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Performance in incompressible flow of plane-walled diffusers with single-plane expansion

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THE PREPARATION OF THIS DATA ITEM

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PERFORMANCE IN INCOMPRESSIBLE FLOW OF PLANE-WALLED DIFFUSERS WITH SINGLE-PLANE EXPANSION

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PERFORMANCE IN INCOMPRESSIBLE FLOW OF PLANE-WALLED DIFFUSERS WITH SINGLE-PLANE EXPANSION

1. NOTATION, UNITS AND DEFINITIONS

Notation and Units

Three coherent systems of units are given below

		SI	British	
A	cross-sectional area of duct	m^2	ft^2	ft^2
B	blockage parameter (see Section 3.2)	—	—	—
b	width of duct between parallel walls of diffuser (see Sketch 1.1)	m	ft	ft
C_{pr}	static-pressure recovery coefficient (see Equation (1.1))	—	—	—
C_{pr}^*	value of C_{pr} attained in a diffuser of optimum area ratio for a given length ratio, L/w_1	—	—	—
C_{pr}^{**}	value of C_{pr} attained in a diffuser of optimum length ratio, L/w_1 , for a given area ratio	—	—	—
K_t	total-pressure loss coefficient (see Equation (1.2))	—	—	—
L	axial length of diffuser (see Sketch 1.1)	m	ft	ft
L_d	length of parallel duct downstream of diffuser (tailpipe) (see Sketch 1.1)	m	ft	ft
L_u	length of parallel duct upstream of diffuser (see Sketch 1.1)	m	ft	ft
Ma	Mach number	—	—	—
m	mass flow rate	kg/s	lb/s	slug/s
p	static pressure	N/m^2	pdl/ft^2	lbf/ft^2
p_t	total pressure (see Equation (1.3))	N/m^2	pdl/ft^2	lbf/ft^2
Re	inlet Reynolds number, $\bar{V}_1 w_1 / \nu_1$	—	—	—
V	local axial flow velocity	m/s	ft/s	ft/s
$\bar{V}$	area-averaged flow velocity, $m/(\rho A)$	m/s	ft/s	ft/s
V_{max}	maximum velocity at a cross section	m/s	ft/s	ft/s

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w	width of duct between diverging walls of diffuser (see Sketch 1.1)	m	ft	ft
α	kinetic energy coefficient, $\frac{1}{\bar{V}^3} \int_A V^3 dA$	—	—	—
δ^*	two-dimensional boundary-layer displacement thickness	m	ft	ft
λ	$(C_{pr} \text{ at given } b/w_1)/(C_{pr} \text{ at } b/w_1 \geq 6)$	—	—	—
ν	fluid kinematic viscosity	m ² /s	ft ² /s	ft ² /s
ρ	fluid density	kg/m ³	lb/ft ³	slug/ft ³
ϕ	divergence angle of one wall of a symmetrical diffuser (i.e. total divergence angle of a symmetrical diffuser = 2ϕ)	degrees	degrees	degrees

Suffixes

1	refers to conditions at diffuser entry
2	refers to conditions at diffuser exit
3	refers to conditions at tailpipe reference point
e	refers to conditions at exit from diffuser or diffuser tailpipe combination

Definitions

The static-pressure recovery coefficient is defined by

$$C_{pr} = \frac{p_e - p_1}{\frac{1}{2}\rho \bar{V}_1^2}, \quad (1.1)$$

and the total-pressure loss coefficient by

$$K_t = \frac{p_{t1} - p_{te}}{\frac{1}{2}\rho \bar{V}_1^2}, \quad (1.2)$$

where suffix e is taken as 2 or 3 according to whether the diffuser has free discharge or tailpipe outlet conditions. The static pressure is assumed constant across sections 1 and 2 or 3 and the total pressure is defined as the mass-averaged value given by

$$p_t = p + \alpha \frac{1}{2}\rho \bar{V}^2. \quad (1.3)$$

The geometry of a typical diffuser and its associated ductwork is shown in Sketch 1.1.



The principal geometrical parameters are related by the equation

and the data in this Item are presented in the form of contours of constant C_{pr} or K_t on a grid of area ratio, A_2/A_1 , and ratio of diffuser length to inlet duct width, L/w_1 . An auxiliary scale of diffuser half-angle, ϕ , is also included.

This Data Item presents information on static-pressure recovery, total-pressure loss and overall flow pattern for fluids flowing through straight-axis, plane-walled diffusers of rectangular section having only one^{*} or two[†] walls diverging. Data are presented for diffusers operating under certain basic conditions noted in Section 3. For other conditions the data available are insufficient to allow more than a general indication of trends to be given in Sections 4 to 6. Examples of the application of the Item are given in Section 7.

The data presented in this Item apply generally for symmetrical diffusers having symmetrical, incompressible ($Ma < 0.2$) entry flow with $Re \geq 5 \times 10^4$ and centre-line turbulence intensity not greater than about 3 or 4[±] per cent. Background information on the derivation of the Figures is given in Sections 4, 5 and 6 which also give guidance on the effects that may be encountered when the conditions above do not apply or when a diffuser geometry lies within the area of a flow regime boundary.

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3.1 Flow Regime Data

The overall flow regime in which a diffuser operates gives an indication of the flow conditions that occur at the outlet. The overall flow regimes for plane-walled diffusers are defined in Table 9.1 and the regime boundaries are given in Figure 1. If the diffuser geometry is within a hatched boundary then Sections 4 to 6 should be consulted for possible effects on the diffuser performance.

3.2 Blockage Parameter

The inlet flow condition covered by this Item, *i.e.* approximately naturally-developed duct flow, can be characterised by use of a blockage parameter or blocked area fraction, B . This is defined as the ratio of the 'blocked area' (due to the presence of boundary layers on the duct walls) to the actual duct area. This ratio may be evaluated* to give

$$B = 1 - \frac{\bar{V}}{V_{max}}. \quad (3.1)$$

For naturally-developing flows the value of the blockage parameter, B_1 , at the inlet to a diffuser may be related approximately to the upstream duct length, L_u/w_1 . The relation does, however, depend on the entry conditions to the upstream duct†. Figure 2 is based mainly on data from Derivation 10 which also provides much of the pressure recovery data. This shows a rate of increase in the blockage parameter that is expected to be typical of normal industrial situations when a diffuser follows a length of straight duct. It should be noted, however, that, in cases where the entry flow to the upstream duct is exceptionally uniform and of very low turbulence, the blockage growth rate may be much more rapid and may take the form shown by the broken line on Figure 2 for a high aspect-ratio duct (Derivation 28).

3.3 Static-Pressure Recovery and Total-Pressure Loss

The data for static-pressure recovery coefficients, C_{pr} , are presented in Figures 4 to 7 for diffusers without tailpipes and in Figure 8 for diffusers with tailpipes. These Figures apply for diffusers with inlet aspect ratio b/w_1 greater than 6 and for values of $b/w_1 < 6$ the correction factor, λ , of Figure 3 should be applied. The appropriate Figure of Figures 4 to 7 for the case considered can be determined from Figure 2 which also gives the blockage parameter, B_1 . The optimum diffuser geometries giving maximum pressure recovery for a given diffuser length and for a given diffuser area ratio, the C_{pr}^* and C_{pr}^{**} lines respectively, are indicated.

The data for total-pressure loss coefficients are given by Figure 9 and Equation (6.2) for diffusers with and without tailpipes respectively and with aspect ratio, $b/w_1 \geq 6$. For $b/w_1 < 6$, Equations (6.4) and (6.2) may be applied, using a value of C_{pr} corrected by reference to Figure 3.

* The blockage parameter can also be expressed in terms of the boundary layer displacement thickness, δ^* . In purely two-dimensional flow, $B = 2(\delta^*/w)$. For three-dimensional flow a knowledge of the variation in δ^* around the duct is desirable but if δ^* is assumed constant then $B = (2(\delta^*/w))(1 + w/b)$.

† Reference 1 discusses this effect for flow in circular ducts.

4. FLOW REGIMES

The overall flow pattern in a plane-walled, single-plane expansion diffuser falls essentially into one of the four main types described in Table 9.1. The boundaries between the regimes, shown in Figure 1, depend on diffuser geometry and on entry flow conditions. The boundaries are shown as hatched bands to allow for uncertainties in the experimental assessment of the operating regimes and some variation from the reference conditions. If the regime of operation is important then a geometry outside the hatched bands should be chosen for the diffuser.

Figure 1 is based principally on data from Derivations 7 and 11 which, together with data from Derivations 8, 16, 17 and 18, suggest that the actual boundaries may be assumed to lie within the upper half of the hatched bands for diffusers with aspect ratio $b/w_1 \geq 1/4$ having symmetrical, incompressible turbulent entry flow with $B_1 < 0.02$ and $Re \geq 5 \times 10^4$. The effect of deviations from these conditions is discussed in the following Sections.

4.1 Turbulent Flow

4.1.1 Variation in location of boundary a–a

Increases in inlet blockage parameter may be expected to move the actual boundary a–a downward within the hatched band. For Re decreasing from 5×10^4 to 5×10^3 the boundary rises about one degree of diffuser half angle, ϕ . A similar rise is suggested at $L/w_1 = 6$ for a very low aspect ratio diffuser, $b/w_1 = 1/10$, by data in Derivation 25. Increase in inlet turbulence intensity tends to rotate the boundary in a clockwise sense about a point near $L/w_1 = 10$ but the data suggest that the hatched band covers the variations for intensities in the range 1 to 5 per cent.

4.1.2 Variation in location of boundary b–b

Increases in inlet blockage parameter may again be expected to move the actual boundary b–b downward within the hatched band. Increases in inlet turbulence intensity from about 1 per cent to 5 per cent move the boundary upwards right across the hatched band (Derivation 7) but data for conical diffusers suggest that the effect levels out for intensities around the higher value. Few data were found on the effect of change of Reynolds number but they suggest that for Re decreasing from 5×10^4 to 5×10^3 the boundary b–b is lowered by about 2 degrees of diffuser half angle, ϕ , (Derivation 7). For changes in Re at higher values, pressure recovery data in Derivations 24 and 26 may be interpreted to imply that the boundary b–b is raised significantly by increase in Re in the range $10^5 < Re < 5 \times 10^5$. Data for $L/w_1 = 6$ from Derivation 25 suggest that between $b/w_1 = 1/4$ and $b/w_1 = 1/10$ the boundary b–b is lowered by about 2 degrees of diffuser half angle.

4.1.3 Variation in location of boundary c–c

No data were found from which to assess the effect of variation in flow parameters on the boundary c–c.

4.2 Laminar Flow

For laminar flow the data of Derivation 22 suggest that the boundaries a–a and c–c of Figure 1 apply but a clearly defined two-dimensional separation regime is not apparent. For geometries from the boundary a–a upwards, two-dimensional separation occurs on one diverging wall but is accompanied by transitory three-dimensional separation from the other diverging wall.

5. STATIC-PRESSURE RECOVERY

Static-pressure recovery coefficients are presented in Figures 4 to 7 for high inlet aspect ratio ($b/w_1 \geq 6$) diffusers without tailpipes and with varying entry flow conditions. Figure 8 presents the coefficients for diffusers with tailpipes. A correction factor, λ , for the effect of varying inlet aspect ratio, *i.e.* varying b/w_1 , is given in Figure 3. These Figures apply basically for incompressible ($Ma < 0.2$), symmetrical inlet flow with Re greater than about 5×10^4 . The geometries for optimum pressure recovery are shown by the C_{pr}^* (optimum for a given diffuser length ratio, L/w_1) and C_{pr}^{**} (optimum for a given area ratio, A_2/A_1) lines on the Figures. Whilst the C_{pr}^* line is quite closely defined by the contours, diffuser geometries over a range of L/w_1 near the C_{pr}^{**} line give substantially the same C_{pr} value. The effects on pressure recovery of various geometrical and flow parameters are discussed in the following Sections.

5.1 Diffusers without Tailpipes

The performance of diffusers without tailpipes is influenced by the condition of the inlet flow. The contours shown in Figures 4 to 7 are based on data for conditions approximating* naturally-developing duct flow, for which condition C_{pr} can be correlated approximately with the inlet blockage parameter, B_1 . Figures 4 to 7 show static-pressure recovery coefficient contours for several ranges of values of B_1 . The appropriate Figure can be determined either directly from a knowledge of the value of B_1 or from Figure 2 which indicates the ranges of entry length ratio, L_u/w_1 , for which Figures 4 to 7 apply.

At the flow regime boundary between two-dimensional separation and jet flow a step change in C_{pr} occurs. In the jet flow regime C_{pr} is approximately constant at a value of about 0.25.

The values of C_{pr} given in Figures 4 to 7 are average values for the specified range of B_1 . Within each range of B_1 the actual value of C_{pr} varies with B_1 but is within ± 10 per cent of the average values.

The data of Figures 4 and 5 are estimated to be within ± 0.05 in C_{pr} except that the uncertainty increases in the region of the flow regime boundaries b-b and c-c due to uncertainty in the regime boundaries. Figures 6 and 7 are subject to larger uncertainty as few data are available for these conditions. Figures 3 to 6 are based on data from Derivations 6, 8, 9, 10 and 13, while Figure 7 is a tentative extrapolation from Figures 3 to 6 supported by data from Derivation 19.

The shape of the contours in the region below the C_{pr}^* line is thought to arise from interactions between the secondary flow in the rectangular cross section and the initial transitory separation.

5.2 Diffusers with Tailpipes

When a diffuser is fitted with a tailpipe the effect on C_{pr} of variations in inlet conditions is considerably reduced, provided that the tailpipe is long enough for more or less complete pressure recovery to take place. In general, for diffusers with naturally-developing inlet flow, a tailpipe length, L_d , of about $4w_2$ will allow full pressure recovery but for some geometries in the two-dimensional separation regime longer tailpipes may be required.

Figure 8 presents pressure recovery contours for diffuser-tailpipe combinations where L_d lies between $4w_2$ and $8w_2$. Few data were available (Derivations 3, 4, 18 and 19) and it has been assumed that, as for conical diffusers, there is no significant variation in C_{pr} with inlet conditions or with tailpipe length in the range $4 \leq L_d/w_2 \leq 8$. In view of the considerable interpolation and extrapolation required to produce it, Figure 8 should be regarded as tentative.

* In most cases the upstream duct included a trip wire to ensure a turbulent boundary layer at the diffuser entry.