increasing wall angle on the outlet flow are difficult to quantify. However, a general indication of the state of the flow can be obtained by considering the flow regime in which the diffuser geometry lies. Sketch 3.2 shows the location of the flow regime boundaries from ESDU 73024, as a function of geometry, for conical diffusers with corresponding descriptions of flow given in Table 3.1. Similar flow regime charts for rectangular or annular diffusers can be found in ESDU 74015 or 75026 respectively.



Sketch 3.2 Flow regime boundaries for conical diffusers

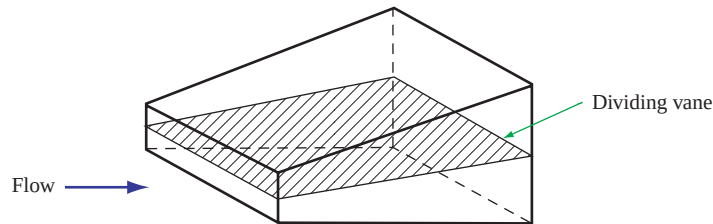
TABLE 3.1 Description of the Flow Regimes Indicated on Sketch 3.2

Flow regime	Descriptions of flow patterns	Sketch	Typical features of outlet conditions
Attached flow (below aa, Sketch 3.2).	Steady flow, attached throughout diffuser.		Similar to inlet conditions but thicker boundary layer.
Transitory separation (between aa and bb, Sketch 3.2).	Separated regions form at walls and move downstream as bubbles, separation intermittent and scattered. Below the boundary of appreciable separation (a'a', Sketch 3.2), separation is on a small scale and is confined mainly to the area near the outlet.		Unsteady flow condition, intermittently asymmetric velocity profile. Outlet conditions deteriorate as geometry moves upwards from the boundary a'a' but below this boundary unsteadiness has little significant effect on overall flow.
Jet flow (above bb, Sketch 3.2).	Flow separates all round a circumference.		Essentially steady conditions, central core surrounded by separated flow annulus.

4. VANES AND SPLITTERS

4.1 Dividing Vanes in Rectangular Diffusers

Dividing vanes are used to split the diffuser into a number of smaller diffusion passages. Each passage is designed to have a modest wall angle resulting in good performance characteristics. The simplest and most effective vane system utilises flat rectangular plates that split the flow as shown in Sketch 4.1.

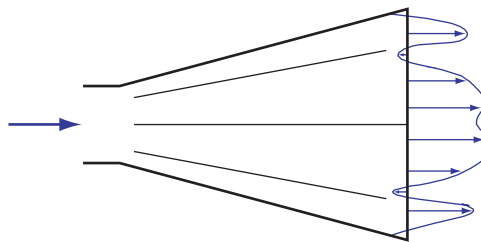


Sketch 4.1 Diffuser with rectangular vane

4.1.1 Effect of vanes on diffuser performance

An indication of the performance improvements attainable using vanes can be obtained from Figure 1. The ratio C_{prI}/C_{prI}^* is obtained from Section 2.3. Although no experimental data were available, an indication of the total-pressure loss can be obtained from Equation (2.3).

The vane passages may give distorted exit velocity profiles as shown in Sketch 4.2.



Sketch 4.2 Typical exit velocity profile resulting from vanes⁷³

4.1.2 Design recommendations for vane systems in rectangular diffusers

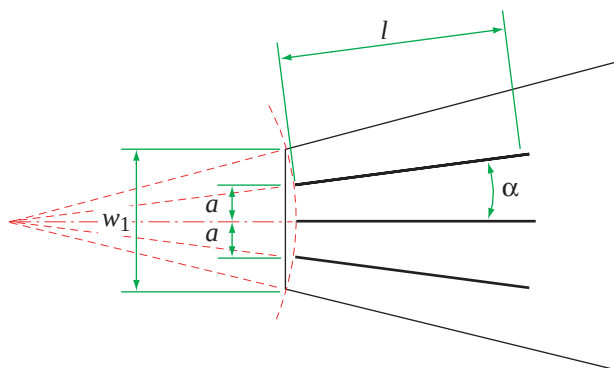
The design recommendations are derived from Derivations 24, 33 and 73 which cover the following geometries and flow conditions.

- (1) Rectangular single-plane expansion diffusers.
- (2) Aspect ratios, b/w_1 , of 1, 6 and 8.
- (3) Area ratios between 1.5 and 6.9.
- (4) Wall angles, ϕ , up to 40° .
- (5) Inlet widths, w_1 , between 76 mm and 305 mm.
- (6) Inlet Reynolds numbers between 2×10^5 and 1×10^6 .
- (7) Inlet blockage parameters, B_1 , between 0.0074 and 0.12.
- (8) Symmetrical inlet velocity profiles.

The optimum vane configuration is insensitive to aspect ratio, Reynolds number and inlet blockage

parameter over the range of reported data. For asymmetric inlet flows the vane passages should be adjusted in order to capture equal mass flow rates, otherwise distorted exit flows will result.

The design recommendations are as follows. The notation is defined in Sketch 4.3.



Sketch 4.3 Rectangular vane parameters

- (1) The vanes should be symmetrically positioned.
- (2) The value of α should be made as close as possible to 7° .
- (3) The spacing of the vanes can be obtained from

$$a = \frac{w_1}{N+1}. \quad (4.1)$$

- (4) The leading edges of the vanes should lie on the radius line drawn through the throat wall intersection.
- (5) The vane length can be calculated from the following equation

$$l = a(12.85 - \alpha)/0.234, \quad (4.2)$$

where α is the vane angle obtained from

$$\alpha = \frac{2\phi}{N+1}. \quad (4.3)$$

If the value of l obtained from Equation (4.2) is larger than the diffuser length, the vanes should extend only to the diffuser exit.

- (6) The vanes should have sharp leading edges and a thickness of the order of 3% to 6% of w_1 is recommended.

4.2 Conical Vanes

When conical vanes are installed in a conical diffuser the resulting geometry is similar to a series of concentric annular diffusers as shown in Sketch 4.4.