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AUTOMATIC MEASUREMENT SYSTEM FOR DETERMINATION OF LEAKAGE FLOW RATE IN COMPRESSED AIR PIPELINE SYSTEM

Ryszard Dindorf, Piotr Wos

Kielce University of Technology, Faculty of Mechatronics and Machine Building, al. 1000-lecia Państwa Polskiego 7, 25-314 Kielce, Poland (✉ *dindorf@tu.kielce.pl*, +4841 342 4481, *wosf@tu.kielce.pl*)

Abstract

A new method of indirect flow rate measurement in a pneumatic pipeline system was developed by the authors. The method enables to measure the controlled leakage in a branch line and was used to construct automatic measuring systems auditing the compressed air systems (CAS) piping. In the CAS audit the volume and cost of the leakage in a compressed air pipeline system is evaluated. Based on the authors' patent, an automatic measuring system (AMS) for measurement of the leakage flow rate in industrial compressed air system piping, was developed. The AMS consists of a measurement device (MD) and a control system (CS). In the measurement device (MD) a novel bifunctional pneumatic proportional control valve is used. The AMS system will be used in the new research project "Mobile laboratory of compressed air system audit" based on the authors' concept.

Keywords: compressed air system, leakage flow rate, automatic measuring system.

1. Introduction

The purpose of the compressed air systems (CASs) is to deliver the compressed air energy (CAE) to the end-use pieces of equipment [1, 2]. The compressed air needs to be delivered with enough volume, appropriate quality and pressure to properly power the pneumatic components. But after use, the compressed air is released directly into the atmosphere. A typical industrial pneumatic system – compressed air system (CAS) consists of three main parts: a compressed air production plant, a pipeline system and pneumatic equipment (air actuators, air devices, air tools). Compressed air is widely used in almost all industries; companies use compressed air for many purposes, especially in automatic production lines, to drive and control the machinery, etc. [3]. Production of compressed air consumes 10% of the total consumption of electric energy in the industrial sector in the European Union [4, 5]. A poorly designed pneumatic system can increase energy costs, cause equipment failures, reduce production efficiency, and increase maintenance requirements. There are also many examples of wastages of compressed air in the industry [6]. The main causes of energy waste are leaks, pressure drops, over-pressurization, misuse of compressed air, and poor management of pneumatic systems [7]. In general, the causes of most losses in the CAS piping can be classified into three main groups: leakage of air from the system, artificial demand, and inadequate use [8]. Leakage is one of the largest sources of

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energy losses in pneumatic pipeline systems, and its removal for the purpose of improving energy efficiency of compressed air is both simplest and cheapest. Leakage tests can be easily performed, but identifying leakage points and computation of the leakage flow rate is a laborious task. Leaks not only waste energy but also cause pressure drops that worsen the operation of air-driven equipment and tools, thereby reducing the production efficiency. Leaks are responsible for considerable waste, frequently of up to 50% of energy consumption. In order to reduce leakage and improve energy efficiency of the CAS piping, it is necessary to carry out the CAS audit to detect leaks and eliminate their causes, review piping infrastructure, reduce pressure, fix existing leaks, prevent new leaks, identify and eliminate inappropriate use of compressed air. The first step to reduce compressed air energy costs involves measurement and monitoring of energy consumption of the compressor as well as the flow rates and operating air pressure in the pipeline. Because of the measurement environment complexity, the measurement of leaks will be influenced by error-causing factors: the temperature effect, the pressure fluctuations in the pipes, etc. The cost of CAS audit is incomparably low relative to the benefits resulting from reducing the energy consumption after eliminating leakage in industrial compressed air pipelines.

The direct measurements of flow rate are primarily applied to measure the air consumption in companies and to determine the performance data of compressors. A flowmeter installed in a main distribution line can show an increased leakage and waste of compressed air in the pneumatic pipeline system. The direct method of leakage measurement with a flowmeter requires placing the flowmeter either directly in the pipeline or in its bypass. A disadvantage of this method is the need to adjust the measuring range of the flowmeter to the leak volume in a pneumatic system. In addition, installation of a flowmeter is expensive, and the leakage volume varies. In order to reach sufficient resolution of the flow rate, an optimum measurement range should be close to the operating range. If the flow rate falls below 10 per cent of the maximum measured value, the measurement accuracy decreases. For measurement of the flow rates in CAS piping, a thermal-mass flowmeter is usually used. It is directly connected by ball valves and flow counters to the pneumatic system. A flow station DS 300 operating in a large measurement range enables to record consumption values and to determine leakages in pneumatic systems [9]. A Testo 6441 compressed-air counter makes it possible to carry out accurate compressed-air consumption measurements, consumption and leak monitoring and flow measurements in a compressed air system [10].

The industry standard and the best practice is to use an ultrasonic leak detection method. Operators of the ultrasonic equipment, and those analysing the leak detection survey, should be trained to an appropriate level according to Recommended Practice SNT-TC-1A or an equivalent standard [11]. The detectors are simple to use and can detect leaks inaudible to the human ear. Moreover, a plant downtime is not required to perform a leak detection audit, because background noise does not interfere with its results. A VP Leak Detector is a practical tool for any leak detection in air piping [12]. An ultrasonic leak detector (LD 300) enables the maintenance personnel to confirm the diagnosis results on the spot by being able to clearly discriminate among various equipment sounds [13]. An automatic leak detection system (ALDS) employing an ultrasonic device reduces the human labour costs and increases the leak detection frequency [14]. Sentinel I-24 is the latest and most technologically advanced leak testing instrument produced by Cincinnati Test System (CTS) [15]. A novel air-leak diagnosis and localization method based on infrared thermography is described in the papers [16, 17] and [18]. Infrared (IR) technology uses thermos-vision cameras to display and measure the thermal energy radiated by an object. Those cameras enable a very accurate non-contact temperature measurement. In almost all compressed air systems, a malfunction or air leak are accompanied with a temperature change.

An indirect method of measuring the leakage flow rate consists in measuring the pressure in a compressed air pipeline. A pressure sensor can be easily integrated with the piping. The pressure can be measured and recorded over a longer time at short intervals. In this method, all the air-operated end-use equipment is turned off. The indirect standard method of leakage measurement makes use of "draining the compressed air receiver" and "load/unload control system of compressor" [19]. In the papers [20, 21] a new method with a parallel connection measuring the gas leakage flow based on a standard flow is developed. In this method an instantaneous measurement of the leakage flow rate in a pipeline is enabled by employing the standard flow.

The authors have proposed a new approach to the compressed air leakage measurement method based on measurement of the flow through a controlled valve in a branch line [22, 23]. In the previous papers the authors discussed the design, construction and testing of a portable measurement device LT-I 200 for measurement of the air leakage flow rate in a pneumatic pipeline. In the present paper a new theoretical basis for indirect leakage measurement with determining the maximum measuring time t_{Lcm} is presented. Based on the patented automatic measuring system (AMS) a new measurement system of the leakage flow rate in industrial compressed air piping was built. The AMS consists of a measurement device (MD) and a control system (CS). In the MD a novel bifunctional pneumatic proportional control valve is used. The paper presents the results obtained by AMS and – for the first time – assessment of the uncertainty of leakage flow rate measurement. To analyse the flow rate measurement uncertainty a method based on the guide to the expression of uncertainty in measurement (GUM) was used.

2. Basics of measurement method

To measure the leakage flow rate in a branch line a flowmeter and an adjustable control flow valve were used. The adjustable control valve enables to adjust the controlled flow to the leakage range in a compressed air pipeline. Thus it is possible to measure the leakage flow rate in a wide range, from very small (local) values to very large ones, e.g. during a severe damage to the pneumatic equipment. An advantage of using the flowmeter in a branch line, as compared with the standard flow through a fixed orifice, is that knowing the flow characteristics, control valve parameters and volume of receiver and pipeline is not required. The proposed method is convenient and practical for automatic measurement of the leakage flow rate in any compressed air pipeline system. A diagram of the leakage flow rate measurement system used in compressed air pipelines, based on the controlled flow in a branch line is shown in Figure 1.

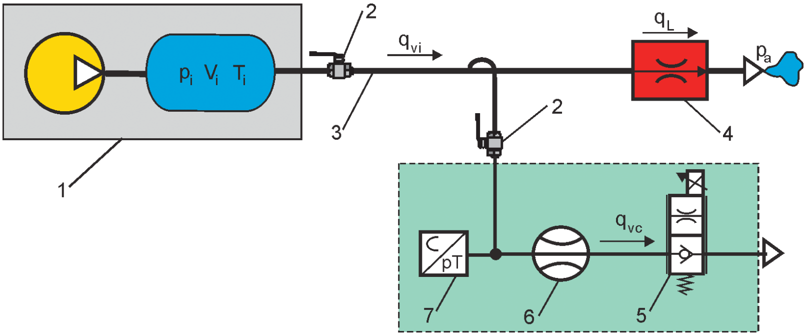

Fig. 1. Diagram of the measurement system based on the controlled flow in a branch line: 1 – compressor air station, 2 – shut-off ball valves, 3 – pipeline, 4 – leak point in a pipeline (leak orifice), 5 – 2/2-position/way adjustable control valve, 6 – flowmeter, 7 – pressure and temperature transducer.

With the new indirect method the compressed air leakage is estimated by measurement of pressure drop ratios in time intervals (Figure 2):

1. For the leakage measurement without the controlled flow, when control valve 5 is closed, the pressure drop ratio p_{Lu}/p_{Ld} in the time interval t_L is measured.
2. For the leakage mea surement with the controlled flow, when control valve 5 is open, the pressure drop ratio p_{Lcu}/p_{Lcd} in the time interval t_{Lc} and the flow rate q_{vc} are measured.

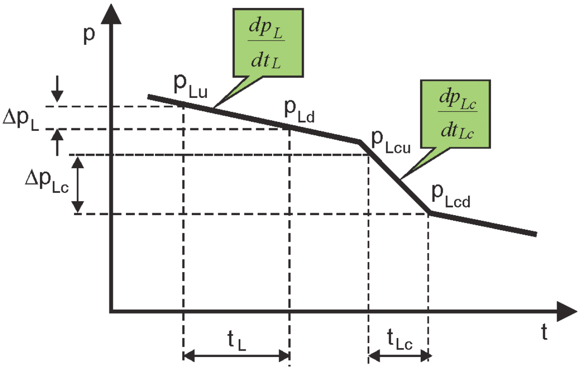

Fig. 2. Pressure drop ratios in compressed air pipelines during the measurement of leakage flow rate based on the controlled flow in a branch line.

The measurement method of compressed air leakage in pipelines based on the controlled flow consists in determining the relation between the air leakage flow rate q_L in a leak point of pipeline and the controlled air flow rate q_{vc} directly measured by the flowmeter in a branch line [3].

2.1. New method for determining leakage flow rate

Most authors consider temperature during the measurement to be the atmospheric temperature which means that the state of compressed air in the pipeline system during discharge remains isothermal. In fact, in a pneumatic system the state of polytropic or adiabatic discharge exists. A mass flow in the control area of a pneumatic system of volume V is written as:

$$\dot{m} = \lim_{\Delta t \to 0} \frac{\Delta m}{\Delta t} = \frac{dm}{dt} = \frac{d(\rho V)}{dt} = \rho \frac{dV}{dt} + V \frac{d\rho}{dt}, \tag{1}$$

where: m – mass, ρ – density, V – a storage volume of receiver and piping.

For a constant volume $V = \text{const}$ of the compressed air pipelines, the left component of the right-side of Equation (1) is omitted, and we obtain:

$$\dot{m} = V \frac{d\rho}{dt}. \tag{2}$$

Equation (2) for the i-th state of the isentropic expansion is written as follows:

$$\dot{m}_i = V_i \frac{d\rho_i}{dt} = \left(\frac{p_i}{p_0}\right)^{-\frac{\kappa-1}{\kappa}} \frac{V_0 \rho_0}{\kappa p_0} \frac{dp_i}{dt} = \left(\frac{dp_i}{p_0}\right)^{-\frac{\kappa-1}{\kappa}} \frac{V_0}{\kappa R T_0} \frac{dp_i}{dt} = \frac{V_i}{\kappa R T_i} \frac{dp_i}{dt}, \tag{3}$$

where: T_0, p_0 – initial absolute values of temperature and pressure, T_i, p_i – actual absolute values of temperature and pressure, V_0, V_i – initial and actual values of volume, R – a specific gas constant, for dry air 287 J/(kg K), κ – a heat capacity ratio.

Based on Equation (3), taking into account the Clapeyron equation for ideal gas, the volume flow rate q_i for i-th state of compressed air in a pneumatic pipeline is written:

$$q_{\mathrm{v}i} = \dot{m}_i / \rho_i = \frac{V_i}{\kappa R T_i \rho_i} \frac{dp_i}{dt} = \frac{V_i}{\kappa p_i} \frac{dp_i}{dt}\,. \tag{4}$$

For a small pressure drop it can be roughly assumed that the flow rate q_i through leak orifices for choked conditions is steady ($q_{\mathrm{v}i} \approx \mathrm{const}$). After integrating both sides of Equation (4) we obtain:

$$\int_0^{t_i} dt = \frac{V_i}{\kappa q_{\mathrm{v}i}} \int_{p_d}^{p_u} \frac{dp}{p}\,, \tag{5}$$

where: p_u, p_d – upstream and downstream absolute pressure values, t_i – a time interval. When the compressor and all air-operated end-use equipment are turned off, the compressed air flow equations in two states, determined from Equation (5), are written as:

– for air leakage without the controlled flow $q_{\mathrm{v}i} = q_L$,

$$\int_0^{t_L} dt = \frac{V_i}{\kappa q_L} \int_{p_{Ld}}^{p_{Lu}} \frac{dp}{p} \quad \Rightarrow \quad t_L = \frac{V_i}{\kappa q_L} \ln\left(\frac{p_{Lu}}{p_{Ld}}\right), \tag{6}$$

– for air leakage with the controlled flow $q_{\mathrm{v}i} = q_L + q_{\mathrm{v}c}$,

$$\int_0^{t_{Lc}} dt = \frac{V_i}{\kappa (q_L + q_{\mathrm{v}c})} \int_{p_{Lcd}}^{p_{Lcu}} \frac{dp}{p} \quad \Rightarrow \quad t_{Lc} = \frac{V_i}{\kappa (q_L + q_{\mathrm{v}c})} \ln\left(\frac{p_{Lcu}}{p_{Lcd}}\right), \tag{7}$$

where: p_{Lu}, p_{Ld} – upstream and downstream absolute pressure values during leakage without the controlled flow, p_{Lcu}, p_{Lcd} – upstream and downstream absolute pressure values during leakage with the controlled flow. t_L – a measurement time during air leakage without the controlled flow, t_{Lc} – a measurement time during air leakage with the controlled flow, q_L – a total air leakage flow rate through the leak point of a pneumatic pipeline, $q_{\mathrm{v}c}$ – an average volumetric air flow rate through the adjustable control unit (measured by a flowmeter).

The conversion of Equations (6) and (7) results in the following formula used to calculate an air leakage flow rate based on the controlled flow in a branch line:

$$q_L = q_{\mathrm{v}c} \frac{\ln\left(\frac{p_{Lu}}{p_{Ld}}\right) t_{Lc}}{\ln\left(\frac{p_{Lcu}}{p_{Lcd}}\right) t_L - \ln\left(\frac{p_{Lu}}{p_{Ld}}\right) t_{Lc}}\,. \tag{8}$$

Then, a practical formula for calculating the total flow rate of leakage in a compressed air system using the indirect method with the controlled flow in a branch line has the form [23]:

$$q_L = K_K K_T\, q_{\mathrm{v}c} \frac{\ln\left(\frac{p_{Lu}}{p_{Ld}}\right) t_{Lc}}{\ln\left(\frac{p_{Lcu}}{p_{Lcd}}\right) t_L - \ln\left(\frac{p_{Lu}}{p_{Ld}}\right) t_{Lc}}\,, \tag{9}$$

where: K_K – a calibration factor dependent on the measurement conditions, K_T – a correction factor dependent on the temperature measurement,

$$K_T = \frac{T_m}{T_N}, \tag{10}$$

where: T_m – temperature of measurement, T_N – temperature at ANR conditions of reference, $T_N = 293.15$ K.

3. New automatic measuring system (AMS)

Finally, a patented automatic measuring system (AMS) for automatic indirect measurement of the leakage flow rate in a pneumatic pipeline was developed [24]. A schematic of the AMS system for indirect measurement of the leakage flow rate connected to a branch of the pneumatic pipeline is shown in Figure 3.

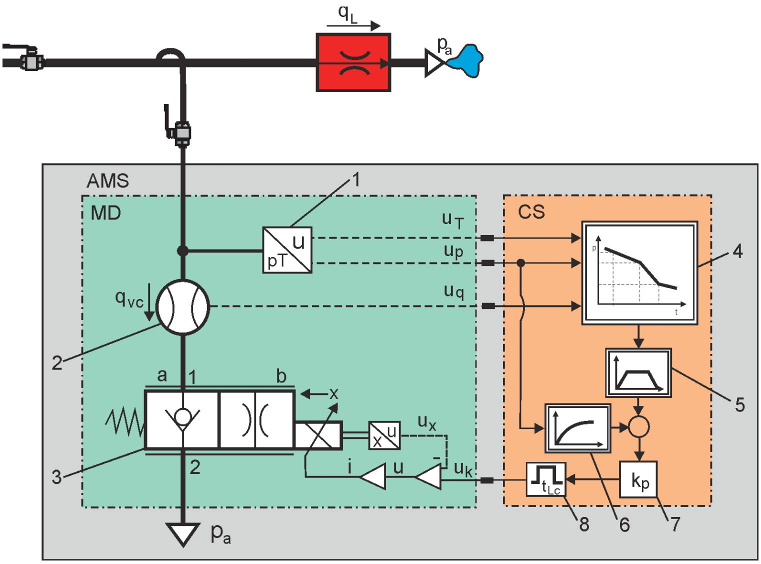

Fig. 3. The schematic diagram of a automatic measurement system for indirect measurement of leakage flow rate on the branch of the pneumatic pipeline: AMS – automatic measuring system, MD – measurement device, CS – control system.

The AMS system consists of a measurement device (MD) and control systems (CSs). The control system CS constitutes the direct control layer and is connected to the measurement device MD. The real-time control system CS generates samples in relation to the speed at which the measured and controlled parameters are processed. The measuring device (MD) comprises a pressure and temperature transducer 1, a thermal flowmeter 2 and a special bifunctional pneumatic 2/2 (2-way, 2-position) proportional controlled valve 3. The control system CS contains a calculation module of leakage 4, a calculation module forming the reference signal 5, a calculation module of the valve flow rate 6, a control unit 7, and a valve-setting unit 8. The control system (CS) is designed to work with the measurement device MD that reads out voltage signals from the pressure and temperature transducer 1 (u_T, u_p) and the thermal flowmeter 2 (u_q). The control system generates also an output voltage signal (u_k) to the 2/2 bifunctional pneumatic proportional control valve 3. The valve-setting unit 8 limits the set signal t_{Lc}. The bifunctional pneumatic proportional control valve 3 of a novel design is shown in Figure 4 [24]. This valve performs two control functions: in the closed position *a* it functions as a shut-off valve, whereas in the open position *b* it functions as a proportional throttle valve. The measurement of leakages by means of the control system CS includes: calibration, measurement without the controlled flow and measurement of the controlled flow.

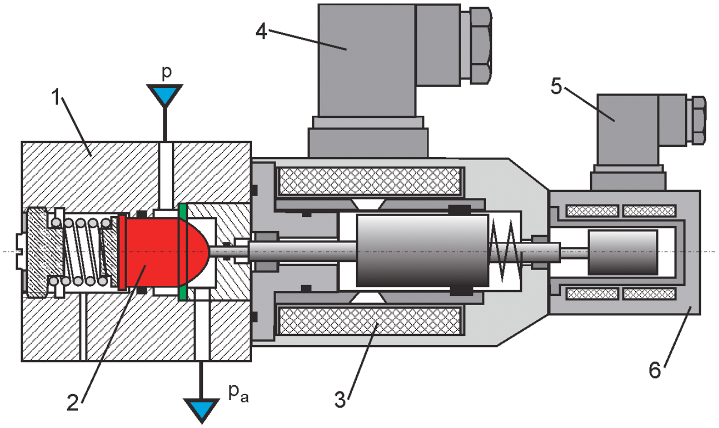

Fig. 4. The view of cross-section of the bifunctional pneumatic control valve: 1 – control unit, 2 – valve spool, 3 – proportional solenoid, 4 – input signal, 5 – feedback signal, 6 – position transducer.

During the measurement path calibration in a constant time t_{Lc}, the pressure drop through valve 3 is defined. On the basis of the measured pressure p in the pipeline, the critical pressure p_{cr} approaching the values for a choked flow in control valve 3 is determined. By measuring the time constant τ of the compressed air discharge from a pneumatic valve a set time t_{Lc} is selected. When the measurements of leakage without the controlled flow are performed, and control valve 3 is closed, module 4 records the upper p_{Lu} and lower p_{Ld} pressure values in t_L, which enables to determine the pressure drop ratio p_{Lu}/p_{Ld} caused by the leakage q_L of compressed air in the pipeline. Then, when the measurements of leakage with the controlled flow are carried out, and control valve 3 is opened, block 4 records the upper p_{Lcu} and lower p_{Lcd} pressure values in t_{Lc}, which enables to determine the pressure drop ratio p_{Lcu}/p_{Lcd} due to the leakage in the pipeline as well as the valve flow to the atmosphere. To carry out the controlled flow, the block forming control unit 7 that generates a voltage of a limited duration t_{Lc} at the control valve 3 input was used. To keep the measurement time for a constant flow rate q_{Lc} through control valve 3, a feedback signal from the valve determines the adjustment error. After the measurements are completed the leakage flow rate q_L is calculated according to Equation (9).

3.1. Determining maximum measurement time t_{Lcm}

The maximum measurement time t_{Lcm} during air leakage with the controlled flow was estimated. For this purpose, Equation (3) of mass flow rate of compressed air through the control valve is written as follows:

$$q_m = \frac{V_i}{\kappa R T_i} \frac{dp_i}{dt}, \tag{11}$$

where: q_m – a mass flow rate through the control valve in the choked condition in kg/s:

$$q_m = C\rho_N p_i \sqrt{\frac{T_N}{T_i}}, \tag{12}$$

where: C – a sonic conductance of the control valve in m^3/(s Pa), ρ_N, T_N – density and temperature values in the standard conditions ANR ($\rho_N = 1.185$ kg/m^3, $T_N = 293.15$ K).

After integrating both sides of Equation (11) and substituting (12), we obtain:

$$\int_0^{t_{Lcm}} dt = \frac{V_i}{C\rho_N \sqrt{\frac{T_N}{T_i}}\kappa R T_i} \int_{p_c}^{p_0} \frac{dp}{p} = \tau \int_{p_c}^{p_0} \frac{dp}{p}, \tag{13}$$

where: p_0 – an inlet pressure, p_c – a critical pressure, t_{Lcm} – a maximum measurement time, τ – a time constant of polytropic air expansion in pipelines:

$$\tau = \frac{V_i}{C\rho_N \sqrt{T_i T_N}\,\kappa R}. \tag{14}$$

After solving the integral (13) we obtain the following formula for the maximum measurement time during air leakage with the controlled flow:

$$t_{Lcm} = \tau \ln\left(\frac{p_0}{p_c}\right). \tag{15}$$

The voltage pulse time t_{Lc} at the control valve 3 must be less than t_{Lcm}.

4. Measurement results

The calibration of the measuring instrument has been carried out so that the test measurements are made within the leakage range. The measurement results can be transferred to a graphical software, such as LabView. To compare the direct and indirect measurement results of leakage flow rate in the tested pneumatic pipeline, a relative error δ_L was calculated according to the equation:

$$\delta_L = \left|\frac{q_L - q_{Lm}}{q_{Lm}}\right| 100\%, \tag{16}$$

where: q_{Lm} – a direct measurement value of leakage flow rate, q_L – an indirect measurement value of leakage flow rate.

An example of measurement results is shown in Table 1.

The automatic measurement device has been tested and two results of flow rate $q_{\mathrm{vc}}(t)$ and pressure drop $p(t)$ are shown in Figure 5.

It is observed that during the transition from the first to the second measuring interval, after the valve has been activated the pressure disturbances take place. The results of measurements of parameters $p(t)$, $q_{\mathrm{vc}}(t)$ and calculations of leakage flow rate q_L for the analysed samples are summarized in Table 2.

Table 1. Measurement results.

No.	**Temperature** T_m**[K]**	**Pressure** p_m**[MPa]**	**Direct measurement of leakage flow rate** q_{Lm} **[m^3/s]**	**Indirect measurement of leakage flow rate** q_L **[m^3/s]**	**Relative error of measurement** δ_L**[%]**
1	313	0.487	0.0000788	0.0000818	3.81
2	314	0.499	0.0000766	0.0000733	4.43
3	315	0.510	0.0000683	0.0000711	4.15
4	313	0.505	0.0000633	0.0000611	3.42
5	312	0.512	0.0000600	0.0000621	3.60

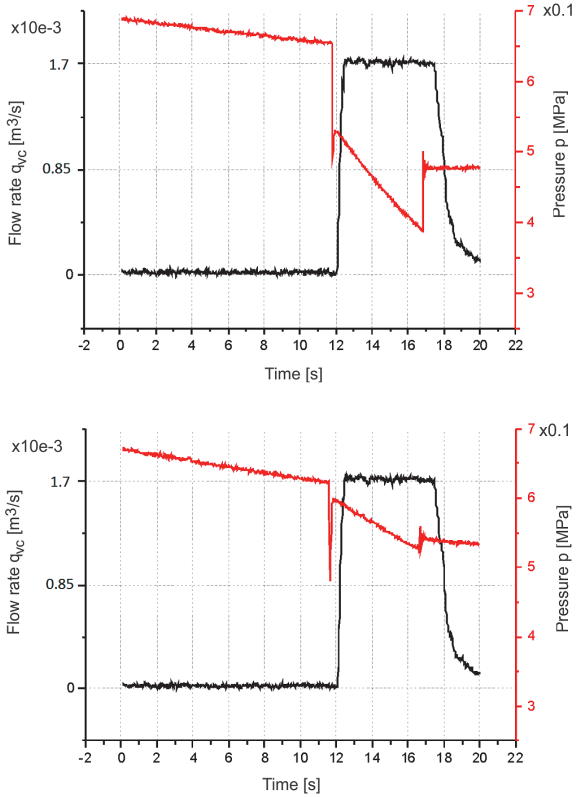

Fig. 5. A sample graph of the measurement results of flow rate $q_{\text{vc}}(t)$ and pressure $p(t)$.

Table 2. The results of measurement tests.

No.	**Temperature** T_m**[K]**	**Pressure** p_{Lu}**[MPa]**	**Time interval** t_L **[s]**	**Pressure** p_{Lcu}**[MPa]**	**Time interval** t_{Lc} **[s]**	**Controlled flow rate** q_{vc} **[m^3/s]**	**Leakage flow rate** q_L **[m^3/s]**
1	314	0.68	8	0.47	2	0.0017	0.0001183
		0.66		0.42			
2	314	0.67	8	0.57	2	0.0017	0.00043
		0.63		0.53			

4.1. Uncertainty of leakage flow rate measurement

The uncertainty of leakage flow rate measurement during the calibration of the measuring instrument was determined. The calculated error in the leakage flow rate q_L depends on the measurement error of every parameter:

$$q_L = f(q_{\mathrm{v}m},\ p_m,\ T_m), \tag{17}$$

where: $q_{\mathrm{v}m}$ – a volume flow rate measured by the thermal flowmeter TSI 4043, p_m, T_m – pressure and temperature values measured by the transducer ATM/T (dual output).

The accuracy of the thermal-mass flowmeter TSI 4043 is $eq_m = \pm 2\%$ of readout ($q_{\mathrm{v}n} = 200\ \mathrm{l/min} = 0.00033\ \mathrm{m^3/s}$), and the accuracy values of the ATM/T pressure and temperature transducer are $ep_m = \pm 0.5\%$ FS ($p_n = 10$ bar $= 1$ MPa) and $eT_m = \pm 1\%/1.5\mathrm{K}$ ($T_n = 373.15$ K), respectively.

The measured volume flow rate $q_{\mathrm{v}m}$ through the valve in the chocked state was transformed from (12):

$$q_{\mathrm{v}m} = C\,p_m\sqrt{\frac{T_N}{T_m}}\,, \tag{18}$$

where in the sonic conductance C is difficult to determine:

$$C = \frac{q_{\mathrm{v}m}}{p_m}\sqrt{\frac{T_m}{T_N}}\,. \tag{19}$$

According to ISO 6358-2 [25], the uncertainty of the sonic conductance C can by calculated by the following equation:

$$\frac{sC}{C} = \sqrt{\left(\frac{sq_{\mathrm{v}m}}{q_{\mathrm{v}n}}\right)^2 + \left(\frac{sp_m}{p_n}\right)^2 + 0.25\left(\frac{sT_m}{T_n}\right)^2} = 0.0268\,, \tag{20}$$

where: $sq_{\mathrm{v}m}$, sp_m, sT_m – experimental standard deviation values of flow rate, pressure and temperature, $q_{\mathrm{v}n}$, p_n, T_n – nominal values of flow rate, pressure and temperature.

To analyse the measurement uncertainty of a flow rate, a method based on the guide to the expression of uncertainty in measurement (GUM) [26] was used. The type B standard uncertainty $u_B(q_{\mathrm{v}m})$ of the average measured flow rate $q_{\mathrm{v}m}$ (18) can be calculated from the law of propagation of uncertainties as the geometric sum of partial differentials:

$$\begin{aligned} u_B(q_{\mathrm{v}m}) &= \sqrt{\left(\frac{\partial q_{\mathrm{v}m}}{\partial C}\right)^2 u^2(C) + \left(\frac{\partial q_{\mathrm{v}m}}{\partial p_m}\right)^2 u^2(p_m) + \left(\frac{\partial q_{\mathrm{v}m}}{\partial T_m}\right)^2 u^2(T_m)} = \\ &= \sqrt{\left(p_m\sqrt{\frac{T_N}{T_m}}\right)^2\left(\frac{\Delta C}{2}\right)^2 + \left(C\sqrt{\frac{T_N}{T_m}}\right)^2\left(\frac{\Delta p_m}{\sqrt{3}}\right)^2 + \left(-\frac{C\,p_m\sqrt{T_N}}{2\sqrt{T_m^3}}\right)^2\left(\frac{\Delta T_m}{\sqrt{3}}\right)^2} \\ &= 1.7293\ 10^{-6}\ \ \mathrm{m^3/s}\,, \end{aligned} \tag{21}$$

where: $u^2(C)$ – variance of the sonic conductance estimated on the assumption of the normal probability distribution, $u^2(p_m)$, $u^2(T_m)$ – variance values of the pressure and temperature measurements as resulting from the processing error at p/T transmitters determined on the assumption of the rectangular probability distribution.

Based on the result of the uncertainty (21), the relative standard uncertainty of the flow rate was determined:

$$\delta q_{\mathrm{v}m} = \frac{u_B(q_{\mathrm{v}m})}{q_{\mathrm{v}m}}\ 100\% = 2.5\%. \tag{22}$$

5. Conclusions

A new method of indirect measurement of the flow rate in a compressed air pipeline system was developed by the authors. The method enables to measure the controlled leakage in a branch line and was used to construct automatic measuring systems for the compressed air systems (CAS) audit. Based on the authors' patent application an automatic measuring system (AMS) for measurement of the leakage flow rate in industrial compressed air piping systems was developed. The AMS consists of a measurement device (MD) and control systems (CS). In the measurement device (MD) a novel bifunctional pneumatic proportional control valve was used. The AMS system for estimation of the air leakage flow rate in pneumatic pipeline systems was designed, constructed and tested. The device was used to test the accuracy of the measurement method and to compare the direct and indirect results of the leakage flow rate with those obtained for a standard pneumatic pipeline. After the direct and indirect measurement results of leakage flow rate in the tested pneumatic pipeline had been compared, the relative error δ_L was calculated. Considering the average values of measured parameters, the relative standard uncertainty of the flow rate is equal to $\delta q_{vm} = 2.5\%$. After performing measurements for the same initial conditions it was found that the relative error of flow measurement did not exceed 5%, which is acceptable in a CAS audit. After testing the AMS system the factors that influence the accuracy of measurements were either eliminated or minimized, e.g. the pressure pulsation after excessive control of the directional control valve and maintaining the choked flow through the throttle valve. If the pressure decreases rapidly and the leakage flow rate is huge, temperature has to be considered. In the proposed measurement method of compressed air leakage the volume V of pipeline is not taken into account, which is not the case in the traditional methods of the compressed air leakage measurement. The branch connections of measurement equipment do not require pipeline disassembly or modification. The AMS system, as a portable device, can be used to measure leakages at any time and in any place of a compressed air pipeline, that is, the main pipeline, a distribution line and a connection line. The AMS system will be used in the new research project "Mobile laboratory of compressed air systems' audit", which seeks to implement a mobile laboratory for auditing industry compressed air systems.

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