DEVELOPMENT OF A METHOD FOR DETERMINING MICRO-LEAKS AND VOLUMETRIC EFFICIENCY IN PNEUMATIC CYLINDERS

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ABSTRACT

Tightness is one of the most important feature of any hydraulic or pneumatic component. Proper operation and efficiency dependent on it. This paper describes the new method for internal tightness measurement for pneumatic cylinders. Thanks to its simple design it is possible to perform fast test operations with a high quality. Versatility allows testing in few configurations to get the optimum results. Method can be successfully applied in mass production processes.

**KEYWORDS:** Micro-Leaks, Pneumatic Cylinders, Volumetric Efficiency

INTRODUCTION

The most important factor for the proper operation of any hydraulic or pneumatic cylinder is to provide high internal tightness. Sealing nodes have a decisive impact on the quality of the final product, its proper use and energy efficiency of the entire system. Currently used test and measurement equipment does not detect the presence of micro-leaks in a short period of time. This is because of the use of conventional test methods based on the measurements using various kinds of turbines, heat-resistive sensors or pitot and Prandtl tubes. The use of the above measurement methods does not provide sufficient accuracy for low flow rates. The absence of rapid and accurate method to determine micro-leaks at the manufacturing stage of the product directly contribute to the production of motors with lower volumetric efficiencies, and therefore with large energy loss during a long service time. Therefore, as part of the Lower Silesian Voucher for Innovations, a new method for determining the micro-leaks and volumetric efficiency for pneumatic cylinders has been developed

TEST METHOD

The idea of determining the micro-leaks is based on measurements of the pressure drop on capillary tube or local resistance located between the test object and standard part. During test the pressure in the system is set to maximum allowable level resulting from the strength of tested cylinder. In the case of full tightness of tested cylinder pressure drop across the capillary or local resistance is equal zero, $p_1-p_2=0$.

Scheme of the pneumatic system for measurements of the internal tightness is shown in Figure 1. The system consists of a pressure regulator (1), which is connected to an external air supply. Solenoid valves (2) close the air supply when system is set to the required pressure and the cylinders: tested (6) and standard (7) are filled. High accuracy pressure transducer (3) located before and after the throttling element (8) is used to determine the pressure drop. In addition, the system has converter (9) for measuring the absolute pressure. The entire system is protected by a safety valve (4), whose task is to prevent a pressure increase above the permissible value. Drain solenoid valve (5) is used to deflate the air

from the system, test cylinder (6) and standard cylinder (7). The proposed method for determination of micro-leaks is universal and allows testing in three different ways.
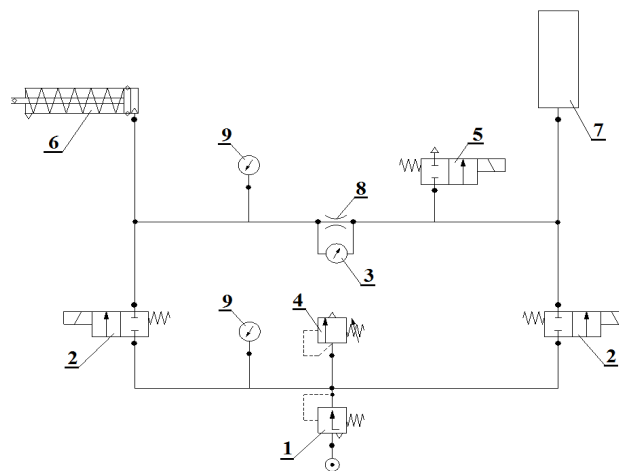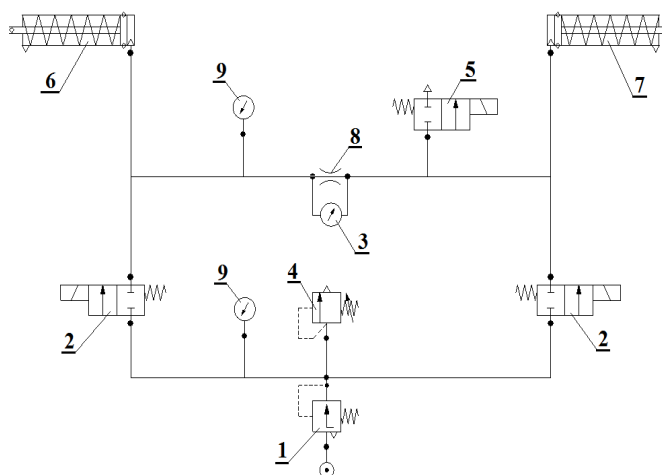

1 – Pressure Regulator, 2 – Shut-Off Solenoid Valve, 3 – High-Resolution Transducer for Differential Pressure Measurement, 4 – Safety Valve, 5 – Drain Solenoid Valve, 6 – Tested Cylinder, 7 – Standard Element, 8 – Throttling Element, 9 – Transducer for Absolute Pressure Measurement

**Figure 1: Scheme of the Measurement System for Determination of
Internal Leakages in Pneumatic Cylinders**

Test with Reference Part

The standard element in Figure 1 is replaced with reference part, which in terms of geometric and material is a faithful copy of the tested cylinder, i.e. has the same length, diameter, wall thickness, is made of the same material, etc. Method is recommended for testing parts which may deform and are exposed to mechanical and thermal effects.
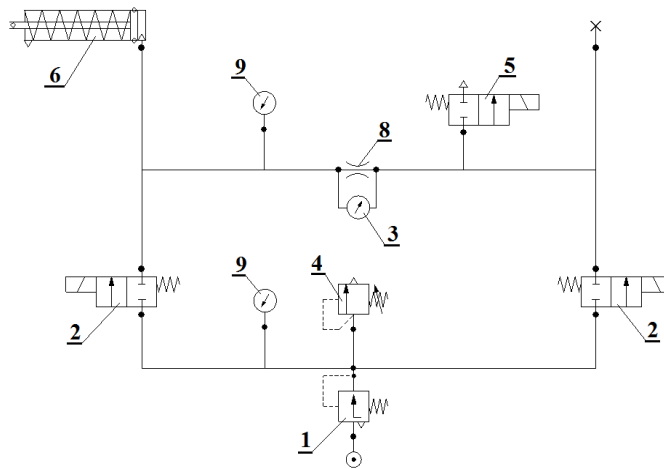

1 – Pressure Regulator, 2 – Shut-Off Solenoid Valve, 3 – High-Resolution Transducer for Differential Pressure Measurement, 4 – Safety Valve, 5 – Drain Solenoid Valve, 6 – Tested Cylinder, 7 – Reference Cylinder, 8 – Throttling Element, 9 – Transducer for Absolute Pressure Measurement

**Figure 2: Scheme of the Measurement System for Determination of
Internal Leakages in Pneumatic Cylinders**

Test without Standard Element

The standard element in Figure 1 is removed and the end is plugged. The error during test may occur due to lack

of volume on the reference side, which according to adopted methodology is recommended. Therefore this type of test can be performed only for cylinders with very small internal volumes.
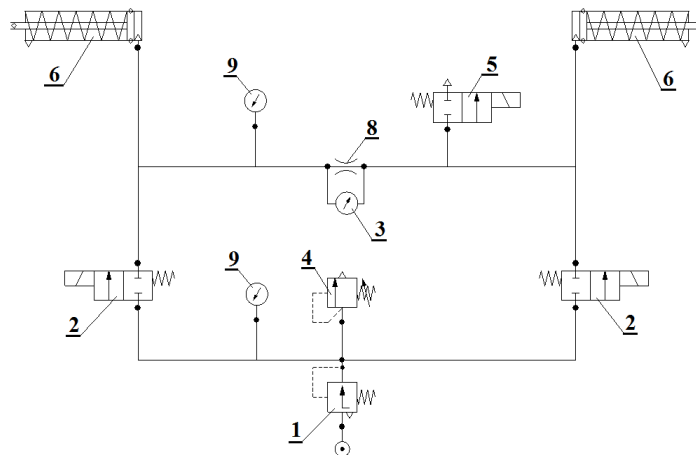

1 – Pressure Regulator, 2 – Shut-Off Solenoid Valve, 3 – High-Resolution Transducer for Differential Pressure Measurement, 4 – Safety Valve, 5 – Drain Solenoid Valve, 6 – Tested Cylinder, 8 – Throttling Element, 9 – Transducer for Absolute Pressure Measurement

**Figure 3: Scheme of the Measurement System for Determination of
Internal Leakages in Pneumatic Cylinders**

Simultaneous Test of Two Parts

The method is most efficient because the standard element is replaced by second tested element. The proposed method can be applied only in the case of a small amount of defective parts (less than 1%). In such a case it is unlikely to connect at the same time two faulty parts (probability less than 0.1 ‰.)

1 – Pressure Regulator, 2 – Shut-Off Solenoid Valve, 3 – High-Resolution Transducer for Differential Pressure Measurement, 4 – Safety Valve, 5 – Drain Solenoid Valve, 6 – Tested Cylinder, 8 – Throttling Element, 9 - Transducer for Absolute Pressure Measurement

**Figure 4: Scheme of the Measurement System for Determination of
Internal Leakages in Pneumatic Cylinders**

Test Cycle

The test cycle consists of the following basic steps (see Figure 5):

- **Filling:** The pressure in the system increases to the value required for testing, after reaching the target pressure valves cut-off the air flow from the outside source;

- **Pressure Stabilization:** The pressure between tested element and standard element equalize; the temperature and pressure in the system and both elements stabilize; in case of a large leak in the system pressure will drop rapidly;

- **Testing:** Pressure changes between tested element and reference volume are measured; defined differential pressure should be within the permissible pressure drop;

- Draining of the system.

The test consists of five phases.

Table 1: Five Phases of the Test

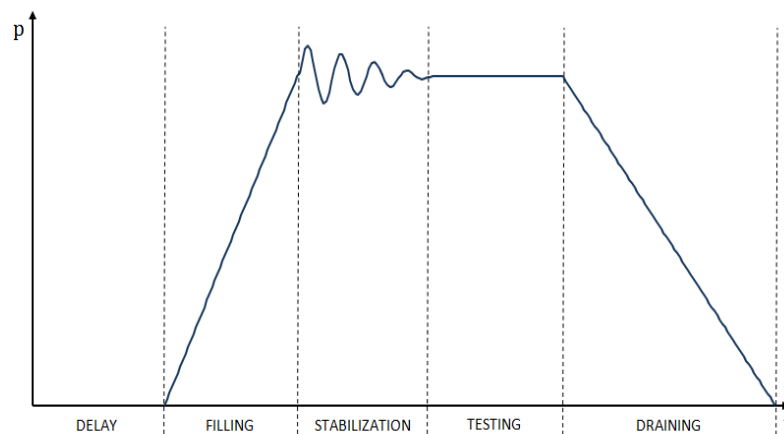|	1	2	3	4	5	
Start	Connection time	Filling time	Stabilization time	Testing time	Draining time	End of the cycle

Figure 5: Cyclogram of Cylinder Testing

Gap Definition

Determination of the threshold limit for the leakage is a separate and very important issue. To make a proper assessment of whether a product is tight (decision pass/fail) the threshold value of the leakage has to be determined. In general, this value is given in the technical specification of the product. If the product is tight we can assume that for given operating conditions and quality criteria the possible leakage value is below the allowable tolerance.

Leakage size through the throttle gap is dependent on the geometry of the gap and the type of flow (laminar or turbulent). In the case of capillary tube (small hole diameter in relation to its length) the flow is laminar. The further considerations omit turbulent flow that occurs in rough pipes (in this case must take into account Darcy–Weisbach equation with a flow resistance described by Nikuradse equation). According to above assumptions, the flow rate can be described by the Hagen-Poiseuille equation, therefore [1] [2]:

$$\Delta Q = k_1 f_d \Delta p \tag{1}$$

while

$$k_1 = \frac{d^2}{32\mu l} \tag{2}$$

where: k_1 – factor of proportionality,

   f_d – area of the gap,

For sharp edge orifice turbulent flow occurs, thus:

$$\Delta Q = k_2 f_d \sqrt{\Delta p} \tag{3}$$

while

$$k_2 = \sqrt{\frac{2}{\xi\rho}} = C_d\sqrt{\frac{2}{\rho}} \tag{4}$$

The equations can be written in the general form describing the flow through throttle gap of any type:

$$\Delta Q = kf_d\Delta p^n$$

In case of capillary gap $k = k_1$, and $n = 1$. Relationship $\Delta Q = f(\Delta p)$ then will be defined by formula (1). Its graphic representations is straight line which starts from origin of coordinates and with slope equal to $k_1 f_d$. For orifices $k = k_2$, a $n = 0.5$. Graphic characteristics of such gaps is a parabola with vertex lying at the origin. The comparison of both characteristics shows that the course of the volumetric flow rate as a function of the pressure drop for capillary tube is favourable. It is because there is a linear proportionality between pressure drop and flow rate.

For orifices with rounded edges, and capillaries of relatively short length the exponent can be taken from range $1 > n > 0.5$.
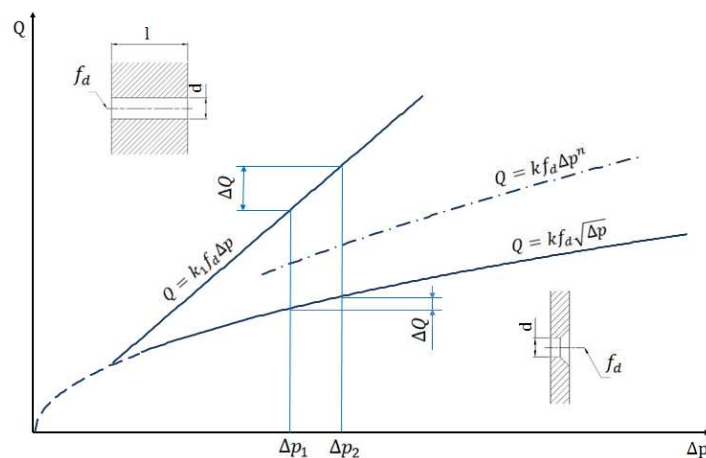

Figure 6: Static Characteristics of Considered Local Resistances

The relationship l/d which describes ratio of the length to the diameter of the gap can be helpful while determining the type of the gap. For high values of l/d flow is similar to that appearing in the capillary tube that is, for n = 1.

Smaller values of l/d will make the flow rate course similar to that described by equation (3) which describes orifices (n = 0.5). It is easy to notice the analogy between how the changes of l/d and the exponent n influence the flow characteristics through the gap. Graph showing the changes in the flow, taking into account l/d, and n is shown in Figure 7.
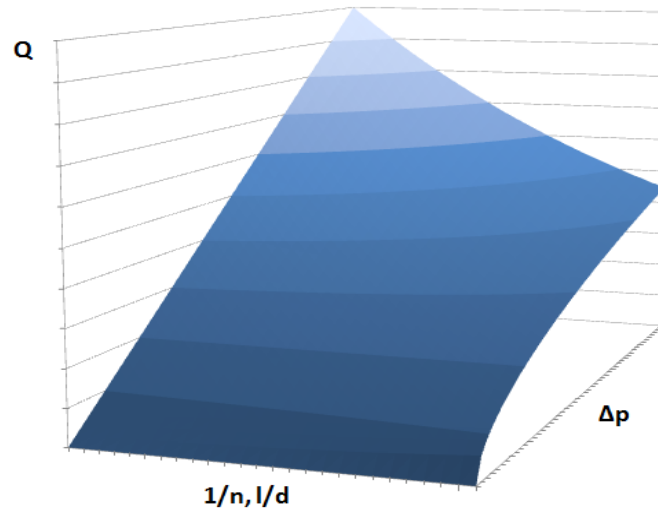

**Figure 7: Static Characteristics of the Local Resistance Including Ratio of
Length to Diameter of the Gap**

Volumetric efficiency of the test cylinders is the ratio of theoretical absorption Q_t to the actual absorption Q_{rz}. Actual absorption is greater than the theoretical by value ΔQ (micro leakage), hence we get [3]:

$$\eta_v = \frac{Q_t}{Q_{rz}} = \frac{Q_t}{Q_t + \Delta Q} \tag{5}$$

If we want to detect small leaks in a short time (productivity requirements of the production line) we must use appropriately sensitive transducers with high measurement resolution. When the test pressure is on the level of few bars it is impossible using one transducer to precisely measure at the same time the pressure value of 1 bar (10^6 Pa) and small value of pressure drop about 1 or 10 Pa. In this case, the combination of high sensitivity measurement with good productivity is only possible by using a differential pressure gauge with high accuracy. Control of the small changes in pressure should be carried out in relation to the pressure of the standard element.

Measurement Circuit

The measuring system used to measure the pressure difference is composed of a piezoelectric sensor, the signal amplifier and the data collector. As a result of changes in pressure, crystal in the sensor generates a charge which, through low-noise cable, shall be transferred to the charge amplifier. The primary function of the amplifier is to convert the high-impedance signal to a low-impedance voltage signal that is then recorded. In addition, properly selected amplifier should have a low input capacitance to ensure high sensitivity and a large input resistance to provide a small current leakage.

In the end, the piezoelectric transducer cannot be directly connected to the measuring instrument, because of the large input resistance, which should be transformed by a special electronic circuits for low-impedance output. Only this will ensure the proper operation with measuring and analyzing equipment.
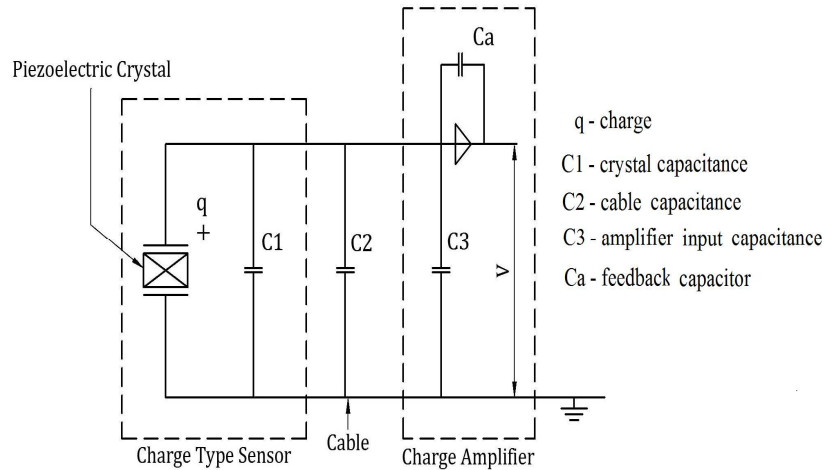
Figure 8: Scheme of the Charge System

Each of the elements in the described measurement circuit has a capacitance C, allowing him to accumulate electric charge. This charge is leaking during the time, and the speed of this leakage depends primarily on the feedback resistor and capacitor in the charge amplifier. This leads to a characteristic exponential course deformation of pressure changes registered by the piezoelectric sensor. As a result of this phenomenon signal measured by piezoelectric sensor has a different course than the actual signal. It is shown pictorially in Figure 9. A positive charge is formed when the pressure increases and the negative charge when the pressure decreases. Both charges are stored in the circuit of measuring system and then are gradually discharged. Leakage time (discharge time) of the charge can be described by the formula (6).

$$U(t) = U_0 \cdot e^{-\frac{t}{RC}}$$

(6)

where: U - Measured voltage,

U_0 - Voltage at the start of the discharge,

t - Time from the beginning of the discharge,

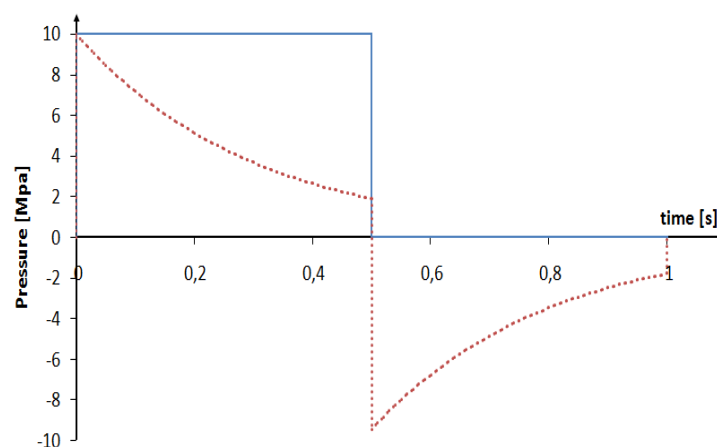RC - Relaxation factor of the circuit.

Figure 9: Comparison of Actual and Measured Pressure with Piezoelectric Sensor (Solid Line - Actual Course, Dashed Line - Measured Course)

Knowledge of the capacitor discharge phenomenon allows such correction of the measured course to get the real course.

CONCLUSIONS

This paper presents a new method for determining micro-leaks in pneumatic cylinders. Measurements will be used to determine volumetric efficiency of the cylinder and allow for an assessment of its quality. Due to the high versatility, the evaluation can be performed in three different configurations, depending on the conditions and the type of tested parts. One of the big advantages of this method is the possibility of quick change of the test specimens which allows the measurement of large quantities in a relatively short period of time. Especially in the case of testing two parts at the same time. This method is suited to the testing of mass production products.

Thanks to the mathematical description of the changes in flow rate all the components of the measurement system can be appropriately selected, especially the transmitter to measure differential pressure.

Components of the measurement system have high resistance to changes of temperature. This allows to perform measurements in a wide range of temperatures. Even in case of very low temperatures. Dehumidified air widely used in pneumatic systems will minimize the risk of freezing of sensitive measuring elements, which are responsible for the accuracy of the measurements. With such a wide range of application method allows to carry out measurements even in the most extreme conditions, often required for the production of components for the automotive industry.

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