

Measurement of fluid flow in closed conduits —

Part 1: Pressure differential devices —

Section 1.4 Guide to the use of devices specified in Sections 1.1 and 1.2

Committees responsible for this British Standard

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British Compressed Air Society
 British Gas plc
 Department of Energy (Gas and Oil Measurement Branch)
 Department of Trade and Industry (National Engineering Laboratory)
 Electricity Industry in United Kingdom
 Energy Industries Council
 GAMBICA (BEAMA Ltd.)
 Institute of Measurement and Control
 Institute of Petroleum
 Institute of Trading Standards Administration
 Institution of Gas Engineers
 Institution of Mechanical Engineers
 Society of British Gas Industries
 Water Services Association of England and Wales

The following bodies were also represented in the drafting of the standard, through subcommittees and panels:

Engineering Equipment and Materials Users' Association
 Institution of Water and Environmental Management
 United Kingdom Offshore Operators' Association

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Foreword

This Section of BS 1042 has been prepared under the direction of the Industrial-process Measurement and Control Standards Policy Committee. It supersedes BS 1042-1.4:1984, which is withdrawn.

This is Section 1.4 of a series of Sections of BS 1042 on the measurement of fluid flow in closed conduits, as follows:

Section 1.1 Specification for square-edged orifice plates, nozzles and venturi tubes in circular cross section conduits running full

Section 1.2 Specification for square-edged orifice plates and nozzles (with drain holes, in pipes below 50 mm diameter, as inlet and outlet devices) and other orifice plates

Section 1.3 Method of measurement of gas flow by means of critical flow Venturi nozzles.

Section 1.5 Guide to the effect of departure from the conditions specified in Section 1.1

Section 1.1 specifies the geometry and method of use of orifice plates, nozzles and Venturi tubes inserted in conduit running full, to measure the flowrate of the fluid in the conduit. It is technically equivalent to ISO 5167:1980 published by the International Organization for Standardization (ISO). It should be noted that guidance on the effects of departure from the conditions specified in BS 1042-1.1 can be found in BS 1042-1.5:1987.

An index to Sections 1.1, 1.2 and 1.4 is provided in this Section, to facilitate the rapid cross-referencing of subject matter.

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Summary of pages

This document comprises a front cover, an inside front cover, pages i and ii, pages 1 to 33 and a back cover.

This standard has been updated (see copyright date) and may have had amendments incorporated. This will be indicated in the amendment table on the inside front cover.

Section 1. General

1 Scope

This Section of BS 1042 provides sample calculations, physical data and other additional information for using the pressure differential devices specified in BS 1042-1.1 and BS 1042-1.2.

NOTE The titles of the publications referred to in this standard are listed on the inside back cover.

2 Symbols

The symbols used in this standard are given in Table 1.

Table 1 — Symbols

Symbol	Represented quantity	Dimensions M: mass L: length T: time θ : temperature	SI unit
A	Cross-sectional area	L^2	m^2
C	Coefficient of discharge, $C = \frac{\alpha}{E}$	dimensionless	
d	Diameter of orifice or throat of primary device at operating conditions	L	m
D	Upstream internal pipe diameter at operating conditions	L	m
E	Velocity of approach factor, $E = (1 - \beta^4)^{-1/2}$	dimensionless	
F_A, F_B	Correction factors	dimensionless	
k	Uniform equivalent roughness	L	m
p	Static pressure of the fluid	$ML^{-1}T^{-2}$	Pa
q_m	Mass flowrate	MT^{-1}	kg/s
q_v	Volume flowrate	L^3T^{-1}	m^3/s
Re	Reynolds number	dimensionless	
Re_D, Re_d	Reynolds number referred to D or d	dimensionless	
t	Temperature of the fluid	θ	$^{\circ}C$
X	Acoustic ratio, $X = \frac{\Delta p}{P_1 k}$	dimensionless	
α	Flow coefficient	dimensionless	
β	Diameter ratio, $\beta = \frac{d}{D}$	dimensionless	
Δp	Differential pressure	$ML^{-1}T^{-2}$	Pa
ε	Expansibility (expansion) factor	dimensionless	
k	Isentropic exponent	dimensionless	
μ	Dynamic viscosity of the fluid	$ML^{-1}T^{-1}$	Pa s
ν	Kinematic viscosity of the fluid, $\nu = \frac{\mu}{\rho}$	L^2T^{-1}	m^2/s
ρ	Density of the fluid	ML^{-3}	kg/m^3
τ	Pressure ratio, $\tau = \frac{p_2}{p_1}$	dimensionless	

NOTE 1 Other symbols used in this standard are defined at their place of use.

NOTE 2 Some of the symbols used in this standard are different from those used in BS 1042-1.1.

NOTE 3 Subscript 1 refers to the cross section at the plane of the upstream pressure tapping. Subscript 2 refers to the cross section at the plane of the downstream pressure tapping.

Section 2. Calculations

3 General

In clauses 4 to 7, typical design calculations for the design of orifice plates, nozzles, venturi tubes and venturi nozzles are given.

The principal design calculations that are commonly required for pressure differential devices are:

- assessment of the differential pressure and calculation of the diameter of an orifice (or nozzle or venturi throat) for a stated flow of a given fluid in a given pipe at specified conditions of pressure and temperature;
- calculation of the differential pressure for a stated flow of a given fluid at known temperature and pressure, for a pressure differential device and pipe of known diameter;
- calculation of the flowrate, given the fluid, pressure differential device diameter and pipe diameter, differential pressure and fluid pressure and temperature;
- calculation of the overall uncertainty of the installation for a given flowrate.

Items a) and d) are particularly relevant to the design of a new installation whereas b) and c) are applicable to working installations. The method of calculating the overall uncertainty is described in clause 11 of BS 1042-1.1:1992.

The precise sequence of the calculation will depend upon the information required and on the choice of pressure differential device.

The calculations are based on the assumption that the size of the pipe needed to carry the fluid is known.

4 Information required

4.1 General

The following information is required regarding the installation:

- maximum, normal and minimum flowrates (i.e. will one flowmeter cover this flow range?);

NOTE Where reference volumes are used, the pressure and temperature should be clearly stated; general statements such as "standard pressure and temperature (S.T.P.)" should not be relied upon.

- accuracy required;
- maximum permissible pressure loss.

4.2 Pipe

The following information is required regarding the pipe:

- material, temperature coefficient of expansion;
- operating temperature;

- internal diameter, how obtained (the mean of six measurements or as specified in the relevant pipe standards), uniformity;
- layout, e.g. upstream, downstream fittings, straight lengths (influence on β limits);
- attitude, i.e. vertical, horizontal or sloping;
- internal roughness of pipe.

4.3 Pressure differential device

The following information is required regarding the pressure differential device:

- type (e.g. squared-edged orifice plate, nozzle, venturi);
- suitability for the application;
- limits on d , D , β and Re_D ;
- mounting, i.e. slip plate, carrier;
- tappings, i.e. location, number of, diameter;
- material, temperature coefficient of expansion, operating temperature;
- diameter;
- drain hole diameter;
- strength of orifice plate material to calculate deformation under flow conditions.

4.4 Fluid

The following information is required regarding the fluid:

- state and composition;
 - operating temperature and pressure (and local barometric pressure if appropriate);
 - density at operating conditions;
- NOTE For gases density at reference conditions is also often required.
- viscosity at operating conditions;
 - for compressible fluids only, isentropic exponent (ratio of specific heats for ideal gases);
 - nature of flow, i.e. viscous or turbulent.

4.5 Differential pressure measuring device

The following information is required regarding the differential pressure measuring device:

- type (microdisplacement, displacement), wet or dry (i.e. manometric or mechanical), calibration correction factors;
- span (fixed or adjustable), maximum permitted pressure loss for the installation in question;
- maximum operating pressure and temperature of the pressure difference measuring device;
- corrosion resistance (to metered fluid).

4.6 Basic equations

The basic equations for the following are required:

- mass flow or volumetric flow;
- compressible or incompressible fluids;
- Reynolds number;
- uncertainties.

5 Basic equations

In the calculation sequences that follow, SI units are used. If it is the user's practice to use other units, these should be converted into the appropriate SI units.

The following equations for mass flowrate, q_m , and volume flowrate, q_v , are given in 5.1 of BS 1042-1.1:1992.

$$\begin{aligned} q_m &= \alpha \varepsilon \frac{\pi}{4} d^2 (2\Delta p \rho_1)^{1/2} \\ &= CE \varepsilon \frac{\pi}{4} d^2 (2\Delta p \rho_1)^{1/2} \\ q_v &= \alpha \varepsilon \frac{\pi}{4} d^2 (2\Delta p / \rho_1)^{1/2} \\ &= CE \varepsilon \frac{\pi}{4} d^2 (2\Delta p / \rho_1)^{1/2} \end{aligned}$$

where:

$$\begin{aligned} E &= 1/(1 - \beta^4)^{1/2} \\ \beta &= d/D \end{aligned}$$

If the flowmeter is to be calibrated in units of volume flowrate referred to standard (or other specified) conditions of pressure and temperature, q_o , then the following equation should be used, the suffix "0" denoting standard conditions of pressure and temperature.

$$q_o = q_v \frac{\rho_1}{\rho_0}$$

The above equations enable calculations described in items a) to c) of clause 3 to be made. Since α , C , E , d and p are unknown, the equations can be transposed to:

$$\begin{aligned} CE\beta^2 &= \frac{4q_m}{\varepsilon \pi D^2 (2\Delta p \rho_1)^{1/2}} \\ &= \frac{4q_v}{\varepsilon \pi D^2 (2\Delta p / \rho_1)^{1/2}} \end{aligned}$$

The values of d and D in the above equations are to be corrected for the effect of fluid temperature. At temperatures within 10 °C of the temperature at which D and d are determined, the measured diameter values are sufficiently accurate, but at temperatures outside this range, corrections for expansion or contraction are necessary.

It is also convenient to transpose the equations for Reynolds number (Re_D and Re_d) given in 3.3.2 of BS 1042-1.1:1992 into the following.

$$Re_D = \frac{4q_m}{\pi D \mu_1} = \frac{4q_v}{\pi D \nu_1}$$

and

$$Re_d = \frac{4q_m}{\pi d \mu_1} = \frac{4q_v}{\pi d \nu_1}$$

NOTE In the equations for mass flowrate the dynamic viscosity, μ , is used and for volume flowrate the kinematic viscosity, ν , is used. However, as the dynamic viscosity is equal to the kinematic viscosity multiplied by the density, the appropriate viscosity can be obtained.

6 Calculation of orifice or throat diameter

6.1 General

The procedure for assessment of the differential pressure and calculation of the orifice or throat diameter to measure a stated flowrate of a given fluid in a given pipeline at specified conditions of pressure and temperature is described. The relevant clause references are given at the beginning of each step.

6.2 Procedure

NOTE See clauses 6 and 7 of BS 1042-1.1:1992, sections 2 and 3 of BS 1042-1.2:1989 and 4.2 and 4.3 of this standard).

Before proceeding with the details of the calculation, check the suitability of the device for the application in question and the general acceptability of the pipeline configuration.

NOTE The example for each item is given in the corresponding item of 6.3.

- Calculate the pipe internal diameter, D , at the operating temperature, t °C, preferably using the measured diameter or if this is not possible the diameter obtained from the relevant pipe standards. (See 12.2.)
- Obtain/calculate the fluid density at reference conditions (required only for gas flows measured in volume units at reference conditions of pressure and temperature). Obtain the compressibility factor of the gas at operating conditions.

e) Obtain/calculate the density and the kinematic or dynamic viscosity of the fluid at operating conditions.

d) Select appropriate equations from clause 5 for $CE\beta^2$ and Re_D according to whether the flowrate is given for mass or volume.

e) Choose a value of Δp taking account of the required pressure loss. Check that $(p_1 - \Delta p)/p_1$ is not less than 0.75. If it is, choose a smaller value of Δp . (It is desirable to keep $(p_1 - \Delta p)/p_1$ as close to unity as possible.)

f) Calculate $CE\beta^2$ appropriate to the device to be used (orifice plate, nozzle, venturi). If the value obtained is outside the range specified for the particular device, the lower (or upper) limits on β and d for the device will not be met. Choose another value of Δp and repeat e) and f). When continuous flow measurements are required over a range of flows, the Re_D value used in these calculations should be calculated using 70 % of the maximum flow to be encountered. (See clause 4, 6.2.2.2, 6.2.3.2, 6.3.2.2, 6.3.3.2, 7.2, 8.2 and 9.2 and of BS 1042-1.2:1989 and Table 2 to Table 6 of this standard.)

g) When an acceptable value of $CE\beta^2$ has been obtained, calculate the approximate values of β and d . The calculation procedure is dependent on the device to be used, as follows.

- 1) Square-edged orifice plates, $D \geq 50$ mm, use Table 2
- 2) ISA 1932 nozzles and rough cast, machined and rough welded convergent venturi tubes, use Table 3.
- 3) Long radius nozzles use Table 4.
- 4) Square-edged orifice plates in the size range $25 \leq D < 50$ mm;

NOTE The Stolz equation for corner tappings given in 8.3.2.1 of BS 1042-1.1:1992 is used for deriving the discharge coefficients provided the minimum Reynolds numbers are above the following values.

$$Re \geq 40\,000\beta^2 \text{ for } 0.23 \leq \beta \leq 0.5$$

$$Re \geq 10\,000 \text{ for } 0.5 \leq \beta \leq 0.7$$

- 5) Square-edged orifice plates with corner tappings when measuring flow into a large space, use procedures 1) and 4).
- 6) ISA 1932 nozzles and venturi nozzles when measuring flow into a large space, use procedure 2).
- 7) Quarter circle orifice plates, use Table 5.
- 8) Eccentric orifice plates, use Table 6.
- 9) Conical entrance orifice plates, calculate β directly. (See 7.5.1 of BS 1042-1.2:1989.)

10) Square-edged orifice plates with corner tappings when measuring flow from a large space, calculate β directly. (See 6.2.2.3 of BS 1042-1.2:1989.)

11) ISA 1932 nozzles and venturi nozzles when measuring flow from a large space, calculate β directly. (See 6.2.3.3 of BS 1042-1.2:1989.)

NOTE β can be calculated directly for procedures 9) to 11) because C has a single predetermined value.

h) Check that the Reynolds number, Re_D or Re_d , is within the permitted limits for the device. If the Reynolds number is greater than the upper limit, then D or d is too small. If the Reynolds number is less than the lower limit, try increasing Δp by reducing d and go back to e).

i) Calculate the relative roughness criterion appropriate to the pipeline material and diameter and check that it is within the permitted limits for the device used. This is vital for high accuracy measurements, especially if D is small. (See 8.3.1, 9.1.6.2, 9.2.6.1 and 10.1.2.6 of BS 1042-1.1:1992.)

j) Calculate the expansibility factor ($\epsilon = 1$ for liquids). There is one equation for square-edged orifices, and another for nozzles and venturis. Use β obtained in g). Note that the acoustic ratio X in the orifice plate equation is equal to $\Delta p/p_1 k$, where k is the isentropic exponent.

For nozzles and venturis, the pressure ratio, τ , which is equal to $1 - \Delta p/p_1$ is also required. When continuous flow measurements over a range of flows is required and Re_D is based on 70 % of the maximum flow [see step f)] then 50 % of the Δp value chosen in step e) should be used. (See 8.3.2.2, 9.1.6.3, and 10.1.6 of BS 1042-1.1:1992 and 6.2.2.4, 6.2.3.4, 7.5.2, 8.5.2 and 9.4.3 of BS 1042-1.2:1989.)

k) Calculate a revised value of $CE\beta^2$ by dividing the value obtained in f) by ϵ . Update the value of β as in step g).

l) Use the revised value of β to calculate C (or α) from the appropriate equation. Use C , and the revised value of β to calculate $CE\beta^2$ (note that $E = 1(1 - \beta^4)^{1/2}$). Compare this result with that of step k). Adjust the value of β and repeat this step until there is agreement to within 0.05 %. (See 8.3.2.1, 9.1.6.2, 9.2.6.2, 10.1.5.2 and 10.1.5.4 of BS 1042-1.1:1992 and 6.2.2.3, 6.2.3.3, 7.5.1, 8.5.1 and 9.4.1 of BS 1042-1.2:1989.)

m) Calculate d from β and D corrected for operating temperature.

n) Correct the value of d obtained in m) to ambient temperature. This is the diameter to which the orifice or throat will be machined unless drain holes are required.

o) Correct d to allow for a drain hole, if appropriate. (See clause 4 of BS 1042-1.2:1989.)

Table 2 — Approximate values of square of $CE\beta^2$ for square-edged orifice plates with corner, D , $D/2$ or flange taps as appropriate

β	$CE\beta^2$ for a Reynolds number, Re_D , of:									
	5×10^3	10^4	2×10^4	3×10^4	5×10^4	7×10^4	10^5	10^6	10^7	10^8
0.23	0.0318	0.0317	0.0317	0.0316	0.0316	0.0316	0.0316	0.0316	0.0316	0.0316
0.24	0.0347	0.0346	0.0345	0.0345	0.0344	0.0344	0.0344	0.0344	0.0344	0.0344
0.26	0.0409	0.0407	0.0406	0.0405	0.0405	0.0405	0.0405	0.0404	0.0404	0.0404
0.28	0.0475	0.0473	0.0472	0.0471	0.0471	0.0470	0.0470	0.0470	0.0469	0.0469
0.30	0.0548	0.0544	0.0543	0.0542	0.0541	0.0541	0.0541	0.0540	0.0540	0.0540
0.32	0.0626	0.0621	0.0619	0.0618	0.0617	0.0617	0.0617	0.0616	0.0616	0.0616
0.34	0.0709	0.0704	0.0701	0.0700	0.0699	0.0698	0.0698	0.0697	0.0697	0.0697
0.36	0.0799	0.0792	0.0789	0.0787	0.0786	0.0785	0.0785	0.0783	0.0783	0.0783
0.38	0.0895	0.0887	0.0882	0.0880	0.0879	0.0878	0.0877	0.0875	0.0875	0.0875
0.40	0.0998	0.0987	0.0982	0.0979	0.0977	0.0976	0.0975	0.0973	0.0973	0.0973
0.42	0.1108	0.1095	0.1087	0.1085	0.1082	0.1081	0.1080	0.1077	0.1076	0.1076
0.44	0.1225	0.1209	0.1200	0.1196	0.1193	0.1192	0.1191	0.1187	0.1186	0.1186
0.46	0.1350	0.1330	0.1319	0.1315	0.1311	0.1310	0.1308	0.1304	0.1303	0.1303
0.48	—	0.1459	0.1446	0.1441	0.1437	0.1435	0.1432	0.1427	0.1426	0.1426
0.50	—	0.1595	0.1580	0.1574	0.1569	0.1566	0.1564	0.1558	0.1556	0.1556
0.52	—	0.1741	0.1723	0.1716	0.1709	0.1706	0.1704	0.1696	0.1694	0.1694
0.54	—	0.1896	0.1874	0.1867	0.1858	0.1855	0.1852	0.1842	0.1840	0.1840
0.56	—	0.2061	0.2035	0.2026	0.2017	0.2012	0.2009	0.1997	0.1995	0.1995
0.58	—	0.2238	0.2207	0.2197	0.2185	0.2180	0.2177	0.2162	0.2159	0.2159
0.60	—	0.2427	0.2389	0.2376	0.2364	0.2358	0.2353	0.2336	0.2333	0.2333
0.62	—	0.2628	0.2584	0.2568	0.2555	0.2547	0.2541	0.2522	0.2518	0.2517
0.64	—	0.2842	0.2793	0.2774	0.2758	0.2749	0.2743	0.2719	0.2714	0.2714
0.66	—	0.3072	0.3016	0.2994	0.2975	0.2965	0.2957	0.2929	0.2923	0.2923
0.68	—	0.3319	0.3256	0.3229	0.3208	0.3195	0.3187	0.3153	0.3146	0.3145
0.70	—	0.3584	0.3499	0.3482	0.3458	0.3443	0.3433	0.3393	0.3385	0.3383
0.72	—	0.3871	0.3772	0.3757	0.3729	0.3711	0.3699	0.3646	0.3635	0.3634
0.74	—	0.4183	0.4068	0.4056	0.4025	0.4003	0.3988	0.3925	0.3912	0.3910
0.76	—	0.4522	0.4390	0.4378	0.4345	0.4325	0.4305	0.4231	0.4216	0.4213
0.78	—	—	0.4756	0.4734	0.4702	0.4682	0.4658	0.4567	0.4549	0.4547
0.80	—	—	0.5129	0.5117	0.5081	0.5061	0.5052	0.4941	0.4919	0.4916

Table 3 — Approximate values of $CE\beta^2$ for ISA 1932 nozzles, and rough cast, machined and rough welded convergent venturi tubes

β	$CE\beta^2$ for venturi tubes			$CE\beta^2$ for ISA 1932 nozzles for a Reynolds number, Re_D , of:						
	Machined	Rough cast	Rough welded	2×10^4	3×10^4	5×10^4	7×10^4	10^5	10^6	10^7
0.30	—	—	—	—	0.0887	0.0890	0.0891	0.0892	0.0893	0.0893
0.316	—	0.0889	—	—	—	—	—	—	—	—
0.32	—	0.1013	—	—	0.1009	0.1013	0.1014	0.1015	0.1017	0.1017
0.34	—	0.1145	—	—	0.1139	0.1143	0.1145	0.1147	0.1149	0.1149
0.36	—	0.1286	—	—	0.1277	0.1283	0.1285	0.1286	0.1289	0.1289
0.38	—	0.1436	—	—	0.1423	0.1430	0.1433	0.1435	0.1438	0.1438
0.40	0.1613	0.1595	0.1597	—	0.1578	0.1587	0.1589	0.1591	0.1596	0.1596
0.42	0.1783	0.1763	0.1765	—	0.1741	0.1751	0.1754	0.1757	0.1762	0.1763
0.44	0.1963	0.1942	0.1944	0.1898	0.1913	0.1924	0.1929	0.1932	0.1938	0.1938
0.46	0.2154	0.2130	0.2133	0.2007	0.2094	0.2107	0.2112	0.2116	0.2123	0.2123
0.48	0.2356	0.2330	0.2332	0.2265	0.2285	0.2299	0.2305	0.2309	0.2317	0.2318
0.50	0.2569	0.2541	0.2543	0.2464	0.2485	0.2502	0.2508	0.2513	0.2521	0.2522
0.52	0.2795	0.2764	0.2766	0.2673	0.2697	0.2715	0.2722	0.2727	0.2736	0.2737
0.54	0.3033	0.3000	0.3003	0.2893	0.2919	0.2939	0.2946	0.2952	0.2962	0.2963
0.56	0.3286	0.3250	0.3253	0.3125	0.3153	0.3174	0.3183	0.3188	0.3199	0.3200
0.58	0.3554	0.3515	0.3519	0.3372	0.3401	0.3422	0.3431	0.3438	0.3449	0.3450
0.60	0.3839	0.3797	0.3801	0.3631	0.3662	0.3684	0.3693	0.3700	0.3712	0.3713
0.62	0.4143	0.4097	0.4101	0.3908	0.3938	0.3961	0.3970	0.3977	0.3989	0.3990
0.64	0.4467	0.4418	0.4423	0.4202	0.4232	0.4254	0.4263	0.4269	0.4281	0.4282
0.66	0.4815	0.4762	0.4767	0.4617	0.4544	0.4565	0.4574	0.4580	0.4591	0.4592
0.68	0.5189	0.5132	0.5137	0.4853	0.4878	0.4897	0.4904	0.4910	0.4919	0.4920
0.70	0.5598	0.5531	0.5537	0.5216	0.5236	0.5251	0.5257	0.5262	0.5270	0.5270
0.72	0.6032	0.5965	—	0.5610	0.5623	0.5633	0.5637	0.5640	0.5645	0.5645
0.74	0.6512	0.6440	—	0.6041	0.6044	0.6046	0.6046	0.6047	0.6048	0.6048
0.76	—	—	—	0.6514	0.6504	0.6495	0.6492	0.6490	0.6486	0.6485
0.78	—	—	—	0.7040	0.7012	0.6990	0.6982	0.6975	0.6964	0.6963
0.80	—	—	—	0.7632	0.7579	0.7540	0.7525	0.7513	0.7493	0.7491

Table 4 — Approximate value of $CE\beta^2$ for long radius nozzles

β	$CE\beta^2$ for a Reynolds number, Re_D of:								
	10^4	2×10^4	5×10^4	10^5	2×10^5	5×10^5	10^6	5×10^6	10^7
0.20	0.0387	0.0391	0.0394	0.0395	0.0396	0.0397	0.0398	0.0398	0.0399
0.22	0.0468	0.0472	0.0476	0.0478	0.0480	0.0481	0.0481	0.0482	0.0482
0.24	0.0556	0.0562	0.0567	0.0569	0.0571	0.0572	0.0573	0.0574	0.0574
0.26	0.0653	0.0659	0.0665	0.0668	0.0670	0.0672	0.0673	0.0674	0.0674
0.28	0.0756	0.0764	0.0772	0.0775	0.0778	0.0780	0.0781	0.0782	0.0783
0.30	0.0868	0.0878	0.0886	0.0890	0.0893	0.0896	0.0897	0.0899	0.0899
0.32	0.9880	0.0999	0.1009	0.1014	0.1017	0.1020	0.1022	0.1024	0.1025
0.34	0.1115	0.1128	0.1140	0.1146	0.1150	0.1153	0.1155	0.1158	0.1158
0.36	0.1251	0.1266	0.1280	0.1286	0.1291	0.1295	0.1297	0.1300	0.1301
0.38	0.1395	0.1413	0.1428	0.1436	0.1441	0.1446	0.1448	0.1452	0.1452
0.40	0.1548	0.1568	0.1585	0.1594	0.1600	0.1606	0.1609	0.1612	0.1613
0.42	0.1710	0.1732	0.1752	0.1762	0.1769	0.1775	0.1778	0.1782	0.1783
0.44	0.1881	0.1906	0.1928	0.1939	0.1947	0.1954	0.1958	0.1963	0.1964
0.46	0.2062	0.2090	0.2115	0.2127	0.2136	0.2144	0.2148	0.2152	0.2154
0.48	0.2252	0.2284	0.2312	0.2326	0.2335	0.2344	0.2349	0.2355	0.2356
0.50	0.2454	0.2489	0.2520	0.2535	0.2546	0.2556	0.2561	0.2568	0.2569
0.52	0.2667	0.2705	0.2740	0.2757	0.2769	0.2780	0.2786	0.2793	0.2795
0.54	0.2892	0.2934	0.2972	0.2992	0.3005	0.3010	0.3023	0.3031	0.3033
0.56	0.3130	0.3177	0.3219	0.3240	0.3255	0.3268	0.3275	0.3284	0.3286
0.58	0.3382	0.3434	0.3480	0.3504	0.3520	0.3535	0.3542	0.3552	0.3554
0.60	0.3650	0.3707	0.3758	0.3783	0.3802	0.3818	0.3826	0.3836	0.3839
0.62	0.3935	0.3998	0.4054	0.4082	0.4101	0.4119	0.4128	0.4140	0.4143
0.64	0.4240	0.4308	0.4369	0.4400	0.4422	0.4441	0.4451	0.4464	0.4467
0.66	0.4566	0.4641	0.4707	0.4741	0.4765	0.4768	0.4797	0.4811	0.4814
0.68	0.4916	0.4998	0.5071	0.5108	0.5134	0.5157	0.5169	0.5184	0.5188
0.70	0.5294	0.5384	0.5464	0.5504	0.5533	0.5558	0.5571	0.5588	0.5592
0.72	0.5705	0.5803	0.5891	0.5935	0.5966	0.5993	0.6007	0.6026	0.6030
0.74	0.6154	0.6262	0.6357	0.6405	0.6439	0.6470	0.6485	0.6505	0.6510
0.76	0.6648	0.6766	0.6871	0.6924	0.6961	0.6994	0.7011	0.7033	0.7038
0.78	0.7197	0.7327	0.7441	0.7499	0.7540	0.7577	0.7595	0.7619	0.7625
0.80	0.7814	0.7956	0.8083	0.8146	0.8191	0.8231	0.8251	0.8278	0.8285

Table 5 — Approximate values of $CE\beta^2$ for quarter circle orifice plates

β	$CE\beta^2$
(0.24) ^a	(0.0445)
0.26	0.0523
0.28	0.0608
0.30	0.0699
0.32	0.0798
0.34	0.0903
0.36	0.1017
0.38	0.1138
0.40	0.1268
0.42	0.1405
0.44	0.1555
0.46	0.1715
0.48	0.1887
0.50	0.2071
0.52	0.2272
0.54	0.2487
0.56	0.2724
0.58	0.2979
0.60	0.3257

^a Value outside recommended limit of use.

Table 6 — Approximate values of $CE\beta$ for eccentric orifice plates

β	$CE\beta$
0.46	0.1358
0.48	0.1484
0.50	0.1619
0.52	0.1761
0.54	0.1911
0.56	0.2074
0.58	0.2243
0.60	0.2427
0.62	0.2619
0.64	0.2824
0.66	0.3044
0.68	0.3275
0.70	0.3524
0.72	0.3789
0.74	0.4077
0.76	0.4387
0.78	0.4722
0.80	0.5089
0.82	0.5496
0.84	0.5945

6.3 Example

NOTE For convenience in the following example, the calculations are performed to 6 significant figures.

Calculate the size of orifice plate needed, using D and $D/2$ tapplings, to measure flowrates of between $0.084 \text{ m}^3/\text{s}$ and $0.264 \text{ m}^3/\text{s}$ of dry air, expressed at $1.01325 \times 10^5 \text{ Pa}$ and 15°C , flowing at 100°C and $5.5 \times 10^5 \text{ Pa}$ gauge in a 0.1018 m diameter pipe of seamless rolled carbon steel in good condition. The pipe diameter is the mean of six measurements taken at a room temperature of 20°C and is accurately known.

a) In this example the coefficient of expansion of carbon steel is taken as $1.1 \times 10^{-5}/\text{K}$, at operating temperature:

$$D = 0.1018 \{ 1 + (1.1 \times 10^{-5})(100 - 20) \}$$

$$= 0.10189 \text{ m}$$

b) The density of dry air, ρ_0 , at $1.01325 \times 10^5 \text{ Pa}$ and 15°C is 1.2255 kg/m^3 . The compressibility factor of air at 100°C and $6.513 \times 10^5 \text{ Pa}$ is 1.0008.

c) Density of the air in the pipeline:

$$\rho_1 = 1.2255 \times \frac{(1.01325 + 5.5)}{1.01325} \times$$

$$\times \frac{288.15}{373.15} \times \frac{0.9996}{1.0008}$$

$$= 6.07587 \text{ kg/m}^3$$

The kinematic viscosity of air at pipeline conditions ν_1 is taken as $3.5822 \times 10^{-6} \text{ m}^2/\text{s}$.

d) Volume flowrate is given, therefore the equations required are:

$$q_v = q_o \rho_o / \rho_1$$

$$CE\beta^2 = \frac{4q_v}{\varepsilon\pi D^2 (2\Delta p / \rho_1)^{1/2}}$$

$$Re_D = \frac{4q_v}{\pi D \nu_1}$$

e) Let $\Delta p = 25\,000 \text{ Pa}$ at maximum flowrate

$$(p_1 - \Delta p) / p_1 =$$

$$\frac{\{(5.5 + 1.01325) \times 10^5\} - 25000}{(5.5 + 1.01325) \times 10^5}$$

$$= 0.9616$$

which is greater than 0.75.

f) Assume $\varepsilon = 1$, then the volume flowrate, q_v , at 100 °C and 6.513×10^5 Pa is:

$$q_v = \frac{0.264 \times 1.2255}{6.07587} = 0.053249 \text{ m}^3/\text{s}$$

$$CE\beta^2 = \frac{4 \times 0.053249}{\pi \times 0.10189^2 \times (2 \times 25000 / 6.07587)^{1/2}} = 0.07199$$

$$Re_D = \frac{4 \times 0.053249 \times 0.7}{\pi \times 0.10189 \times 3.5822 \times 10^{-6}} = 1.3003 \times 10^6$$

g) Using Table 2 and interpolating from the $Re_D = 10^5$ column:

$$\beta = \left\{ \frac{0.07199 - 0.0698}{0.0785 - 0.0698} \times (0.36 - 0.34) \right\} + 0.34 = 0.345034$$

and

$$d = 0.345034 \times 0.10189 = 0.035156 \text{ m}$$

$CE\beta^2$, β , and d are within the permitted limits for D and $D/2$ taps.

The pressure loss (see 8.4 of BS 1042-1.1:1992) is given by:

$$\Delta \bar{w} = \frac{1 - CE\beta^2}{1 + CE\beta^2} \times \Delta p = \frac{1 - 0.072}{1 + 0.072} \times 25000 = 21\,600 \text{ Pa}$$

or 87 % of Δp at maximum flow.

h) Re_D is within the permitted limits (see 8.3.1 of BS 1042-1.1:1992):

$$1260 \beta^2 D \leq Re_D \leq 10^8$$

where D is expressed in millimetres.

i) Using Table 6 of BS 1042-1.1:1981:

$$k/D = \frac{0.1}{1000 \times 0.10189} = 0.981 \times 10^{-3}$$

at worst for the type of pipe used which is within the limits set in Table 3 of BS 1042-1.1:1992.

j) The expansibility factor, ε , is given by:

$$\varepsilon = 1 - \left\{ (0.41 + 0.35 \times \beta^4) \times \frac{\Delta p}{p_1 \kappa} \right\}$$

At maximum flow the isentropic exponent for air at the pipeline conditions is:

$$\kappa = 1.404$$

Therefore:

$$\varepsilon = 1 - \left\{ (0.41 + 0.35 \times 0.3450^4) \times \frac{25000}{(5.5 + 1.01325) \times 10^5 \times 1.404} \right\} = 0.98865$$

NOTE ε has been calculated in terms of maximum flowrate.

$$k) CE\beta^2 \text{ (revised)} = 0.07199 / 0.98865 = 0.07282$$

$$\beta \text{ (updated)} = \left\{ \frac{0.07282 - 0.0698}{0.0785 - 0.0698} \times (0.36 - 0.34) \right\} + 0.34 = 0.3469$$

l) Using the equation in 8.3.2.1 of BS 1042-1.1:1992 for $\beta = 0.3469$, the discharge coefficient is found to be:

$$C = 0.5999$$

Calculating $CE\beta^2$ from the values of β and C just obtained:

$$CE\beta^2 = 0.07272$$

which is less than 0.07280.

By trial and error, increasing β , it is found that $\beta = 0.3471$ gives:

$$C = 0.5999$$

and a calculated value of $CE\beta^2$ that is well within 0.01 % of 0.07280.

To check the validity of the result.:

$$q_{\max} = \frac{6.07587}{1.2255} \times 0.5999 \times \frac{(0.3471)^2}{(1 - 0.3471^4)^{1/2}} \times \frac{\pi}{4} \times 0.10189^2 \times 0.98865 \times (2 \times 25000 / 6.07587)^{1/2} = 0.264 \text{ m}^3/\text{s}$$

at 1.01325×10^5 Pa and 15 °C which is the desired result. (Note that the expansibility factor used in this final equation was calculated using $\beta = 0.3471$.)

m) There is no drain hole, and at pipeline temperature:

$$d = 0.10189 \times 0.3471 \\ = 0.03537 \text{ m}$$

n) Correct d for room temperature:

$$d = 0.03537 \{1 + (1.8 \times 10^{-5})(100 - 20)\} \\ = 35.32 \text{ mm}$$

NOTE For this correction, the coefficient of expansion of stainless steel, from which the plate will be made, is taken as $1.8 \times 10^{-5}/\text{K}$.

7 Calculation of rate of flow

7.1 General

The procedure for calculation of the flowrate, given the pipe and orifice diameters, the physical properties of the flowing fluid, the type of primary device used and the measured pressure difference is described.

NOTE The example for each item is given in the corresponding item of 7.3.

7.2 Procedure

NOTE See 4.2 and 4.3.

Before proceeding with the details of the calculation, check that the pipeline configuration is acceptable.

- Calculate the pipe internal diameter, D , and the orifice (or throat) diameter, d , at the operating temperature t °C. (See 12.2.)
- Calculate the diameter ratio, β .
- Check that D , d and β are within the limits specified in this standard for the device in question.
- Obtain the density, ρ_1 and dynamic viscosity μ_1 of the flowing fluid at pipeline conditions. If they are not quoted explicitly in the calculation information summary:
 - use relevant tables of physical data;
 - (see section 3) calculate ρ_1 and μ_1 from values found in tables at reference conditions; and
 - if the flowrate is required in units of volume (per unit time) at reference conditions of pressure and temperature, the density ρ_0 at these conditions is also required.
- Select appropriate equations from clause 5 for the flowrate and Reynolds number, Re_D , according to whether mass or volume flowrate is required.
- Assume a value of 10^6 for the Reynolds number.
- Calculate an interim value for the discharge coefficient, C (or the flow coefficient if appropriate). (See 6.2 k) and 6.2 l.)

h) Check that $(p_1 - \Delta p_{\max})/p_1$ is not less than 0.75.

i) Check that the roughness of the pipe is within limits. (See 6.2 i.)

j) Calculate the expansibility factor ($\alpha = 1$ for liquids). Note that the isentropic exponent or the ratio of specific heats is required. (See 6.2 j.)

k) Use the above data and the interim value of C to calculate an approximate value of the flowrate.

l) Calculate the Reynolds number, Re_D .

m) Calculate a precise value of C using the above value of Re_D .

n) Calculate a revised value of the flowrate.

o) Repeat the procedure from l) to n) until the difference between the last two calculations of flowrate is less than one part in 10^6 .

7.3 Example

NOTE For convenience in the following example, the calculations are performed to 6 significant figures.

Steam at 20×10^5 Pa absolute and 250 °C is flowing in a well-lagged pipeline. A square-edged orifice plate with corner taps is installed at a distance equal to 50 times the pipe diameter downstream of a single right-angle bend. Another bend is situated at a distance equal to at least 20 times the pipe diameter downstream of the orifice plate. The measured diameters of the pipe (carbon steel) and orifice (stainless steel) are 0.152 m and 0.0835 m respectively. The measured pressure difference is 2.5×10^4 Pa.

Calculate the mass flowrate in kg/s.

Reference to 7.2 and Table 1 of BS 1042-1.1:1992 shows that the pipeline configuration is acceptable, even without calculating the diameter ratio.

a) At pipeline temperature:

$$D = 0.152 \{1 + (1.1 \times 10^{-5}) \times \\ \times (250 - 20)\} = 0.152385 \text{ m} \\ d = 0.0835 \{1 + (1.8 \times 10^{-5}) \times \\ \times (250 - 20)\} \\ = 0.0838457 \text{ m}$$

$$\text{b) } \beta = d/D \\ = 0.550223$$

c) Referring to 8.3.1 of BS 1042-1.1:1992:

β is within limits: $0.23 \leq \beta \leq 0.8$

d is within limit: $d \geq 12.5$ mm.

D is within limits: $50 \text{ mm} \leq D \leq 1\,000 \text{ mm}$

d) The density of steam at 20×10^5 Pa and 250 °C is 8.9686 kg/m^3 .

The dynamic viscosity at 20×10^5 Pa and 250°C is 1.82×10^{-5} Pa s.

e) The mass flowrate is required, therefore the equations to be used are:

$$q_m = CE\varepsilon \frac{\pi}{4} d^2 (2\Delta p \rho_1)^{1/2}$$

$$Re_D = \frac{4q_m}{\pi D \mu_1}$$

f) $Re_D = 10^6$ (assumed).

g) From 8.3.2.1 of BS 1042-1.1:1992:

$$C = 0.5959 + 0.0312\beta^{2.1} - 0.184\beta^8 + 0.0029\beta^{2.5} \left(\frac{10^6}{Re_D} \right)^{0.75}$$

$$= 0.603903$$

h) $(p_1 - \Delta p) \rho_1 = (2000000 - 25000) / 2000000 = 0.9875$

which is greater than 0.75.

i) It is assumed for the purposes of this example that the relative roughness of the pipe walls, k/D is less than 3.8×10^{-4} (see 8.3.1 of BS 1042-1.1:1992).

j) For steam, the isentropic exponent, k , is 1.31.

$$\varepsilon = 1 - (0.41 + 0.35\beta^4)X$$

$$= 1 - (0.41 + 0.35 \times 0.550223^4)X$$

where

$$X = \frac{\Delta p}{p_1^k}$$

$$= \frac{25000}{2000000 \times 1.31}$$

$$\varepsilon = 0.995782$$

k) The approximate flowrate is given by:

$$q_m = CE\varepsilon \frac{\pi}{4} d^2 (2\Delta p \rho_1)^{1/2}$$

$$= 0.603903 \times \left(\frac{1}{1 - 0.550223^4} \right)^{1/2} \times 0.995782 \times \frac{\pi}{4} \times (0.0838457)^2 \times (2 \times 25000 \times 8.9686)^{1/2}$$

$$= 2.33295 \text{ kg/s}$$

l) The Reynolds number:

$$Re_D = \frac{4 \times 2.33295}{\pi \times 0.152385 \times 1.82 \times 10^{-5}}$$

$$= 1071030$$

m) The value of C :

$$C = 0.5959 + 0.0312\beta^{2.1} - 0.184\beta^8 + 0.0029\beta^{2.5} \left(\frac{10^6}{1071030} \right)^{0.75}$$

$$= 0.603871$$

n) The revised value of the flowrate:

$$q_m = 2.33282 \text{ kg/s}$$

o) The revised Reynolds number:

$$Re_D = 1070970$$

p) The revised value of C :

$$C = 0.603871$$

q) The newly revised (and final) value of the flowrate:

$$q_m = 2.33282 \text{ kg/s}$$

Section 3. Physical data

8 Properties

In clauses 9 to 11, information is given to assist the user in determining the physical fluid properties needed for the calculation of the flowrate and the Reynolds number. The properties dealt with are density and viscosity of fluids and the isentropic exponents of gases.

9 Density of fluid

9.1 General

The density of the fluid at the upstream tapping can be determined using a density meter or by measurements of the fluid pressure, temperature and composition. For direct measurement of density using a density meter, see 12.1.

9.2 Density of liquids

The density of liquids varies with temperature; the variation with pressure is so slight that it may usually be ignored. The densities of several liquids at standard reference conditions are given in Table 7 and recommended sources of data for the physical properties of liquids are listed in Appendix A.

9.3 Density of mixtures of liquids

The density (in kg/m³) of a mixture of liquids can often be approximated assuming that the volumes of the components are additive:

$$\rho = (\rho_1 v_1 + \rho_2 v_2 + \dots) / 100$$

where:

- ρ_1, ρ_2 are the densities of the component liquids (in kg/m³) at the working conditions;
- v_1, v_2 are the percentages by volume of the components.
- $\rho = 100 / (m_1 / \rho_1 + m_2 / \rho_2 + \dots)$

where:

- m_1, m_2 are the percentages by mass of the components.

The error involved in assuming that the volumes of the components are additive is in general less the more closely the liquids are related chemically. The assumption is not as a rule valid for mixtures of concentrated solutions of electrolytes.

9.4 Density of gases

The density of gases varies with the temperature and pressure and, for moist gases, with the amount of water vapour present. The densities of several dry gases at standard reference conditions are given in Table 8 and recommended sources of data for the physical properties of gases are listed in Appendix A. Gas density variation with temperature and pressure is given by the gas laws, deviations from the laws for perfect gases being allowed for by a compressibility factor (see 9.8). For dry gases, density can be obtained from the following equation:

$$\rho = \frac{p}{Z_g R_g (t + 273.15)}$$

The density of moist gases at pressures close to atmospheric pressure can be calculated from the following equation:

$$\rho = \frac{p - p_v}{Z_g R_g (t + 273.15)} + \frac{p_v}{Z_v R_v (t + 273.15)}$$

where:

- p is the absolute pressure of the fluid at the upstream tapping (in Pa);
- t is the temperature of the fluid at the upstream tapping (in °C);
- p_v is the partial pressure of the water vapour at the upstream tapping (in Pa);
- Z_g and Z_v are the compressibility factors for the dry gas and the water vapour present respectively (dimensionless);
- R_g and R_v are the gas constants for the gas and water vapour respectively [in J/(kg K)].

Table 7 — Physical properties of selected liquids

Liquid	Density at reference conditions	Dynamic viscosity at reference conditions	Melting point	Boiling point
	kg/m ³	μPa s	K	K
Carbon tetrachloride	1 584	969	250	349.8
Ethyl alcohol	789.4	1 189	159	351.4
Glycerine	1 261	1 410 × 10 ³	291.0	563.0
Kerosines	740 to 840	1 000 to 2 000	below 240	420 to 570
Water	998.2	1 002	273.15	373.15

NOTE Reference conditions: 20 °C, 101.325 kPa

Table 8 — Physical properties of selected gases

Gas	Relative molecular mass	Density at reference conditions	Dynamic viscosity at reference conditions	Isentropic exponent at reference conditions	Critical temperature	Critical pressure	Gas constant
		kg/m ³	μPa s		K	MPa	J/(kg K)
Air	28.96	1.2255	17.96	1.4021	132.55 ^a	3.769 ^a	287.1
Ammonia	17.03	0.7298	10.4	1.32	405.6	11.28	488.2
Carbon dioxide	44.01	1.8922	14.40	1.3000	304.0	7.38	188.9
Carbon monoxide	28.01	1.1860	17.23	1.399	132.91	3.499	296.8
Ethylene	28.054	1.1783	9.99	1.250	282.55	5.05	296.4
Hydrogen	2.02	0.08527	8.730	1.406	33.20	1.297	4116.0
Methane	16.04	0.6804	10.80	1.31	190.53	4.595	518.4
Nitrogen	28.01	1.1861	17.32	1.401	126.2	3.39	296.8
Oxygen	32.00	1.3553	20.15	1.397	154.58	5.043	259.8
Propane	44.10	1.92	7.87	1.14	369.82	4.249	188.5
Steam	18.02	—	—	—	647.14	22.05	461.4

^a Indicates gas mixture where composition can change around the critical region.

NOTE Reference conditions: 15 °C, 101.325 kPa

9.5 Density of gas mixtures

When a gas mixture is to be metered and conditions are such that the constituent gases can be considered to be ideal the density of the mixture can be calculated from the following equation:

$$\rho = \frac{p}{R_M(t + 273.15)}$$

where:

R_M is the gas constant for the mixture given by the following equation:

$$R_M = \frac{1}{100}(m_1 R_1 + m_2 R_2 + \dots)$$

where:

R_1 and R_2 are the gas constants for gases 1 and 2 respectively;

m_1 and m_2 are the percentages by mass of the components.

When the gases cannot be considered to be ideal, methods such as those given in the reference of Appendix A should be used.

9.6 Density of fluid containing impurities

When the fluid contains impurities (in small amounts), the effective density may differ from that of the pure fluid. When the effective density is that of the combined system of pure fluid plus impurities, it is given by either of the following equations:

$$\rho = \rho_f + v_i(\rho_i - \rho_f)/100$$

$$\rho = \rho_f / (1 + m_i(\rho_f - \rho_i)/100\rho_i)$$

where:

ρ_f is the density of the pure fluid (in kg/m³);

ρ_i is the density of the impurities (solid, liquid or gas) (in kg/m³);

v_i is the percentage by volume of gaseous impurities;

m_i is the percentage by mass of solid or liquid impurities.

9.7 Partial pressure of water vapour

The partial pressure of water vapour, p_v (in Pa) is required for calculating the density of moist gases. Determination of the value to two significant figures is adequate. The partial pressure can be found from hygrometric measurements or calculated from the amount of water vapour present by means of one of the following equations.

a) If the absolute humidity, H_v , (that is the mass of water vapour present in unit volume of moist gas expressed in kg/m³) is known then:

$$p_v = 464.9 H_v (t + 273.15)$$

where:

t is the temperature at the upstream tapping (in °C).

b) If the moisture content, H_w , (that is the mass of water vapour present in unit mass of dry gas, both masses being expressed in the same units) is known then:

$$p_v = \frac{H_w p}{\left(\frac{M_w}{M_g}\right) + H_w}$$

where:

p is the absolute pressure at the upstream tapping (in Pa);

M_w and M_g are the relative molecular masses of the water vapour and gas respectively.

c) If the relative humidity, ϕ , (that is, the ratio of the actual vapour pressure, p_v , to the saturation vapour pressure at the same temperature) is known then:

$$p_v = \phi p_{vs}$$

where:

p_{vs} is the saturation vapour pressure at the temperature at the upstream tapping.

Accurate measurement of the amount of water vapour present (the absolute humidity, H_v , or the moisture content, H_w ,) is difficult, particularly in the presence of solid impurities and condensable vapours. The best method is often to take a representative sample of the moist gas from a tapping point upstream of the device (but close to it), care being taken to avoid premature condensation, and then to determine by chemical absorption the weight of water vapour contained in the sampled volume.

At temperatures below 150 °C the relative humidity, ϕ , of moist air can be found by means of wet and dry bulb thermometers exposed to a stream of air sampled from the upstream pipeline.

NOTE For further information, reference should be made to BS 1339.

9.8 Compressibility factor

The ideal gas equation modified for use with real gases may be given as:

$$p = Z\rho R(t + 273.15)$$

where:

Z is the compressibility factor;

ρ is the mass density of the fluid;

R is the gas constant;

t is the temperature of the fluid (in °C).

For a perfect gas obeying the ideal laws, Z is constant and equal to unity for all temperatures and pressures. For real gases the compressibility factor, Z , serves as a measure of the extent of the departure from the ideal gas and this allows the density of the gas to be calculated. Values of Z for various gases may be found in the references listed in Appendix A.

10 Viscosity of fluid

10.1 General

The dynamic viscosity (commonly called the absolute viscosity) of the fluid at the upstream pressure tapping is required for calculating the Reynolds number. It is sufficiently precise if the viscosity is known to two significant figures.

10.2 Viscosity of liquids

While the viscosity of liquids is influenced by both temperature and pressure, in most cases it varies with temperature but barely at all with pressure. The dynamic viscosities of various selected liquids at standard reference conditions are given in Table 7 and further information on viscosities may be found from the references listed in Appendix A. Methods for measuring the viscosity of liquids are described in BS 188.

10.3 Viscosity of gases and vapours

The viscosities of gases and vapours vary with temperature and pressure. The dynamic viscosities of selected gases at standard reference conditions are listed in Table 8 and further information on the viscosities of gases may be found from the references listed in Appendix A, where references for the viscosity of steam are also given.

11 Isentropic exponent

The isentropic exponent, κ , which is needed to calculate the expansibility factor decreases with increase of temperature and increases with increase in pressure. At atmospheric pressure and room temperature the value is about 1.4 for diatomic gases such as O₂, H₂, CO, Cl₂, and air and about 1.3 for triatomic gases such as CO₂ and steam. Values of the isentropic exponent for several gases are listed in Table 8 and further information may be obtained from the references listed in Appendix A.

Section 4. Additional information on measurements and on pulsating and swirling flow

12 Measurements

12.1 Direct density measurement

12.1.1 General

In 5.4.3 of BS 1042-1.1:1992, it is stated that the mass density of the fluid can be measured directly provided that the method employed does not disturb the flow measurement. While fluid density at the pressure differential device upstream tapping is frequently determined from fluid pressure and temperature measurements it is also often desirable to employ direct density measurements.

Commercially available density meters are based on several different physical principles and are made in many varieties. Some of the more common principles are:

- a) vibration, where the frequency of vibration of an immersed element depends upon the fluid density;
- b) Archimedes, where the buoyancy of an immersed object depends upon the fluid density;
- c) nucleonic, where the absorption of radiation depends upon the density of the absorbing medium;
- d) Clausius-Mosotti, where the dielectric strength of a fluid is related to its density;
- e) acoustic, where the speed of sound through the fluid is related to its density;
- f) centrifugal, where the pressure rise due to centrifugal forces depends upon the fluid density.

For use in quantity measuring of flow the density meter should be suitable for continuous on-line measurement.

12.1.2 Density meter installation

NOTE Because of the wide variety of density meters available, it is not possible to give details of all of the types of installation.

It is most important to ensure that the fluid in the density meter is at the same pressure and temperature as the fluid it is desired to measure, or sufficiently close to keep errors within acceptable limits.

The flowrate through the density meter should be optimized to give a reasonable response time to changes in density and maintain the desired temperature. Too high a flowrate can cause problems due to pressure losses and turbulent noise.

The flow direction through the density meter should be chosen to encourage self-cleaning. With gases, vertically downward flow will help prevent the build-up of any solid particles or liquid drops.

With liquids, vertically upward flow will help prevent the build-up of any gas bubbles.

Care should be taken to avoid phase changes in the density meter, particularly condensation with gases and flashing with liquids due to temperature and pressure changes.

It is important that temperature differences (between flowmeter and density meter) and temperature gradients (between instruments and their surroundings) be avoided by the use of thermal insulation where necessary.

All density meter installations should be designed to facilitate maintenance and calibration checks.

Differences in installation allow density meters to be divided into two distinct types as follows:

- a) *Direct insertion density meters.* The direct insertion of the density meter in the pipeline ensures that the fluid in the density meter is at the same pressure and temperature as that in the pipeline. The pipeline should be large enough to accommodate the meter with acceptably low pressure loss.
- b) *Bypass sampling system.* For a bypass sampling system a suitable pressure differential device or pump is required to drive the sample flow around the system. Ensuring a representative sample at the correct pressure and temperature can prove difficult and the density meter should preferably be in physical contact with the pipeline for example by mounting it in thermal contact with the pipe. Both the density meter and associated pipework should be thermally lagged to achieve an acceptable temperature equilibrium.

If filters are used in the system, their pressure loss should be considered.

12.1.3 Density meter locations

At first sight it would appear that there is more freedom in the location of a density meter in liquid service than in gas. With incompressible liquids the density is not affected by local pressure changes in the vicinity of the flowmeter, hence, provided there are not marked temperature changes, all densities are the same. With a compressible gas the density changes with pressure and temperature and can be measured only where the corresponding expansibility factor, ε , is known. However other limits of temperature and pressure capacity and sufficient flow are so severe that the differences between gas and liquid service become minor and they can be considered together. Four examples of possible density meter locations are shown in Figure 1, and further details are as follows.

a) *Upstream of flowmeter.* A direct insertion density meter can be placed sufficiently far upstream of the flowmeter not to interfere with it or upstream of a flow straightener that eliminates flow disturbances produced by the meter. For this type of installation care should be taken to ensure that the temperature at the density meter does not differ significantly from the temperature at the flowmeter upstream pressure tapping.

In gas service it can be assumed that the density measured upstream is equal to the density at entry to the flowmeter and the corresponding value of ε_1 can be used provided that it can also be shown that, in addition to negligible temperature difference existing between density meter and flowmeter, the effects of friction losses of the upstream pipe and/or straightener are negligibly small between the density meter and the upstream tapping at the flowmeter.

b) *Across the flowmeter.* If a density meter is installed in a bypass sampling system across the flowmeter, the flow around the bypass should be kept small compared with the main flow and it should be accounted for. It is important that the density sampling system is independent of the impulse lines to the differential pressure cell and does not interfere with the differential pressure measurement.

In gas service the density meter can be installed symmetrically so as to measure the density, in the mid measurement plane, ρ_M and thus be able to apply the expansibility factor ε_M . (See 12.1.4.)

c) *Downstream of flowmeter.* A direct insertion density meter can be located downstream of the flowmeter. Provided it complies with the requirements of clause 7 of BS 1042-1.1:1992, it will not interfere with either the accuracy or pressure recovery of the flowmeter.

For all density meter locations it should be established that the density at the meter at either the upstream or the downstream tapping points can be determined with sufficient accuracy from the density measured at the density meter location.

12.1.4 Expansibility factor

For a given flowmeter and flowrate the position where the fluid density, ρ , and the corresponding expansibility factor, ε , are measured have to be the same, thus the mass flowrate is obtained from the following equation (see clause 5):

$$\begin{aligned} q_m &= a \frac{\pi}{4} d^2 \varepsilon_1 (2\Delta p \rho_1)^{1/2} \\ &= a \frac{\pi}{4} d^2 \varepsilon_M (2\Delta p \rho_M)^{1/2} \\ &= a \frac{\pi}{4} d^2 \varepsilon_2 (2\Delta p \rho_2)^{1/2} \end{aligned}$$

giving:

$$\varepsilon_1(\rho_1)^{1/2} = \varepsilon_M(\rho_M)^{1/2} = \varepsilon_2(\rho_2)^{1/2}$$

where

suffices 1, M and 2 refer to upstream, mid and downstream measurement planes.

If the differences in density are small and the expansion through the orifice can be considered to be close to isothermal, then the following relationships can be assumed.

$$\rho_1 \propto p_1$$

$$p_M \propto \left(p_1 - \frac{\Delta p}{2}\right)$$

$$\rho_2 \propto (p_1 - \Delta p)$$

giving:

$$\varepsilon_M = \varepsilon_1 \left(\frac{1}{1 - y/2}\right)^{1/2}$$

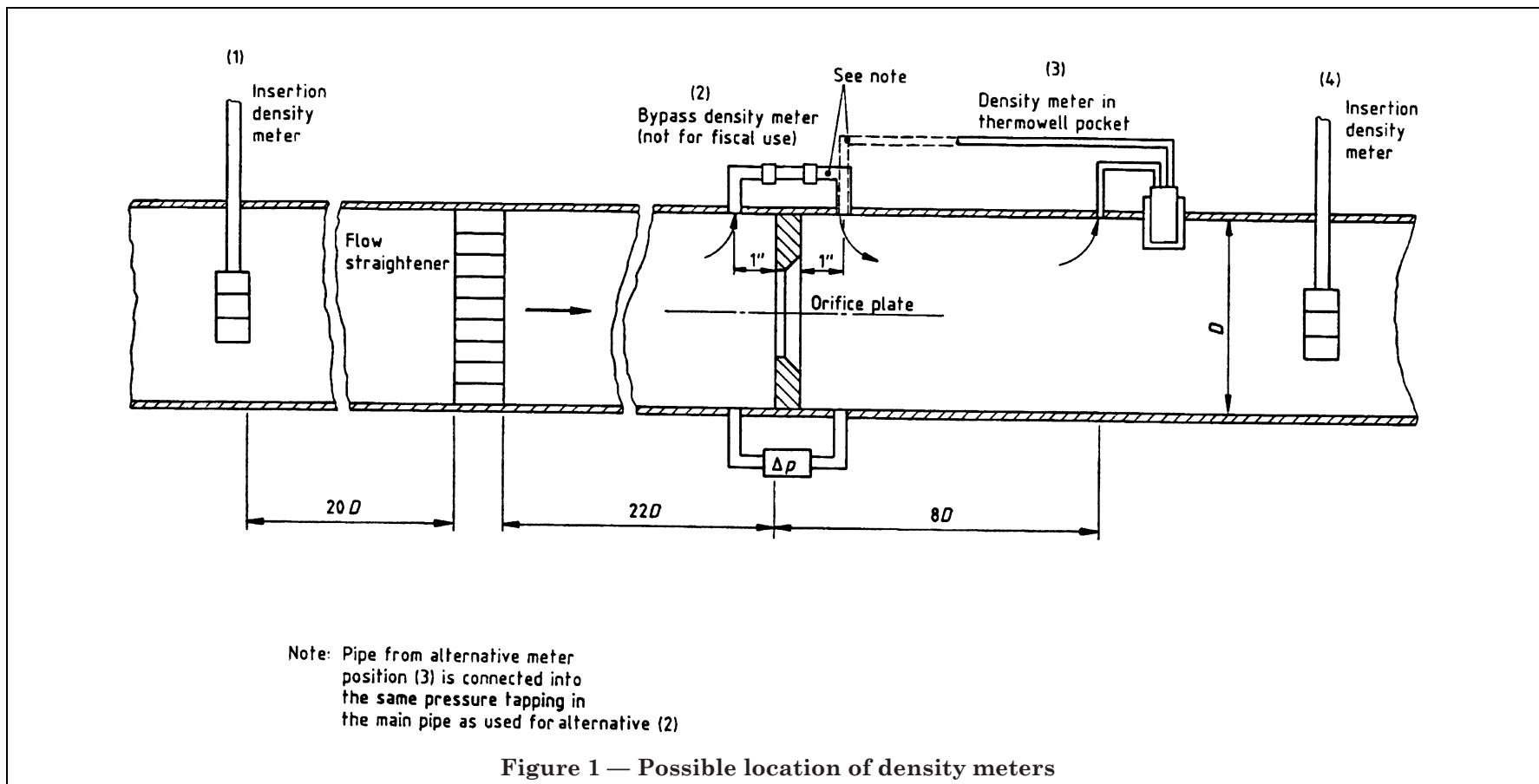
and

$$\varepsilon_M = \varepsilon_1 \left(\frac{1}{1 - y}\right)^{1/2}$$

where

$$y = \frac{\Delta p}{p_1}$$

Hence ε_M and ε_2 can be determined from the values of ε_1 calculated using the equations given for each of the pressure differential devices dealt with in this standard.



12.1.5 Density meter calibration

For accurate work, it is highly desirable and often essential to be able to perform on-site density meter calibration checks and the installation should be arranged to facilitate this. Allowance should be made for any systematic calibration offsets that result from differences in calibration and operational conditions.

One of the simplest checks is to use atmospheric air. Another very useful check is to produce a vacuum to obtain virtually zero density. Meters may be checked using the following.

- a) *Gases*. With gas density meters it is most common to use nitrogen as a calibration fluid. This is because nitrogen is easily available as a very pure gas and its pressure, temperature, density data are well established.
- b) *Liquids*. When calibrating liquid density meters, it is normal to use a mixture of hydrocarbon liquids with hydrometers, a density bottle or pressure pycnometer being used as the reference standard.

12.2 Orifice or throat diameter and pipe diameter

The orifice or throat diameter should be determined by taking the average of measurements of a number of diameters (see requirements for individual devices). All diameters should agree within limits specified for the type of device.

The diameter should be corrected for thermal expansion if the temperature of the device when in use differs from the temperature at which the measurement of the diameter was made.

The corrected diameter, d , is obtained from the measured diameter, d_m , according to the equation:

$$d = d_m \{ 1 + Z_L (t - t_m) \}$$

where

- Z_L is the mean coefficient of linear expansion per kelvin of the material forming the orifice or throat over the temperature range concerned;
- t is the temperature of the device when in use (in °C);
- t_m is the temperature at which the diameter was measured (in °C).

Values of the factor in outer brackets in this equation are given in Figure 2 for selected metals and alloys. The temperature of measurement, t_m , is assumed to be 20 °C.

The value of the pipe diameter used in the calculation of the diameter ratio should also be corrected for thermal expansion.

12.3 Differential pressure

A number of different devices ranging from direct reading U-tube manometers to electronic pressure transducers and transmitters are available for measuring the differential pressure across the pressure differential device.

NOTE Technical details and advice on connections for pressure signal transmissions between the primary flow measurement element and the secondary instrumentation are given in ISO 2186 and information on electrical pressure transmitters is given in BS 4509-1.

12.4 Upstream pressure

The absolute pressure at the upstream tapping is required in the case of compressible fluids in order to calculate the density of the fluid when a density meter is not employed, together with the pressure difference ratio ($\Delta p/p_1$). The absolute pressure is also required in the case of liquids at high pressures. The upstream pressure may be measured by a mercury U-tube for low pressures, and by a Bourdon tube or other type of pressure gauge for high pressures and, as with pressure difference measurements, electrical pressure transducers are now widely used for determination of absolute pressure.

12.5 Upstream temperature

12.5.1 General

The temperature at the upstream pressure tapping is required in order to determine the density of the fluid when a density meter is not employed and also to apply corrections for thermal expansion of the device and the pipe. The absolute temperature (in kelvin) is obtained by adding 273.15 to the measured temperature (in °C). A wide variety of methods of measuring the temperature of fluids is available (see BS 1041). Suitable types of instrument include thermocouple pyrometers, electrical resistance thermometers and mercury-in-glass thermometers.

12.5.2 Position of temperature measurement

Although the measurement should be made at the plane of the upstream pressure tapping, it is not permissible on account of the resulting disturbance to the flow, to insert a thermometer or other temperature measuring instrument into the fluid at this point when a measurement of the pressure difference is being made. In consequence any permanent thermometer should be installed either downstream of the device or sufficiently far upstream not to affect the flow. The minimum upstream and downstream distances are specified in Table 1 of BS 1042-1.1:1992.

The temperature of the fluid at the point of measurement may thus differ from that at the plane of the upstream tapping, especially if the measurement is made downstream and if the pressure difference ratio is large enough to result in an appreciable temperature drop due to adiabatic expansion in the device and downstream pipe. It may be necessary to calibrate the measured temperature against a thermometer temporarily inserted near the upstream pressure tapping.

12.5.3 Precautions for accurate measurement

A measurement of the temperature of a fluid by means of a thermometer installed in a pocket inserted through the pipe wall into the flowing stream at whatever point has been chosen, depends for its accuracy on reducing to a minimum the transfer of heat away from the temperature sensitive portion of the thermometer by conduction through the walls of the pocket and by convection within the pocket. The following precautions should be taken.

The whole of the temperature sensitive portion of the thermometer should lie within a distance of one-quarter of a pipe diameter from the axis of the pipe and the pocket should be sufficiently long for the thermometer to lie within the pipe to the depth of insertion recommended. If this cannot be achieved when the pocket is inserted through the pipe wall at right angles to the axis, the thermometer may be inserted along the axis of the pipe at a bend or tee junction.

The walls of the pocket should be as thin as possible, consistent with safety. This is more readily achieved when the pocket is constructed of corrosion-resistant material.

Undue projection of the pocket outside the pipe should be avoided.

The part of the thermometer projecting outside the pipe and the immediately adjacent pipe walls should be lagged if the temperature of the fluid differs from that of the ambient air by more than approximately 40 °C.

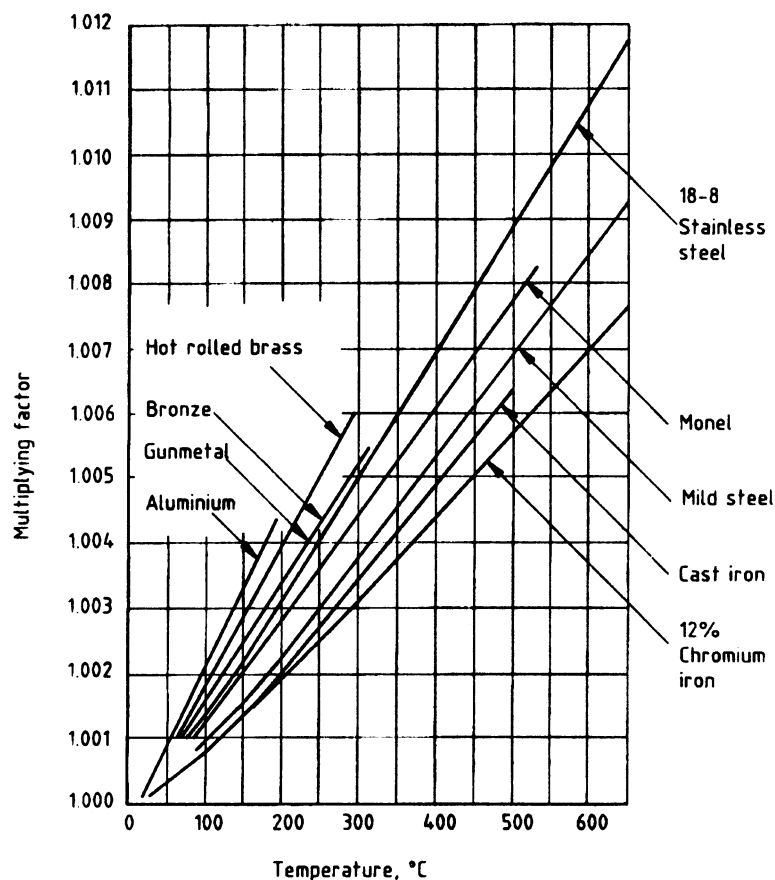


Figure 2 — Multiplying factors for thermal expansion

The mouth of the pocket should be closed to minimize loss of heat by convection, especially at high temperature.

12.5.4 Additional precautions in case of fluctuating temperatures

If the temperature of the fluid is not constant, the accuracy of measurement depends also on reducing to a minimum the time-lag in response resulting from a low rate of heat transfer from the fluid to the temperature sensitive element. The following precautions should be taken.

The walls of the pocket should have a moderately high thermal conductivity and the side in contact with the fluid should be kept clean.

The temperature sensitive portion of the thermometer should be small in size and of low mass and low heat capacity.

There should be good thermal contact between the pocket and the sensitive portion of the thermometer. The space may be filled with a liquid such as hydrocarbon oil, or with high conductivity metal foil or powder such as copper or aluminium.

13 Pulsating flow

13.1 General

The guidance given in this standard is only intended for use in steady flow conditions. When differential pressure flowmeters are used in pulsating flow, the indicated flowrate may be seriously in error. Pulsating flow can be generated by both reciprocating and rotary positive displacement engines, compressors, blowers and pumps, and occasionally by oscillating valves and pressure regulators.

There is often no obvious indication of the presence of pulsations at the flowmeter. They can be detected by means of a hot-wire anemometer or similar device or by means of a fast response differential pressure transducer connected across the primary element.

If pulsations are present, the recommended remedy is to ensure that the flow system contains adequate damping and that the secondary element of the flowmeter is of an appropriate design or is effectively isolated.

13.2 Pulsation effects

13.2.1 Effects on the primary device

The most important effect is due to the square root relationship between flow and differential pressure. In pulsating flow, the time-mean flowrate should be calculated from the mean of the instantaneous values of the square root of the differential pressure. In practice slow response manometric devices are used and the square root of the time-mean differential pressure gives an indicated flowrate larger than the true value. The square root error only depends on the ratio of the root mean square amplitude of the flowrate fluctuation to the mean value (i.e. $q_{v, r.m.s.}/q_v$).

13.2.2 Effects on the secondary device and recommended design rules

Pulsations at the pressure tapings can cause very serious errors in the indicated time-mean differential pressure. These are due to wave action in the connecting leads and to non-linear damping both in the leads and in the differential pressure measuring device itself.

The magnitude of the errors depends not only on the pulsation characteristics but also on the geometry of the secondary device. It is not possible to define a threshold level of negligible pulsation applicable to all designs of secondary device, however, a number of design rules can be given.

For slow response secondary devices used to indicate the time-mean differential pressure in pulsating flow conditions, the rules are as follows.

- a) The bore of the pressure tapping should be uniform and not too small. Piezometer rings should not be used.
- b) Connecting leads should be as short as possible and of the same bore as the tapings. Lead lengths near the pulsation quarter-wave length should be avoided.
- c) Gas volumes should not be included in the leads or sensing element.
- d) Damping resistances in leads and sensing element should be linear. Throttle cocks should not be used.
- e) The natural frequency of the sensing element should be lower than the pulsation frequency.

Where these rules cannot be observed, the secondary device can be effectively isolated from pulsations by the insertion of linear-resistance damping plugs in both connecting leads as close as possible to the pressure tapings.

For a fast response electronic differential pressure transducer, rules a), b) and c) apply together with the following.

f) The mechanical and electronic frequency limits of the transducer should be an order of magnitude greater than the pulsation frequency.

g) The distance along the pressure passage from tapping to sensing element should be small compared with the pulsation quarter-wave length.

h) The device should be geometrically similar on both upstream and downstream sides.

13.3 Pulsation damping

13.3.1 General

Pulsations in gases or vapours can be damped by a combination of volumetric capacity and throttling placed between the pulsation source and the flowmeter. The volumetric capacity can include the volume of any receivers and the pipeline itself provided the axial lengths involved are short compared with the pulsation wavelength. The throttling can be provided by frictional pressure losses in the pipeline, valves and other fittings and including the net pressure loss of the flowmeter itself.

Pulsations in liquid flow can be similarly damped by sufficient capacity and throttling, the capacity being provided by an air vessel in the pipeline.

Alternatively a surge chamber can be used instead of the air vessel.

Expressions are given in 13.3.2 and 13.3.3 for calculating when the damping is adequate to keep metering errors due to pulsation below a given level. The expressions are insufficiently exact to be used to predict actual values of pulsation errors in a given system.

13.3.2 Gas flow

NOTE (See Figure 3).

A parameter that can be used as a criterion of adequate damping in gas flow is the Hodgson number, H_o , defined by:

$$H_o = \frac{V}{\bar{q}_v/f} \frac{\Delta \bar{\omega}'}{p'}$$

where

- V is the volume of the receiver and the pipework between pulsation source and flowmeter;
- \bar{q}_v/f is the time-mean volume flow per pulsation cycle;
- f is the pulsation frequency;
- $\Delta \bar{\omega}'$ is the overall time-mean pressure loss between the receiver and the source of supply (or discharge) at constant pressure;
- p' is the static pressure in the receiver.

Damping will be adequate provided that the following condition is fulfilled:

$$\frac{H_o}{\kappa} > 0.563 \frac{1}{(\Psi)^{1/2}} \frac{q_{v, \text{ r.m.s}}}{\bar{q}_v}$$

where

- κ is the isentropic exponent of the gas or vapour, i.e. the ratio of the specific heat capacities for a gas;
- $q_{v, \text{ r.m.s}}$ is the root mean square value of the fluctuating component of the flowrate measured at the pulsation source;
- \bar{q}_v is the time-mean value of the flowrate;
- Ψ is the maximum allowable percentage error in the indicated flowrate due to pulsation.

13.3.3 Liquid flow

Pulsating liquid flow can be damped by placing either a surge chamber or an air vessel between the pulsating flow source and the primary element. Frequent checks are necessary to ensure that a volume of air is maintained in the air vessel.

In Figure 4, flow is shown with the pulsation source upstream. It is equally possible, however, to have flow with a constant head source upstream and pulsation source downstream.

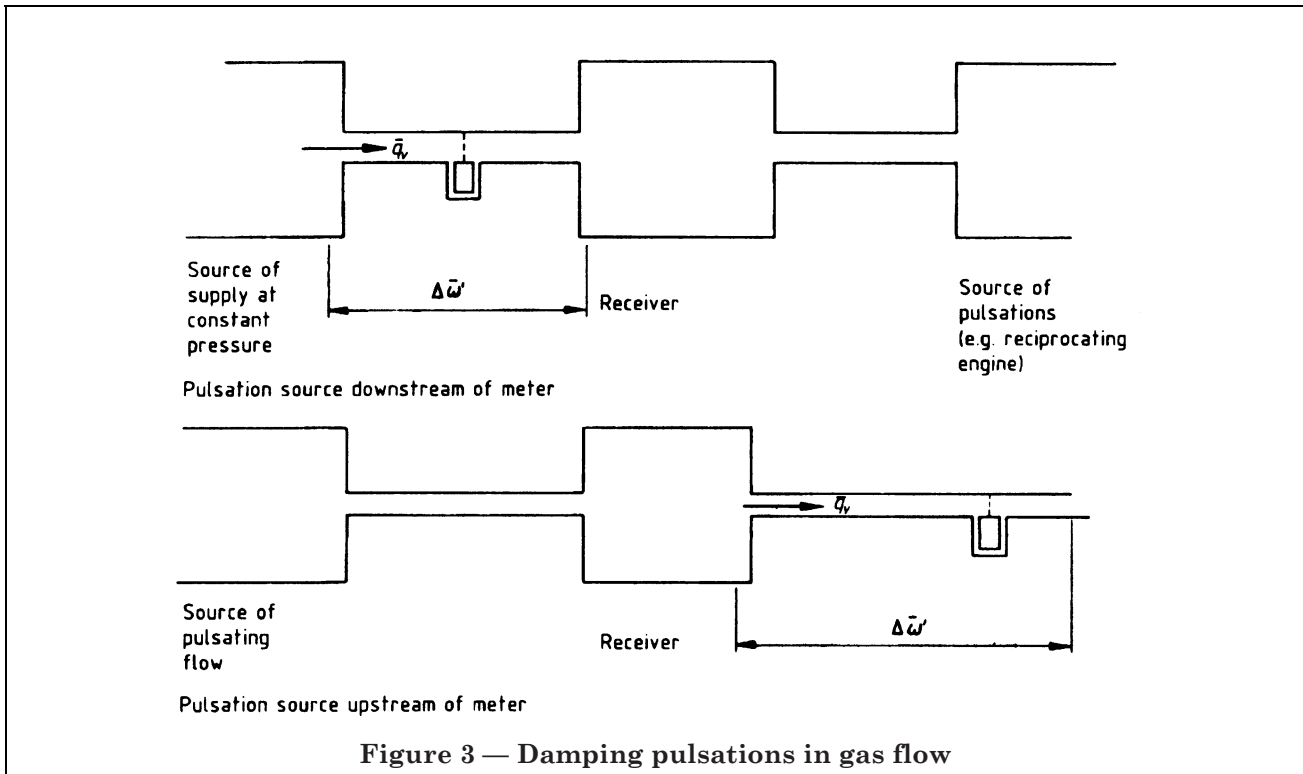


Figure 3 — Damping pulsations in gas flow

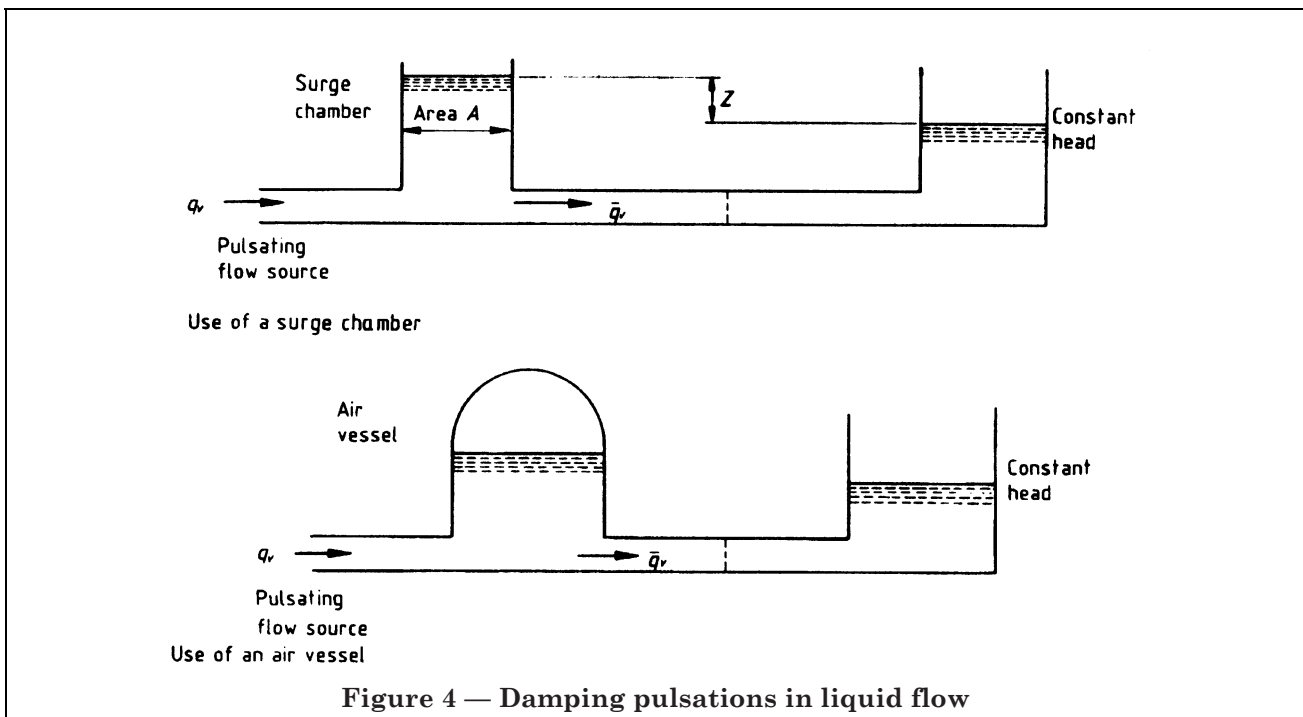


Figure 4 — Damping pulsations in liquid flow

If a surge chamber is used, the criterion for adequate damping is that:

$$\frac{\bar{Z}A}{q_v/f} > 0.563 \frac{1}{(\psi)^{1/2}} \frac{q_{v, r.m.s.}}{\bar{q}_v}$$

where

- \bar{Z} is the time-mean value of the difference in liquid level in the surge chamber and the constant head vessel;
- A is the cross-sectional area of the surge chamber.

The criterion for adequate damping when an air vessel is used is that:

$$\frac{1}{\kappa} \frac{V_o}{\bar{q}_v/f} \frac{\Delta \bar{\omega}}{P_o} \frac{1}{1 + \frac{V_o \rho g}{P_o \kappa S}} > 0.563 \frac{1}{(\psi)^{1/2}} \frac{q_{v, r.m.s.}}{\bar{q}_v}$$

where

- V_o is the volume of the air in the air vessel;
- P_o is the pressure of the air in the air vessel;
- κ is the isentropic exponent for air;
- ρ is the density of the liquid;
- g is the gravitational acceleration;
- S is the free surface area of the liquid in the air vessel.

13.4 Determination of pulsation amplitude

It is always necessary to determine the root mean square amplitude of the undamped flow pulsation $q_{v, r.m.s.}$.

There are a number of methods that can be used to obtain the amplitude and these are set out in order of preference as follows.

- Direct measurement using a linearized hot-wire anemometer or similar device and r.m.s. voltmeter. The r.m.s. value of the fluctuating component of the voltage output should be measured on a *true* r.m.s. meter. Mean-sensing r.m.s. meters should not be used as these will only read correctly for sinusoidal waveforms.
- Using a linearized hot-wire anemometer or similar device and calculating $q_{v, r.m.s.}$ from a recorded time trace.
- Inferring the maximum probable value of $q_{v, r.m.s.}$ from a measurement of $\Delta p_{r.m.s.}/\Delta p$ using the equation:

$$\frac{q_{v, r.m.s.}}{\bar{q}_v} = \frac{1}{2} \frac{\Delta p_{r.m.s.}}{\Delta p}$$

where

$\Delta p_{r.m.s.}$ is the r.m.s. value of the fluctuating component of the differential pressure across the primary element using a fast response pressure transducer under undamped pulsating flow conditions;

Δp is the differential pressure that would be measured across the primary element under steady flow conditions.

d) If methods a), b) or c) cannot be used, the maximum probable value of $q_{v, r.m.s.}$ can be approximately inferred from a measurement of $\Delta p_{r.m.s.}/\Delta \bar{p}_p$ using the following equation:

$$\frac{q_{v, r.m.s.}}{\bar{q}_v} = \left\{ \frac{2}{1 + \left(1 - \frac{\Delta p_{r.m.s.}}{\Delta \bar{p}_p} \right)^2} - 1 \right\}^{1/2}$$

where

$\Delta \bar{p}_p$ is the time-mean differential pressure measured across the primary element under undamped pulsating flow conditions using a fast response pressure transducer.

14 Swirling flow

Swirling motion due to upstream disturbances such as tangential or offset entries, cyclones, vortex separators, partially open valves etc. will usually require damping. Swirling motion is only slowly damped in flow through a pipe and that due to a strong source may persist for a distance of a hundred or more pipe diameters. The effect of swirl on the performance of the pressure differential device depends on the strength of the swirl, its position relative to the axis of the pipe, the type of pressure differential device and its area ratio. The presence of swirl may be detected by a pitot tube or a yaw meter.

Where it is considered that significant swirl exists and the general requirements for flow conditions at the inlet to the primary device, given in 7.4 of BS 1042-1.1:1992, are not met, flow straighteners of the types recommended in 7.3 of BS 1042-1.1:1992 should be installed.

Appendix A References for physical data

A.1 Density

A.1.1 Single-phase flows

A.1.1.1 Liquids

- a) TRC. *The Thermodynamics Research Centre Data Project — Selected values of properties of chemical compounds*. College Station, Texas. TRC, Texas A & M University.
- b) API 44. The American Petroleum Institute Research Program 44. *Selected values of the properties of hydrocarbons and related compounds*. College Station, Texas. TRC, Texas A & M University.
- c) VARGAFTIK, N.B. 1975. *Tables on the thermophysical properties of liquids and gases*. 2nd edition. New York, J. Wiley & Sons.
- d) YAWS, C.L. 1974-6. Physical and thermodynamic properties. Parts 1–21. *Chemical Engineering*. New York, McGraw-Hill, June 1974 November 1976.

A.1.1.2 Gases

- a) *L'Air Liquide* 1976. Gas encyclopaedia. Amsterdam, Elsevier.
- b) See A.1.1.1 c).
- c) See A.1.1.1 a).
- d) See A.1.1.1 b).

A.1.1.3 Steam

- a) THE INTERNATIONAL FORMULATION COMMITTEE. 1967. *The 1967 IFC Formulation for Industrial Use. A formulation of the thermodynamic properties of ordinary water substance prepared by the International Formulation Committee (IFC)*. New York, NY: Amer. Tec. Mec. Eng.
- b) UNITED KINGDOM COMMITTEE ON THE PROPERTIES OF STEAM. 1970. *UK Steam Tables in SI Units*. London, Edward Arnold (Publishers) Ltd.

A.1.2 Mixtures of liquids

- a) LANDOLT-BORNSTEIN. 1974. *Group IV — Macroscopic and technical properties of matter. Volume 1 — Density of liquid systems, Part A : Non-aqueous systems and ternary aqueous systems*. New series. Berlin, Springer-Verlag.
- b) See A.1.1.2 a).

A.2 Compressibility factor for gases and gas mixtures

- a) *BRITISH GAS DATA BOOK. Properties of natural gas: treatment, transmission, distribution and storage. Volume 1*. British Gas Corporation, 1974.
- b) See A.1.1.2 a).

A.3 Isentropic exponent

A.3.1 Gases

- a) See A.1.1.1 c).
- b) See A.1.1.2 a).

A.3.2 Gas mixtures

- a) See A.1.1.2 a).

A.4 Viscosity

A.4.1 Single-phase flows

A.4.1.1 Liquids

- a) TOULOUKIAN, Y.S., SAXENA, S.C., HESLEMANS, P. 1975. *Thermophysical properties of matter. Volume II — Viscosity*. New York, IFI/Plenum.
- b) See A.1.1.1 c).

A.4.1.2 Gases

- a) GOLUBEV, I.F. 1959. *Viscosity of gases and gas mixtures*. Moscow, Fiz. Mat. Gosuderst Izdatel. English translation 1971. Israel Program for Scientific Translation, Jerusalem.
- b) See A.1.1.2 a).
- c) See A.4.1.1 a).
- d) See A.1.1.1 c).

A.4.1.3 Steam

- a) *Release on dynamic viscosity of water substance*. Issued by the International Association for the Properties of Steam 1975. Copies available from the Executive Secretary Dr Howard J White Jr, Office of Standard Reference Data, National Bureau of Standards, Washington DC, 20234, USA. Also summarized in *Rev. Gen. Therm, Fr.*, 1976, (174–175), 559–562.

A.4.2 Mixtures

A.4.2.1 Liquids

- a) LANDOLT-BORNSTEIN. 1969. *Volume II – Properties of matter in its aggregated states. Part 5a: Viscosity and diffusion*. 6th ed. Berlin, Springer-Verlag.

A.4.2.2 Gases

- a) See A.4.1.2 a).
- b) See A.4.1.1 a).
- c) See A.1.1.1 c).

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