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Selection of pneumatic control valves from catalogues †

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Abstract

In a case of computer simulation used for the verification of pneumatic system performance, one of the main problems is that various parameters can be used to describe flow characteristics of the system components. Although the Standard ISO 6358 offers two parameters: the sonic conductance C and the critical static pressure ratio b, these cannot be directly utilised in the selection of elements comprising a pneumatic system. In this paper, we present two algorithms for calculating the volumetric flow rate Q_N and the flow coefficient K_V as a function of sonic conductance C and critical pressure ratio b (recommended by the standard) toward the improved selection of pneumatic control valves.

Keywords: Flow characteristics; Flow coefficient; Pneumatic control valves; Volumetric airflow rate

1. Introduction

During a selection of pneumatic control valves from vendors' catalogues, some calculations are conducted. The main goal of such calculations is to determine the parameters describing flow characteristics of the valves. The flow characteristics [1] can be described by [2]:

- armature nominal diameter d_k;
- volumetric airflow rate in normal conditions Q_{Nnom}[1];
- flow coefficient K_v according to the standard VDI/VDE 2173 [3];
- sonic conductance C and critical pressure ratio b [4]; and
- air – flow coefficient μ [5].

[1] For the overpressure before element p_{nom}= 600 000 Pa and the pressure drop Δp_{nom}= 100 000 Pa.

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Of these, only the first three are utilised in traditional algorithms of calculations. The parameters applied depend on the algorithm that has been selected [2]. According to [2, 6], the sonic conductance C and the critical pressure ratio b should be utilised because:

- two parameters can more precisely describe flow properties;
- they are proposed by a currently valid standard (ISO 6358);
- some parameters determined by algorithms of calculations (e. g., armature nominal diameter d_k) are not strictly connected with flow properties of a pneumatic element, and only a reluctance to try new methods is the reason why they can be found in the vendors' catalogues; and
- they can be converted into other coefficients (e. g., an air – flow coefficient μ [5]) and, thanks to that, they can be used for pneumatic system analysis.

2. Problem formulation

In 1989, the ISO 6358 [4] standard that was introduced described the flow parameters of pneumatic devices. It defined two flow parameters: a sonic conductance C and a critical (static) pressures rate b; the same standard also described the appropriate determination and application methods. The parameters are suitable for comparing the flow properties of two pneumatic elements.

According to the standard ISO 6358 [4], the sonic conductance, the critical pressure ratio, the critical flow, and the mass flow rate are defined as follows:

The sonic conductance C is defined as the ratio of the mass flow $\dot{m}$ through the element to the product of the input gas pressure p_1 as well as its density ρ_N, in the standard conditions ANR[2], for the critical flow:

$$C = \frac{\dot{m}}{p_1 \cdot \rho_N} . \tag{1}$$

The critical pressure ratio b is the maximal value of p_2/p_1, at which the critical flow occurs.

The critical flow is a situation during which the flow in some sub–space of an element is equal to the local sound velocity. It occurs when the inlet pressure p_1 is sufficiently high in comparison to the outlet pressure p_2. The mass flow is then seen as proportional to the inlet pressure p_1 and inversely proportional to the root square of the inlet stream temperature T_1. At the same time, it does not depend upon the outlet pressure p_2

The **mass flow rate** of air is described by the formula:

$$\dot{m} = \frac{p_1}{\sqrt{T_0}} \cdot \rho_N \cdot \sqrt{T_N} \cdot H , \tag{2}$$

where

$$H = \begin{cases} C \ \text{ for } p_2 / p_1 \ \leq \ b \\ C \cdot \sqrt{1 - \left(\frac{p_2/p_1 - b}{1-b} \right)^2} \ \text{ for } b < p_2 / p_1 \leq 1 \end{cases} . \tag{3}$$

Although the ISO standard has been enforced 15 years ago, only few vendors present values of C and b in their catalogues [4]. There are two reasons behind this.

(1) An experimental determination of the sonic conductance and the critical pressure ratio according to ISO 6358 standard is very difficult, especially for elements with good flow properties and large diameters.

(2) There is a lack of algorithms that could make it possible to calculate these parameters on the basis of requirements for a pneumatic system.

For many years, previous works have been carried out on CAD systems for pneumatic driving systems at the Koszalin University of Technology. Selection of pneumatic devices from the vendors' catalogues is an important problem in such systems. As a solution, a previous study highlighted the possibility of using Artificial Neural Networks to augment the calculation of control valves parameters [7]. In this paper, we propose another approach to solve this problem.

Although methods of determining flow parameters as a function of C and b have been presented in [2], there are no methods in the opposite direction. This is the main reason why the reverse task has been formulated:

for the knowing value of a flow parameter (e. g., the flow coefficient K_v) the values of C and b must be determined to make catalogue selection possible.

The task has no direct solution because two values must be calculated from one known parameter. Below, we present the methods of determination of C and b from Q_{Nnom} or K_V.

3. Determination of the sonic conductance *C* and the critical pressure ratio *b* from the nominal volumetric flow rate Q_{Nnom}

The relation between the volumetric flow rate Q [m^3/h] and the mass flow rate $\dot{m}$ [kg/s] in the same conditions is given by:

$$Q = \dot{m} \cdot \frac{3600}{\rho} . \tag{4}$$

Inserting (3) into (4), in case of the nominal flow in the standard conditions Q_N [m^3/h], the relation among the flow value, the sonic conductance value C [m^4·s/kg], the critical pressure ratio value b, and the pressure ratio Y are thus obtained:

$$Q_N = 3600 \cdot C \cdot p_1 \cdot \sqrt{\frac{T_N}{T_0}} \tag{5}$$

for $Y \leq b$ or by:

[2] ANR – the standard conditions (p_N=100000 Pa, T_N=293.15 K)

$$Q_N = 3600 \cdot C \cdot p_1 \cdot \sqrt{\frac{T_N}{T_0}} \cdot \sqrt{1-\left(\frac{Y-b}{1-b}\right)^2} \quad (6)$$

for $Y > b$.

A pressure ratio Y can be defined by:

$$Y = \frac{p_2}{p_1} = 1 - \frac{\Delta p}{p_{1nad} + p_a}. \quad (7)$$

For the nominal flow Q_{Nnom}, when $\Delta p = \Delta p_{nom}$= 100 000 Pa, p_{1nad}= p_{1nom}= 600 000, and p_a= 100 000 Pa we obtain from (7) the pressure ratio Y_{def} = 6/7 ≈ 0.8571. In such a case when $b > Y_{def}$, from relation (5), C is given by:

$$C = C_{\min} = \frac{1}{3600 \cdot 700000} \cdot Q_{Nnom} \cdot \sqrt{\frac{T_0}{T_N}} = \\ = 3.968 \cdot 10^{-10} \cdot Q_{Nnom} \cdot \sqrt{\frac{T_0}{T_N}} \quad (8)$$

In the opposite case when $b < Y_{def}$, from relation (6),

$$C = 3.968 \cdot 10^{-10} \cdot Q_{Nnom} \cdot \sqrt{\frac{T_0}{T_N}} \cdot \frac{1}{\sqrt{1-\left(\frac{Y_{def}-b}{1-b}\right)^2}} = \\ = C_{\min} \cdot \frac{1}{\sqrt{1-\left(\frac{Y_{def}-b}{1-b}\right)^2}} = C_{\min} \cdot W(b) \quad (9)$$

For $b = 0$, the sonic conductance equals 1.9412·C_{min}. Below (Fig. 1, Table 1), the values of coefficients increasing a sonic conductance for the various pressure ratios are presented.

Having known the value of $Q_{N\,nom}$ in normal conditions, the valve selection procedure is as follows:

(1) Determine the minimal value of a sonic conductance C_{min} using Eq. (8).
(2) Find a valve with $b \geq 0.8571$ and $C \geq C_{min}$.
(3) If the pressure rate b of the valve is less than 0.8571 then one should look for a valve with the sonic conductance *W(b)* (Fig. 1, Table 1) times greater than the minimal one ($C \geq C_{min} \cdot W(b)$). The valve that ought to be selected must have the nominal flow rate in normal conditions no less than the required one.

Table 1. Value of the multiplicand *W(b)* increasing minimal sonic conductance C_{min} as function of the critical pressure ratio b for Y_{def} = 0.8571.

b	0	0.1	0.2	0.5	0.7	0.85
$W(b)$	1.9412	1.8495	1.7532	1.4287	1.1738	1.0011

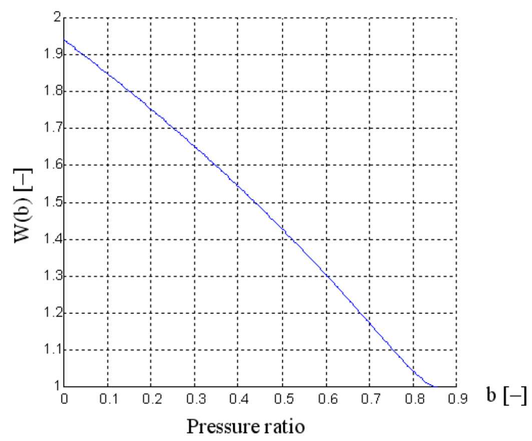

Fig. 1. Dependence of the multiplicand *W(b)* increasing minimal sonic conductance C_{min} as a function of the critical pressure ratio b for Y_{def} = 0.8571.

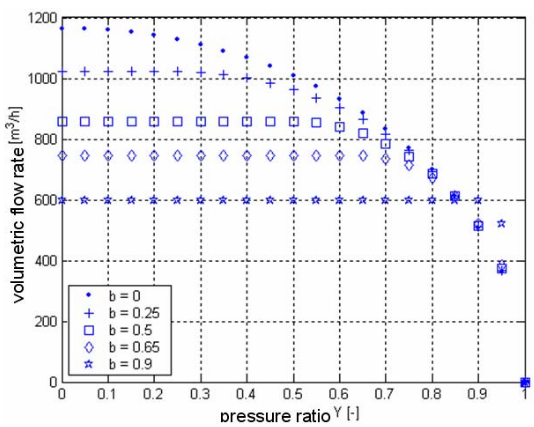

Fig. 2. Dependence of the volumetric flow rate Q_N on the pressure ratio $Y = p_2/p_1$ for control valves with different values of C and b, and the same value of Q_{Nnom} = 600 [m^3/h].

The proposed method results in the selection of valves with various C and b, but always with the same value of a nominal volumetric flow rate Q_{Nnom}. The volumetric flow rate Q_N, as a function of the pressure ratio Y for the selected valves with the nominal volumetric flow rate Q_{Nnom}= 600 m^3/h, is presented in Fig. 2. This is represented by a set of lines crossing each other at point Y_{def} = 0.8571.

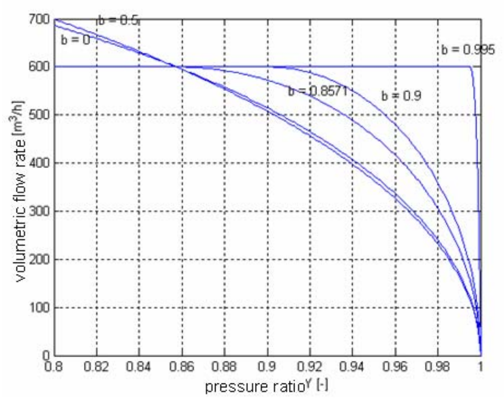

Fig. 3. Dependence of the volumetric flow rate Q_N on the pressure ratio $Y = p_2/p_1$ (Y>0.8) for control valves with different values of C and b, and the same value of Q_{Nnom} = 600 [m^3/h].

4. Determination of the sonic conductance *C* and the critical pressure ratio *b* from the flow coefficient K_v

The value of a coefficient K_V [m^3/h] as a function of a sonic conductance C [m^4·s/kg] and a critical pressures rate b may be given by [4]:

$$K_v = 1.241 \cdot 10^7 \cdot C \cdot \frac{\sqrt{1-\left(\frac{Y-b}{1-b}\right)^2}}{\sqrt{Y \cdot (1-Y)}} . \quad (10)$$

If $Y < b$ then $Y = b$ in the numerator of (10), and if $Y < 0.5$ then $Y = 0.5$ in the denominator of (10).

Assigning:

$$\frac{1}{Z(b)} = \frac{\sqrt{1-\left(\frac{Y-b}{1-b}\right)^2}}{\sqrt{Y \cdot (1-Y)}} \quad (11)$$

and transforming in order to determinate a sonic conductance, we obtain:

$$C = \frac{K_v}{1.241 \cdot 10^7} \cdot Z(b) = 0.8058 \cdot 10^{-7} \cdot K_v \cdot Z(b) . \quad (12)$$

Let us assume that $Y = 0.8571$. For $b \geq Y$ the value of the parameter $Z(b)$ is $Z(b \geq Y)_{Y=0.8571} = 0.35$. The value $b = 0$ produces $Z(b=0)_{Y=0.8571} = 0.6794$. In the analysed case ($Y = 0.8571$), a change from $b = Y$ to $b = 0$ causes an increase of the sonic conductance by $Z(0)_{Y=0.8571}/Z(0.8571)_{Y=0.8571} = 1.9411$.

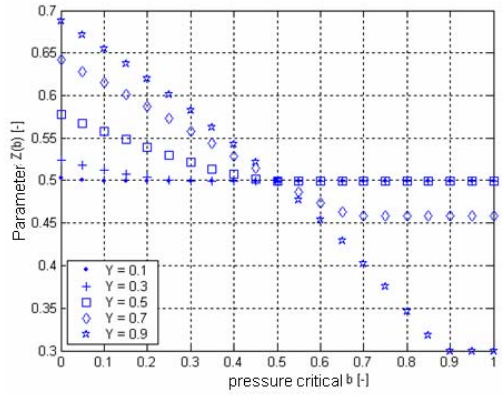

Fig. 4. Dependence of the parameter $Z(b)$ on the pressure critical ratio b for various values of Y.

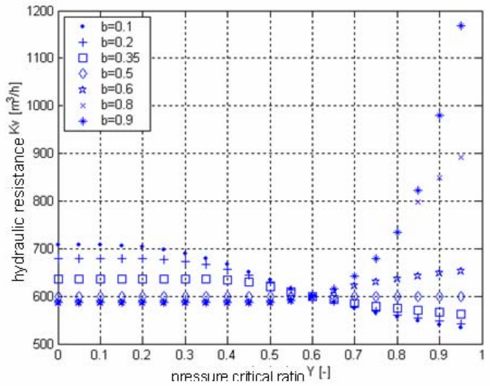

Fig. 5. Dependence of the hydraulic resistance coefficient K_v on the pressure ratio Y for different devices selected from catalogue (Y_{ele} = 0.6). Required K_v = 600 m^3/h.

The same increase of sonic conductance C was obtained for the analysed problem of a nominal volumetric flow rate Q_{Nnom} (section 3). The value of $Z(b)$ as function of the critic pressure rate b for various pressure ratios Y is shown in Fig. 4 below.

Having known the value of the K_v coefficient, the valve selection procedure is as follows:

(1) Assume the value of pressure ratio Y_{ele}.
(2) Determine the value of a coefficient $Z(b)_{Y=Yele}$ using Eq. (11).
(3) Determine the minimal value of a sonic conductance C_{min} using Eq. (12).
(4) Look for the valve with $b \geq Y_{ele}$ and $C > C_{min}$. If the value of a critical pressure ration is less than the assumed one ($b<Y_{ele}$), then the valve selected must have a higher value of a sonic conductance. The value can be determined from (11); the value of coefficient $Z(b)$ from Eq. (10).

The proposed method thus results in the selection of valves with various C and b (depending on the Y_{ele} assumed), but always with the same value of a flow coefficient K_v.

5. Final remarks

In this paper, we presented two methods used to determine the sonic conductance C and the the critical pressure ratio b, when the flow coefficient K_v or the nominal air – flow rate Q_{Nnom} are known. For both approaches, the selected valve has the value of K_v or Q_{Nnom} that is no less than the required one. Among its advantages, the proposed approach enables a selection of the pneumatic control valve from a catalogue when the sonic conductance C and the critical pressure ratio b are given but not the flow coefficient K_v or the nominal air – flow rate Q_{Nnom}, after which the traditional methods of calculation and selection can be utilized; moreover, it also allows for an interconnection of pneumatic system synthesis and analysis. To date, the parameters applied in the traditional calculation algorithms (K_v or Q_{Nnom}) could not be converted into the air – flow coefficient μ [5]. Now, it can be achieved through two steps: from K_v or Q_{Nnom} into C and b, (thanks to the proposed algorithms) and next C and b into μ [6].

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