INTERNATIONAL STANDARD

ISO 6358-3

First edition
2014-10-01

Pneumatic fluid power — Determination of flow-rate characteristics of components using compressible fluids —

Part 3: Method for calculating steady-state flow-rate characteristics of systems

Transmissions pneumatiques — Détermination des caractéristiques de débit des composants —

Partie 3: Méthode de calcul des caractéristiques de débit stationnaire des assemblages

Reference number
ISO 6358-3:2014(E)

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Published in Switzerland

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

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The committee responsible for this document is ISO/TC 131, *Fluid power systems*, Subcommittee SC 5, *Control products and components*.

This first edition of ISO 6358-3, together with ISO 6358-1 and ISO 6358-2, cancels and replaces ISO 6358:1989 which has been technically revised. However, Parts 2 and 3 are new standards whose scopes were not included in ISO 6358:1989.

ISO 6358 consists of the following parts, under the general title *Pneumatic fluid power — Determination of flow-rate characteristics of components using compressible fluids*:

— *Part 1: General rules and test methods for steady-state flow*

— *Part 2: Alternative test methods*

— *Part 3: Method for calculating steady-state flow-rate characteristics of systems*

Introduction

In pneumatic fluid power systems, power is transmitted and controlled through a gas under pressure within a circuit. Components that make up such a circuit are inherently resistive to the flow of the gas, and it is necessary, therefore, to define and determine the characteristics that describe their flow-rate performance.

ISO 6358:1989 specified a method to determine the flow-rate characteristics of pneumatic valves, based upon a model of converging nozzles. The method included two characteristic parameters: sonic conductance, *C*, and critical pressure ratio, *b*, used in a proposed mathematical approximation of the flow behaviour. The result described flow performance of a pneumatic valve from choked (sonic) flow to subsonic flow.

Experience has demonstrated that many pneumatic valves have converging-diverging characteristics that do not fit the ISO 6358:1989 model very well. A change was necessary to take into account the influence of the flow velocity on pressure measurements. Furthermore, new developments have allowed the application of this method to additional components beyond pneumatic valves. However, this now requires the use of four parameters (*C*, *b*, *m*, and Δp_c) to define the flow performance in both the choked (sonic) and subsonic regions.

This part of ISO 6358 uses a set of four flow-rate characteristic parameters determined from test results. These parameters are described as follows and are listed in decreasing order of priority:

— The sonic conductance, *C* corresponding to the maximum flow rate (choked), is the most important parameter. This parameter is defined by the upstream stagnation conditions.

— The critical back-pressure ratio, *b*, representing the boundary between choked and subsonic flow, is second in importance. Its definition differs here from the one in ISO 6358:1989 because it corresponds to the ratio of downstream to upstream stagnation pressures.

— The subsonic index, *m*, is used if necessary to represent more accurately the subsonic flow behaviour. For components with a fixed flow path (i.e. one that does not vary with pressure or flow rate), *m* is distributed around 0,5. In these cases, only the first two characteristic parameters *C* and *b* are necessary. For many other components, *m* varies widely; in these cases, it is necessary to determine *C*, *b* and *m.*

— The parameter Δp_c, is the cracking pressure. This parameter is used only for pneumatic components that open with increasing upstream pressure, such as non-return (check) valves or one-way flow control valves.

Several changes to the test equipment were made to overcome apparent violations of the theory of compressible fluid flow. This included expanded inlet pressure-measuring tubes to satisfy the assumptions of negligible inlet velocity to the item under test and to allow the inlet stagnation pressure to be measured directly. Expanded outlet tubes allowed the direct measurement of downstream stagnation pressure to better accommodate different component models. The difference between stagnation pressure upstream and downstream of a component means a loss of pressure energy.

For testing a component with a large nominal bore, to shorten testing time or to reduce energy consumption, it is desirable to apply the methods specified in ISO 6358-2, which covers a discharge test and a charge test as alternative test methods.

This part of ISO 6358 can be used to calculate without measurements an estimate of the overall flow rate characteristics of a system of components and piping. In most cases, the flow rate characteristics of components are determined in accordance with Parts 1 or 2 of ISO 6358; however, the flow rate characteristics of some components are expressed by flow rate coefficients other than those defined in ISO 6358. Formulas to calculate nearly equivalent flow rate characteristics are given.

Pneumatic fluid power — Determination of flow-rate characteristics of components using compressible fluids —

Part 3: Method for calculating steady-state flow-rate characteristics of systems

1 Scope

This part of ISO 6358 specifies a method that uses a simple numerical technique to estimate without measurements the overall flow-rate characteristics of a system of components and piping with known flow-rate characteristics.

The formulae used in this part of ISO 6358 describe the behaviour of a compressible fluid flow through a component for both subsonic and choked flows.

NOTE The conductance of a tube, silencer or filter is influenced by the upstream pressure, so the values of C and b are only valid for the upstream pressure at which they are determined.

This part of ISO 6358 also provides methods to obtain equivalent flow-rate characteristics for components whose flow-rate characteristics differ from those defined in the ISO 6358 series.

2 Normative references

The following referenced documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 5598, *Fluid power systems and components — Vocabulary*

ISO 6358-1:2013, *Pneumatic fluid power — Determination of flow-rate characteristics of components using compressible fluids — Part 1: General rules and test methods for steady-state flow*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 5598 and ISO 6358-1 apply. For the purposes of this part of ISO 6358, the term 'component' also includes piping.

4 Symbols and units

The symbols and units used in this part of ISO 6358 shall be in accordance with ISO 6358-1 and Table 1.

Table 1 — Symbols and units

Symbol	Description	SI unit
b_{pipe}	Critical back-pressure ratio of pipe, tube or hose	–
C_{pipe}	Sonic conductance of pipe, tube or hose	$m^3/(s·Pa)$(ANR)
d	Inside diameter of pipe, tube or hose	m
L	Length of pipe, tube or hose	m
λ	Average friction factor of a pipe, tube or hose depending on the Reynolds number	–
p_{s2}	Static pressure downstream of the pipe, tube or hose	Pa
T	Absolute stagnation temperature	K
γ	Ratio of specific heat capacities (for air, it equals 1,4)	–
k	Friction coefficient of the pipe, tube or hose resulting from experimental tests	–
Re	Reynolds number of the flow within the pipe, tube or hose	–
μ	Dynamic viscosity	Pa.s
$p_{11}, p_{12}, p_{1i}, p_{1n}$	Upstream pressure at inlet of each component (stagnation pressure)	Pa
$p_{21}, p_{22}, p_{2i}, p_{2n}$	Downstream pressure at outlet of each component (stagnation pressure)	Pa
NOTE See Annex D for additional symbols used in that annex.		

The subscripts used in this part of ISO 6358 shall be in accordance with ISO 6358-1 and Table 2.

Table 2 — Subscripts used in this part of ISO 6358

Subscript	Description
i	Number of the component (valve, silencer, etc.) or the piping (pipe, tube, hose, connector, etc.), with i = 1 at the start of the system and n at the end
pipe	Relating to the static downstream pressure of the piping when expressed using a friction factor depending on the Reynolds number
e	Relating to the inlet
f	Relating to the final component
j	Index of step calculation of the system

5 Calculation hypotheses

5.1 General

The following hypotheses are considered for the flow-rate characteristics of the equivalent system:

— Flow is assumed to be adiabatic, to take into consideration that stagnation temperatures at the inlet of each component are identical to each other.

— For components connected in series, the outlet pressure of one component is the same as the inlet pressure of the following component.

— For components connected in parallel, the inlet pressure to each component is the same, and the outlet pressure from all components is the same.

5.2 Relationships among component flow-rate characteristics

When

$$b < \frac{p_2}{p_1} \leq 1 - \frac{\Delta p_c}{p_1}$$

the flow is subsonic, so the relationship of a component's mass flow rate to its flow-rate characteristics is as shown in Formula (1):

$$q_m = C \rho_0 p_1 \sqrt{\frac{T_0}{T_1}} \left[1 - \left(\frac{\frac{p_2}{p_1} - b}{1 - \frac{\Delta p_c}{p_1} - b} \right)^2 \right]^m \quad (1)$$

when

$$\frac{p_2}{p_1} \leq b$$

the flow is choked, so the relationship of a component's mass flow rate to its flow-rate characteristics is as shown in Formula (2):

$$q_m^* = C \rho_0 p_1^* \sqrt{\frac{T_0}{T_1^*}} \quad (2)$$

when

$$1 - \frac{\Delta p_c}{p_1} < \frac{p_2}{p_1} \leq 1$$

the mass flow rate is zero, so the relationship of a component's mass flow rate to its flow-rate characteristics is as shown in Formula (3):

$$q_m = 0 \quad (3)$$

NOTE The symbols used in Formulae (1), (2) and (3) are from ISO 6358-1 and are not used in the remainder of this part of ISO 6358. The formulae are described here for general reference and have specific application later in this part of ISO 6358.

5.3 Flow-rate characteristics

5.3.1 General

Before applying the calculation procedure described either in Clause 6 for components connected in series or in Clause 7 for components connected in parallel, the flow-rate characteristics of all components should be expressed in accordance with the ISO 6358 series.

If the flow-rate characteristics of some components are expressed by methods other than the ISO 6358 series, the values of C, b, m and Δp_c can be obtained in accordance with 5.3.2 or 5.3.3 and Annex D.

5.3.2 Flow-rate characteristics of piping defined by its geometric dimensions

5.3.2.1 General

Pipes, tubes and hoses are defined by their length L and inside diameter d. When these are included in an assembled system, either formulas based on traditional fluid mechanics, given in 5.3.2.2, or the formulas based on test results, given in 5.3.2.3, shall be used. The formulas based on test results are based on testing conducted in accordance with ISO 6358-1 at 500 kPa (5 bar). A maximum error of ± 15 % can be expected due to the variation in the tolerances of inside diameters. Details of the test results are described in Annex D. Additional information on the development of the theoretical formulas is given in D.2.3.

5.3.2.2 Formulas using the friction factor dependent on the Reynolds number

5.3.2.2.1 Using the traditional friction factor λ, which is dependent on the Reynolds number, Formulae (4) to (7) can be used to calculate the flow-rate characteristic parameters of a pipe, tube or hose. These formulae can be applied with any gas that can be considered as a perfect gas. Further information about the theoretical aspects related to these formulae is given in Annex D.

$$C_{\text{pipe}} = \frac{\pi}{4\rho_0\sqrt{RT_0}} \frac{d^2}{\sqrt{\left(1+\frac{\lambda L}{d}\right)+\sqrt{\frac{2}{\gamma(\gamma+1)}}\sqrt{1+\frac{\lambda L}{d}}+\frac{1}{\gamma(\gamma+1)}}} \tag{4}$$

$$b_{\text{pipe}} = 1-\frac{1}{1+\frac{1}{\sqrt{\frac{\gamma(\gamma+1)}{2}}\sqrt{1+\frac{\lambda L}{d}}}+\frac{1}{\gamma(\gamma+1)\left(1+\frac{\lambda L}{d}\right)}} \tag{5}$$

$$m_{\text{pipe}} = 0{,}5 \tag{6}$$

$$\Delta p_{c\text{pipe}} = 0 \tag{7}$$

NOTE The parameters calculated in Formulae (4) to (7) have the subscript “pipe” to indicate that they relate to the downstream static pressure in the pipe, tube or hose.

5.3.2.2.2 In Formulae (4) to (7), the average Darcy friction factor λ is dependent on the Reynolds number as shown in Formula (8); the Reynolds number is determined using Formulae (9) and (10):

$$\lambda = \frac{1}{\left(1{,}8\log_{10}(Re)-1{,}64\right)^2} \tag{8}$$

NOTE Formula (8) is the Filonenko formula, which is used with smooth circular pipes and a turbulent flow (given for Reynolds numbers higher than 4000, see reference[2] in the bibliography). Other formulas that can be found in the literature can also be used for the expression of the friction factor as a function of the Reynolds number. See D.2.3.2 for further information.

5.3.2.2.3 The Reynolds number, Re is the dimensionless parameter correlating the viscous behaviour of Newtonian fluids, as shown in Formula (9):

$$Re = \frac{4q_m}{\pi\, d\, \mu} \tag{9}$$

5.3.2.2.4 The parameter μ is the dynamic viscosity. The fluid temperature dependency can be taken into account, for example, in accordance with the Sutherland law expressed by Formula (10), which is valid for air:

$$\mu = \mu_r \left(\frac{T_e}{T_r}\right)^{3/2} \left(\frac{T_r + S}{T_e + S}\right) \tag{10}$$

where:

- μ_r is the dynamic viscosity for the Sutherland reference temperature T_r equal to $1{,}712 \times 10^{-5}$ Pa.s;
- T_r is the Sutherland reference temperature, equal to 273 K;
- S is the Sutherland constant, equal to 110,4 K.

which gives

$$\mu = 1{,}455 \times 10^{-6} \frac{{T_e}^{3/2}}{T_e + 110{,}4}$$

5.3.2.2.5 In the case of air (where γ = 1,4), Formulae (4) and (5) become Formulae (11) and (12):

$$C_{pipe} = \frac{2{,}28 \times 10^{-3} d^2}{\sqrt{\left(1 + \frac{\lambda L}{d}\right) + 0{,}77\sqrt{1 + \frac{\lambda L}{d}} + 0{,}3}} \tag{11}$$

$$b_{pipe} = 1 - \frac{1}{1 + \frac{0{,}77}{\sqrt{1 + \frac{\lambda L}{d}}} + \frac{0{,}3}{1 + \frac{\lambda L}{d}}} \tag{12}$$

5.3.2.3 Flow-rate characteristics of piping, based on test results

NOTE Formulae (13) to (18) give the flow-rate characteristics of the pipe or tube at a constant inlet pressure of 500 kPa (5 bar).

5.3.2.3.1 Formulae (13) to (16) are based on the results of testing conducted in accordance with ISO 6358-1 with air and can be used to calculate the flow-rate characteristic parameters of a pipe or tube. Measurement results for polyurethane tubes are given in G.4 of ISO 6358-1:2013. Further information is given in D.2.4.

$$C = \frac{\pi d^2}{2 \times 10^3 \sqrt{k \frac{L}{d} + 1}} \tag{13}$$

$$b = 4{,}8 \times 10^2 \frac{C}{d^2} \tag{14}$$

$$m = 0{,}58 - 0{,}1b \tag{15}$$

$$\Delta p_c = 0 \tag{16}$$

5.3.2.3.2 The parameter k is a diameter-dependent friction coefficient determined from test results. It is dependent only on the inside diameter of the pipe or tube and not on the flow conditions.

For resin tubes, determine k by using Formula (17):

$$k = 2{,}35\times10^{-3} d^{-0{,}31} \quad (17)$$

For steel tubes, determine k by using Formula (18):

$$k = 3{,}61\times10^{-3} d^{-0{,}31} \quad (18)$$

5.3.2.3.3 For other inlet pressures, calculate the corresponding flow-rate characteristics using the pressure dependence coefficient K_p for sonic conductance equal to 2×10^{-7} [-/Pa], in accordance with ISO 6358-1.

5.3.3 Components whose flow-rate characteristics are expressed by historically used flow-rate parameters or equivalent length of straight pipe

When the flow-rate characteristics of a component are expressed by historically used flow-rate parameters, for example, nominal flow rate q_N, C_v or K_v, or in terms of an equivalent length of straight pipe or tube, a rough evaluation of compressible flow-rate characteristics can be obtained using the guidance provided in Annex D.

6 Organization of calculations for systems of components connected in series

6.1 General

Consider a system of components connected in series as illustrated in Figure 1. The same mass flow rate q_m of fluid passes through all components when the system is in a steady-state condition.

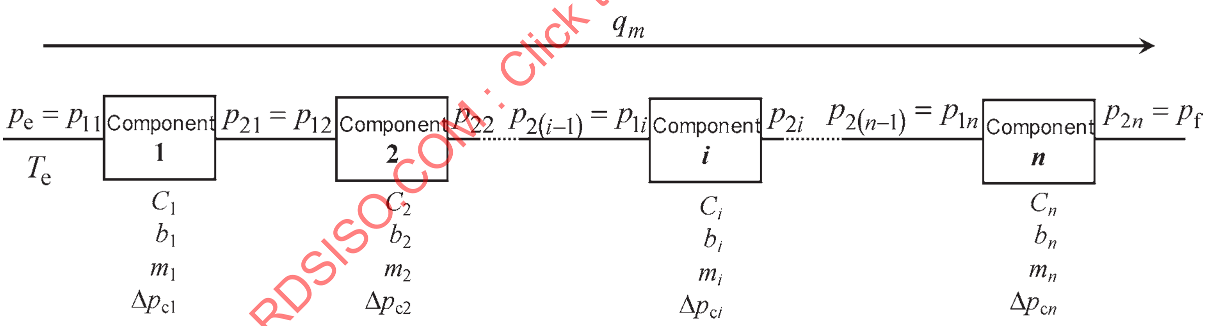


Figure 1 — System of components connected in series

The aim of the method specified in this clause is to obtain a single set of flow-rate characteristics for the system, determined from the flow-rate characteristics of the components and piping as illustrated in Figure 2.

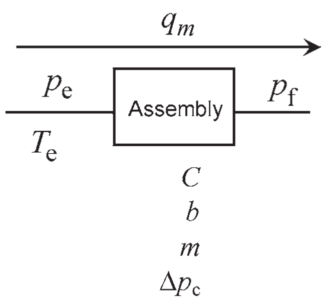


Figure 2 — Equivalent system

6.2 Given parameters

For the calculation of the flow-rate characteristics of a system of components connected in series, the following parameters shall be given:

— the inlet pressure (p_e) to the system, which is the upstream pressure to the first component (p_{11});

— the stagnation temperature of the fluid, T_e, at the entrance to the system. For the calculation, the flow is assumed to be adiabatic, so the stagnation temperature is assumed to be the same everywhere in the system.

6.3 Calculation principle

Consider the system of components connected in series as shown in Figure 1. Its flow-rate characteristics are determined from a sequence of five main calculation steps as described in the following paragraphs and in Figure C.1.

Because cracking pressure can be determined independently, it is done as the first step:

a) step 1 – calculation of the cracking pressure Δp_c;

b) step 2 – if some components are pipes, tubes or hoses, defined by their friction factor, calculation of an initial value for their sonic conductance;

c) step 3 – determination of the sonic conductance C;

d) step 4 – determination of the critical back-pressure ratio b and subsonic index m; and

e) step 5 – if the system includes any components with a pressure dependency, calculation of pressure dependence coefficient K_p.

Step 2 and step 5 are optional, depending on the type of components of the system.

Step 3 and step 4 require the same calculation principle, which consists of the determination of the outlet pressure of the components connected in series p_f for given subsonic mass flow rates q_m. For a given mass flow rate q_m, and a fixed inlet pressure p_e, the calculation consists of determining the outlet pressure of each component, p_{2i}, starting with the first component and proceeding through to the last component.

6.4 Calculation of the cracking pressure Δp_c (step 1)

The cracking pressure for the system is equal to the total sum of the cracking pressure values Δp_{ci} of each component, as shown in Formula (19):

$$\Delta p_c = \sum \Delta p_{ci} \quad (19)$$

6.5 Calculation of an initial value for their sonic conductance if some components are pipes, tubes or hoses defined by their friction factor (optional step 2)

If some components are pipes, tubes or hoses defined by their friction factor, calculate, for each of them, an initial value for the sonic conductance C^{init} as:

$$C^{init} = \frac{\pi d^2}{4} \frac{1}{\rho_0 \sqrt{RT_0}} \sqrt{\gamma \left(\frac{2}{\gamma + 1} \right)^{\frac{\gamma+1}{\gamma-1}}} \quad (20)$$

NOTE This formula gives the maximum value of the sonic conductance the pipe can reach if its length is reduced to its minimum. It corresponds to the sonic conductance of an ideal converging nozzle of same diameter. The calculated value can thus lead to an over-estimation of the true value for the pipe under consideration, but it provides an initial value to use to begin the calculations.

6.6 Determination of the sonic conductance *C* (step 3)

6.6.1 Principle of calculation

The sonic conductance of the system is smaller than the individual conductance of its components. To calculate the sonic conductance C of the system, it is necessary to determine the choked mass flow rate $q_m{}^*$ corresponding to the inlet pressure p_e.

This choked mass flow rate cannot be calculated explicitly, but it corresponds to the maximum subsonic mass flow rate that can be reached by the system. It is determined by trials, taking different values of mass flow rate q_m defined as a percentage of the theoretical maximum mass flow rate $(q_m)_{MAX}$. This theoretical maximum mass flow rate through the system $(q_m)_{MAX}$ is given by the most restrictive component.

The choked mass flow rate $q_m{}^*$ is the maximum subsonic mass flow rate for which the final downstream pressure p_f of the system can be calculated. See Figure C.4.

6.6.2 Calculation of theoretical limit of the maximum mass flow rate $(q_m)_{MAX}$

First, determine the smallest value of sonic conductance C among all the components in the system, C_{MIN}, using Formula (21), and calculate $(q_m)_{MAX}$ using Formula (22).

$$C_{MIN} = \min(C_1, C_2, ..., C_i, ..., C_n) \quad (21)$$

$$(q_m)_{MAX} = C_{MIN}\,\rho_0 p_e \sqrt{\frac{T_0}{T_e}} \quad (22)$$

6.6.3 Determination of the choked mass flow rate $q_m{}^*$

The maximum subsonic mass flow rate is determined by trials, taking different values of mass flow rate q_m defined as a percentage ($\eta \le 1$) of the theoretical maximum mass flow rate, as shown in Formula (23):

$$q_m = \eta (q_m)_{MAX} \quad (23)$$

6.6.3.1 First, set $\eta = 1$

6.6.3.2 The upstream pressure of the first component is the inlet pressure of the system, as expressed by Formula (24):

$$p_{11} = p_e \quad (24)$$

6.6.3.3 For the given mass flow rate q_m, calculated using Formula (23), calculate the outlet pressure of each component, p_{2i}, starting with the first component and proceeding through to the last component using the procedure described in the following paragraphs.

6.6.3.3.1 The upstream pressure for a subsequent component or piping is the calculated downstream pressure of the previous one, as shown in Formula (25):

$$p_{1i} = p_{2(i-1)} \text{ for } i > 1 \quad (25)$$

6.6.3.3.2 The downstream pressure p_{2i} of component i can be calculated, using Formula (27), only in a subsonic condition, which means only when the given mass flow rate q_m, is less than the choked flow rate in component i.

$$q_m < C_i \rho_0 p_{1i} \sqrt{\frac{T_0}{T_e}} \tag{26}$$

If this condition is not satisfied, a negative square root occurs in Formula (27).

6.6.3.3.2.1 If Formula (26) is satisfied, calculate the downstream pressure p_{2i} of component i from the mass flow rate q_m and its upstream pressure p_{1i}, using Formula (27). See Figure C.6.

$$p_{2i} = p_{1i} \left[b_i + \left(1 - \frac{\Delta p_{ci}}{p_{1i}} - b_i \right) \sqrt{1 - \left(\frac{q_m}{C_i \rho_0 p_{1i}} \sqrt{\frac{T_e}{T_0}} \right)^{\frac{1}{m_i}}} \right] \tag{27}$$

If component i is a pipe or tube defined by a friction factor, first calculate:

— the dynamic viscosity for the temperature T_e, using Formula (10);

— the Reynolds number Re using Formula (9);

— the friction factor using Formula (8);

— the flow-rate characteristic parameters using Formulae (4) to (7) or (11), (12), (6) and (7) in the case of air. See Figure C.5.

If component i is a pipe or tube defined by a friction factor, Formula (27) gives only the downstream static pressure of the pipe, p_{s2i}. In this case, calculate the downstream stagnation pressure p_{2i} using Formula (28), which comes from Formula (A.1) of ISO 6358-1:2013:

$$p_{2i} = p_{s2i} \left(\frac{1}{2} + \sqrt{\frac{1}{4} + \frac{\gamma - 1}{2\gamma} RT_e \left(\frac{q_m}{\frac{\pi d^2}{4} p_{s2i}} \right)^2} \right)^{\frac{\gamma}{\gamma - 1}} \tag{28}$$

6.6.3.3.2.2 If there is a component for which Formula (26) is not satisfied, the outlet stagnation pressure of the last component p_{2n}, cannot be calculated because the flow rate determined by Formula (23) is too high, and a negative square root occurs in Formula (27). In this case, decrease the value of η in a series of iteration steps of 0,0001, and repeat the calculations described in 6.6.3.3 until the result for the outlet stagnation pressure is a real number .

6.6.3.3.3 Stop the iteration for the first value of η (the highest value of η) for which the outlet stagnation pressure of the last component p_{2n}, can be calculated. This value is the final pressure of the components connected in series, as expressed by Formula (29):

$$p_f = p_{2n} \tag{29}$$

The mass flow rate calculated from Formula (23) with this last value of η is the maximum subsonic flow rate that can be reached by the system and shall be considered as the choked mass flow rate q_m*. This calculation can also be performed using either a dichotomy method or an oscillation technique that zeroes in on the highest value of η (to at least four decimal places) that results in a real number value for the outlet stagnation pressure. See A.2.5 for an example.

NOTE An example of a resulting data spreadsheet is shown in A.2.

6.6.4 Calculation of the sonic conductance *C*

Calculate the sonic conductance *C* using Formula (30):

$$C = \frac{q_m^{\ *}}{\rho_0 p_e} \sqrt{\frac{T_e}{T_0}} \tag{30}$$

6.7 Determining the critical back-pressure ratio *b* and subsonic index *m* (step 4)

6.7.1 Calculation of subsonic flow data

6.7.1.1 In order to determine the flow-rate characteristics *b* and *m* for the system, it is necessary to calculate a series of flow rates in the subsonic region. These flow rates $q_m{}^j$ are a percentage of the choked mass flow rate $q_m{}^*$ obtained using Formula (31):

$$q_m{}^j = \beta^j q_m{}^* \tag{31}$$

6.7.1.2 The 16 values of flow ratios β^j defined in Table 3 make it possible to obtain a sufficient number of points on the subsonic flow curve for the system.

Table 3 — Values of flow ratio

j	β^j
1	1
2	0,995
3	0,98
4	0,95
5	0,9
6	0,85
7	0,8
8	0,75
9	0,7
10	0,6
11	0,5
12	0,4
13	0,3
14	0,2
15	0,1
16	0,01

6.7.1.3 For each of the 16 values of the mass flow rates $q_m{}^j$, calculate downstream pressures of the components and piping up to the final downstream pressure $p_f{}^j$ of the system using the same calculation principle as the one described in 6.6.3.3. Use Formulae (24), (25), (27) and (29). Convert static pressures to stagnation pressures if necessary (as described in 6.6.3.3.2.1) using Formula (28). See Figure C.7.

6.7.2 Determination of flow-rate characteristics *b* and *m*

Use the least-square method to calculate the critical back-pressure ratio *b* and the subsonic index *m*, as follows:

Use Formula (32) to calculate $q_{m_{\text{cal}}}{}^1$, $q_{m_{\text{cal}}}{}^2$,..., $q_{m_{\text{cal}}}{}^j$,...for each value of the final downstream pressure of the components connected in series $p_f{}^1$, $p_f{}^2$,...$p_f{}^j$,... obtained in 6.7.1.3 for the given values of subsonic mass flow rate $q_m{}^1$, $q_m{}^2$,..., $q_m{}^j$,... .

$$q_{m_{\text{cal}}}{}^j = C\rho_0 p_e \sqrt{\frac{T_0}{T_e}} \left[1 - \left(\frac{\frac{p_f{}^j}{p_e} - b}{1 - \frac{\Delta p_c}{p_e} - b} \right)^2 \right]^m \quad (32)$$

Use Formula (34) to determine b and m so that the total sum, E, of the square difference, $\delta q_m{}^j$, is at its minimum possible value. The parameter $\delta q_m{}^j$ is the difference between the value of the flow rate $q_m{}^j$ used in the calculation of the outlet pressure $p_f{}^j$ in 6.7.1.3 and the flow rate $q_{m_{\text{cal}}}{}^j$ calculated in accordance with Formula (32), calculated with the previously determined values of C and Δp_c, as shown in Formula (33):

$$\delta q_m{}^j = q_m{}^j - q_{m_{\text{cal}}}{}^j \quad (33)$$

$$E = \sum \left(\delta q_m{}^j \right)^2 \quad (34)$$

Examples of these calculations are shown in Annex A.

6.8 Calculation of pressure dependence coefficient K_p (optional step 5)

6.8.1 If the system includes any components with a pressure dependency, the pressure dependence coefficient K_p of the system shall be calculated in accordance with the procedures described in 6.8.2 to 6.8.5.

6.8.2 Change p_e into $p_e + \Delta p_e$ (for example, $\Delta p_e = 3 \times 10^5$ Pa).

6.8.3 Determine the flow-rate characteristics as follows:

a) for components that have a pressure dependency characterized by a pressure dependence coefficient K_p, calculate their corresponding sonic conductance using Formula (E.4) in ISO 6358-1:2013;

b) for pipes or tubes whose flow-rate characteristics can be expressed using a friction factor depending on the Reynolds number, calculate, for each of them, an initial value for the sonic conductance C^{init} in accordance with Clause 6.5.

6.8.4 Calculate the sonic conductance of the system $C_{\Delta pe}$ corresponding to $p_e + \Delta p_e$ in accordance with the procedure described in 6.6.2 to 6.6.4.

6.8.5 Calculate the pressure dependence coefficient K_p in accordance with Formula (35).

$$K_p = \frac{1 - \left(C / C_{\Delta p_e} \right)}{\Delta p_e} \quad (35)$$

where C is the sonic conductance at p_e.

7 Organization of calculations for systems of components connected in parallel

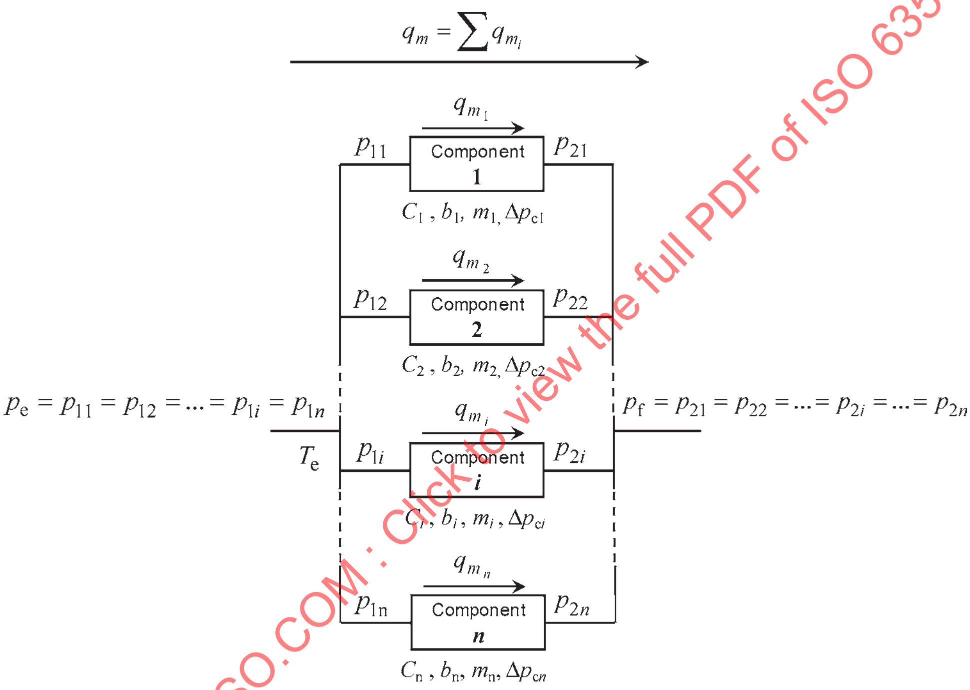
7.1 General

Consider a system of components connected in parallel as shown in Figure 3. The sum of the mass flow rates passing through each component is equal to the mass flow rate of the system q_m. It is assumed that the system has a single set of flow-rate characteristics determined from the characteristics of the individual components, as shown in Figure 2.

It is assumed that:

— the inlet pressure (p_e) of the system is the upstream pressure of all the components (p_{11}, p_{12}, ···, p_{1i}, ·· p_{1n});

— the outlet pressure (p_f) of the system is the downstream pressure of all the components (p_{21}, p_{22}, ···, p_{2i}, ·· p_{2n}).



NOTE The symbols used in Figure 3 are defined in Tables 1 and 2.

Figure 3 — System of components connected in parallel

7.2 Given parameters

For the calculation of the flow-rate characteristics of a system of components that are connected in parallel, the following parameters are given:

— the inlet pressure of the system, p_e;

— the temperature of the fluid, T_e.

7.3 Calculation principle

Consider the system of components connected in parallel as shown in Figure 3. The flow-rate characteristics for this system are determined in three main steps:

a) step 0 – if some components are pipes, tubes or hoses, determination of their flow characteristics for the given inlet pressure;

b) step 1 – determination of the sonic conductance C;

c) step 2 – determination of the cracking pressure Δp_c; and

d) step 3 – determination of the critical back-pressure ratio b and subsonic index m.

7.4 Determination of flow characteristics of pipes, tubes or hoses for the given inlet pressure (step 0)

Determine the flow characteristics of each pipe, tube or hose, if the system contains these types of components, for the given inlet pressure (p_e), by applying the following procedure:

a) calculate an initial value of its sonic conductance C^{init} using Formula (20),

b) calculate the corresponding theoretical maximum mass flow rate using Formula (36):

$$\left(q_m\right)_{MAX} = C^{init} \rho_0 p_e \sqrt{\frac{T_0}{T_e}} \tag{36}$$

c) determine its choked mass flow rate q_m* for the given inlet pressure (p_e) and its sonic conductance C using the procedure described in 6.6.3 and 6.6.4,

d) determine its critical back-pressure ratio b and subsonic index m using the procedure described in 6.7.

See Figure C.9.

7.5 Determination of the sonic conductance C (step 1)

Determine the sonic conductance of the system, which is equal to the sum of the sonic conductance C_i, of each component, using Formula (37):

$$C = \sum_{i=1}^{n} C_i \tag{37}$$

7.6 Determination of the cracking pressure Δp_c (step 2)

Determine the cracking pressure of the system, which is equal to the minimum value of the cracking pressure, Δp_{ci}, of each component, using Formula (38):

$$\Delta p_c = \min(\Delta p_{c1}, \Delta p_{c2}, ..., \Delta p_{ci}, ..., \Delta p_{cn}) \tag{38}$$

7.7 Determination of the critical back-pressure ratio b and subsonic index m (step 3)

7.7.1 Calculation of subsonic flow data

In order to determine the critical back-pressure ratio, b, and the subsonic index, m, of the system, create data for the mass flow rate and pressure ratio of the system in the subsonic area in accordance with the following procedure:

a) determine the minimum critical back-pressure ratio of all components in parallel using Formula (39):

$$b_{min} = \min(b_1, b_2, ..., b_i, ..., b_n) \tag{39}$$

b) for b_{min} and for values of pressure ratio $\left(\frac{p_f}{p_e}\right)^j$ distributed either in fixed steps or variable steps (see Table 4 for an example of variable steps) and larger than b_{min}, calculate the mass flow rates of each component $q_{mi}^{\ j}$ using Formulae (1) to (3) and then the mass flow rates $q_m^{\ j}$ of the system using Formula (40):

$$q_m^{\ j} = \sum_{i=1}^{n} q_{mi}^{\ j} \qquad (40)$$

Table 4 — Examples of values of pressure ratio

j	$\left(\frac{p_f}{p_e}\right)^j$
1	1
2	0,995
3	0,98
4	0,95
5	0,9
6	0,85
7	0,8
8	0,75
9	0,7
10	0,6
11	0,5
12	0,4
13	0,3
14	0,2
15	0,1
16	0,05

7.7.2 Determination of flow-rate characteristics *b* and *m*

Use the least-square method to calculate the critical back-pressure ratio *b* and the subsonic index *m*, as follows:

a) use Formula (32) to calculate $q_{m\text{cal}}^{\ 1}$, $q_{m\text{cal}}^{\ 2}$,..., $q_{m\text{cal}}^{\ j}$,...for each value of the pressure ratios of the system $\left(\frac{p_f}{p_e}\right)^1, \left(\frac{p_f}{p_e}\right)^2 ..., \left(\frac{p_f}{p_e}\right)^j$,......... obtained in 7.7.1 and for b_{min}, and the previously determined values of C and Δp_c.

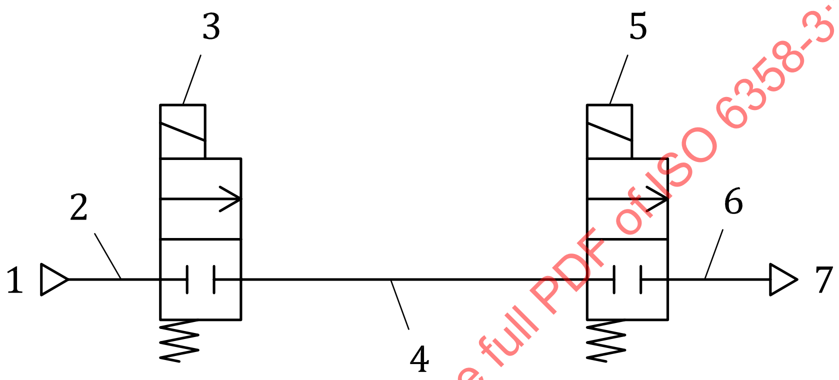
b) determine b and m so that the total sum, E, of the square difference, $\delta q_m^{\ j}$, is at its minimum possible value. The parameter $\delta q_m^{\ j}$ is the difference between the values of the mass flow rate, $q_{m\text{cal}}^{\ j}$, obtained using Formula (32) and the mass flow rate, $q_m^{\ j}$ determined for the same pressure ratios $\left(\frac{p_f}{p_e}\right)^j$ in 7.7.1 and for b_{min}.

Annex A
(informative)

Example calculation for a system of components connected in series

A.1 System of components connected in series

A.1.1 Figure A.1 shows the system of components used in this example.



Key

1 inlet
2 $p_e = p_{11}$
3 component 1
4 component 2: tube with inside diameter of 8 mm and a length of 5 m
5 component 3
6 $p_{23} = p_f$
7 outlet

Figure A.1 — System used in this example

A.1.2 When the flow-rate characteristics of the tube are calculated using the friction factor depending on the Reynolds number, the flow-rate characteristics C_{pipe} and b_{pipe} of the tube are calculated for each value of mass flow rate q_m in accordance with 5.3.2.2. The parameters of the tube are thus only its geometrical dimensions as shown in Table A.1.

Table A.1 — Flow-rate characteristics of components, measured individually

Characteristic or parameter	Component		
	1	**2 (tube)**	**3**
C in m^3/(s.Pa)(ANR) or d in m	4,023E-08 m^3/(s.Pa)(ANR)	8,00E-03 m	2,699E-08 m^3/(s.Pa)(ANR)
b or L, in m	0,267	5 m	0,403
m	0,520	–	0,500
Δp_c in Pa	0	0	0

A.1.3 Data for the compressed air parameters indicated in 6.2 are shown in Table A.2.

Table A.2 — Compressed air parameters, units and values

Parameter	Unit	Value
ρ_0	–	1,185
T_0	K	293,15
T_e	K	293
P_e	Pa	600 000
γ	–	1,4
R	J/kg.K	287

A.1.4 As step 1, the cracking pressure of the system is calculated using Formula (19), with the cracking pressure of the tube being 0 in accordance with Formula (7) ($\Delta p_{c2} = 0$):

$$\Delta p_c = \Delta p_{c1} + \Delta p_{c2} + \Delta p_{c3} = 0 \qquad \text{(A.1)}$$

A.1.5 As step 2, the initial value for the sonic conductance of the tube, C_2^{init}, is calculated using Formula (20):

$$C_2^{\ init} = \frac{\pi d^2}{4} \frac{1}{\rho_0 \sqrt{RT_0}} \sqrt{\gamma \left(\frac{2}{\gamma + 1} \right)^{\frac{\gamma+1}{\gamma-1}}} = 1{,}001 \times 10^{-7}\ \mathrm{m}^3/(\mathrm{s.Pa})(\mathrm{ANR}) \qquad \text{(A.2)}$$

A.2 Illustration of the determination of the sonic conductance *C* (step 3)

A.2.1 First, the theoretical maximum mass flow rate, $(q_m)_{MAX}$ is calculated in accordance with 6.6.2 from the sonic conductance of components 1 and 3 given in Table A.1 and the initial value for the sonic conductance of the tube C_2^{init} calculated in Formula (A.2):

$$C_{MIN} = \min(C_1, C_2^{\ init}, C_3) = 2{,}699 x 10^{-8}\ \mathrm{m}^3/(\mathrm{s.Pa})(\mathrm{ANR}) \qquad \text{(A.3)}$$

$$(q_m)_{MAX} = C_{MIN}\ \rho_0 p_e \sqrt{\frac{T_0}{T_e}} = 1{,}919 x 10^{-2}\ \mathrm{kg/s} \qquad \text{(A.4)}$$

A.2.2 Table A.3 illustrates the calculation procedure described in 6.6.3 using the theoretical maximum mass flow rate calculated by Formula (A.4) for an inlet pressure of 0,6 MPa (6 bar) and decreasing the value of η from $\eta = 1$, by steps of 0,0001.

For each value of η, the mass flow rate is calculated from Formula (23):

$$q_m = \eta (q_m)_{\mathrm{MAX}}$$

for component 1, its upstream pressure is the inlet pressure of the system (Formula (24)):

$$p_{11} = p_{\mathrm{e}} = 6\times 10^5 \mathrm{Pa} \tag{A.5}$$

Its downstream stagnation pressure can be calculated only if the mass flow rate is less than its sonic mass flow rate for its upstream conditions [Formula (26)]:

$$q_m < C_1 \rho_0 p_{11} \sqrt{\frac{T_0}{T_{\mathrm{e}}}} \ , \tag{A.6}$$

If the condition in Formula (A.6) is not satisfied for the current value of η [that is, a negative square root occurs in Formula (27)], decrease η until Formula (A.6) is satisfied (that is, until the result for the outlet stagnation pressure is a real number). Using Formula (27), the downstream stagnation pressure is then calculated by Formula (A.7).

$$p_{21} = p_{11} \left[b_1 + \left(1 - \frac{\Delta p_{\mathrm{c1}}}{p_{11}} - b_1 \right) \sqrt{1 - \left(\frac{q_m}{C_1 \rho_0 p_{11}} \sqrt{\frac{T_{\mathrm{e}}}{T_0}} \right)^{\frac{1}{m_1}}} \right] \tag{A.7}$$

For component 2, its upstream pressure is the outlet pressure of component 1 (Formula (25) for $i = 2$):

$$p_{12} = p_{21} \tag{A.8}$$

Component 2 is a tube. First, calculate the dynamic viscosity from the inlet temperature using Formula (10):

$$\mu = 1{,}455\times 10^{-6} \frac{T_{\mathrm{e}}^{3/2}}{T_{\mathrm{e}} + 110{,}4} = 1{,}809\times 10^{-5} \mathrm{Pa.s} \tag{A.9}$$

To obtain the flow-rate characteristic parameters of the tube for the given mass flow rate, use Formula (9) to calculate the Reynolds number, Formula (8) to calculate the friction factor, Formula (11) to calculate its sonic conductance C_{pipe}; Formula (12) to calculate b_{pipe}:

$$Re = \frac{4 q_m}{\pi \, d \, \mu} \tag{9}$$

$$\lambda = \frac{1}{\left(1{,}8 \log_{10}(Re) - 1{,}64\right)^2} \tag{8}$$

$$C_{\mathrm{pipe}} = \frac{2{,}28\times 10^{-3} d^2}{\sqrt{\left(1 + \frac{\lambda L}{d}\right) + 0{,}77\sqrt{1 + \frac{\lambda L}{d}} + 0{,}3}} \tag{11}$$

$$b_{\text{pipe}} = 1 - \frac{1}{1 + \frac{0,77}{\sqrt{1+\frac{\lambda L}{d}}} + \frac{0,3}{1+\frac{\lambda L}{d}}} \tag{12}$$

Its downstream static pressure can be calculated only if the mass flow rate is less than its sonic mass flow rate for its upstream conditions [Formula (26)]:

$$q_m < C_{\text{pipe}} \rho_0 p_{12} \sqrt{\frac{T_0}{T_{\text{e}}}} \ , \tag{A.10}$$

If condition in Formula (A.10) is not satisfied for the current value of η [that is, a negative square root occurs in Formula (27)], decrease η until Formula (A.10) is satisfied (that is, until the result for the outlet stagnation pressure is a real number). Using Formula (27), the downstream stagnation pressure is then calculated by Formula (A.11).

$$p_{s22} = p_{12} \left[b_{\text{pipe}} + \left(1 - \frac{\Delta p_{\text{cpipe}}}{p_{12}} - b_{\text{pipe}}\right) \sqrt{1 - \left(\frac{q_m}{C_{\text{pipe}} \rho_0 p_{12}} \sqrt{\frac{T_{\text{e}}}{T_0}}\right)^{\frac{1}{m_{\text{pipe}}}}} \right] \tag{A.11}$$

Calculate the downstream stagnation pressure p_{22} of the pipe using Formula (28):

$$p_{22} = p_{s22} \left(\frac{1}{2} + \sqrt{\frac{1}{4} + \frac{\gamma - 1}{2\gamma} R T_e \left(\frac{q_m}{\frac{\pi d^2}{4} p_{s22}} \right)^2} \right)^{\frac{\gamma}{\gamma - 1}} \tag{A.12}$$

For component 3, its upstream pressure is the outlet pressure of component 2 [Formula (25) for i = 3]:

$$p_{13} = p_{22} \tag{A.13}$$

Its downstream stagnation pressure can be calculated only if the mass flow rate is less than its sonic mass flow rate for its upstream conditions [Formula (26)]:

$$q_m < C_3 \rho_0 p_{13} \sqrt{\frac{T_0}{T_{\text{e}}}} \ , \tag{A.14}$$

Condition in Formula (A.14) can be tested with an “IF” functional test to determine whether the flow rate used in the trial step is too high. If it is too high, Formula (27) results in a negative square root. To avoid this, the “IF” function can be programmed to advance the value of η until Formula (A.14) is satisfied. Using Formula (27), the downstream static pressure is then calculated as shown in Formula (A.15), – and the result for the outlet static pressure is a real number.

$$p_{23} = p_{13} \left[b_3 + \left(1 - \frac{\Delta p_{c3}}{p_{13}} - b_3\right) \sqrt{1 - \left(\frac{q_m}{C_3 \rho_0 p_{11}} \sqrt{\frac{T_{\text{e}}}{T_0}}\right)^{\frac{1}{m_3}}} \right] \tag{A.15}$$

According to Formula (A.16), the final pressure of the system is:

$$p_{\text{f}} = p_{23} \tag{A.16}$$

Table A.3 — Determination of subsonic (choked) mass flow rate

Step 3: Determination of maximum subsonic mass flow rate for determining *C*										
Outlet TOTAL pressure of each component in subsonic flow conditions only										
		Component 1 $p_{11} = p_e$ Formula (A.5)	Component 2 (tube) $p_{12} = p_{21}$ Formula (A.8)						Component 3 $p_{13} = p_{22}$ Formula (A.13)	
Flow ratio η	**Mass flow rate** q_m **[kg/s]** from Formula (23): $q_m = \eta(q_m)_{MAX}$	p_{21} **[Pa]** from Formula (A.7)	***Re*** see Formula (9)	λ see Formula (8)	C_{pipe} **[m³/(s.Pa)(ANR)]** from Formula (11)	b_{pipe} from Formula (12)	**Static pressure** p_{s22} **[Pa]** from Formula (A.11)	**Total pressure** p_{22} **[Pa]** from Formula (A.12)	p_{23} **[Pa]** from Formula (A.15) $p_f = p_{23}$ (A.16)	**System sonic conductance [m³/s.Pa)(ANR)]** see Formula (30)
0,759	1,4569E-02	535164	128179	0,0175	3,778E-08	0,199	446835	454750		
0,7589	1,4567E-02	535182	128162	0,0175	3,778E-08	0,199	446880	454792		
0,7588	1,4565E-02	535200	128145	0,0175	3,778E-08	0,199	446926	454835		
0,7587	1,4563E-02	535218	128128	0,0175	3,778E-08	0,199	446971	454877		
0,7586	1,4561E-02	535236	128111	0,0175	3,778E-08	0,199	447017	454920		
0,7585	1,4559E-02	535253	128095	0,0175	3,778E-08	0,199	447062	454962		
0,7584	1,4557E-02	535271	128078	0,0175	3,778E-08	0,199	447107	455005		
0,7583	1,4555E-02	535289	128061	0,0175	3,778E-08	0,199	447153	455047	**188045**	**2,047E-08**

A.2.3 Table A.3 shows that using the calculation principle described in 6.6.3, the maximum value of η for which the final pressure of the system of components connected in series, p_f, can be calculated is 0,7583.

A.2.4 As a result, the maximum subsonic mass flow rate is 0,014555 kg/s, calculated in accordance with Formula (23). The sonic conductance C is calculated using Formula (A.17):

$$C = \frac{q_m^{\ *}}{\rho_0 p_e} \sqrt{\frac{T_e}{T_0}} = 2{,}047 \times 10^{-8} \mathrm{m}^3/(\mathrm{s.Pa})(\mathrm{ANR}) \quad \text{(A.17)}$$

A.2.5 Oscillation method to determine maximum subsonic mass flow rate

Using the same data as in Table A.3, begin with the initially value of η = 1,0 but decrease η in steps of 0,1 until a value for the last outlet stagnation pressure is a real number (see Table A.4). Then increase the value of η by 0,05 (or more) until the outlet stagnation pressure value is not a real number. Then, decrease the values of η in a series of smaller steps. Continue this oscillation process until a value for the outlet stagnation pressure is a real number and the value of η (at least 4 decimal places) is the largest possible. The last steps for this oscillation method can be performed in one row of the spreadsheet by continuously changing the value of η, as shown in Table A.4.

A.3 Illustration of the determination of *b* and *m* (step 4)

A.3.1 The critical back-pressure ratio b and the subsonic index m are determined using the procedure described in 6.7 and illustrated in Tables A.5 and A.6 and Figure A.2.

The calculation procedure of the final pressure of the system, shown in Table A.5, is the same as in A.2.2 except that the mass flow rate values are calculated using Formula (A.18) for the 16 values of flow ratios β^j defined in Table 3:

$$q_m^{\ j} = \beta^j q_m^{\ *} \quad \text{(A.18)}$$

Table A.4 — Oscillation method to determine subsonic (choked) mass flow rate

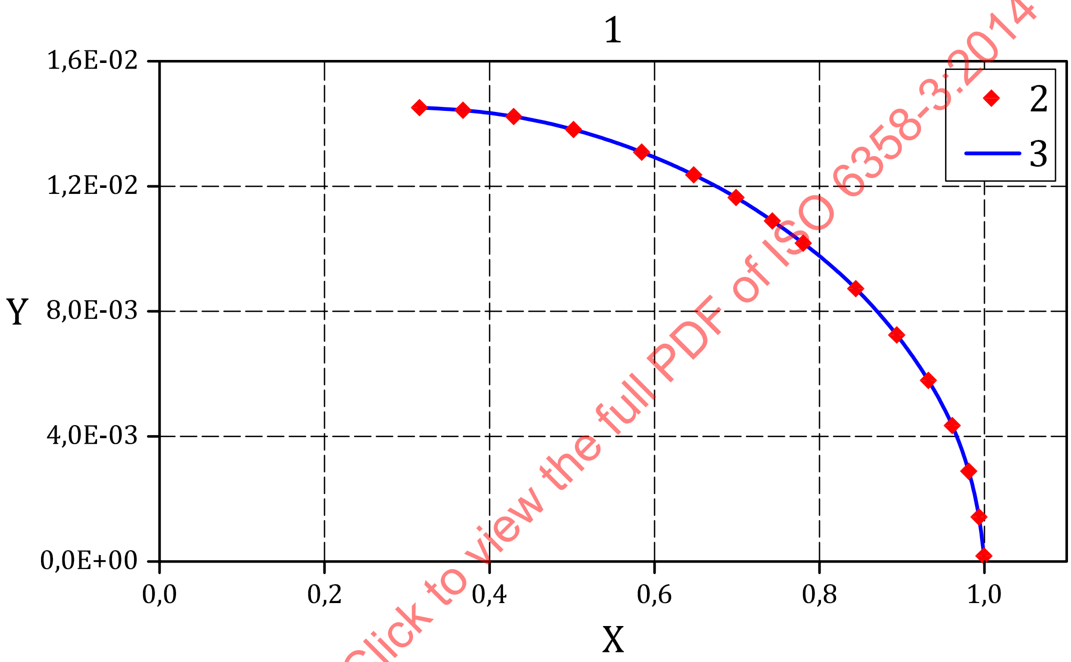
Step 3: Determination of maximum subsonic mass flow rate for determining *C*											
Outlet TOTAL pressure of each component in subsonic flow conditions only											
		Component 1 $p_{11} = p_e$ Formula (A.5)	Component 2 (tube) $p_{12} = p_{21}$ Formula (A.8)						Component 3 $p_{13} = p_{22}$ Formula (A.13)		
Flow ratio η	**Mass flow rate** q_m **[kg/s]** from Formula (23): $q_m = \eta(q_m)_{MAX}$	p_{21} **[Pa]** from Formula (A.7)	Re see Formula (9)	λ see Formula (8)	C_{pipe} **[m³/(s.Pa)(ANR)]** from Formula (11)	b_{pipe} from Formula (12)	**Static pressure** p_{s22} **[Pa]** from Formula (A.11)	**Total pressure** p_{22} **[Pa]** from Formula (A.12)	p_{23} **[Pa]** from Formula (A.15) $p_f = p_{23}$ (A.16)	**System sonic conductance [m³/s.Pa)(ANR)]** see Formula (30)
1	1,9195E-02	482147	168879	0,0166	3,866E-08	0,203	288172	309562	Not possible	
0,9	1,7275E-02	506777	151991	0,0169	3,833E-08	0,201	369577	383050	Not possible	
0,8	1,5356E-02	527588	135103	0,0173	3,795E-08	0,199	427269	436467	Not possible	
0,76	1,4588E-02	534986	128348	0,0175	3,779E-08	0,199	446381	454324	Not possible	
0,7583	1,4555E-02	535289	128061	0,0175	3,778E-08	0,199	447153	455047	188045	2,047E-08
0,7	1,3436E-02	545182	118215	0,0178	3,753E-08	0,197	471855	478229	32958	**1,889E-08**

Table A.5 — Calculation of subsonic flow data when p_e = 0,6 MPa (6 bar)

Calculation of downstream pressures for determining *b* and *m* (subsonic flow data)										
Outlet TOTAL pressure of each component in subsonic flow conditions only										Simulation
		Component 1 $p_{11} = p_e$ Formula (A.5)	Component 2 (tube) $p_{12} = p_{21}$ Formula (A.8)						Component 3 $p_{13} = p_{22}$ Formula (A.13)	
Flow ratio β	**Mass flow rate** q_m **[kg/s]** from Formula (31)	p_{21} **[Pa]** from Formula (A.7)	*Re* see Formula (9)	λ see Formula (8)	C_{pipe} **[m³/(s.Pa) (ANR)]** from Formula (11)	b_{pipe} from Formula (12)	**Static pressure** p_{s22} **[Pa]** from Formula (A.11)	**Total pressure** p_{22} **[Pa]** from Formula (A.12)	p_{23} **[Pa]** from Formula (A.15) $p_f = p_{23}$ (A.16)	**Error** δq_m **[%]**
1	**1,4555E-02**	535289	128061	0,0175	3,778E-08	0,199	447153	455047	188045	0,14
0,995	1,4483E-02	535963	127421	0,0175	3,777E-08	0,199	448863	456649	219780	0,33
0,98	1,4264E-02	537958	125500	0,0176	3,772E-08	0,198	453903	461371	256708	0,37
0,95	1,3828E-02	541835	121658	0,0177	3,762E-08	0,198	463592	470462	300502	0,27
0,9	1,3100E-02	547967	115255	0,0179	3,744E-08	0,197	478665	484636	350064	0,08
0,85	1,2372E-02	553704	108852	0,0181	3,726E-08	0,196	492517	497692	387589	0,08
0,8	1,1644E-02	559062	102449	0,0184	3,707E-08	0,195	505262	509731	418460	0,20
0,75	1,0917E-02	564055	96046	0,0186	3,686E-08	0,194	516993	520831	444801	0,27
0,7	1,0189E-02	568693	89643	0,0189	3,663E-08	0,193	527785	531060	467718	0,31
0,6	8,7333E-03	576949	76836	0,0195	3,613E-08	0,190	546784	549106	505724	0,28
0,5	7,2777E-03	583897	64030	0,0203	3,553E-08	0,187	562629	564196	535602	0,13
0,4	5,8222E-03	589584	51224	0,0214	3,479E-08	0,183	575571	576551	558953	0,14
0,3	4,3666E-03	594041	38418	0,0229	3,383E-08	0,178	585765	586306	576689	0,53
0,2	2,9111E-03	597278	25612	0,0252	3,245E-08	0,171	593284	593522	589333	1,06
0,1	1,4555E-03	599284	12806	0,0302	3,003E-08	0,158	598108	598167	597132	1,62
0,01	1,4555E-04	599991	1281	0,0640	2,146E-08	0,113	599967	599968	599958	3,14

Table A.6 — Calculated flow-rate characteristics of the system when p_e = 0,6 MPa (6 bar)

Characteristic or parameter	Component			System
	1	2 (tube)	3	
C in m³/(s.Pa)(ANR) or d in m	4,023E-08 m³/(s.Pa) (ANR)	8,00E-03 m	2,699E-08 m³/(s.Pa) (ANR)	2,047E-08
b or L, in m	0,267	5 m	0,403	0,277
m	0,520	–	0,500	0,535
Δp_c in Pa	0	–	0	0



Key

X p_2/p_1
Y mass flow rate in kg/s
1 system of pneumatic components
2 q_m (determined in accordance with 6.7.1)
3 $q_{m_{cal}}$ (determined in accordance with 6.7.2)

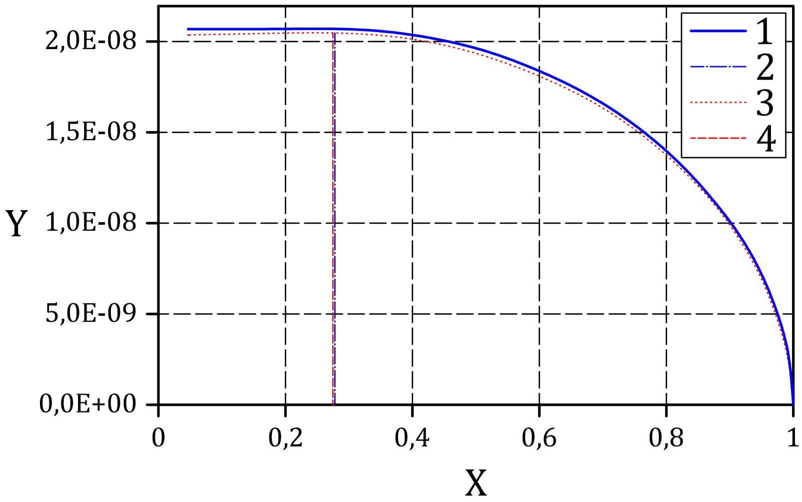
NOTE The calculation can also be done using the flow-rate characteristics of the tube calculated using the formulae in 5.3.2.3 based on test results.

Figure A.2 — Comparison of mass flow-rates determined by calculated association in accordance with 6.7.1 and results of determination of system characteristics in accordance with 6.7.2 for p_e = 0,6 MPa (6 bar)

A.4 Calculation using a different inlet pressure

A.4.1 The same calculation procedure can be applied for an inlet pressure of 1 MPa (10 bar). Table A.7 shows the calculated flow-rate characteristics.

A.4.2 Figure A.3 shows the difference between the conductance curves for both inlet pressures. This is due to the friction losses in the tube, depending on the Reynolds number.



Key

X p_2/p_1

Y conductance in m³/(Pa.s)(ANR)

1 conductance calculated at an inlet pressure of 1 MPa (10 bar)

2 value of *b* at an inlet pressure of 1 MPa (10 bar)

3 conductance calculated at an inlet pressure of 0,6 MPa (6 bar)

4 value of *b* at an inlet pressure of 0,6 MPa (6 bar)

Figure A.3 — Conductance curves of the system for inlet pressures of 1 MPa (10 bar) and 0,6 MPa (6 bar)

Table A.7 — Calculated flow-rate characteristics of the system when p_e = 1 MPa (10 bar)

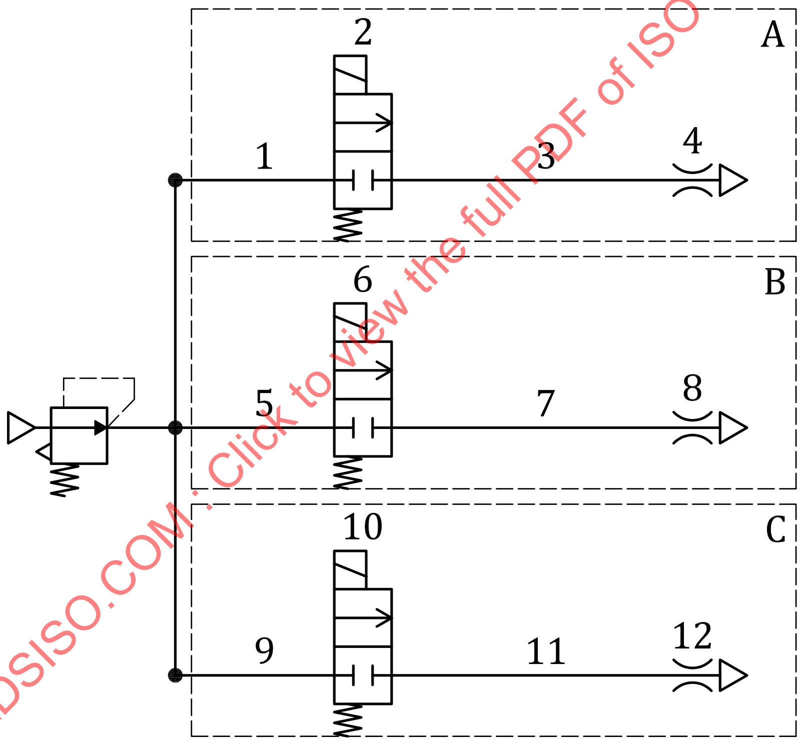
Characteristic or parameter	Component			System
	1	2 (tube)	3	
C in m³/(s.Pa)(ANR) or *d* in m	4,023E-08 m³/(s.Pa) (ANR)	8,00E-03 m	2,699E-08 m³/(s.Pa) (ANR)	2,07E-08
b or *L*, in m	0,267	5 m	0,403	0,280
m	0,520	–	0,500	0,533
Δp_c in Pa	0	–	0	0

Annex B
(informative)

Example calculation for an air blow circuit whose components are connected in parallel

B.1 Air blow circuit

A diagram of the air blow circuit considered in this example is shown in Figure B.1. The specifications of each component and part of the piping are given in Table B.1. The parts of the piping between the outlet of the pressure regulator and upstream of each parallel subcircuit are large enough for the upstream pressure of each subcircuit to be the same as the inlet pressure of the circuit.



Key

A subcircuit A
B subcircuit B
C subcircuit C
1 piping A-1
2 valve A
3 piping A-2
4 nozzle A
5 piping B-1
6 valve B
7 piping B-2
8 nozzle B
9 piping C-1
10 valve C
11 piping C-2
12 nozzle C

NOTE Inlet pressure = 0,5 MPa (5 bar) or 1 MPa (10 bar)

Figure B.1 — Air blow circuit diagram

B.2 Calculation results

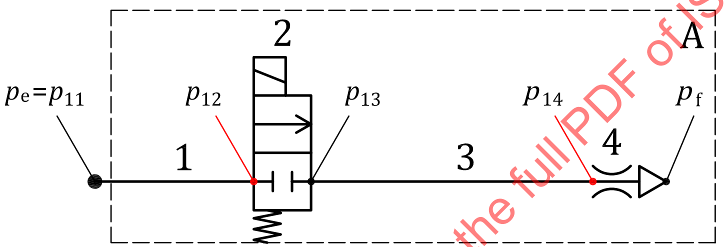
B.2.1 The results of calculations performed in accordance with Clauses 6 and 7 are shown in Table B.1.

B.2.2 The flow-rate characteristics of each piping are calculated using Formulae (13), (14), (15) and (17) in 5.3.2.3. Upper values were calculated using a p_e = 500 kPa (5 bar), and the lower values in brackets were calculated using a p_e = 1000 kPa (10 bar), with a pressure dependency coefficient of $2 \times 10^{-7} Pa^{-1}$. Calculations can also be done for each piping using the friction factor, which is dependent on the Reynolds number, in accordance with 5.3.2.2.

B.3 Supplemental explanation

B.2.1 General

This subclause provides some additional practical explanations regarding the air blow subcircuit sizing. Figure B.2 shows the typical structure of the subcircuit under study with some additional descriptions and Table B.1 shows the results of calculation for four different subcircuits (Subcircuit A to subcircuit D).



Key

A subcircuit *i*

1 piping *i* −1

2 valve *i*

3 piping *i* −2

4 nozzle *i*

Figure B.2 — Typical air blow subcircuit with additional descriptions

B.2.2 Pressure distributions and evaluation values

Table B.2 shows the results of the calculation of pressure distributions, flow rates, transmission powers and relative cost of each subcircuit in Figure B.2. Figure B.3 shows the pressure distributions, and Figure B.4 shows the ratios of the evaluation values compared to Subcircuit A in Figure B.2.

Table B.1 — Results of calculation of flow-rate characteristics performed in accordance with Clauses 6 and 7

Circuit	Component or piping	Specifications[a]				Results of components connected in series[b]				Results of components connected in parallel[c]		
		Dimensions[d]	C^e	b	m	C^e	b	m		C^e	b	m
Subcircuit A	Piping A-1	Φ4 × 2 m	0,917x10−8 (1,01x10−8)	0,28 (0,30)	0,55 (0,55)	0,606x10−8 (0,669x10−8)	0,12 (0,14)	0,56 (0,57)	SYSTEM	3,15x10−8 (3,27x10−8)	0,28 (0,29)	0,53 (0,55)
	Valve A	—	5,9x10−8	0,40	0,51							
	Piping A-2	Φ4 × 3 m	0,766x10−8 (0,843x10−8)	0,23 (0,25)	0,56 (0,56)							
	Nozzle A	Φ4	2,3x10−8	0,44	0,55							
Subcircuit B	Piping B-1	Φ8 × 2 m	5,28x10−8 (5,81x10−8)	0,40 (0,44)	0,54 (0,54)	1,92x10−8 (1,97x10−8)	0,34 (0,35)	0,56 (0,56)				
	Valve B	—	5,9x10−8	0,40	0,51							
	Piping B-2	Φ8 × 3 m	4,52x10−8 (4,98x10−8)	0,34 (0,37)	0,55 (0,54)							
	Nozzle B	Φ4	2,3x10−8	0,44	0,55							
Subcircuit C	Piping C-1	Φ6 × 2 m	2,57x10−8 (2,83x10−8)	0,34 (0,38)	0,55 (0,54)	0,627x10−8 (0,635x10−8)	0,37 (0,39)	0,52 (0,53)				
	Valve C	—	3,00x10−8	0,42	0,51							
	Piping C-2	Φ6 × 3 m	2,18x10−8 (2,40x10−8)	0,29 (0,32)	0,55 (0,55)							
	Nozzle C	Φ2,2	0,68x10−8	0,42	0,51							

a See B.2.2.

b The flow-rate characteristics are calculated in accordance with Clause 6.

c The flow-rate characteristics are calculated in accordance with Clause 7.

d Diameters of piping and nozzles are the nominal inner diameters in mm.

e The unit for sonic conductance C is $m^3/(s \cdot Pa)$(ANR).

f See Figure B.2 and subclause B.3.

Table B.1 *(continued)*

Circuit	Component or piping	Specifications[a]				Results of components connected in series[b]				Results of components connected in parallel[c]		
		Dimensions[d]	C^e	*b*	*m*	C^e	*b*	*m*		C^e	*b*	*m*
Subcircuit D f	Piping D-1	Φ6 × 2 m	0,917x10−8 (1,01x10−8)	0,21 (0,30)	0,56 (0,55)	0,185x10−8 (0,188x10−8)	0,43 (0,42)	0,54 (0,53)				
	Valve D	—	0,80x10−8	0,48	0,51							
	Piping D-2	Φ6 × 3 m	0,766x10−8 (0,843x10−8)	0,17 (0,25)	0,56 (0,56)							
	Nozzle D	Φ2,2	0,20x10−8	0,46	0,51							

a See B.2.2.

b The flow-rate characteristics are calculated in accordance with Clause 6.

c The flow-rate characteristics are calculated in accordance with Clause 7.

d Diameters of piping and nozzles are the nominal inner diameters in mm.

e The unit for sonic conductance *C* is $m^3/(s \cdot Pa)$(ANR).

f See Figure B.2 and subclause B.3.

Table B.2 — Pressure distributions and evaluation values

Subcircuit	Pressure [a] kPa					Flow rate [b] m³/s(ANR)	Transmission power [c] kW	Relative cost [d]
	$p_e = p_{11}$	p_{12}	p_{13}	p_{14}	p_f			
Subcircuit A	500	403	401	132	100	$3{,}01 \times 10^{-3}$	0,073	1,00
Subcircuit B	500	476	458	418	100	$9{,}62 \times 10^{-3}$	0,732	1,07
Subcircuit C	500	487	480	461	100	$3{,}13 \times 10^{-3}$	0,245	0,81
Subcircuit D	500	488	481	463	100	$0{,}927 \times 10^{-3}$	0,073	0,49

a Pressure is calculated in accordance with Clause 6.

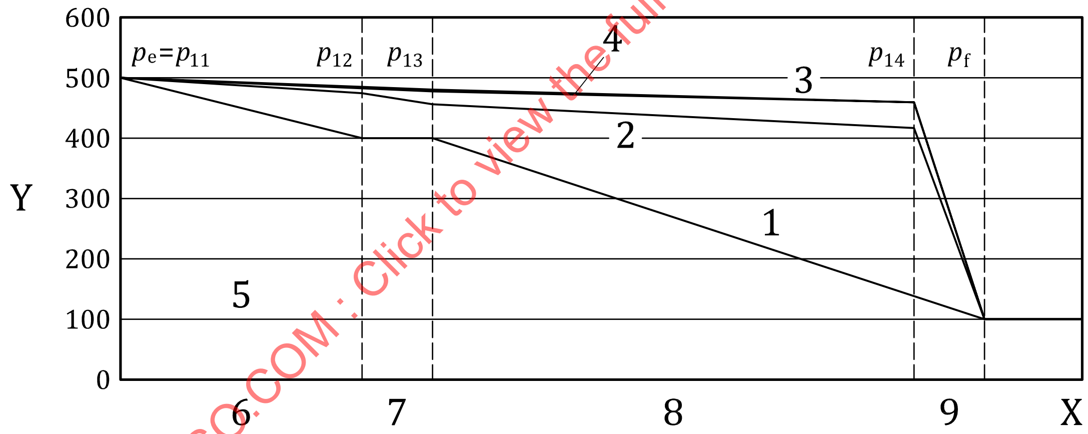
b Mass flow rate, q_m, is calculated in accordance with Clause 6, and volume flow rate, q_v, is calculated using the following formula:

$$q_v = \frac{q_m}{\rho_0} \text{ m}^3/\text{s(ANR)}$$

c Transmission power, P, is the power of compressed air blowing from the nozzle and is calculated using the following formula:

$$P = p_f q_v \left(1 - \frac{p_f}{p_{14}}\right) \text{ kW}$$

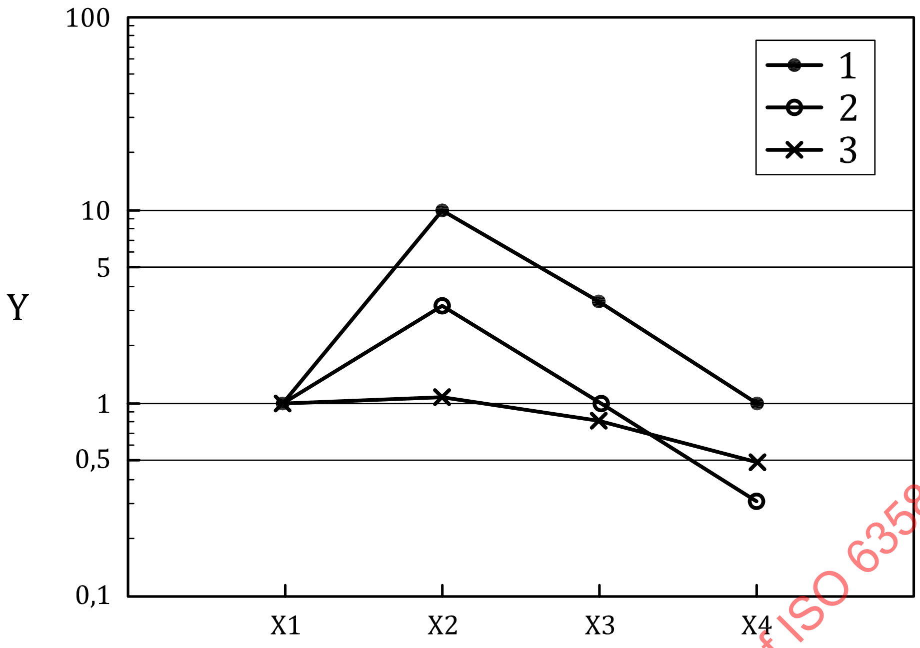
d Cost is the ratio of integrated price of piping, valve and nozzle compared to subcircuit 1.



Key

X component
Y pressure in kPa
1 subcircuit A
2 subcircuit B
3 subcircuit C
4 subcircuit D
5 atmospheric pressure
6 piping-1
7 valve
8 piping-2
9 nozzle

Figure B.3 — Pressure distributions



Key

X subcircuit

Y ratio

1 transmission power

2 flow rate

3 relative cost

Figure B.4 — Ratios of evaluation values compared to Subcircuit A

B.2.3 Incorrect sizing

The pressure drop at Piping 1-1 and Piping 1-2 in Subcircuit A is extremely large, so the inlet pressure p_{14} of the nozzle is decreased to 132 kPa. The inside diameter, 4 mm, of the piping is too small. Subcircuit A is a typical case of incorrect sizing that is relatively expensive but provides small capability.

B.2.4 Correct sizing

The inside diameter of Piping 2-1 and Piping 2-2 in Subcircuit B is 8 mm. The pressure drop in the piping is decreased to about 14 % of the pressure drop in Subcircuit A, and the inlet pressure of the nozzle maintains a high level of 400 kPa or higher. The cost of Subcircuit B is just 7 % higher than that of Subcircuit A, but the flow rate is 3,2 times larger, and the transmission power is 10 times larger. Subcircuit B is a typical case of correct sizing that provides large capability.

B.2.5 Improved sizing

The sizing of Subcircuit C provides a flow rate that is almost the same as that of Subcircuit A. The inside diameter of Piping 3-1 and Piping 3-2 is larger than that of Subcircuit A by 6 mm; the sonic conductance C of the valve is about 50 % of the valve in Subcircuit A; and the diameter of the nozzle is decreased from 4 mm to 2,2 mm. The inlet pressure of the nozzle maintains a high level of 461 kPa. Subcircuit C achieves the same flow rate (in other words, the same air consumption) as that of Subcircuit A, but the cost is 20 % less, and the transmission power is 3,4 times larger. Subcircuit C is a typical case of improved sizing that costs less and provides large capability.

B.2.6 Optimal sizing

The sizing of Subcircuit D provides a transmission power that is almost the same as that of Subcircuit A. The sonic conductance C of the valve is decreased from 5,9 dm^3/(s.bar) to 0,8 dm^3/(s.bar), and the diameter of the nozzle is decreased from 4 mm to 1,2 mm, compared to Subcircuit A. The inlet pressure of the nozzle maintains a high level of 463 kPa. Although Subcircuit D achieves air blow performance that is almost the same as that of Subcircuit A, the cost of the system is reduced by about 50 %, and air consumption is reduced to about 33 %, of that of Subcircuit A. Subcircuit D is a typical case of optimal sizing that costs the least and provides greater energy efficiency.

B.2.7 Pressure dependency

Table B.1 shows, in the brackets, the results of calculation in a case in which the pressure dependency coefficient of the piping is $2x10^{-7}Pa^{-1}$, and the inlet pressure is 1000 kPa. Compared to the case in which the inlet pressure is 500 kPa, the sonic conductance C of the piping itself is 10 % larger, and the back-pressure ratio b is 0,02 or 0,04 larger, but m is almost same. The sonic conductance C of Subcircuit A, is also 10 % larger, due to the incorrect sizing.

However, the influence of the inlet pressure on the sonic conductance C of Subcircuit B, resulting from correct sizing, is reduced to 2,6 % and that of Subcircuit C and Subcircuit D is reduced to 1,5 %. In other words, pressure dependency or calculation errors related to the piping almost disappear when improved or optimal sizing is used to design a system.

Annex C
(informative)

Flow charts of calculation procedures

C.1 Calculation procedures for components connected in series

The flow chart in Figure C.1 illustrates the calculation procedures given in 6.4 to 6.8.

The flow charts in Figures C.2 to C.7 illustrate the calculation procedures of the different subroutines used.

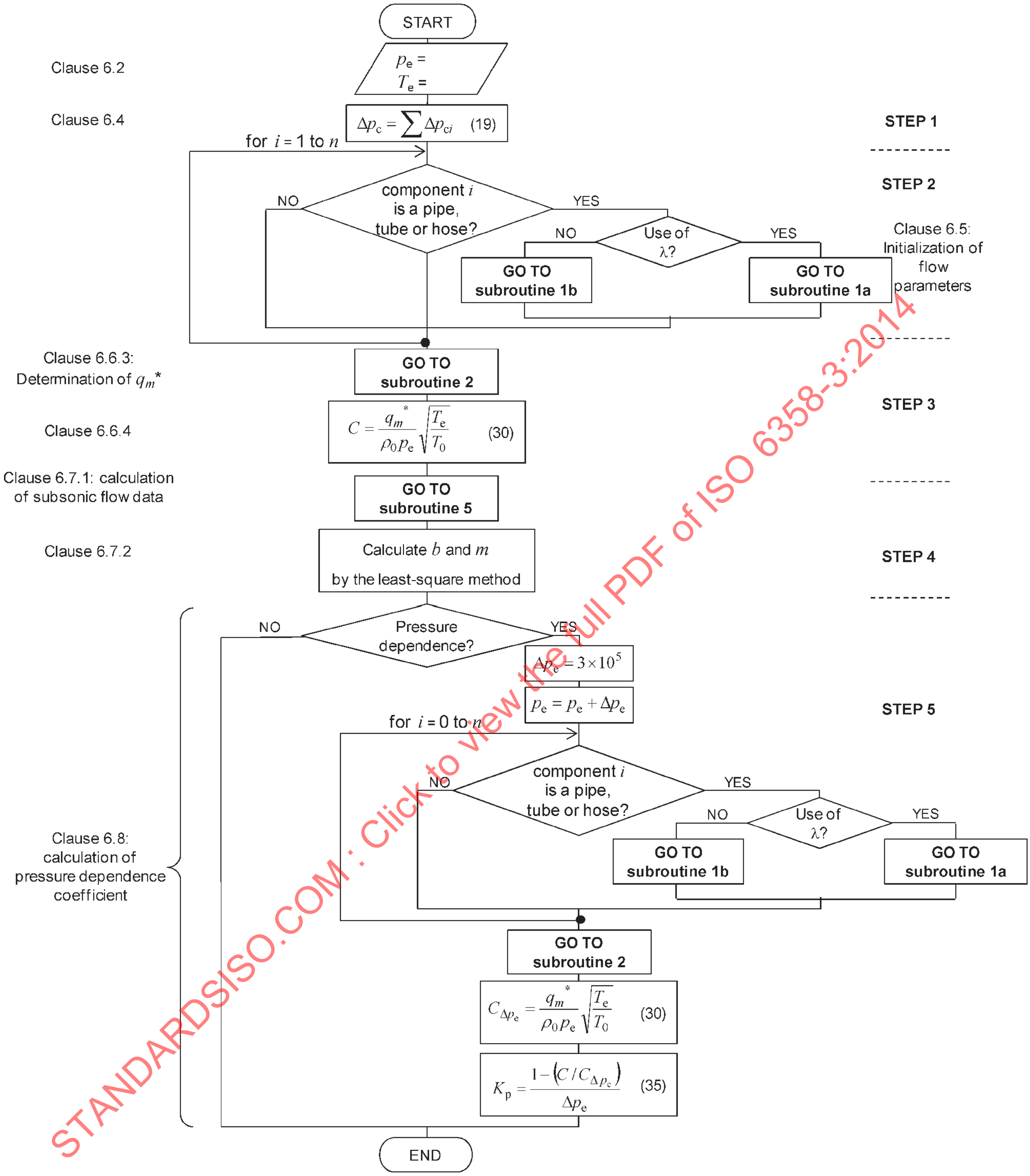


Figure C.1 — Flow chart illustrating calculation procedures for components connected in series

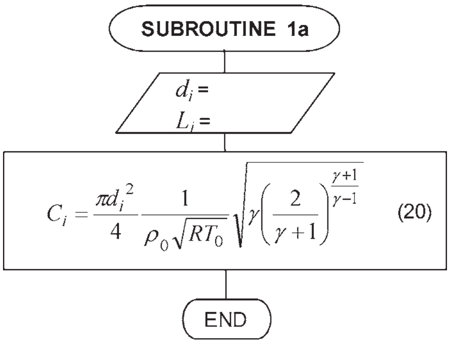


Figure C.2 — Flow chart illustrating the subroutine 1a: calculation of the initial value of the sonic conductance of the pipe, tube or hose using the friction factor λ in accordance with 6.5

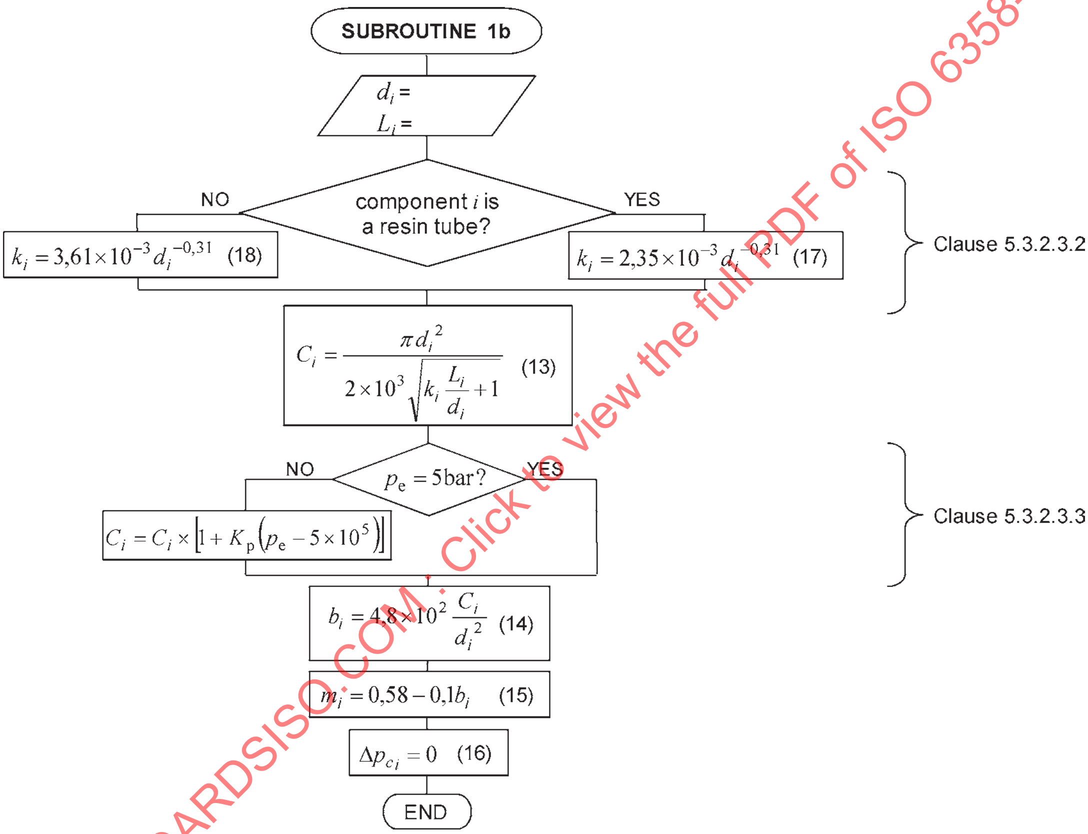


Figure C.3 — Flow chart illustrating the subroutine 1b: calculation of the flow parameters of the pipe, tube or hose based on test results with air in accordance with 5.3.2.3

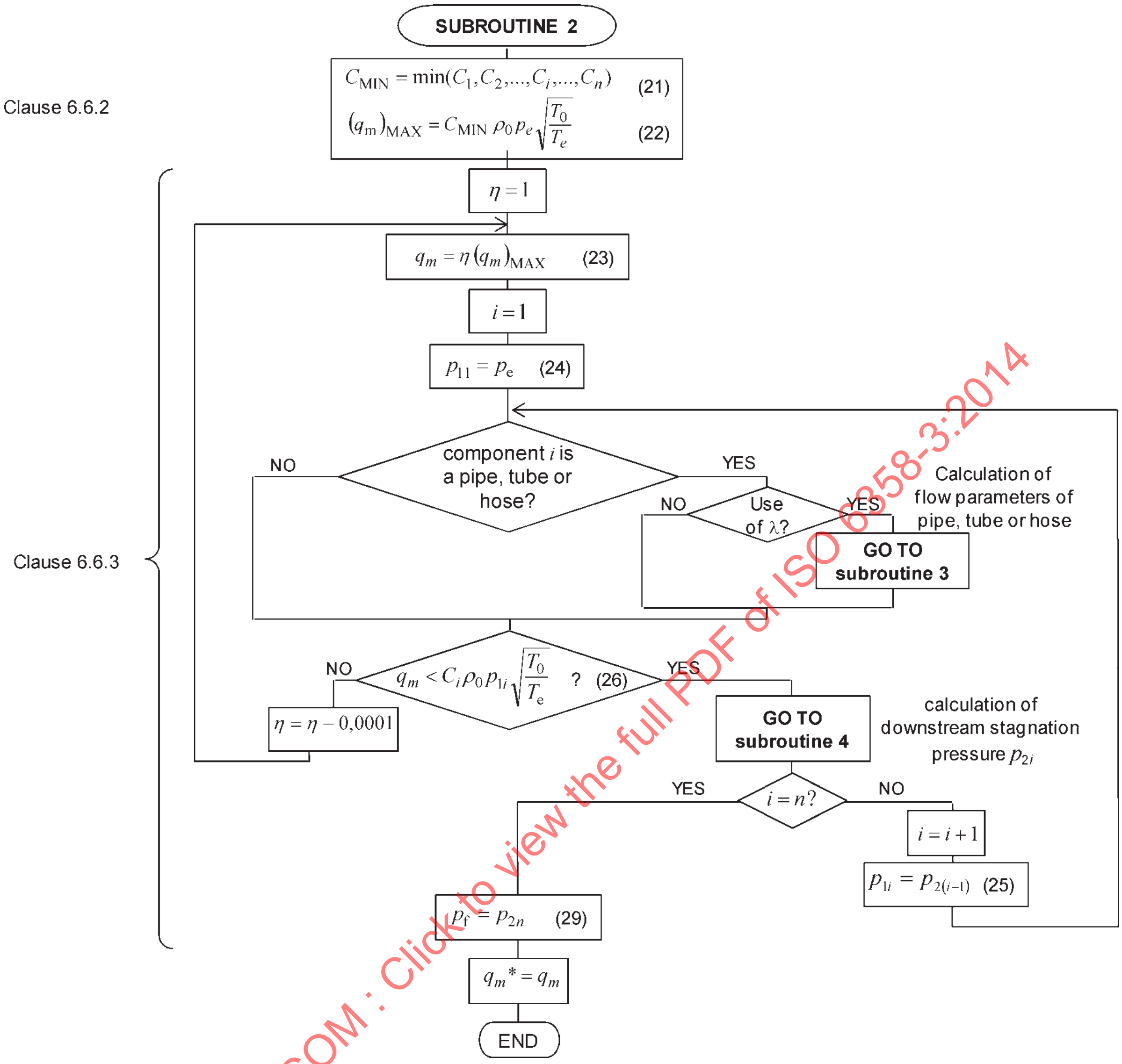


Figure C.4 — Flow chart illustrating the subroutine 2: determination of the choked mass flow rate of the system in accordance with 6.6.3

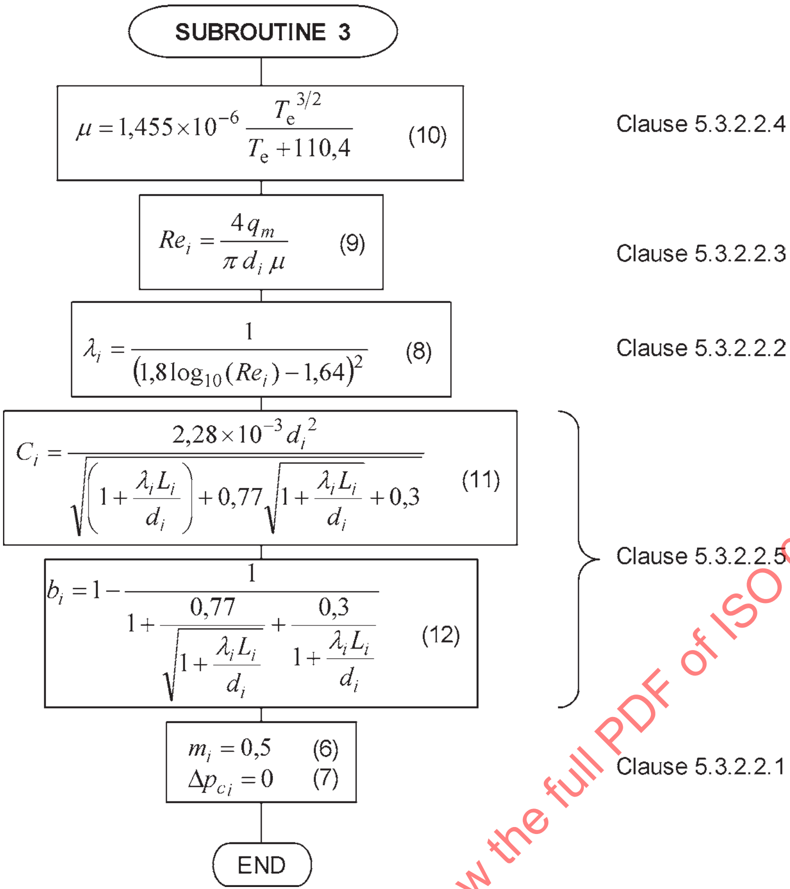


Figure C.5 — Flow chart illustrating the subroutine 3: calculation of the flow parameters of the pipe, tube or hose using the friction factor λ dependent on the Reynolds number in accordance with 5.3.2.2 (case of air)

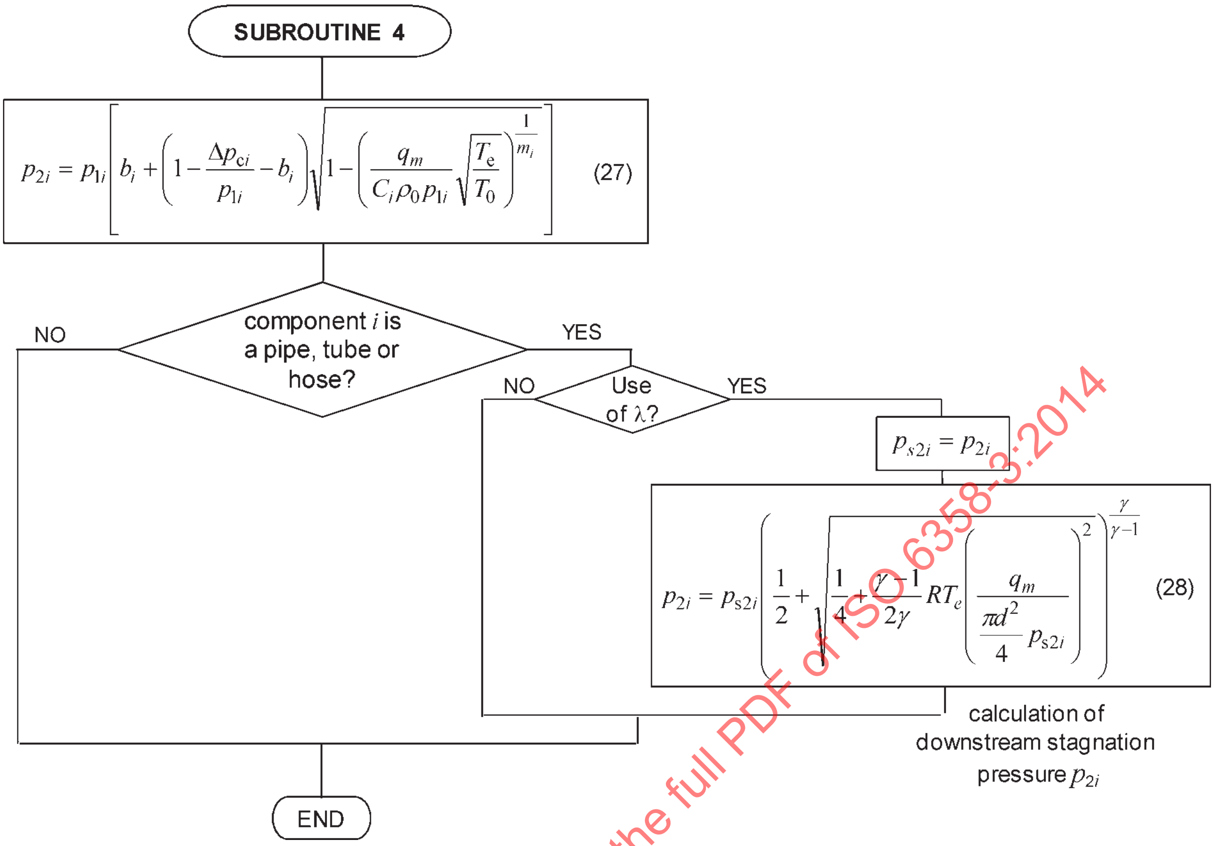


Figure C.6 — Flow chart illustrating the subroutine 4: calculation of downstream stagnation pressure p_{2i} in accordance with 6.6.3.3.2.1

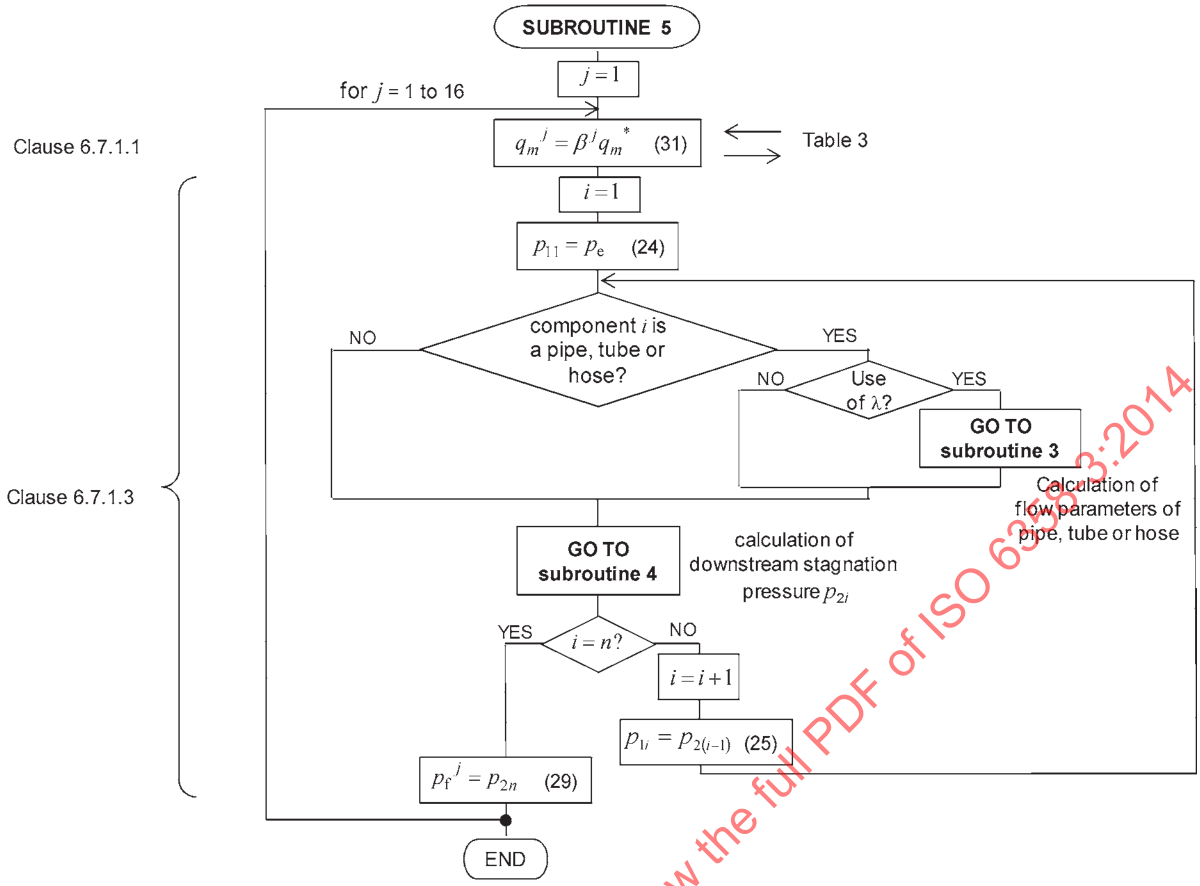


Figure C.7 — Flow chart illustrating the subroutine 5: calculation of subsonic flow data for the system in accordance with 6.7.1

C.2 Calculation procedures for components connected in parallel

The flow chart in Figure C.8 illustrates the calculation procedures given in 7.4 to 7.7.

The flow chart in Figure C.9 illustrates the calculation procedures subroutine 6 used in the flow chart in Figure C.8.

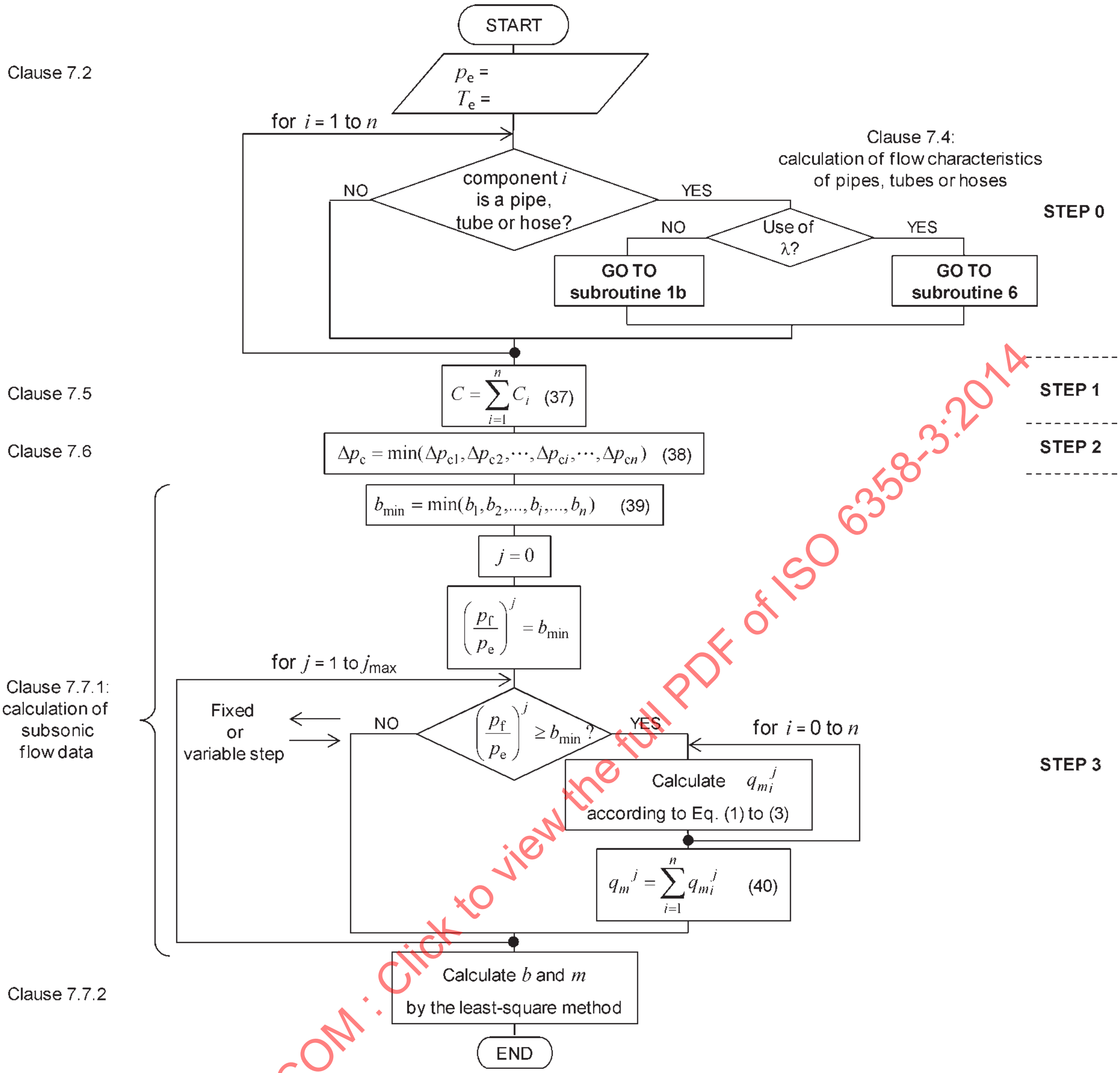


Figure C.8 — Flow chart illustrating calculation procedures for components connected in parallel

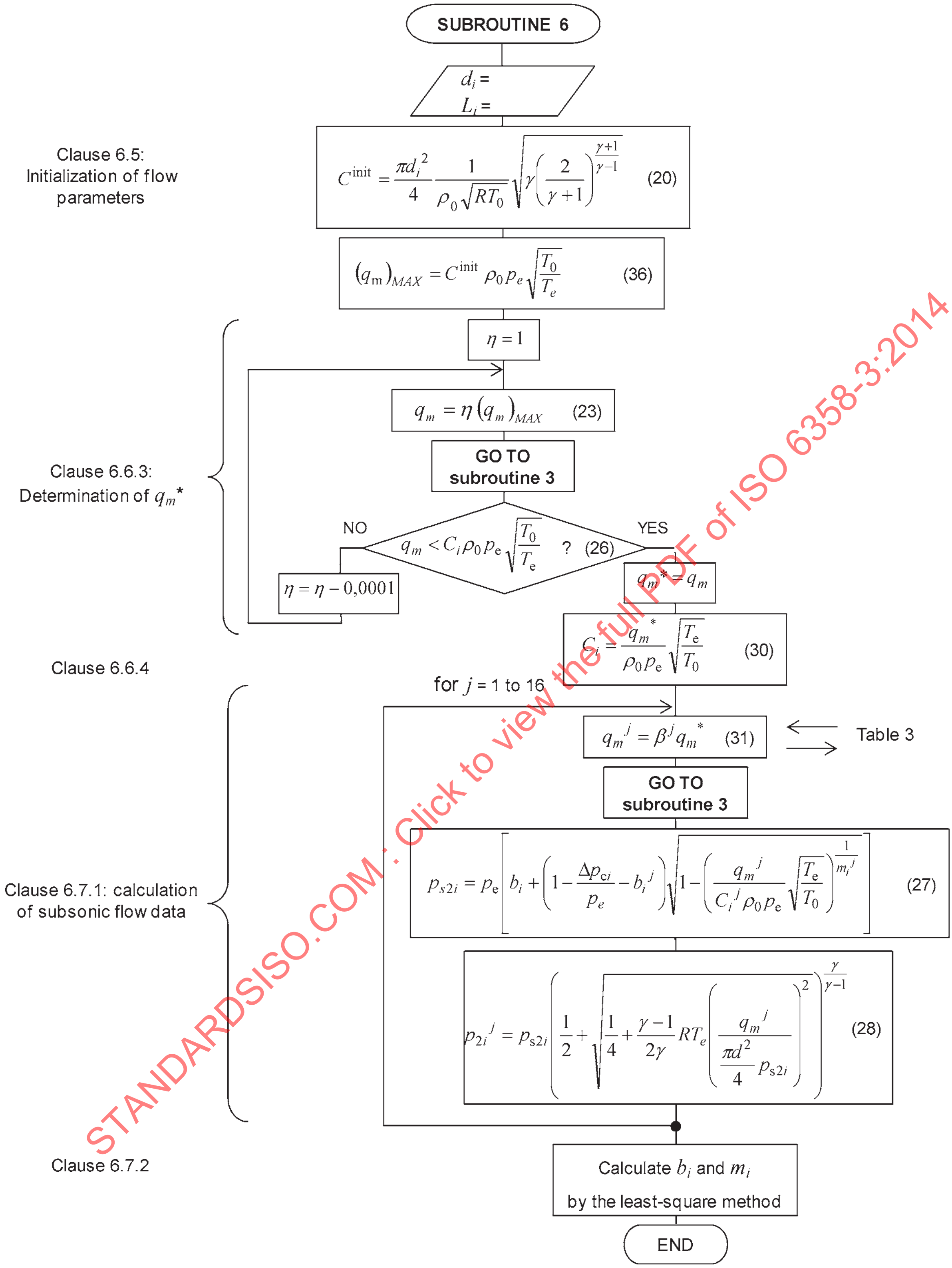


Figure C.9 — Flow chart illustrating the subroutine 6: calculation procedure to determine the flow rate characteristics of a tube, pipe or hose at upstream pressure p_e using the friction factor λ dependent on the Reynolds number in accordance with 7.4

Annex D
(informative)

Additional information concerning components whose flow rate characteristics are not expressed in accordance with the ISO 6358 series

D.1 General

D.1.1 This annex provides additional information about components and piping whose flow-rate characteristics are not expressed in accordance with the ISO 6358 series, that is, using C, b, m and Δp_c; these components include:

a) parts of piping (pipe, tube or hose) defined by their geometric dimensions (see D.2);

b) globe valves and connectors whose flow-rate characteristics are expressed in relation to an equivalent length of straight pipe or tube (see D.3); and

c) valves whose flow-rate characteristics are expressed by historically-used flow rate parameters (see D.4).

D.1.2 Symbols in addition to those given in Table 1 and used in this annex are given in Table D.1.

Table D.1 — Additional symbols

Symbol	Description	Unit
α	Flow coefficient [a]	–
ζ	Global pressure loss coefficient of a component	–
A	Effective area	m^2
C_V	Flow coefficient	b
K_V	Flow coefficient [a]	$m^3.h^{-1}.bar^{-0,5}$
L_{eq}	Equivalent length of straight pipe or tube	m
L_{pipe}	Length of pipe or tube	m
p_{s1}	Static pressure upstream of pipe or tube	Pa
q_N	Nominal flow rate [c]	dm^3/min (ANR)
S	Geometric area	m^2
s	Compressibility effect coefficient	–

a See EN 1267:2012[3] for definition.

b The value of C_V is based on the square root of the pressure in psi divided by US gallons per minute.

c See VDI 3290 Guideline:1962[8] and VDMA specification 24575:2007–06[9] for definition.

D.2 Pipes or tubes defined by their geometric dimensions (see 5.3.2)

D.2.1 General

D.2.1.1 The flow-rate characteristics of a pipe or tube with a length *L* and an inside diameter *d* can be determined by the methods specified in 5.3.2.2 or 5.3.2.3.

D.2.1.2 D.2.2 provides practical information about the geometrical definition of pipes or tubes.

D.2.1.3 D.2.3 explains how Formulae (4) to (7) can be derived from analytical considerations. In this case, the pipe or tube is characterized using the friction factor, which varies with the Reynolds number.

D.2.1.4 D.2.4 provides justification for Formulae (13) to (18) for pipes or tubes used with air.

D.2.2 Allowable dimensional differences of resin tubes

Resin tubes are produced by extrusion moulding, and the tolerances on the outside diameter and wall thickness given in Table D.2 have been taken from ISO 14743:2004 (reference[4] in the bibliography). The last column of Table D.2 gives the allowable dimensional difference on the internal cross-section, based on the tolerances on the outside diameter and wall thickness. The sonic conductance of the tubes is directly proportional to the internal cross-section, so if the inside diameter is used to determine the flow-rate characteristics, this evaluation should be based on the premise that the results are distributed within this range.

Table D.2 — Dimensions and tolerances for resin tubes and allowable dimensional difference

Material	Size	Outside diameter × inside diameter	Outside diameter mm		Wall thickness mm		Allowable dimensional difference on internal cross section %
			nom.	tol.	nom.	tol.	
Polyamide	4	4 × 2,5	4	±0,08	0,75	±0,08	+20 −18
	6	6 × 4	6	±0,08	1,0	±0,08	±12
	8	8 × 6	8	±0,08	1,0	±0,08	±8
	10	10 × 7,5	10	±0,08	1,25	±0,08	+7 −6
	12	12 × 9	12	±0,1	1,5	±0,08	±6
Polyurethane	4	4 × 2,5	4	±0,1	0,75	+0,1 −0,05	+17 −23
	6	6 × 4	6	±0,1	1,0	+0,1 −0,05	+10 −14
	8	8 × 5,5	8	±0,1	1,25	+0,1 −0,05	+7 −11
	10	10 × 7	10	±0,15	1,5	+0,15 −0,07	+8 −12
	12	12 × 8	12	±0,15	2,0	+0,15 −0,07	+7 −11

D.2.3 Pipe or tube whose flow-rate characteristics are expressed using the friction factor dependent on the Reynolds number

D.2.3.1 Use of the flow coefficient

D.2.3.1.1 Generally, it is convenient to use the flow coefficient α relative to the geometric area of the outlet of the component (S_2). This approach is valid for incompressible flow and can be extended to compressible flow in accordance with Formula (D.1), which is based on Bernouilli's equation for incompressible fluids and which defines the coefficient:

$$\alpha = \frac{1}{\sqrt{\zeta + 1 - \left(\frac{S_2}{S_1}\right)^2}} \tag{D.1}$$

where

S_1 is the geometric area of the inlet of the component;

S_2 is the geometric area of the outlet of the component.

D.2.3.1.2 One advantage of this flow coefficient α is that it is additive. That means that the global flow coefficient α characterizing a system consisting of a number of components "*i*," connected in series and characterized by flow coefficients α_i relative to the geometric area of their outlets S_i, can be expressed by the relationship given in Formula (D.2):

$$\frac{1}{S_2^2 \alpha^2} = \sum_i \frac{1}{S_i^2 \alpha_i^2} \tag{D.2}$$

NOTE Formulae (D.1) and (D.2) are from EN 1267:2012 (see reference[3] in the Bibliography).

D.2.3.1.3 Two flow-rate parameters can then be defined (see[5] in the Bibliography):

The effective area A of the flow path, which is the product of the geometric area of the outlet of the component and the flow coefficient, as shown in Formula (D.3):

$$A = \alpha \times S_2 \tag{D.3}$$

The compressibility effect coefficient s, which takes into account the gas compressibility effect when the flow rate is subsonic. It is expressed by the relationship given in Formula (D.4), except in the case of a diverging nozzle:

$$s = 1 + \frac{\alpha}{\sqrt{\frac{\gamma(\gamma+1)}{2}}} + \frac{\alpha^2}{\gamma(\gamma+1)} \tag{D.4}$$

D.2.3.1.4 Using parameters A and s, the mass flow rate can also be approximated by using Formulae (D.5) and (D.6), which relate, respectively, to upstream and downstream static pressures (p_{s1} and p_{s2}) (see reference[5] in the bibliography):

in subsonic flow ($\Delta p_s < p_{s1}/s$):

$$q_m = A\sqrt{\frac{2\Delta p_s}{RT_1}\left(p_{s1} - \frac{s}{2}\Delta p_s\right)} \tag{D.5}$$

NOTE Formula (D.5) corresponds to an approximation of the mass flow rate at constant upstream conditions by a quarter of an ellipse.

in sonic flow ($\Delta p_s \geq p_{s1}/s$):

$$q_m^* = \frac{A p_{s1}^*}{\sqrt{sRT_1^*}} \tag{D.6}$$

where $\Delta p_s = p_{s1} - p_{s2}$.

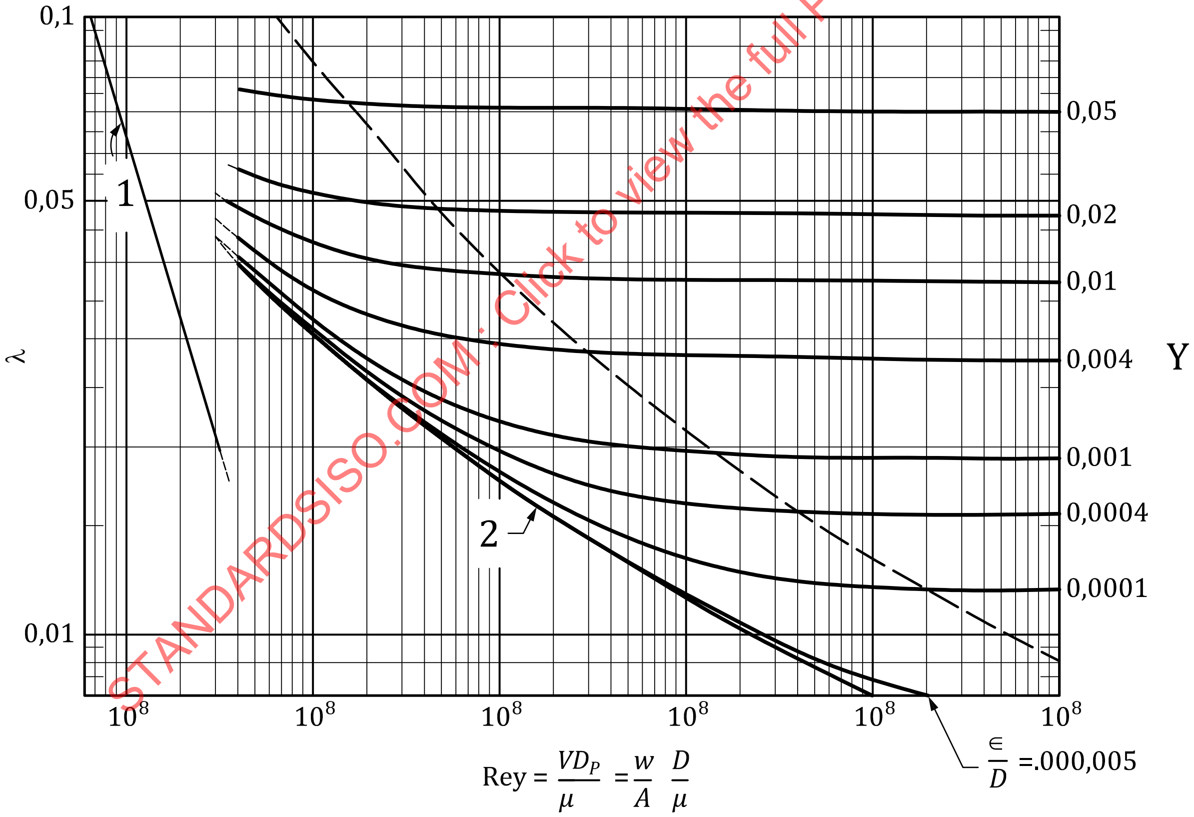
D.2.3.2 Case in which the flow-rate characteristics of a pipe or tube are expressed by a friction factor

D.2.3.2.1 In the case of flow through a pipe or tube with a constant cross-sectional area, with an inside diameter d and a length L and taking friction losses into account, the pressure loss coefficient ζ can be calculated in accordance with Formula (D.7):

$$\zeta = \frac{\lambda L}{d} \tag{D.7}$$

where λ is the average Darcy friction factor.

NOTE The Darcy friction factor λ, which is equal to four times the Fanning friction factor, is based on the well-known Moody diagram shown in Figure D.1 and is valid for compressible subsonic flow (see reference[6] in the bibliography), which is the case of association calculation.



Key

X $Re = \frac{\rho V d}{\mu} = \frac{q_m}{S}\frac{d}{\mu}$

Y relative roughness: $\frac{\varepsilon}{d}$

1 laminar flow: $f = \frac{\lambda}{4} = \frac{16}{Re}$

2 smooth pipes or tubes

Figure D.1 — Friction factor by Moody diagram (see reference[7] in the bibliography)

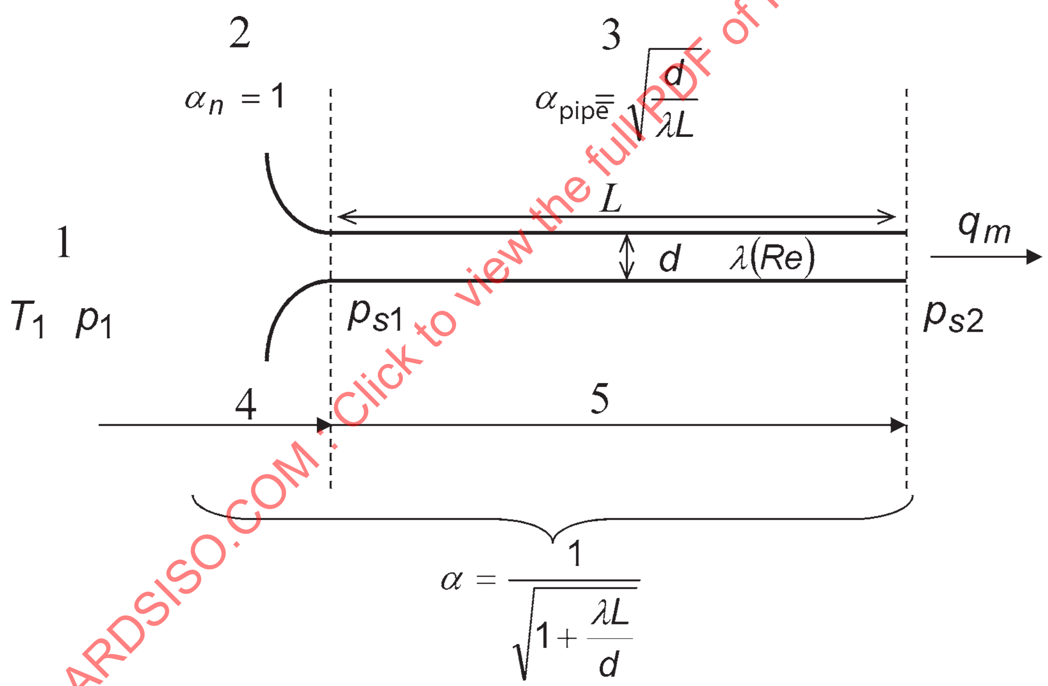
D.2.3.2.2 The flow coefficient α_{pipe} of the pipe or tube is then determined using Formula (D.8):

$$\alpha_{pipe} = \frac{1}{\sqrt{\zeta}} = \sqrt{\frac{d}{\lambda L}} \qquad \text{(D.8)}$$

D.2.3.2.3 Formulae (D.5) and (D.6) are relative to static pressures, while flow-rate characteristics determined in accordance with the ISO 6358 series are relative to stagnation pressures. To take into account pipes and tubes in the calculation of flow-rate characteristics of a system, it is necessary to convert, respectively, the pipe's upstream stagnation pressure to static pressure, and the pipe's downstream static pressure to stagnation pressure. In accordance with the definition of stagnation pressure, these conversions correspond to isentropic transformations. They are given in D.2.3.3 for the upstream side of the pipe or tube and in D.2.3.5 for the downstream side of the pipe or tube.

D.2.3.3 Isentropic transformation on the upstream side of the pipe or tube

D.2.3.3.1 On the upstream side of the pipe or tube, the isentropic transformation between the stagnation pressure and the static pressure is equivalent to feeding the tube through an ideal converging nozzle with an inlet that is very large compared to the throat area (that is, the pipe inlet area), as shown in Figure D.2.



Key

1	upstream stagnation conditions	4	isentropic evolution
2	nozzle	5	adiabatic evolution
3	pipe or tube		

Figure D.2 — Upstream isentropic transformation modelled by an ideal converging nozzle

D.2.3.3.2 For the ideal nozzle with an inlet area that is very large compared to its throat area, the flow coefficient determined using Formula (D.1) is $\alpha_n = 1$.

D.2.3.3.3 Using the additive property given in Formula (D.2), the flow coefficient α of the association of the nozzle and the pipe or tube is expressed in accordance with Formula (D.9):

$$\alpha = \frac{1}{\sqrt{1+\frac{\lambda L}{d}}} \qquad \text{(D.9)}$$

D.2.3.3.4 The compressibility effect coefficient defined by Formula (D.4) is then expressed in accordance with Formula (D.10);

$$s = 1 + \frac{1}{\sqrt{\frac{\gamma(\gamma+1)}{2}}\sqrt{1+\frac{\lambda L}{d}}} + \frac{1}{\gamma(\gamma+1)\left(1+\frac{\lambda L}{d}\right)} \tag{D.10}$$

and the effective area by Formula (D.11):

$$A = \frac{1}{\sqrt{1+\frac{\lambda L}{d}}} \times \frac{\pi d^2}{4} \tag{D.11}$$

D.2.3.4 Flow-rate characteristics of the pipe or tube

D.2.3.4.1 When considering the upstream pressure p_1 of the nozzle (which corresponds to the upstream stagnation pressure of the pipe or tube) and the downstream static pressure of the pipe or tube p_{s2}, Formulae (D.5) and (D.6) can be rewritten using as flow-rate characteristics the sonic conductance C_{pipe} and the critical pressure ratio b_{pipe} of the pipe or tube, as shown in Formulae (D.12) and (D.13):

in subsonic flow $\left(\frac{p_{s2}}{p_1} > b_{pipe}\right)$:

$$q_m = C_{pipe}\rho_0 p_1 \sqrt{\frac{T_0}{T_1}}\sqrt{1-\left(\frac{\frac{p_{s2}}{p_1}-b_{pipe}}{1-b_{pipe}}\right)^2} \tag{D.12}$$

in sonic flow $\left(\frac{p_{s2}}{p_1} \le b_{pipe}\right)$:

$$q_m^* = C_{pipe}\rho_0 p_1^* \sqrt{\frac{T_0}{T_1^*}} \tag{D.13}$$

D.2.3.4.2 Flow-rate characteristics C_{pipe} and b_{pipe} can then be calculated from the effective area A and the compressibility effect coefficient s using Formulae (D.14) and (D.15):

$$C_{pipe} = \frac{A}{\rho_0\sqrt{sRT_0}} \tag{D.14}$$

$$b_{pipe} = 1 - \frac{1}{s} \tag{D.15}$$

Formulae (D.14) and (D.15) combined with Formulae (D.10) and (D.11) lead to Formulae (4) and (5), which give the flow-rate characteristics of the pipe or tube, taking into consideration its upstream stagnation pressure and its downstream static pressure.

NOTE Formulae (D.12) and (D.13) have the same form as Formulae (1) and (2), with $m_{pipe} = 0,5$ and $\Delta p_{c\,pipe} = 0$.

D.2.3.5 Isentropic transformation on the downstream side of the pipe or tube

On the downstream side of the pipe or tube, the isentropic transformation between the static downstream pressure p_{s2} and the stagnation pressure p_2 can be calculated using Formula (A.1) in ISO 6358-1:2013.

