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Pneumatic fluid power — Determination of flow-rate characteristics of components —

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

Transmissions pneumatiques — Détermination des caractéristiques de débit des composants —

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

[Revision of first edition (ISO 6358-3:1989) and ISO/DIS 6358-5]

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Foreword

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ISO 6358-3 was prepared by Technical Committee ISO/TC 131, *Fluid power systems*, Subcommittee SC 5, *Control products and components*.

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

— *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 assemblies*

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 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 will vary 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 an assembly 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 —

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

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 an assembly of components and piping with known flow-rate characteristics.

A total of four independent coefficients, C (sonic conductance), b (critical back-pressure ratio), m (subsonic index) and Δp_c (cracking pressure), may be used to describe the relationship between the flow rate and pressure drop of a component in a pneumatic system. These flow-rate characteristics are determined for each component in accordance with the measurement methods described in parts 1 and 2 of ISO 6358. The relationships described in these parts of ISO 6358 cover two types of compressed air flow in the components: subsonic flow and choked flow.

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 ISO 6358.

2 Normative references

The following referenced documents are indispensable for the application of this document. 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 6358-1:201X, *Pneumatic fluid power — Determination of flow-rate characteristics of components using compressible fluids — Part 1: General rules and test methods for steady-state flow* (to be published)

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 5598 and ISO 6358-1 and the following apply.

4 Symbols and units

4.1 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
d	Inside diameter of pipe, tube or hose	m
L	Length of pipe, tube or hose	m
λ	Average friction factor of a pipe or tube depending on the Reynolds number	–
p_{s2}	Static pressure downstream of the pipe or tube	Pa
γ	Ratio of specific heat capacities (for air, it equals 1,4)	–
k	Friction coefficient of the pipe or tube resulting from experimental tests	–
Re	Reynolds number of the flow within the pipe or tube	–
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.		

4.2 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
p	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 assembly

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 and outlet pressure for each component are the same.

5.2 Relationships among component flow-rate characteristics

5.2.1 In subsonic flow, the relationship of a component's mass flow rate to its flow-rate characteristics is shown in Equation (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 $b < \frac{p_2}{p_1} < 1 - \frac{\Delta p_c}{p_1}$

5.2.2 In choked flow, the relationship of a component's mass flow rate to its flow-rate characteristics is shown in Equation (2):

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

when $\frac{p_2}{p_1} \le b$

5.2.3 When the mass flow rate is zero, the relationship of a component's mass flow rate to its flow-rate characteristics is shown in Equation (3):

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

when $1 - \frac{\Delta p_c}{p_1} \le \frac{p_2}{p_1} \le 1$

NOTE The symbols used in Equations (1), (2) and (3) are from ISO 6358-1 and are not used in the remainder of this part of ISO 6358. The equations are described here for general reference and will 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 ISO 6358.

If the flow-rate characteristics of some components are expressed by methods other than ISO 6358, the values of C, b, m and Δp_c can be obtained in accordance with 5.3.2 or 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, in accordance with 5.3.2.2, or the formulas based on test results, in accordance with 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.2.2.

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, equations (4) to (7) can be used to calculate the flow-rate characteristic parameters of a pipe, tube or hose. These equations can be applied with any gas that can be considered as a perfect gas. Further information about the theoretical aspects related to these equations is given in Annex D.

$$C_p = \frac{\pi}{4\rho_0\sqrt{RT_0}} \frac{d^2}{\sqrt{\left(1+\frac{\lambda L}{d}\right)+\sqrt{\frac{2}{\gamma(\gamma+1)}}\sqrt{1+\frac{\lambda L}{d}}+\frac{1}{\gamma(\gamma+1)}}} \quad (4)$$

$$b_p = 1-\frac{1}{1+\frac{1}{\sqrt{\frac{\gamma(\gamma+1)}{2}}\sqrt{1+\frac{\lambda L}{d}}}+\frac{1}{\gamma(\gamma+1)\left(1+\frac{\lambda L}{d}\right)}} \quad (5)$$

$$m_p = 0{,}5 \quad (6)$$

$$\Delta p_{c\,p} = 0 \quad (7)$$

NOTE The parameters calculated in Equations (4) to (7) have the subscript "*p*" to indicate that they relate to the downstream static pressure in the pipe, tube or hose.

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

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

NOTE Equation (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 [1] 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.2.2.2 for further information.

5.3.2.2.3 The Reynolds number, *R*e is the dimensionless parameter correlating the viscous behaviour of Newtonian fluids, as shown in Equation (9):

$$\mathrm{Re} = \frac{4\,q_m}{\pi\, d\, \mu} \quad (9)$$

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 law expressed by Equation (10), which is valid for air:

$$\mu = \mu_0 \sqrt{\frac{T_e}{T_0}} = 1{,}069 \times 10^{-6} \sqrt{T_e} \tag{10}$$

5.3.2.2.5 In the case of air, Equations (11) and (12) can replace, respectively, Equations (4) and (5):

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

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

5.3.2.3 Formulas for air, based on test results

5.3.2.3.1 Equations (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 H.4 of ISO 6358-1:201X. Further information is given in D.2.3.

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

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

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

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

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.

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

$$k = 2{,}35 \times 10^{-3} d^{-0{,}31} \tag{17}$$

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

$$k = 3{,}61 \times 10^{-3} d^{-0{,}31} \tag{18}$$

5.3.2.3.3 Equations (13) to (18) give the flow-rate characteristics of the pipe or tube for an inlet pressure of 500 kPa (5 bar). For other inlet pressures, calculate the corresponding flow-rate characteristics using the pressure dependence coefficient K_p for sonic conductance equal to 2 $\times 10^{-7}$ [-/Pa], in accordance with ISO 6358-1.

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

When the flow-rate characteristics of a component are expressed by incompressible-flow parameters, for example, 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 Organisation of calculations for assemblies of components connected in series

6.1 General

Consider an assembly of components connected in series as illustrated in Figure 1: the same mass flow rate q_m of fluid passes through all components.

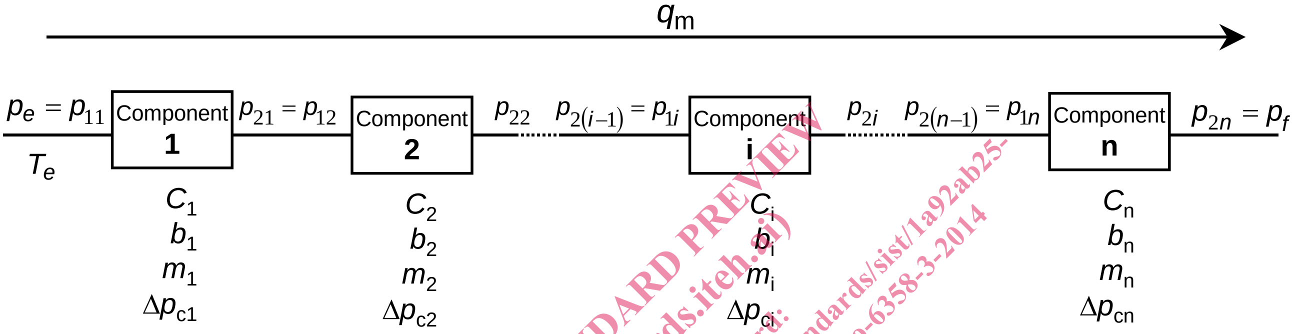

Figure 1 — Assembly of components connected in series

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

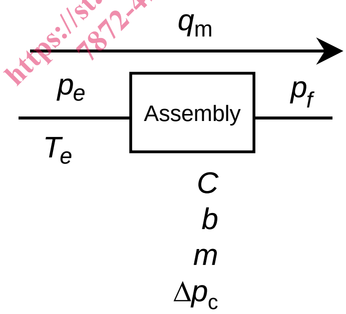

Figure 2 — Equivalent assembly

6.2 Imposed parameters

For the calculation of the flow-rate characteristics of an assembly of components connected in series, the following parameters are imposed:

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

— the temperature T_e of the fluid.

6.3 Calculation principle

6.3.1 General

Consider the assembly of components connected in series as shown in Figure 1. The flow-rate characteristics of this assembly are determined in three main steps:

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

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

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

Steps 1 and 3 require the same calculation principle described below and consist of the determination of the outlet pressure of the components connected in series p_f for given subsonic flow rates q_m.

For a given mass flow rate q_m, flowing through each component at subsonic flow 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.

6.3.2 Calculation of the downstream pressure p_{2i}

6.3.2.1 General case

6.3.2.1.1 The downstream pressure p_{2i} of component *i* can be calculated only in a subsonic condition, which means that to calculate the downstream pressure p_{2i} of component *i*, the mass flow rate shall be less than the choked flow rate, as determined by Equation (19):

$$q_m < C_i \rho_0 p_{1i} \sqrt{\frac{T_0}{T_e}} \tag{19}$$

6.3.2.1.2 Rearranging the subsonic relationship with the knowledge of the flow-rate characteristics of component *i*, its downstream pressure p_{2i} can be expressed as a function of the mass flow rate q_m and of its upstream pressure p_{1i} as shown in Equation (20), but only if the mass flow rate is less than the choked flow rate, as verified by Equation (19):

$$p_{2i} = p_{1i} \left[b_i + \left(1 - \frac{\Delta p_{ci}}{p_{1i}} - b_i \right) \sqrt{1 - \left(\frac{q_m}{C_i \rho_0 p_{1i}} \sqrt{\frac{T_e}{T_0}} \right)^{\frac{1}{m_i}}} \right] \tag{20}$$