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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

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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For an explanation on the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the WTO principles in the Technical Barriers to Trade (TBT) see the following URL: Foreword - Supplementary information

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	$m^3/(s \cdot Pa)$(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

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

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

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

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

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

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.

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

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

$$m_{\text{pipe}} = 0{,}5 \quad (6)$$

$$\Delta p_{c\text{pipe}} = 0 \quad (7)$$

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):

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

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):

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

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

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

where:

μ_r is the dynamic viscosity for the Sutherland reference temperature T_r equal to 1,712 × 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):

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

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

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.

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

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

$$m = 0,58 - 0,1b \qquad (15)$$

$$\Delta p_c = 0 \qquad (16)$$

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):

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

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

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

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.

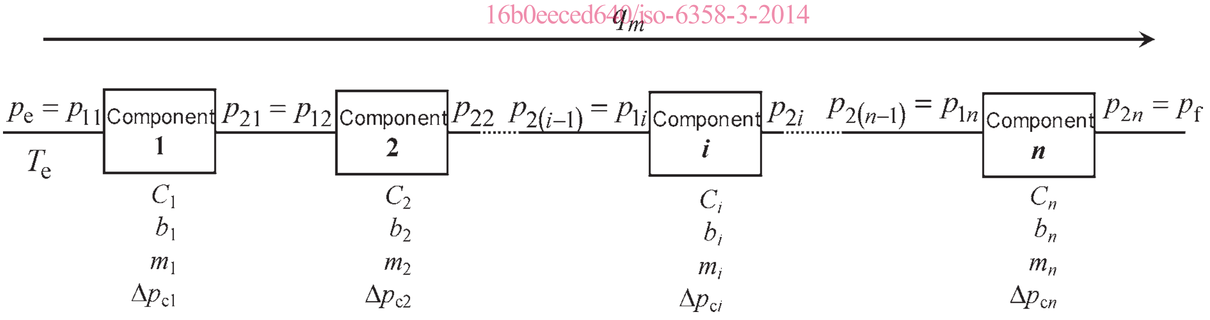

Figure 1 — System of components connected in series

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.

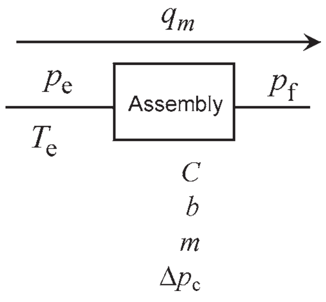

Figure 2 — Equivalent system

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):

$$\Delta p_c = \sum \Delta p_{ci} \tag{19}$$

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:

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

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 $(q_m)_\mathrm{MAX}$. This theoretical maximum mass flow rate through the system $(q_m)_\mathrm{MAX}$ 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 $(q_m)_\mathrm{MAX}$

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

$$C_\mathrm{MIN} = \min(C_1,C_2,\ldots,C_i,\ldots,C_n) \qquad (21)$$

$$\left(q_\mathrm{m}\right)_\mathrm{MAX} = C_\mathrm{MIN}\, \rho_0 p_e \sqrt{\frac{T_0}{T_e}} \qquad (22)$$

6.6.3 Determination of the choked mass flow rate $q_\mathrm{m}{}^*$

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):

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

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):

$$p_{11} = p_\mathrm{e} \qquad (24)$$

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):

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

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.

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

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.

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

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 $p_{2\mathrm{i}}$ using Formula (28), which comes from Formula (A.1) of ISO 6358-1:2013:

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

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):

$$p_\mathrm{f} = p_{2n} \tag{29}$$

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.