EXPERIMENTAL AND THEORETICAL METHODS TO EVALUATE THE PRESSURE LOSSES IN AIR DISTRIBUTION LINES

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Abstract

Modern pipes for compressed air distribution lines are made of aluminium alloy and built by means of manufacturing extrusion processes. This kind of pipe needs a suitable mathematical formulation providing performances, in terms of pressure drop and flow-rate.

To this aim in this work a methodology based both on experimental tests and a theoretical approach was carried out. Analytical formulations were performed providing best experimental data fitting and range of applicability. Performances of most common line components (straight pipes, elbows, straight fittings and tees) made of different commercial sizes were evaluated carrying out experimental tests by means of a properly instrumented test bench.

Experimental and theoretical results were in good agreement, thus validating the proposed formulation.

Keywords: pressure losses, pipe, pneumatic component.

1 Introduction

A network of pipes and connecting elements are widely used in industrial applications. They must be provided to distribute the compressed air from a compressor installation to the various point of air consumption and to guarantee low pressure drop (between the compressor installation and the points of air consumption) and minimum leakage.

Therefore particular attention must be devoted to sizing compressed air distribution lines, in fact the pressure losses along the line must be as low as possible to ensure that both the flow-rate and the pressure delivered to the user circuits are correctly distributed.

Flow-rate and pressure losses in a pneumatic line can be evaluated if the various components making up the line have been characterized experimentally using an appropriate test bench, or if mathematical models are available which provide a close approximation of line behavior and are also simple to use.

The literature (Falkman, 1975; Reynolds, 1971; Zagarola and al, 1996; Barenblatt and Chorin, 1997; Carello and al, 1998) presents different theoretical and experimental methods for determining pressure drop in relation to flow-rate for a given line component, taking into account both the resistance and friction characteristics of smooth lines and the effect of line roughness. To establish which approach is most reliable, the results of an experimental analysis must be compared with those obtained through a theoretical model.

This paper presents the results of experimental tests carried out on pneumatic line components with a cylindrical cross section including, in particular: straight pipes, elbows, straight fittings and tees. Four different sizes were considered, viz., 25 mm, 32 mm, 50 mm and 63 mm. Components under test are made of aluminum by a manufacturing extrusion process that allows low roughness and good smoothness; because pipes are not perfectly smooth a suitable mathematical formulation was performed providing performances (pressure drop and flow-rate) with a better accuracy then those obtained by classic formulations.

The proposed formulas are simple to use and make it possible to determine the performance of all line components. They are thus an effective tool for pneumatic system design and verification.

2 Experimental Technique

2.1 Test Rig and Procedure

Experimental flow-rate tests were carried out on the test bench shown in Fig. 1.

Developed by Belforte et al. (1986), the test bench is provided with an orifice plate flow meter, and automatically calculates flow-rate from acquisition of: tem-

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perature T, pressure p_u upstream of the orifice plate, and pressure drop Δp_d across the orifice plate, as indicated in ISO 5167 (1980). Pressure upstream of the orifice plate can be regulated by means of pressure reducer R_1, while pressure p_1 upstream of component under test C is set using pressure reducer R_2. Pressure p_2 downstream of the component is regulated through flow control valve R. Silencer S reduces exhaust noise.

Tests were carried out establishing pressure p_1 and increasing air-flow through the component by means of flow control valve R. Volume flow-rate Q and pressure drop $\Delta p = (p_1 - p_2)$ were measured simultaneously, in accordance with ISO 6358 (1989).

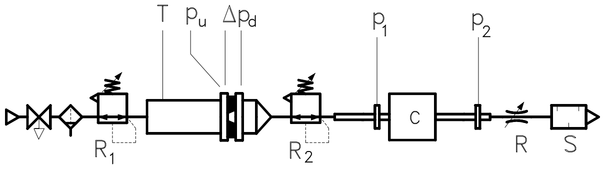

Fig. 1: *Test bench scheme*

2.2 Type of Components

Tests were carried out using straight pipes and connecting elements (elbows, straight fittings and tees) consisting of aluminum with an average surface roughness ε = 1μm. Four different inside diameters D were considered (25 mm, 32 mm, 50 mm, 63 mm).

Figure 2 shows a schematic view of the straight pipe, whose total length was L_0 = 5 m for all sizes considered. Particular attention was devoted to the pressure measurement points; upstream pressure p_1 was measured at a distance $L_1 = 10 \cdot D$ from the flow inlet, while downstream pressure p_2 was measured at a distance $L_2 = 3 \cdot D$ from the flow outlet (as required by ISO 6358 (1989)).

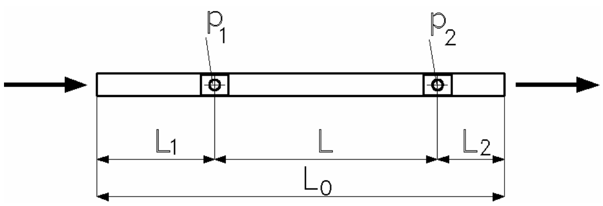

Fig. 2: *Pressure measurement points on the straight pipe*

The experimental pressure drop $\Delta p = (p_1 - p_2)$ thus applies to a pipe of length L of 4.675 m, 4.584 m, 4.35 m and 4.181 m, with inside diameters D of 25 mm, 32 mm, 50 mm and 63 mm respectively.

Figure 3a shows the connecting elements (elbow, straight fitting and tees), which were characterized experimentally by installing upstream and downstream pipe segments with measurement points as indicated in Fig. 3b. By way of example, elbow and pipe installation is shown schematically in Fig. 3c: in accordance with the requirements of ISO 6358 (1989), pressures upstream and downstream of the element are measured after the air has traveled through a pipe segment of length L_1.

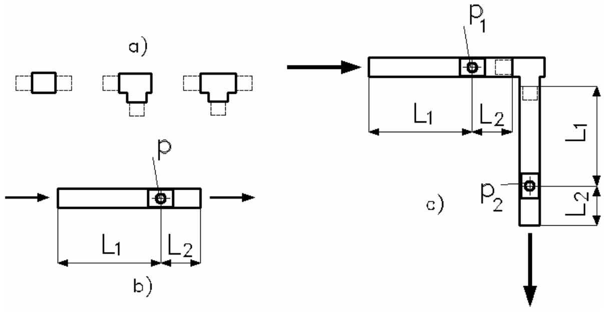

Fig. 3: *Example of a connecting element*

The tees were tested by plugging one outlet and routing the air in different directions to determine the influence of air direction on pressure drop.

The experimental pressure drop represents both the localized losses in the connecting element, and from the losses in the pipe segments at inlet (of length L_2) and at outlet (of length L_1). The pressure loss occurring as air flows through the fitting or connection was calculated by subtracting the pressure drop in both pipe segments (total length $L_1 + L_2$) from the experimental pressure drop.

3 Data Analysis

3.1 Straight Pipes Pressure Losses: Theoretical and Experimental Comparison

Several authors (Falkman, 1975; Reynolds, 1971; Zagarola et al., 1996; Barenblatt and Chorin, 1997) have presented formulas that can be used to calculate pressure drop in compressed air distribution lines; these formulas may be theoretical or empirical, i.e., based entirely on experimental data. The authors (Carello et al., 1998) have already developed an experimental test method to evaluate pressure losses in straight pipes.

All of these approaches are based on Eq. 1, which applies to both laminar and turbulent flow:

$$\Delta p = p_1 - p_2 = P_1 - P_2 = \lambda \cdot \rho \cdot \frac{w^2}{2} \cdot \frac{L}{D} \tag{1}$$

Mass flow-rate can be expressed by Eq. 2 and 3.

$$G = \rho \cdot Q_V = \rho \cdot \frac{\pi \cdot D^2}{4} \cdot w \tag{2}$$

$$G = \rho_N \cdot Q_N \tag{3}$$

Where Q_V and Q_N indicate volume flow-rate respectively in test and standard conditions.

Air density ρ under test conditions is linked to air density ρ_N in standard conditions by the following relation:

$$\rho = \rho_N \cdot \frac{P_1}{P_N} \cdot \frac{T_N}{T} \tag{4}$$

Applying Eqs. 1, 2, 3 and 4 yields:

$$\Delta p = \lambda \cdot \frac{8 \cdot L \cdot \rho_N \cdot Q_N^2}{\pi^2 \cdot D^5} \cdot \frac{T}{T_N} \cdot \frac{P_N}{P_1} \tag{5}$$

where: Q_N, P_1 and T are the magnitudes measured and computed by the test bench.

In Eq. 5, it is important that the dimensionless friction coefficient λ be correctly specified ($\lambda = \lambda$ *(*Re, *ε/D))*, considering that it is dependent on the Reynolds number, pipe roughness and relative roughness. The dependence of λ on parameter ε/D is negligible in the case of smooth pipes.

The Reynolds number for a pipe of constant circular cross-section is:

$$\mathrm{Re} = \frac{4 \cdot \rho_N \cdot Q_N}{\pi \cdot D \cdot \mu} \tag{6}$$

Air viscosity μ was calculated using the data given in the CRC Handbook (1981).

The formulations proposed by Blasius and by Prandtl were used as the basis for the following expression for λ, which applies to smooth pipes with Reynolds numbers up to 10^{10}:

$$\lambda = \frac{1}{(0.75 \cdot \ln(\mathrm{Re}) - 1.15)^2} \tag{7}$$

The value for the dimensionless friction coefficient λ determined with Eq. 7 can be applied in Eq. 5 to calculate pressure loss as a function of flow-rate.

To achieve a closer approximation between theoretical and experimental characteristics, for pipes that are not perfectly smooth, Eq. 7 was modified by introducing an appropriate dimensionless coefficient c, with Reynolds numbers up to 10^6, thus yielding the expression:

$$\lambda = \frac{1}{(0.75 \cdot \ln(\mathrm{Re}) - 1.15 - c \cdot \mathrm{Re})^2} \tag{8}$$

Coefficient c makes allowance for the fact that, in reality, the pipes have a certain slight surface roughness. This is why c is dependent on pipe diameter and becomes smaller as diameter increases; the values of c are shown in Table 1.

Table 1: Straight pipe: coefficient c for calculating λ

D (mm)	c
25	$1.1\ 10^{-6}$
32	$0.9\ 10^{-6}$
50	$0.6\ 10^{-6}$
63	$0.5\ 10^{-6}$

The theoretical pressure drop can be calculated as a function of flow-rate with Eq. 5, using the coefficient λ given by Eq. 8. This pressure drop closely approximates the pressure drop measured experimentally throughout the entire range of upstream flow-rates and pressures considered.

Figures 4 and 5 compare the experimental (symbols) and theoretical (continuous lines) curves for pressure drop versus flow-rate for two different pipe sizes (D = 25 mm and D = 63 mm) and for different upstream pressures. As can be seen, the proposed theoretical formulation for calculating pressure drop provides a very good fit with the experimental results, as it does for the other pipe sizes taken into consideration.

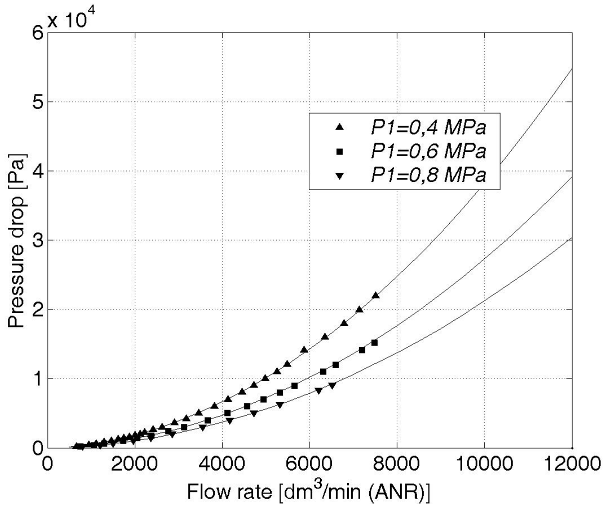

Fig. 4: *Pressure drop vs. flow-rate: theoretical and experimental results for straight pipes D = 25 mm*

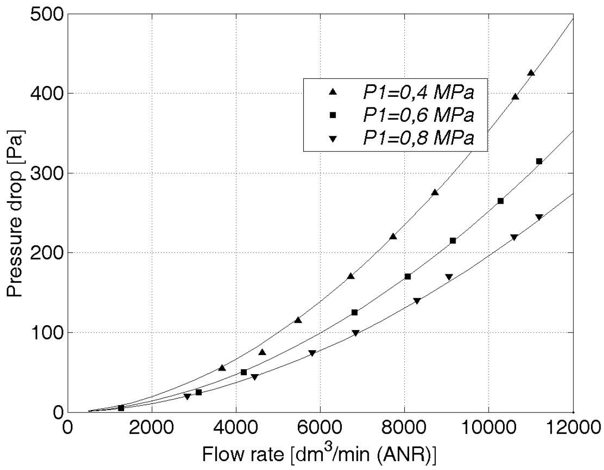

Fig. 5: *Pressure drop vs. flow-rate: theoretical and experimental results for straight pipes D = 63 mm*

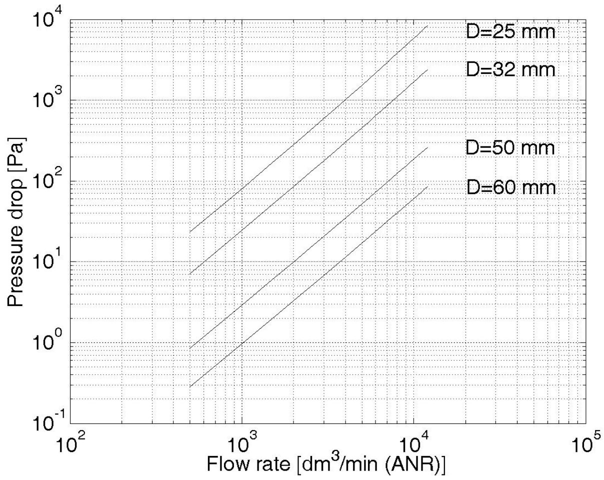

Fig. 6: *Pressure drop per linear meter vs. flow-rate for straight pipes*

For any given upstream pressure and flow-rate, increasing the pipe's inside diameter will result in a lower pressure drop. Likewise, for any given diameter and flow-rate, increasing upstream pressure will reduce pressure losses.

In view of the consistency of the results obtained for all pipe sizes considered, we could conclude that the proposed formulation can be used for flow-rates above those considered in the investigation as well as for operating pressures exceeding those employed in the tests.

By means of experimental results and taking into account the pipe's length L the pressure drop per linear meter has been computed and referred in Fig. 6. In particular the pressure drop per linear meter versus flow-rate for all pipe sizes at an upstream pressure of 0.6 MPa is shown. For the sake of clarity, axes are shown on a logarithmic scale. This graph is a useful tool for evaluating distributed pressure losses on a theoretical basis at the time a pneumatic line is designed. For diameters different from those here considered an interpolation method can be used.

3.2 Connecting Elements Pressure Losses: Theoretical and Experimental Comparison

The following empirical relation was used for the connecting elements:

$$\Delta p = K_{\mathrm{G}} \cdot \frac{Q_{\mathrm{N}}^2}{P_1} \tag{9}$$

where K_G is a coefficient which depends both on the type of element in question and on its size. The value of K_G is that which, introduced in Eq. 9, provides the best fit between the theoretical and experimental curves.

Table 2 shows values of constant K_G obtained for each type and size of connecting element considered.

By way of example, Figs. 7, 8 and 9 (for D = 50 mm) show the experimental data (symbols) and the theoretical curves obtained using Eq. 9 (continuous lines) for pressure drop versus flow-rate at different upstream pressures for the elbows, straight fitting and tees respectively.

The theoretical and experimental curves are quite close, which was also the case for the other connecting element sizes considered in the investigation.

Table 2: Connecting elements: coefficients K_G

K_G [s·bar/m³]	*D* 25 mm	*D* 32 mm	*D* 50 mm	*D* 63 mm
Straight fitting	0.38	0.14	0.032	0.013
Elbow	92	41	4.0	0.95
Three-way fitting (branched flow)	90	40	4.8	2.0

Equation 9 can be used during both design and verification, as coefficient K_G is constant and characteristic of each element.

For the tees (Fig. 9) the air flow direction influences on the component's characteristics. Tests were carried out with flow entering from an inlet in the straight segment and issuing through an outlet into the branch line; the other straight outlet was plugged. This configuration was chosen because it is commonly used in actual applications.

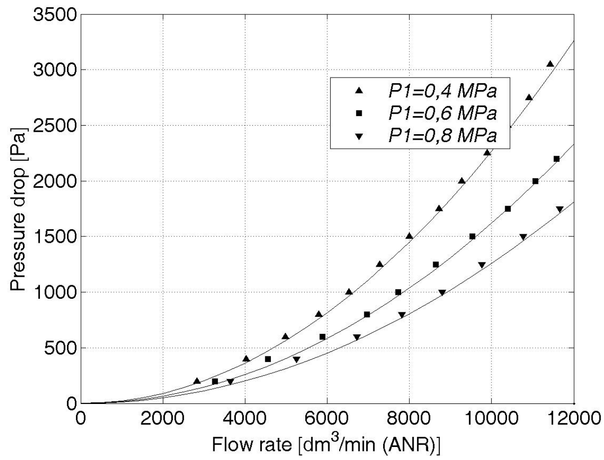

Fig. 7: *Pressure drop vs. flow-rate: theoretical and experimental results for elbows D = 50 mm*

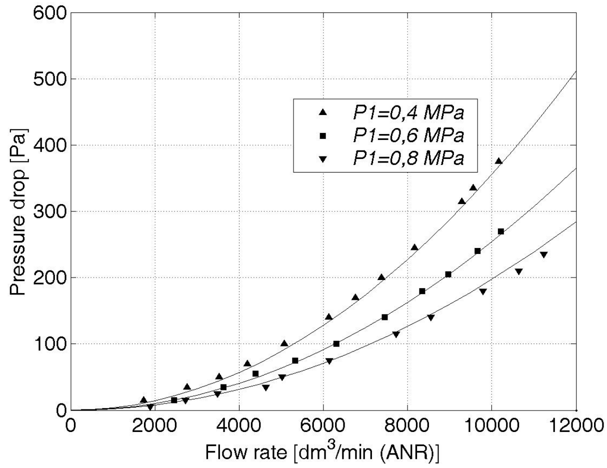

Fig. 8: *Pressure drop vs. flow-rate: theoretical and experimental results for straight fittings D = 50 mm*

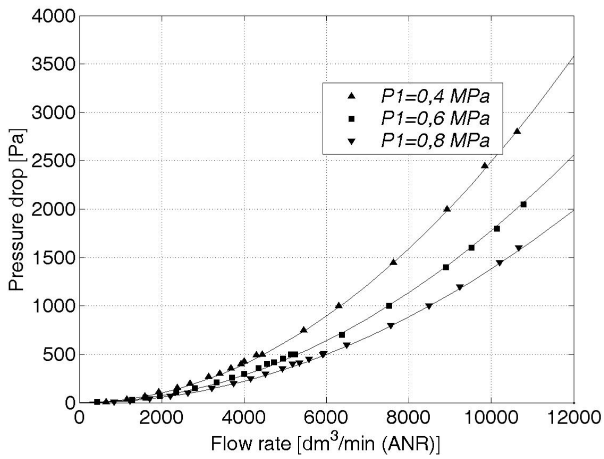

Fig. 9: *Pressure drop vs. flow-rate: theoretical and experimental results for tees D = 50 mm*

4 Conclusions

In a compressed air distribution network it is important to evaluate the pressure losses caused by long lengths of piping and connecting elements (such as elbows, straight fittings and tees), and to determine how these pressure losses are affected by upstream pressure and flow-rate.

The investigation considered pipes and connecting elements made of aluminum alloy in different sizes commonly used in industrial applications. Regarding the straight pipes a theoretical formula was improved and proposed for calculating pressure losses as a function of flow-rate; the formula is valid for all pipe sizes considered in the investigation, and takes pipe roughness, inside diameter and test conditions (pressure, temperature and density) into account. Extensive experimental validation allows us to conclude that this formula can also be used to evaluate pressure losses for other pipe sizes and working conditions.

For the pipe the pressure drop per linear meter was also identified, as it is a useful tool for designing and verifying pneumatic systems. For connecting elements, a formula was proposed whereby the concentrated pressure loss caused by the connection can be calculated using an appropriate coefficient.

Nomenclature

L	pipe length	[m]
D	pipe inside diameter	[m]
Δp	pressure drop for a pipe of length L and diameter D	[Pa]
p	relative pressure	[Pa]
P	absolute pressure	[Pa]
λ	dimensionless friction coefficient	
ε	pipe roughness	[m]
ε/D	pipe relative roughness	
ρ	air density	[kg/m^3]
μ	air viscosity	[kg/(ms)]
w	mean air velocity	[m/s]
G	mass flow-rate	[kg/s]
Q	volume flow-rate	[m^3/s]
T	absolute temperature	[K]
Re	Reynolds number	
c	coefficient for straight pipe	
K_G	coefficient for connecting elements	

Subscripts

1	upstream
2	downstream
N	Standard Reference Conditions ANR
V	test conditions

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