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THE PREPARATION OF THIS DATA ITEM

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PERFORMANCE OF CONICAL DIFFUSERS IN SUBSONIC COMPRESSIBLE FLOW

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PERFORMANCE OF CONICAL DIFFUSERS IN SUBSONIC COMPRESSIBLE FLOW

1. NOTATION

		SI Units
A	flow area	m^2
A_E	effective flow area, $\int_A \frac{\rho v dA}{\rho_0 v_0}$	m^2
B	blockage ratio, $(A - A_E)/A$ (approximately $2\delta^*/R$ for thin boundary layers)	—
b	ratio of one-dimensional static pressure, p , to entropy-mean static pressure, p , see Section 2.4	—
c_p	specific heat capacity at constant pressure	J/kg K
c_v	specific heat capacity at constant volume	J/kg K
C_{pr}	static pressure recovery coefficient, see Section 2.4 and Table 2.1	—
C_{pr}^*	optimal value of C_{pr} for given length ratio L/R_1	—
C_{pr}^{**}	optimal value of C_{pr} for given area ratio A_2/A_1	—
D	diameter	m
H	boundary layer shape parameter, δ^*/θ	—
I	local turbulence intensity, q/v	—
I_G	diffuser inlet turbulence parameter, $\frac{1}{V_0} \left[\frac{\int_0^R \rho v q^2 r dr}{\int_0^R \rho v r dr} \right]^{1/2}$	—
K_t	total-pressure loss coefficient, see Section 2.4	—
K_t^*	minimum value of K_t for given length ratio L/R_1	—
K_t^{**}	minimum value of K_t for given area ratio A_2/A_1	—
L	axial length of diffuser	m
L_d	length of straight, parallel duct downstream of diffuser (tailpipe)	m
L_u	length of straight, parallel duct upstream of a point $1.5D_1$ from diffuser, see Sketch 2.1	m

M	Mach number	—
m	total mass flow rate	kg/s
p	static pressure	N/m ² (Pa)
p_t	total pressure	N/m ² (Pa)
q	turbulence velocity, $[\overline{v_x'^2} + \overline{v_y'^2} + \overline{v_z'^2}]^{1/2}$, where v_x', v_y', v_z' are orthogonal components; often only component in x -direction, v_x' , is known, in which case, assuming isotropy, $q \approx [3\overline{v_x'^2}]^{1/2}$.	m/s
R	radius	m
r	local radius	m
R_g	gas constant (= 287.1 for air)	J/kg K
Re	Reynolds number, $\overline{V}_1 D_1 / \nu_1$	—
T	static temperature	K
T_t	total temperature	K
V	velocity in one-dimensional flow	m/s
$\overline{V}$	area averaged mean velocity, $m/\rho A$	m/s
v	local velocity	m/s
$\overline{v}$	time mean local velocity	m/s
x	axial coordinate	m
y	coordinate normal to duct wall	m
α	kinetic energy coefficient, see Section 2.4	—
β	momentum coefficient, see Section 2.4 and Table 2.1	—
γ	ratio of specific heat capacities, c_p/c_v	—
δ^*	boundary-layer displacement thickness, $\int_0^R \left[1 - \frac{\rho v}{\rho_0 v_0}\right] \frac{r}{R} dr$	m
θ	boundary-layer momentum thickness, $\int_0^R \frac{\rho v}{\rho_0 v_0} \left[1 - \frac{v}{v_0}\right] \frac{r}{R} dr$	m
η	diffuser efficiency (see Section 2.4 and Table 2.1); sometimes called effectiveness or conversion efficiency	—
μ	dynamic viscosity	N s/m ²

ν	kinematic viscosity	m^2/s
ρ	fluid density	kg/m^3
ϕ	angle between diffuser wall and diffuser axis (total angle = 2ϕ)	degree

Subscripts

e	exit plane of diffuser and tailpipe, see Sketch 2.1
0	mainstream or outside boundary layer
opt	optimum value
t	total or stagnation conditions
1	inlet plane of diffuser ($1.5D_1$ upstream of pipe-cone junction, see Sketch 2.1)
2	exit plane of diffuser, see Sketch 2.1

Superscript

$'$	time dependent variable
-----	-------------------------

Mean variables are denoted by a bar over a symbol, for example, $\bar{p}_t$; the type of mean is important and is identified in the text.

2. INTRODUCTION

2.1 Purpose and Scope of this Data Item

This Data Item enables static pressure recovery to be predicted and total-pressure loss and flow pattern* estimated for subsonic compressible flow through straight-axis conical diffusers (right cones). The effects of various geometrical and flow parameters on diffuser performance are discussed. By selection of a geometry it enables a subsonic diffuser of required performance to be designed or, alternatively, enables the performance of a diffuser of specified geometry to be assessed.

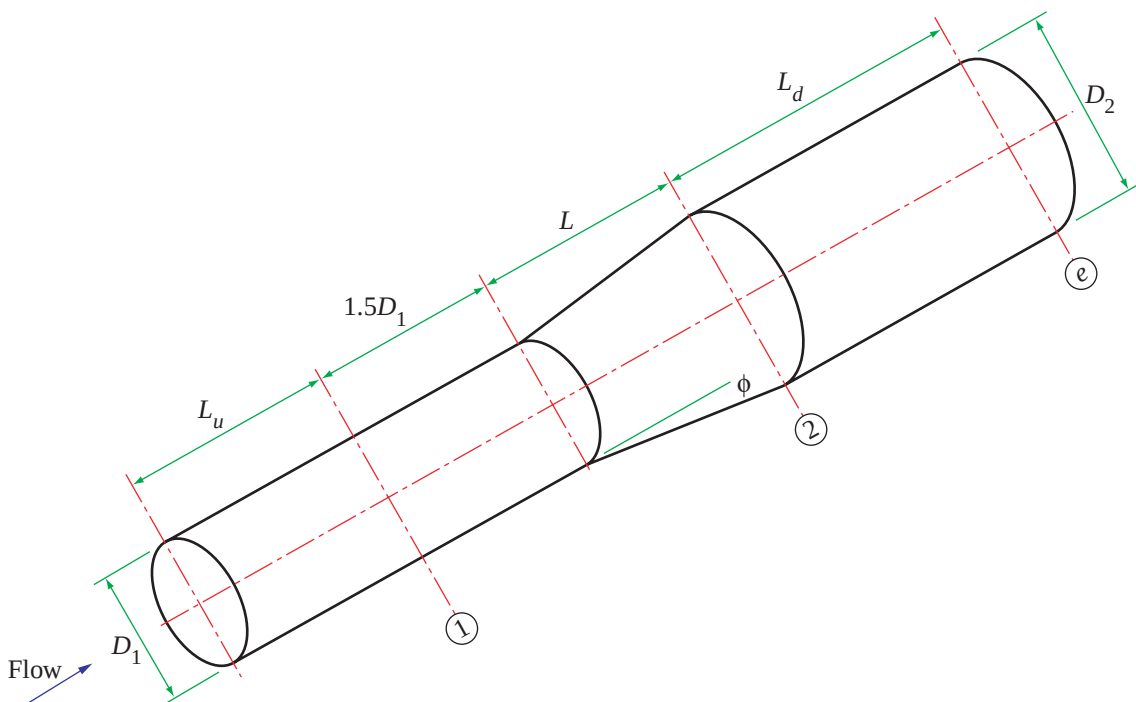
Performance is considered primarily in terms of static pressure rise for a range of entry mean Mach numbers, $0.2 \leq \bar{M}_1 \leq 0.8$, and a range of entry duct lengths, $0 \leq L_u/D_1 \leq 36$.

Other influences such as Reynolds number, velocity profile shape, turbulence level, shock-wave/boundary layer interaction upstream of the diffuser and the approach to choking are considered as a guide to understanding the behaviour and performance of such diffusers and as an aid to design or performance assessment.

Guidance on the estimation of total-pressure loss from static pressure rise is given.

2.2 Diffuser Geometry

The geometry of a typical conical diffuser and its associated ductwork is shown in Sketch 2.1. For the case of a diffuser with free discharge the diffuser exit plane 2 forms the end of the system.



Sketch 2.1 Typical conical diffuser geometry

* Flow pattern refers to flow regime and velocity profile.

The principal geometrical parameters are related by

$$\frac{A_2}{A_1} = \left[1 + \frac{L}{R_1} \tan \phi \right]^2 \quad (2.1)$$

and the performance maps in this Item are presented in the form of contours of C_{pr} on an orthogonal grid of area ratio, A_2/A_1 , and the ratio of diffuser length to inlet duct radius, L/R_1 , with lines of constant diffuser total angle, 2ϕ , as an auxiliary scale.

2.3 Background Information

ESDU 76027¹ gives a comprehensive introduction to the design and performance of diffusers generally and ESDU 73024², 74015³⁰ and 75026³¹ give detailed performance data for conical, plane-walled and annular diffusers. ESDU 87015³ considers methods of performance improvement. However, these Items are only applicable to incompressible flow.

A user coming to this Data Item without previous knowledge of diffuser behaviour and performance is directed to the first two Data Items above (and to the final one if seeking performance improvement). The user should first become familiar with diffuser function, regime behaviour, performance parameters (static pressure recovery coefficient, C_{pr} , total-pressure loss coefficient, K_t , efficiency or effectiveness, η , and kinetic energy coefficient, α), optimality defined by C_{pr}^* , C_{pr}^{**} , K_t^* and K_t^{**} , insufficient and inefficient diffusion and the influence of inlet flow conditions. A good understanding and familiarity with one-dimensional gas dynamics is also required.

In this Data Item the influence of compressibility (implied by inlet Mach numbers greater than about 0.2) and the spatial non-uniformity of the flows involved necessitates a formal reconsideration of the definitions of performance parameters with particular reference to total-pressure losses. Also required is the establishment, and understanding of the implications, of suitable mean-variable systems used in the one-dimensional description of the spatially non-uniform compressible flows involved.

2.4 Performance Parameters

Table 2.1 defines the performance parameters, static pressure recovery coefficient, C_{pr} , total-pressure loss coefficient, K_t , and diffuser effectiveness, η , in terms of mean flow variables.

The first column of the Table shows the parameter definitions for one-dimensional incompressible flow.

The second column shows the definitions for incompressible, spatially non-uniform flow. The density is constant and the static pressure is assumed uniform across the duct at measurement stations 1 and e . However the velocity varies across the duct and a simple mean variable set is required. The incompressible flow model is essentially isothermal and of constant density. The set of mean variables is

$$\bar{\rho} = \rho = \bar{\rho}_t, \quad \bar{p} = p, \quad \bar{T} = T \equiv T_t, \quad \bar{V}, \quad \alpha, \quad \beta.$$

The mean velocity, $\bar{V}$, is defined as

$$\bar{V} = \frac{1}{A} \int_A v dA. \quad (2.2)$$

The mean static pressure, $\bar{p}$, is given by

$$\bar{p} = p,$$

the measured static pressure for the one-dimensional parallel flow.

The mean total pressure, $\bar{p}_t$, is mass weighted, giving

$$\bar{p}_t = \frac{1}{m} \int_A p_t dm \quad (2.3)$$

or
$$\bar{p}_t = \frac{1}{m} \int_A (p + \frac{1}{2} \rho v^2) dm,$$

which can be also expressed as

$$\bar{p}_t = \bar{p} + \alpha \frac{1}{2} \rho \bar{V}^2, \quad (2.4)$$

where the kinetic energy coefficient, α , is given by

$$\alpha = \frac{1}{\frac{1}{2} m \bar{V}^2} \int_A \frac{1}{2} v^2 dm. \quad (2.5)$$

TABLE 2.1 Diffuser Performance Parameters

	Incompressible One-Dimensional Spatially Uniform	Incompressible Spatially Non-Uniform	Compressible Spatially Non-Uniform
	ρ constant $\bar{p} \equiv p; C_{pr} \leq 1; \alpha \equiv 1$ $\bar{p}_t = p + \frac{1}{2}\rho V^2$	ρ constant $\bar{p} \equiv p; C_{pr} \leq 1; \alpha \neq 1$ $\bar{p}_t = \frac{1}{m} \int_A p_t dm$	ρ varies $\bar{p} \neq p; C_{pr} \leq 1; \alpha \neq 1$ $\log_e \bar{p}_t = \frac{1}{m} \int_A \log_e p_t dm$
C_{pr}	$\frac{p_e - p_1}{\frac{1}{2}\rho V_1^2}$	$\frac{p_e - p_1}{\frac{1}{2}\rho \alpha_1 (\bar{V}_1)^2}$	$\frac{\bar{p}_e - \bar{p}_1}{\bar{p}_{t1} - \bar{p}_1}$
K_t	$\frac{p_{t1} - p_{te}}{\frac{1}{2}\rho V_1^2}$	$\frac{\bar{p}_{t1} - \bar{p}_{te}}{\frac{1}{2}\rho \alpha_1 (\bar{V}_1)^2}$	$\frac{R_g T_t \log_e (\bar{p}_{t1} / \bar{p}_{te})}{\frac{1}{2}\alpha_1 (\bar{V}_1)^2}$ * $\equiv \frac{\text{Irreversibilities}}{\text{Inlet kinetic energy flux}}$
η	$\frac{p_e - p_1}{\frac{1}{2}\rho V^2 [1 - (A_1 / A_2)^2]}$ $\equiv \frac{\text{Actual } \Delta p}{\text{Ideal } \Delta p}$	$\frac{p_e - p_1}{\frac{1}{2}\rho [\alpha_1 (\bar{V}_1)^2 - \alpha_e (\bar{V}_e)^2]}$ $\equiv \frac{\text{Actual } \Delta p}{\text{Ideal } \Delta p}$	$1 - \frac{R_g T_t \log_e (\bar{p}_{t1} / \bar{p}_{te})}{\frac{1}{2}[\alpha_1 (\bar{V}_1)^2 - \alpha_e (\bar{V}_e)^2]}$ $\equiv 1 - \frac{\text{Irreversibilities}}{\text{Kinetic energy conversion}}$
$\frac{1}{m} \int_A \frac{1}{2} v^2 dm = \alpha_{\frac{1}{2}} (\bar{V})^2; \quad \frac{1}{m} \int_A v dm = \beta \bar{V}; \quad K_t = (1 - \eta) [1 - \alpha_e (\bar{V}_e)^2 / \alpha_1 (\bar{V}_1)^2].$			

* See Section 3.6 for more conventional K_t definition.

The kinetic energy coefficient, α , is a convenient lumped parameter enabling the kinetic energy flux to be described in terms of the other mean variables without the use of integral forms. A coefficient, β , describing momentum flux, is written similarly as

$$\beta = \frac{1}{m \bar{V}} \int_A v dm. \quad (2.6)$$

The third column of Table 2.1 shows the definitions of diffuser performance parameters for compressible, spatially non-uniform flow; here a more complicated mean-variable system is required, see Derivations 4, 5 and 6. Note that now density varies so that $\bar{\rho}_t > \bar{\rho}$ and also $\bar{p} \neq p$. The mean total-pressure, p_t , is defined as a mass weighted logarithmic mean,

$$\log_e \bar{\rho}_t = \frac{1}{m} \int_A \log_e p_t dm, \quad (2.7)$$

which ensures conservation of entropy flux (see Derivation 4).

The compressible flow model is adiabatic, of constant total temperature $\bar{T}_t = T_t$ and specific heat capacities (γ is constant), and the flow is assumed parallel and of constant static pressure at a cross section. These assumptions are consistent with an adiabatic gas flow of constant Prandtl number* equal to unity and are considered valid for Prandtl numbers near to unity, for example, air. The set of mean variables is

$$\bar{\rho}, \bar{\rho}_t, \bar{p}, \bar{p}_t, \bar{T}, T_t, \bar{V}, \bar{M}, \alpha, \beta, b.$$

The Mach number, M , is introduced as a derived fundamental variable, important in recognising the influence of compressibility effects. The quantity b recognises that $\bar{p} \neq p$, the assumed constant static pressure, by writing $p = b\bar{p}$. Consideration of flows with variable T_t , p and γ is found in Derivations 4 and 7.

In the third column of Table 2.1, the term $R_g T_t \log_e [\bar{p}_{t1} / \bar{p}_{te}]$ represents the specific energy equivalent of the irreversibilities arising in the diffuser flow. The definitions of C_{pr} , K_t and η reduce systematically from right to left to the definitions in the second and first columns, as firstly the density is assumed constant and as secondly the flow is assumed to be spatially uniform (rigorously one-dimensional).

Note also the definitions of C_{pr} in columns two and three include in the denominator the difference between the total pressure $\bar{p}_{t1}$ and the static pressure $\bar{p}_1$. It is thus ensured that $C_{pr} \leq 1$ and these definitions differ in this respect from those in earlier Data Items.

In the lowest compartment of Table 2.1 will be found the relationship between K_t and η ,

$$K_t = (1 - \eta) \left[1 - \frac{\alpha_e (\bar{V}_e)^2}{\alpha_1 (\bar{V}_1)^2} \right]. \quad (2.8)$$

This is a complicated relationship in general terms, depending on the ratio of the kinetic energy fluxes at exit and inlet. The approximate relationship,

$$K_t = (1 - \eta),$$

applies only when $\bar{V}_e \rightarrow 0$ (very large A_e) or if the exit kinetic energy is lost by free discharge. See also the discussion in Sections 2.3.2 and 2.3.4 of ESDU 76027¹ on the implications of high α_e in Equation (2.8) implying low K_t (note that high α_e also implies low C_{pr}) and on the distinction between insufficient and inefficient diffusion.

* The Prandtl number of a fluid is defined as (dynamic viscosity $\times$ specific heat capacity at constant pressure) / thermal conductivity.

2.5 How to Use this Data Item

- (i) Users unfamiliar with diffuser performance should refer to the Data Items mentioned in Section 2.3 for a general discussion of diffuser behaviour.
- (ii) Proceed to the maps in Section 3.3 to obtain values of C_{pr} and other unknown parameters.
- (iii) Follow the steps in either of the two worked examples given, as appropriate.
- (iv) Proceed to Sections 4 and 5 for consideration of other possible influences.
- (v) Assess resultant design or performance.
- (vi) Re-assess the design or performance in terms of static pressure rise and total-pressure loss.

3. PERFORMANCE DEPENDENCE ON INLET GEOMETRY AND MACH NUMBER

3.1 The Diffuser Inlet Condition

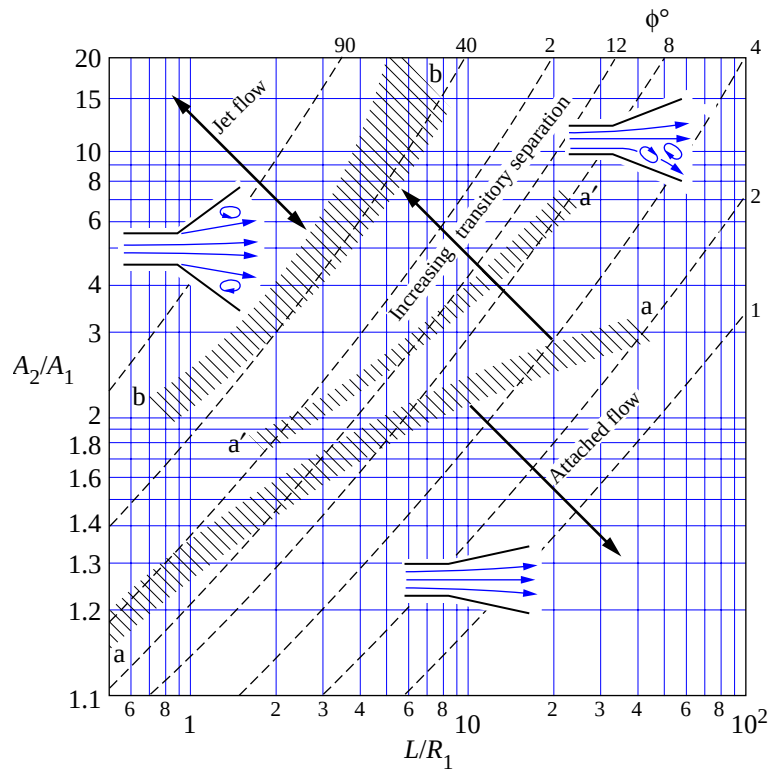
Conical diffuser design involves determining one of the two main geometrical parameters (length or area ratio) if the other is given. The optimum value of that parameter is considered to be the one yielding the maximum pressure recovery, minimum internal losses, and least non-uniform velocity profile at the diffuser exit. Compromise may be necessary.

For the proper design of a diffuser, its inlet flow condition needs to be known or estimated. This is defined in terms of five flow parameters: the inlet mean Mach number, M_1 , Reynolds number, Re , boundary layer blockage ratio, B_1 , shape parameter, H_1 , and turbulence level^{14,26}. A minimum of three input parameters are needed. The inlet Mach number must always be known but the inlet Reynolds number is found to have little influence on diffuser performance so long as the boundary layer at inlet is turbulent^{9,25} (but see Section 4.1). Of the other parameters, B_1 and I_G are the more important. Typical values of B_1 and I_G for developing pipe flow are given in Figures 1 and 2 respectively. Figure 1 indicates that compressibility has no significant effect on the value of the blockage ratio, B_1 , with deviations from the incompressible correlation showing no definite trend. However, Figure 2 shows clearly that bigger values of I_G are expected for compressible flow. For naturally-developing pipe flow, the design situation is simply defined in terms of L_u/D_1 and the entry Mach number.

The performance of a diffuser is normally evaluated from measurements in its inlet plane, which is strictly the plane of geometrical transition from the parallel pipe to diffuser, and its exit plane. However, the geometrical transition, especially when it is sharp, creates a non-uniform static pressure distribution across the plane of geometrical transition which, in addition to the strong streamline curvature effects there, makes measurements difficult to analyse. To avoid this difficulty, it is usual to take the diffuser inlet section some distance upstream of the geometrical transition, thus avoiding the effects of flow instabilities and unsteadiness in the transition plane and, more importantly, attributing the transition losses to the diffuser. In the majority of the sources of data, Derivations 10 to 14, this distance was **1.5 pipe diameters** and accordingly it was selected as the basis for the performance maps presented in this Data Item. Data from other sources, where different distances were used, were corrected to allow for notional frictional pressure drop in the entry region.

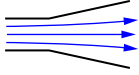
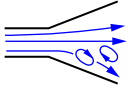
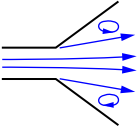
3.2 Outlet Flow Specification

The state of the outlet flow depends on the geometry. Sketch 3.1, taken from ESDU 73024², shows the location of the flow regime boundaries as a function of geometry with corresponding descriptions of the flow given in Table 3.1. No experimental data are available on the influence of Mach number on the regime boundaries. Theoretically, the expectation would be that the lower end of aa would move lower (leaving the upper end of aa little affected) and $a'a'$ would move nearer to aa for inlet Mach numbers significantly greater than 0.2.



Sketch 3.1 Flow regime boundaries for conical diffusers

TABLE 3.1 Description of Flow Regimes indicated on Sketch 3.1

Flow regime	Description of flow patterns	Sketch	Typical features of outlet conditions
Attached flow (below aa , Sketch 3.1).	Steady flow, attached throughout diffuser.		Similar to inlet conditions but thicker boundary layer.
Transitory separation (between aa and $b b$, Sketch 3.1).	Separated regions form at walls and move downstream as bubbles, separation intermittent and scattered. Below the boundary of appreciable separation ($a'a'$, Sketch 3.1), 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 3.1).	Flow separates all round a circumference.		Essentially steady conditions, central core surrounded by separated flow annulus.

3.3 Performance Maps

Figures 3 to 18 give the pressure recovery coefficient contours for a wide range of subsonic inlet Mach numbers and inlet pipe lengths for steady, non-swirling subsonic flow in conical diffusers with naturally-developing boundary-layer type inlet flow and with tailpipes but with the exit measuring station at the end of the divergence. The effect on performance of different conditions is discussed in Section 4.

The maps were constructed using experimental data from Derivations 8 to 17, together with the correlated data from Derivation 2. The data were corrected as necessary to allow for variations in the definition of C_{pr} and the system used to obtain mean values, and for the differences in the distance upstream of the entrance corner where inlet conditions were measured. If a reported C_{pr} value for a specific geometry and inlet condition was found to be more than 30% in deviation from the bulk of the data for that geometry under comparable inlet conditions, that data point was excluded.

The maps show a general deterioration in diffuser performance as the inlet Mach number increases, especially for the case of longer inlet pipes (larger inlet boundary layer blockage). For example, Figure 18 shows that, with $\bar{M}_1 = 0.8$ and $L_u/D_1 > 30$, it is impossible to obtain $C_{pr} = 0.75$ with a diffuser of any length or area ratio.

Moreover, the maps indicate that whatever the diffuser inlet conditions ($\bar{M}_1$ and B_1) might be, the best overall pressure recovery is always in the region of area ratio $A_2/A_1 = 7$ to 10 and $L/R_1 = 38$ to 44, which corresponds to a diffuser total angle of 5 to 6°. In practice, the designer can seldom design for the best overall performance because of constraints such as a fixed area ratio or a fixed length.

On each of the sixteen maps presented, two important design lines are shown as broken lines. The C_{pr}^* line is the locus of points that define the diffuser area ratio producing maximum pressure recovery in a diffuser of prescribed non-dimensional length. If this area ratio is not attained, the length of the diffuser

will be excessive and the surface friction unnecessarily high, whereas if it is exceeded premature separation will result. The C_{pr}^{**} line is the locus of points that define the diffuser non-dimensional length producing maximum pressure recovery in a diffuser of prescribed area ratio.

In almost all the maps, the C_{pr}^* line lies above the line of first appreciable stall, while with moderate area ratios near to 2 both the C_{pr}^* and C_{pr}^{**} lines extend into the transitory stall region. This means that optimum performance is obtained with unsteady stall within the diffuser, and the designer must be aware of possible implications at other points in the flow system.

The designer may thus need to choose a performance that is not optimum in the interests of achieving flow steadiness and less sensitivity to inlet conditions.

3.4 How to Use the Maps

Three design cases are considered as follows.

Case I. To determine diffuser performance for known inlet conditions and known geometry.

Select the appropriate map for the given inlet conditions, interpolating, if necessary, for L_u/D and M .

Read off the expected pressure recovery coefficient, C_{pr} , for the geometrical parameters and review how far the design is off the optimum geometry for these inlet conditions.

Note: Diffuser performance may, of course, be predicted over a range of inlet Mach numbers, if desired, by using the appropriate performance maps for the given geometry.

Case II. To determine optimum diffuser for known inlet conditions with constrained length.

Select the appropriate map for the given inlet conditions, interpolating, if necessary, for L_u/D and M .

At the specified value of L/R_1 , the optimum area ratio can be obtained from the C_{pr}^* line. The optimum diffuser angle can be interpolated or obtained more accurately from the relation

$$\phi = \tan^{-1} \left[\frac{\sqrt{(A_2/A_1)} - 1}{L/R_1} \right]. \quad (3.1)$$

The maximum pressure recovery coefficient, C_{pr} , to be expected can be interpolated from the values on the contour lines.

Case III. To determine optimum diffuser for known inlet conditions with fixed area ratio.

Select the appropriate map for the given inlet conditions, interpolating, if necessary, for L_u/D and M .

At the specified value of A_2/A_1 , the optimum diffuser length can be obtained from the C_{pr}^{**} line. The optimum diffuser angle can be interpolated or obtained from Equation (3.1).

The maximum pressure recovery coefficient, C_{pr} , to be expected can be interpolated from the values on the contour lines.