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Compressible flow of gases

Pressure losses and discharge coefficients of orifice plates, perforated plates and thick orifice plates in ducts

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THE PREPARATION OF THIS DATA ITEM

The work of the permanent professional staff of the Engineering Sciences Data Unit on this particular Item was monitored and guided by the Internal Flow Panel which had the following constitution

Chairman	
Mr N.G. Worley	— Babcock Power Ltd
Members	
Mr J. Bacon	— Rolls-Royce Ltd, Derby
Mr J. Campbell	— Ove Arup Partnership
Dr D.J. Cockrell	— Leicester University
Mr D.H. Freeston*	— Auckland University, New Zealand
Dr G. Hobson	— GEC Turbine Generators Ltd, Rugby
Prof. J.L. Livesey	— Salford University
Mr D.S. Miller	— British Hydromechanics Research Association
Mr B. Payne	— Kellogg International Corporation
Dr D. Pollard	— GEC Power Engineering Ltd, Whetstone.

* Corresponding Member

The Internal Flow Panel has benefited from the participation of members from several engineering disciplines. In particular, Dr G. Hobson has been appointed to represent the interests of mechanical engineering as the nominee of the Institution of Mechanical Engineers and Mr B. Payne has been appointed to represent the interests of chemical engineering as the nominee of the Institution of Chemical Engineers.

The work on this Item was carried out in the Internal Flow and Physical Properties Group of the Engineering Sciences Data Unit under the supervision of Mr R. Partington, Group Head. The member of staff who undertook the technical work involved in the initial assessment of the available information and the subsequent development of the Item was

Mrs L.I. Kurtul	— Engineer.
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The computer program was written by

Dr S.A. Logan	— Engineer.
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with the assistance of Mr D.T.L. Richards.

The person with overall responsibility for the work in this subject area is Dr F. Iudicello, Head of Fluid Mechanics, Internal Flow Group.

The ESDU Fluid Mechanics, Internal Flow Series is recognised as a valuable source of validated data and methods by the Institution of Mechanical Engineers and its Thermofluids Group is involved in continually reassessing the scope and focus of the content of this Series.

COMPRESSIBLE FLOW OF GASES PRESSURE LOSSES ACROSS ORIFICE PLATES, PERFORATED PLATES AND THICK ORIFICE PLATES IN DUCTS

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COMPRESSIBLE FLOW OF GASES

Pressure losses across orifice plates, perforated plates and thick orifice plates in ducts

1. NOTATION AND UNITS

		SI Unit
A	cross-sectional area	m^2
A_f	total area of openings in plate	m^2
A_u	cross-sectional area of duct in which plate is placed	m^2
a	speed of sound in fluid	m/s
C_D	discharge coefficient of orifice or plate (ratio of actual mass flow to maximum that could be passed through total orifice area, A_f , at theoretical velocity obtained for appropriate pressure ratio)	—
$C_{D\alpha \approx 0}$	value of C_D when $\alpha \approx 0$	—
C_D^*	mean value of C_D that gives maximum mass flow rate ($C_D^* = q_2^*/q_{crit}$)	—
D	diameter of circular duct or equivalent diameter of non-circular duct ($4A_u/\text{perimeter}$)	m
d	diameter or equivalent diameter of orifice (diameter of inner surface of orifice) or of one hole in perforated plate	m
K_i	pressure-loss coefficient for incompressible flow, based on upstream kinetic pressure, $\frac{1}{2}\rho_1 V_1^2$	—
K'_i	pressure-loss coefficient for incompressible flow, based on kinetic pressure at entry to orifice, $\frac{1}{2}\rho_2 V_2^2$ ($K'_i = \alpha^2 K_i$)	—
K_t	total-pressure loss coefficient, based on upstream kinetic pressure, $\frac{1}{2}\rho_1 V_1^2$	—
K'_0	value of K'_i corresponding to $t/d = 0$	—
$K'_{0.8}$	value of K'_i corresponding to $t/d = 0.8$	—
k_s	static-pressure drop coefficient, based on dynamic pressure at entry to orifice, $k_s = \Delta p_s / (p_{t2} - p_2)$	—
k_t	total-pressure loss coefficient, based on dynamic pressure at entry to orifice, $k_s = \Delta p_t / (p_{t2} - p_2)$	—
M	mean Mach number	—

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M_2^*	mean Mach number at entry to orifice that gives maximum mass flow rate	–
m	rate of mass flow through duct	kg/s
p	static pressure	N/m ²
Δp_s	static-pressure drop due to plate (see Sketch 4.1)	N/m ²
p_t	total pressure	N/m ²
Δp_t	total-pressure loss due to plate	N/m ²
q	mass flow function based on total pressure, p_t	–
	$\left(q = \frac{m \sqrt{RT_t}}{Ap_t} = \sqrt{\gamma} M \left(1 + \frac{(\gamma-1)}{2} M^2 \right)^{-\frac{1}{2} \left(\frac{\gamma+1}{\gamma-1} \right)} \right)$	
q_{crit}	critical mass flow function evaluated for $M = 1$	–
	$\left(q_{crit} = \sqrt{\gamma} \left(\frac{\gamma+1}{2} \right)^{-\frac{1}{2} \left(\frac{\gamma+1}{\gamma-1} \right)} \right)$	
q_2^*	mean mass flow function at entry to orifice that gives maximum mass flow rate (see Section 3.1)	–
	$\left(q_2^* = \sqrt{\gamma} M_2^* \left(1 + \frac{(\gamma-1)}{2} M_2^{*2} \right)^{-\frac{1}{2} \left(\frac{\gamma+1}{\gamma-1} \right)} \right)$	
R	gas constant	J/(kg K)
Re_d	Reynolds number based on hole diameter and mean velocity at entry to holes, $md/A_u \alpha \mu_1 (= V_1 d / \alpha \nu_1)$	–
T	static temperature	K
T_t	total temperature	K
t	thickness of plate (see Sketch 2.1)	m
V	mean velocity, $m/\rho A$	m/s
α	porosity or area ratio, A_f/A_u	–
γ	ratio of specific heat capacity at constant pressure to that at constant volume	–
Λ	correction factor for effect of compressibility	–
λ_a	correction factor for effect of plate thickness for $t/d < 0.8$, $(\lambda_a = K'_i / K'_0)$	–

λ_b	correction factor for effect of plate thickness for $t/d \geq 0.8, (\lambda_b = K'_i / K'_{0.8})$	–
λ_t	correction factor for effect of compressibility on total-pressure loss $\lambda_t = K_t / K'_i$	–
λ_{sc}	correction factor for effect of compressibility on static-pressure drop $\lambda_{sc} \Lambda = k_s / K'_i$	–
$(\lambda_{sc})_{\alpha q_2^* \approx 0}$	value of λ_{sc} when $\alpha q_2^* \approx 0$	–
λ_{tc}	correction factor for effect of compressibility on total-pressure loss $\lambda_{tc} \Lambda = k_t / K'_i$	–
μ	dynamic viscosity of fluid	N s/m ²
ν	kinematic viscosity of fluid, μ/ρ	m ² /s
ρ	density of fluid	kg/m ³

Subscripts

a	refers to correction factor for effect of plate thickness for $t/d < 0.8$
b	refers to correction factor for effect of plate thickness for $t/d \geq 0.8$
$crit$	refers to critical value of mass flow function evaluated for $M = 1$
d	refers to Reynolds number based on hole diameter
f	refers to orifice area
i	refers to incompressible flow conditions
s	refers to static pressure
sc	refers to static-pressure compressibility correction factor
t	refers to total pressure and temperature
tc	refers to total-pressure compressibility correction factor
u	refers to duct area
0	refers to incompressible flow loss coefficient when $t/d = 0$
0.8	refers to incompressible flow loss coefficient when $t/d = 0.8$

m	refers to measured value of pressure	}	see Sketch 4.1
1	refers to conditions at station upstream of orifice in region of fully-developed flow		
2	refers to conditions at entry to orifice		
3	refers to conditions at station downstream of recovery plane		

Superscripts

'	refers to pressure-loss coefficient based on kinetic pressure at entry to orifice, $\frac{1}{2}\rho_2 V_2^2$
*	refers to maximum mass flow rate conditions

2. INTRODUCTION

This Data Item provides total- and static-pressure loss coefficients and discharge coefficients for the flow of gases through sharp-edged orifice plates, perforated plates and thick orifice plates installed in ducts of constant area. The data are given in terms of a mass flow function* based on conditions at entry to the orifice.

The method for calculating compressible flow pressure-loss coefficients and discharge coefficients is outlined in Section 4.2.

The method for calculating pressure losses for incompressible flow, appropriate for the flow of liquids, is given in ESDU 81039†.

The data in this Item are applicable under the following conditions.

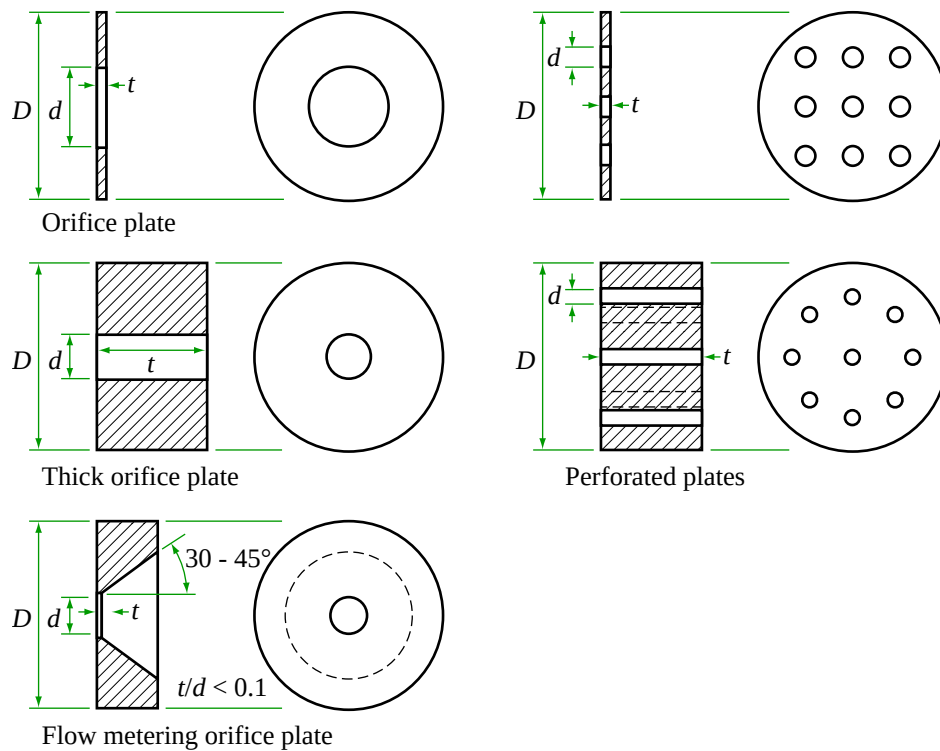
- (i) For the flow of gases whose behaviour closely approximates that of a perfect gas‡. It is necessary to use the compressible flow values even at low upstream Mach numbers since, although the upstream Mach number in the duct may be low, the Mach number in the smaller orifice area will be higher and the flow may be approaching conditions where compressibility effects are significant.
- (ii) For the subsonic flow of gases up to the condition of choking.
- (iii) For fully-developed flow in regions upstream and downstream of the orifice (see Section 4.1).
- (iv) For Reynolds numbers, Re_d , greater than about 10^4 (see Section 3.2).
- (v) For components having sharp edges free from any chamfering or rounding since such edge profiles can considerably reduce the values of the pressure-loss coefficients. The presence of burrs would also affect the pressure loss.
- (vi) For thin and thick orifices. Separate correlations are provided for $t/d < 0.8$ and $t/d \geq 0.8$, corresponding to separated flow and reattached flow respectively under incompressible flow conditions. For incompressible flow conditions, the flow may be either separated or reattached for $0.6 < t/d < 1.0$ and it is uncertain as to which correlation will be appropriate**. The use of orifices in this thickness range should be avoided as flow fluctuation, vibration and noise may occur. For compressible flow conditions, unstable flows may occur in the range $0.1 < t/d < 1.0$ and this thickness range should be avoided in design. Section 3.1 discusses the effect of plate thickness on the flow.
- (vii) For symmetrical systems with single and multiple circular openings in circular ducts. Sketch 2.1 illustrates examples of typical components (see Section 2.1 for notes on non-circular ducts and openings).

* ESDU 74028 provides information on mass flow functions.

† Some of the incompressible flow data given in ESDU 81039 are reproduced in Figures 1, 2 and 3 of this Item as part of the calculation procedure for estimating compressible flow parameters.

‡ Most common gases, including air, may be considered to behave as perfect gases provided that the liquefaction or the dissociation temperatures are not approached.

** For values of t/d in the range of $0.6 < t/d < 1.0$, the loss coefficient, K_l' , may be obtained from either the separated- or reattached- flow correlations. For separated flow, the curves given in Figure 2 can be extrapolated to $t/d = 1.0$ and for reattached flow, Equation (5.1) can be used to find K_l' when $0.6 < t/d < 0.8$.



Sketch 2.1 Typical components

2.1 Non-circular Ducts and Openings

Some data for perforated plates with square holes are given in Derivation 16 and some data for perforated plates in rectangular-sectioned ducts were included in the correlation in Derivation 19. No systematic departures from the correlations presented here were found in these cases, but the available data only cover values of α up to about 0.6. For high values, $\alpha > 0.8$ say, the effects of the system geometry are likely to become more significant and application of the data to components not shown in Sketch 2.1 will be less reliable and should be made with caution.

3. SOME GENERAL FEATURES OF THE FLOW THROUGH ORIFICES

Except at very low Reynolds numbers (Re_d less than about 10), or at conditions where compressibility effects are significant, the flow through a sharp-edged orifice initially separates from the sharp entrance edge. Downstream of this, the flow may either remain separated right through the orifice or may reattach to the wall of the orifice. The orifice thickness/diameter ratio, t/d , at which the flow changes from one condition to the other will be influenced by flow parameters such as Reynolds number and Mach number and by geometrical parameters such as porosity, α . In common with most separation phenomena there is likely to be a range of values of t/d over which either condition may occur with a discontinuity in the pressure loss coefficient when the changeover takes place.

3.1 The Effect of Compressibility

Gases and vapours are highly compressible. Whether or not compressibility is important in a particular installation can be ascertained from the Mach number of the flow. The important Mach number as regards a thin orifice is that in the vena contracta, and in the case of a thick orifice it is the orifice outlet Mach number. The Mach number is dependent on the local static to total pressure ratio of the flow. If the local static to total pressure ratio falls to 0.528 (calculated for diatomic gases for which $\gamma = 1.4$), sonic velocity corresponding to a Mach number of 1 will occur. Following the onset of sonic flow, subsonic flow calculation procedures no longer apply. The important effects of compressibility in thin orifices are as follows.

- (i) Density changes through an orifice give rise to complex relationships between inlet duct velocities and velocities in the vena contracta.
- (ii) Compressibility modifies the separated-flow region; the vena contracta increases in area and moves upstream as the Mach number rises.
- (iii) Sonic velocity first occurs at the vena contracta in a plane normal to the flow. Since sonic velocity occurs within the flow, and not at a solid boundary, downstream conditions can still influence conditions upstream of the sonic plane.
- (iv) The effect of decreasing the downstream to upstream pressure ratio across an orifice, below that necessary for the onset of sonic velocity, is to move the sonic velocity location upstream towards the orifice until, at a sufficiently low pressure ratio, sonic velocity occurs in the orifice (see Sketch 3.1). Once sonic velocity occurs at a solid boundary, the flow through the orifice is said to be choked ($q_2 = q_2^*$). With choked flow the mass flow through an orifice depends only on the inlet flow conditions. For $\alpha \approx 0$, the downstream to upstream pressure ratio required to choke an orifice is 0.035 ($\gamma = 1.4$).
- (v) At sufficiently low overall pressure ratios with sonic velocity in the orifice, a complex shock wave pattern occurs downstream of the orifice. Static pressures may not become constant across a pipe for several pipe diameters downstream of the orifice.

Additional effects in thick orifices are as follows.

- (i) Flow reattachment within an orifice occurs nearer the inlet as Mach numbers rise. This is the result of the vena contracta growing in area and moving upstream towards the inlet.

- (iii) Long orifices choke at their outlets ($q_2 = q_2^*$), with the result that velocities are subsonic everywhere within the orifice at all pressure ratios.

The Effect of Reynolds Number

Data for Reynolds numbers less than about 10 000 (including data for laminar flow which exist for Re_d less than about 2 000) may be obtained from References 1 to 5.

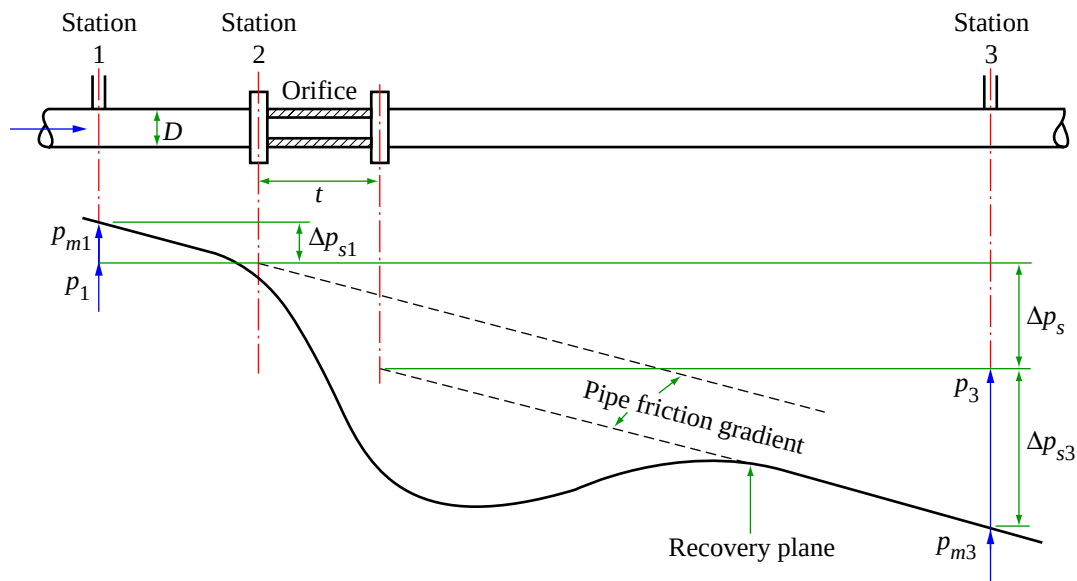


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4. DEFINITION AND CALCULATION OF PRESSURE LOSSES AND DISCHARGE COEFFICIENTS

4.1 Definition of Pressure Loss

Sketch 4.1 shows a typical experimental static pressure distribution along the axis of a duct containing an orifice plate. The recovery plane is approximately $6D$ downstream* from a single orifice⁷. It is recommended that for a perforated plate a value of $6d/\sqrt{\alpha}$ be taken for the distance of the recovery plane from the plate.



Sketch 4.1 Definition of pressure loss

The static-pressure drop is defined by

$$\begin{aligned}\Delta p_s &= (p_{m1} - \Delta p_{s1}) - (p_{m3} + \Delta p_{s3}) \\ &= p_1 - p_3,\end{aligned}\quad (4.1)$$

where p_{m1} and p_{m3} are static pressures measured in the system at stations 1 and 3 respectively and p_1 and p_3 are static pressures at the same points but corrected for pipe friction losses up to the entry and beyond the exit of the orifice. The quantities Δp_{s1} and Δp_{s3} are the friction losses in the straight pipes upstream and downstream of the orifice. The total-pressure loss, Δp_t , is defined similarly. Stations 1 and 3 are strictly taken to be in regions of fully-developed flow but, provided that the velocity profile is symmetrical and not far removed from that appropriate to fully-developed flow, no significant effect of inlet velocity profile is found.

A method of calculating pipe friction losses for compressible flow is given in ESDU 74029.

* The axial static-pressure gradient associated with the frictional flow in a straight pipe is not strictly recovered for about $30D$ downstream of the component although a distance of $6D$ may usually be assumed with no significant loss in accuracy.

4.2 Calculation of Pressure Loss and Discharge Coefficient

The total-pressure loss, Δp_t , and static-pressure drop, Δp_s , are calculated from

$$\Delta p_t = (p_{t2} - p_2)k_t, \quad (4.2)$$

and
$$\Delta p_s = (p_{t2} - p_2)k_s. \quad (4.3)$$

The coefficients k_t and k_s are calculated as follows:

$$k_t = \lambda_{tc} \Lambda K'_i, \quad (4.4)$$

and
$$k_s = \lambda_{sc} \Lambda K'_i. \quad (4.5)$$

The coefficient K'_i is calculated as follows:

for $t/d < 0.8$,
$$K'_i = K'_0 \lambda_a, \quad (4.6)$$

and for $(t/d) \geq 0.8$,
$$K'_i = K'_{0.8} \lambda_b. \quad (4.7)$$

The basic coefficients K'_0 and $K'_{0.8}$ are given in Figure 1. The correction factors, λ_a , and λ_b , for the effect of t/d are given as functions of α and t/d in Figures 2 and 3, respectively.

The mean mass flow function at entry to the orifice that gives maximum mass flow rate, q_2^* , is presented as a function of α and t/d in Figures 4 and 5 for $t/d < 0.8$ and $(t/d) \geq 0.8$, respectively.

Figure 6 gives the compressibility correction factor, λ_{tc} , as a function of q_2 and q_2^* for $0 < \alpha < 0.95$ and $0 < t/d < 7.0$ when $q_2/q_2^* < 0.85$. Figures 7 and 8 give λ_{tc} as a function of α , q_2 and q_2^* for $t/d < 0.8$ and $(t/d) \geq 0.8$ respectively, when $q_2/q_2^* < 0.85$.

Figure 9 gives the compressibility correction factor, $(\lambda_{sc})_{\alpha q_2^* \approx 0}$, as a function of q_2 and q_2^* . For other values of αq_2^* , it is first necessary to find the value of Δp_t . Appendix A gives the calculation procedure for obtaining the static-pressure drop when $\alpha q_2^* \neq 0$.

Figure 10 gives the correction factor Λ as a function of q_2 .

Figure 11* presents the discharge coefficient, C_D , as a function of q_2 and k_t for $k_t > 1$ since for pressure-loss coefficients in excess of unity, it is generally more usual to express the pressure losses in discharge coefficient form. Figures 12 and 13 present discharge coefficient, $C_{D\alpha \approx 0}$ as a function of t/d and q_2 when $\alpha \approx 0$ for $t/d < 0.8$ and $t/d \geq 0.8$, respectively.

* Values of C_D^* are presented as a function of α and t/d in Figures B1 and B2 of Appendix B to enable a comparison to be made with other data, but these figures can also be used in conjunction with Figure 11 to establish the discharge coefficient for subsonic flow up to the condition of choking.

5. RANGES OF APPLICABILITY* OF PRESSURE LOSS COEFFICIENT DATA

5.1 Incompressible Flow of Liquids and Gases

Figures 1 (K'_0) and 2 present pressure loss coefficients for the separated-flow regime ($0 < t/d < 0.8$). Experimental data in the ranges $0 < t/d < 0.6$ and $0 < \alpha < 1.0$ were correlated with an r.m.s. error of 9.5 per cent.

Figures 1 ($K'_{0.8}$) and 3 present pressure-loss coefficients for the reattached-flow regime ($t/d \geq 0.8$). For higher values of t/d than are given in the figures, the pressure-loss coefficients may be calculated from the empirical equation¹⁹

$$K'_i = \left\{ \left[\left(0.872 - 0.015 \frac{t}{d} - 0.08 \frac{d}{t} \right) (1 - \alpha^{3.3}) + \alpha^{3.3} \left(1 + 0.134 \sqrt{\frac{t}{d}} \right)^{-1} \right]^{-1} - \alpha \right\}^2. \quad (5.1)$$

Equation (5.1) (and Figure 3) correlated experimental data in the ranges $0.98 < t/d < 7.1$ and $0 < \alpha < 0.48$ with an r.m.s. error of 3.8 per cent.

5.2 Compressible Flow of Gases

The curves in Figures 4 and 5 apply for $\gamma = 1.4$ (diatomic gases). The experimental data were in the range $0 < \alpha < 0.44$ and $0 < t/d < 0.69$ for Figure 4, and $0 < \alpha < 0.13$ and $1.0 < t/d < 2.67$ for Figure 5. For other values of γ , the theoretical methods of Derivations 9 and 13 may be used or, alternatively, the semi-empirical approach of Derivation 11 gives values for thin orifices.

The curves in Figures 6, 7, 8 and 9 apply for $\gamma = 1.4$. Experimental data were in the range $0 < \alpha < 0.13$, $0.06 < t/d < 0.7$ for $t/d < 0.8$, and $0 < \alpha < 0.13$, $1.19 < t/d < 2.67$ for $t/d \geq 0.8$. The data showed large scatter, particularly for values of q_2/q_2^* above about 0.9. For other values of γ , the correlations given for $\gamma = 1.4$ can be used to obtain a first estimate of the magnitude of the pressure loss. For more accurate values, the semi-empirical approach of Derivation 11 may be used for thin orifices in conjunction with the equation

$$\lambda_{tc} = \lambda_t \left(1 + \frac{(\gamma - 1)}{2} M_1^2 \right)^{\frac{1}{\gamma - 1}}. \quad (5.2)$$

The curve in Figure 10 applies for $\gamma = 1.4$. For other values of γ , the equation

$$\Lambda = \frac{\frac{1}{2} \gamma M_2^2}{\left[\left(1 + \frac{(\gamma - 1)}{2} M_2^2 \right)^{\frac{\gamma}{\gamma - 1}} - 1 \right] \left[1 + \frac{(\gamma - 1)}{2} M_2^2 \right]^{\frac{1}{\gamma - 1}}}, \quad (5.3)$$

should be used.

For values of t/d greater than about 7.0, it is more appropriate to sum the losses for a sudden contraction

* The ranges of applicability of the major parameters are summarised in Table C.1 of Appendix C and are based on the ranges of experimental data used to derive the information presented.

(ESDU 78007), a sudden expansion (ESDU 72011) and a friction loss in the parallel section (ESDU *74029).

Sources of pressure-loss coefficient data for incompressible and compressible flow are detailed in Appendix C.

The curves in Figures 11, 12 and 13 were derived from Figures 1 to 10 and apply for $\gamma = 1.4$.

* This Data Item applies only to conditions of fully-developed flow, *i.e.* away from the entrance region.