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AIR FLOW RATE IN PNEUMATIC COMPONENTS: CALCULATIONS AND EXPERIMENT

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Summary: *The formulas for calculating the air flow rate in pneumatic components given in [1, 2, 3] were compared. Flow rating parameters, sonic conductance C and critical pressure ratio b are descripted together with two methods for they determining. It was experimentally proven the mass flow rate continuously increases when diminishing the pressure ratio. The new concept, conventional critical pressure ratio, was introduced. The usefulness of this idea was confirmed by own results and by the results given in [2].*

1. NOMENCLATURE

$A = \sqrt{2k/[(k-1)/R]}$

$b = \varepsilon_{1*}$

C – sonic conductance,

C_D – discharge coefficient,

f – inlet port area,

f' – orifice area,

k – ratio of specific heats,

$\dot{m}$ – mass flow rate, kg/s,

p_a – atmospheric pressure,

p_1 – inlet static pressure,

p_0 – inlet stagnation pressure,

Q – volumetric flow rate,

R – gas constant,

T_0 – absolute stagnation inlet temperature,

$\varepsilon_0 = p_2/p_0$

$\varepsilon_1 = p_2/p_1$

φ_0, φ_1, φ_{ref} – flow functions,

ρ – gas density.

Subscripts

N – standard reference atmosphere [4],

$*$ – critical (sonic, choked) conditions.

2. INTRODUCTION

Calculation the air flow rate in pneumatic components play the key role in pneumatic systems theory. The problem is formulated as follows. For a given gas pressure and temperature T_0 and given outlet pressure, find the mass flow rate through pneumatic component.

Static p_1 or stagnation (total) p_0 pressure may be considered as inlet pressure (Fig. 1).

To solve the problem it is necessary to know flow rating parameters and appropriate formulas as well. The formulas are different in each of the two flow regimes: subsonic and sonic flow. Manufacturers of pneumatic components often present in their catalogues flow performances in the form of charts. For example as a relative pressure drop Δp%

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$$\Delta p\% = \frac{p_1 - p_2}{p_1 - p_a} \cdot 100\% \tag{1}$$

versus volumetric flow rate for various relative (above atmospheric) inlet pressures.

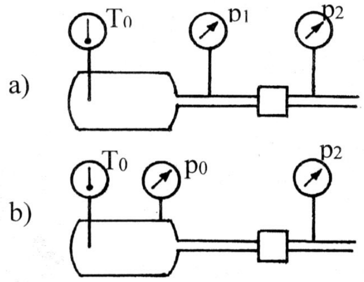

Fig. 1. Static (a) or stagnation (b) pressure may be considered as inlet pressure, c – component under the test

3. BASIC FORMULAS

According to [1] the only flow rating parameter for pneumatic component is the flow coefficient μ, and the mass flow rate is given by

$$\dot{m} = \mu\, \dot{m}_s \tag{2}$$

where isentropic mass flow rate $\dot{m}$ has the form

$$\dot{m}_s = f \frac{p_0}{\sqrt{T_0}} A\, \varphi_0$$

$$\text{if } 0 \le \varepsilon_0 \le \varepsilon_{0*} \text{ then } \varphi_0 = \sqrt{\varepsilon_{0*}^{\frac{2}{k}} - \varepsilon_{0*}^{\frac{k+1}{k}}}$$

$$\text{if } \varepsilon_{0*} < \varepsilon_0 \le 1 \text{ then } \varphi_0 = \sqrt{\varepsilon_0^{\frac{2}{k}} - \varepsilon_0^{\frac{k+1}{k}}}$$

The basic assumption in this isentropic model is the critical pressure ratio

$$\varepsilon_{0*} = [2/(k+1)] \uparrow [k/(k-1)]$$

is constant for a given gas. For air we have k = 1.4 so $\varepsilon_{0*} = 0.52828$. Formula (2) is widely used in [1] to calculate the time of filling and emptying chambers of constant and varying volume.

In [2] the formula to calculate the mass flow through an orifice has the form

$$\dot{m} = C_D \dot{m}_{ref} \tag{3}$$

where

$$\dot{m}_{ref} = f' \frac{p_0}{\sqrt{T_0}} A\, \varphi_{ref} \tag{4}$$

$$\text{if } 0 \le \varepsilon_0 \le \varepsilon_{0*} \text{ then } \varphi_{ref} = \varphi_0 / \left(1 + \frac{2}{\Pi}\varepsilon_{0*}^{\frac{1}{k}}\right) \tag{5}$$

$$\text{if } \varepsilon_{0*} < \varepsilon_0 \le 1 \text{ then } \varphi_{ref} = \varphi_0 / \left(1 + \frac{2}{\Pi}\varepsilon_{0}^{\frac{1}{k}}\right) \tag{6}$$

In the formulas (3) to (6) inlet stagnation pressure is used. On the contrary, in ISO 6358 standard [3] inlet static pressure occurs and the formula is

$$\dot{m} = \frac{p_1}{\sqrt{T_0}} \rho_N \sqrt{T_N}\, \varphi_1 \tag{7}$$

where

$$\text{if } 0 \le \varepsilon_1 \le \varepsilon_{1*} \text{ then } \varphi_1 = C \tag{8}$$

$$\text{if } \varepsilon_{1*} < \varepsilon_1 \le 1 \text{ then } \varphi_1 = C\sqrt{1 - \left(\frac{\varepsilon_1 - \varepsilon_{1*}}{1 - \varepsilon_{1*}}\right)^2} \tag{9}$$

For any pneumatic component the C and $\varepsilon_1{*} \equiv b$ values should be determined experimentally. The major advantage of this model is taking into consideration the fact that b is not a constant value for all components. For each pneumatic component b is different depending on the shape of internal flow duct.

4. METHODS FOR DETERMINING C AND b

4.1. The ISO method

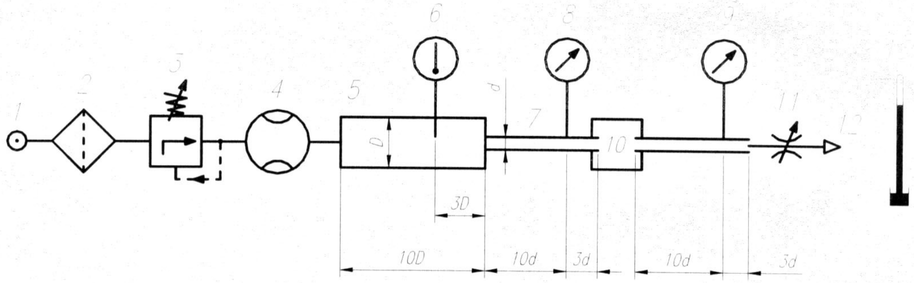

Fig. 2 Test circuit according to ISO 6358: 1 – compressed gas source, 2 – filter, 3 – pressure regulator, 4 – flow rate measuring device, 5 – temperature measuring tube, 6 – temperature measuring instrument, 7 – measuring tubes, 8 – upstream pressure gauge, 9 – downstream pressure gauge, 10 – component under test, 11 – flow control valve, 12 – outlet to the atmosphere, 13 – barometer

The test circuit to determine C and b taken from [3] is shown in Fig. 2. Pressure p_1 should be maintained constant of not less than 0.5 MPa during the test procedure. Using the flow control valve 11 the downstream pressure should be decreased until further decrease no longer produce an increase in the mass flow rate. This is the indication of choked flow. Sonic conductance C is calculated from (7) after substituting $\varphi_1 = C$ see (8). Knowing C we can calculate $\varepsilon_1^* \equiv b$ from (7) and (9) for several flow rates less than choked flow rate.

4.2. New method

The ISO method has two disadvantages. First, if the component under test has little pressure losses then exceptionally large flow generating equipment is required to obtain choked flow. The second, it is difficult to know if the flow is choked, because for most pneumatic components the mass flow rate continuously rises when downstream pressure, and pressure ratio, diminishes.

The new approach is developed [5]. The small pressure ratios is easy to obtain using a vacuum reservoir to which the ambient air flows through component tested (Fig. 3). The other role of the reservoir it is a measuring device. It is possible to calculate mass flow rate after differentiating instant mass of the air remaining in the reservoir with respect to the time. Instant mass is calculated from gas pressure and temperature histories inside the reservoir using the equation of gas state.

The results of experiment are presented in the form

$$\varphi_1 = \frac{\dot{m}\sqrt{T_0}}{p_1}\cdot\frac{1}{\rho_N\sqrt{T_N}}$$

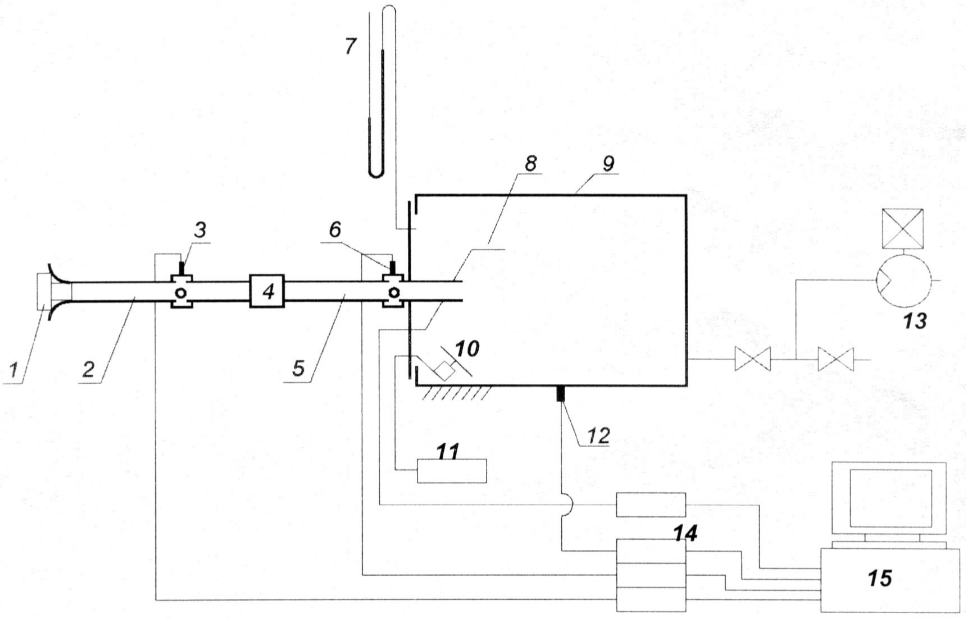

Fig. 3. The new test circuit: 1 – cork to initiate the flow, 2 – inlet measuring tube, 3, 6, 12 – pressure transducers, 4 – component under test, 5 – outlet measuring tube, 7 – vacuometer, 8 – gas temperature transducer, 9 – measuring tank, 10 – mixer, 11 – mixer supply, 13 – vacuum pump, 14 – amplifiers, 15 – computer equipped with A/D card

resulting from (7) as a function of ε_1 (thick line on Fig. 4). The results were then approximated by means of a straight line and a quarter of an ellipse, using least-squares fit method (thin line on Fig. 4). C and b we can find as an ordinate and an abscissa respectively, of the common point of these two lines.

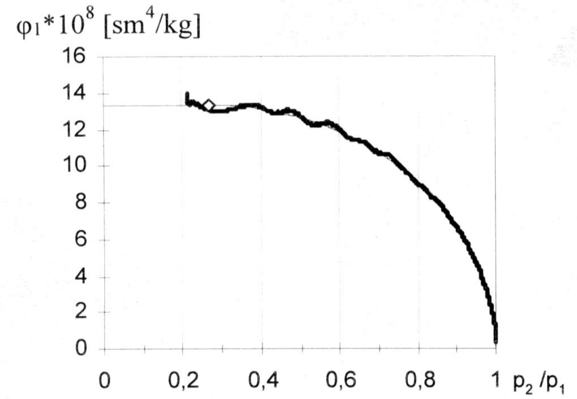

Fig. 4 Test results, approximating lines and the point (C, b)

It is clear from Fig. 4 that b is not a real critical pressure ratio because if $\varepsilon_l < b$ then φ_l is not a constant value. The more proper name of b seems to be *conventional* critical pressure ratio.

5. CONVENTIONAL CRITICAL PRESSURE RATIO APPLICATION

5.1. Flow characteristics calculation

The new method of determining C and b was verified by comparing the flow characteristics Δp% versus volumetric flow rate obtained two ways, Fig. 5. Relative pressure drop was calculated from (1), (7) and (9) for $C = 13.3*10^{-8}$ [s m^4/kg] and b = 0.27. Experiments were carried out on the test stand shown on Fig. 1a. A good agreement is evident.

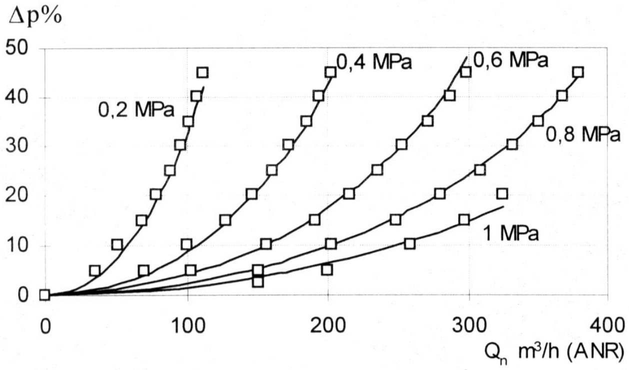

Fig. 5 The flow characteristics of the G1/2 air filter for various relative inlet pressures: points – experiment, lines – results of calculation

5.2. Comments on the results presented in [2]

In [2] measurements of C_D defined by (3) are reported. Experiments were performed in Rensselaer Polytechnic Institute (Troy, NY) gas-dynamics inflow facility. Components under tests were sharp-edged orifices of various f'/f ratios. All results are collected in Fig. 6 taken from [2]. Summarising the result authors stated only that each set of points defines unique curve.

Let us try to reconstruct the curves using the idea of conventional critical pressure ratio b_0 (differs from b). From (3) and (4) we have

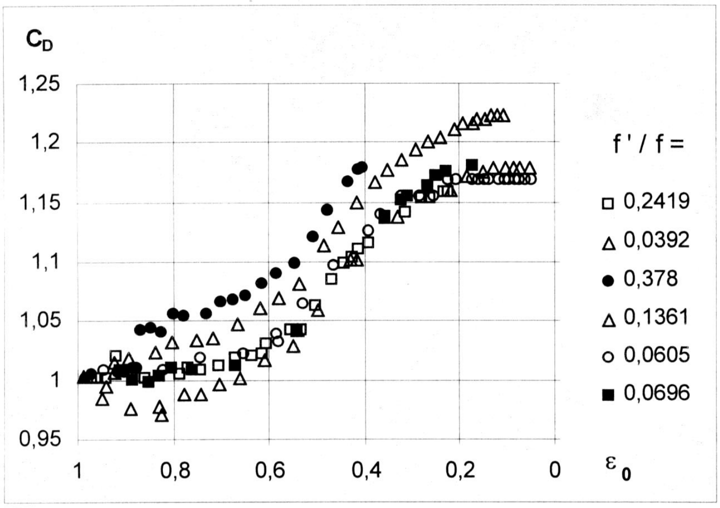

Fig. 6 Coefficient of the discharge versus pressure ratio for various orifice area to inlet port area ratios [2]

$$C_D = \frac{\dot{m}}{\dot{m}_{ref}} = \frac{\psi(\varepsilon_0)}{\varphi_{ref}(\varepsilon_0)} \tag{10}$$

$\varphi_{ref}(\varepsilon_0)$ is given by (5) and (6) but $\psi(\varepsilon_0)$ is unknown function which may be approximated by a straight line and a quarter of an ellipse

$$\text{if } 0 \le \varepsilon_0 \le \varepsilon_{0*} \text{ then } \psi(\varepsilon_0) = \text{const} \tag{11}$$

$$\text{if } \varepsilon_{0*} < \varepsilon_0 \le 1 \text{ then } \psi(\varepsilon_0) = \sqrt{1 - \left(\frac{\varepsilon_0 - b_0}{1 - b_0}\right)^2} \tag{12}$$

By means of a trials and errors method a pair of two such values (const, b_0) were searched, which assures the best fit to experimental results (Fig. 7). It was found const = 0.507 and $b_0 = 0.08$ for $f'/f = 0.1361$ and const = 0.482 and $b_0 = 0.14$ for $f'/f = 0.2419$. The good agreement is evident also in this case.

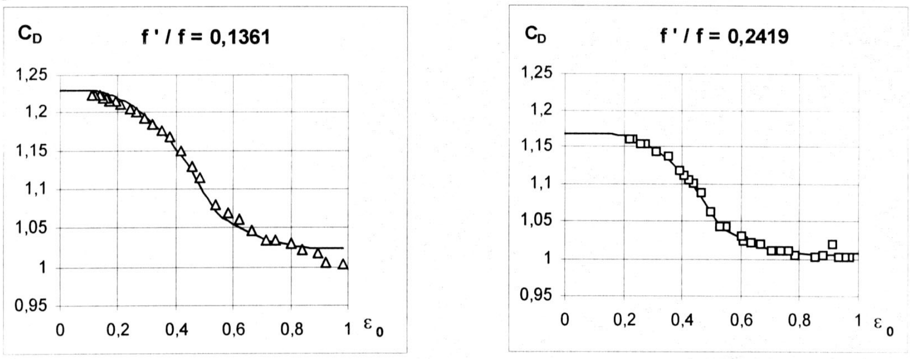

Fig. 7 Experimental results (points) [2] and the results of calculation (lines) according to formulas (11) and (12)

6. CONCLUSIONS

The new method for determining C and b for pneumatic components is more convenient than the method described in [3]. It was necessary to introduce the idea of *conventional* critical pressure ratio because of non one-dimensionality of the flow in tested components. The usefulness of this idea was confirmed by comparison the calculated results with pressure drop curves and with coefficients of the discharge experimentally obtained.

7. REFERENCES

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[3] ISO 6358 *Pneumatic fluid power – Components using compressible fluids – Determination of flow-rate characteristics*

[4] ISO 8778 *Pneumatic fluid power – Standard reference atmosphere*

[5] Iwaszko J. *Opory przepływu powietrza przez elementy pneumatyczne.* Prace naukowe Politechniki Warszawskiej, Mechanika z. 177, r. 1999 (in Polish)