Automatic device for indirect measurement of leakage flow rate in compressed air pipeline

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Abstract. The new measurement method of compressed air leakage flow rate in compressed air pipeline is proposed. In this method, the automatic measuring device is connected to a branch of the pipeline. The measuring device can be used to measure compressed air leakage in any place of compressed air pipeline: in main line, distribution line and connection line. The proposed measurement methods of compressed air leakage in pipeline are independent of receiver and compressor parameters, which is not the case with traditional method measuring leaks by emptying the receiver.

1. Introduction

The purpose of the compressed air piping system is to deliver compressed air to the points of usage. The compressed air needs to be delivered with enough volume, appropriate quality, and pressure to properly power the components that use the compressed air. Compressed air is costly to manufacture. A poorly designed compressed air system can increase energy costs, promote equipment failure, reduce production efficiencies, and increase maintenance requirements. Compressed air is one of the most expensive utilities in an industrial facility. The main causes of energy waste are leaks, pressure drops, over-pressurization, misuse of jets and poor compressor management [7], [8]. Also the leakage is usually the largest source of energy waste associated with compressed air usage. Table 1 provides an indication of the cost of leaks.

Table 1. Cost of compressed air leaks [1].

| Equivalent hole diameter (mm) | Leakage flow air lost per leak (l/s) | Loss of energy (kWh) | Cost of air leak (€) |
|------------------------------|-------------------------------------|----------------------|---------------------|
|                              | 6 bar | 12 bar | 6 bar | 12 bar | 6 bar | 12 bar |
| 1                            | 1.2   | 1.8    | 0.3   | 1.0    | 144   | 480    |
| 3                            | 11.1  | 20.8   | 3.1   | 12.7   | 1,488 | 6,096  |
| 5                            | 30.9  | 58.5   | 8.3   | 33.7   | 3,984 | 16,176 |
| 10                           | 123.8 | 235.2  | 33.0  | 132.0  | 15,840| 63,360 |

While designing energy saving compressed air systems various methods are applied to reduce energy losses and minimize energy consumption. Compressed air system maintenance is particularly important to avoid excessive loss through leaks:
• Leaks not only waste energy but also cause pressure drops that adversely affect the operation of air-using equipment and tools.
• Leaks are responsible for considerable waste, frequently up to 40 to 50% of consumption.
• 15% leakage is considered to be an acceptable rate.

Leakage can occur at a number of points in a compressed air pneumatic pipeline system. Some of these are listed below: branch line connection, rubber hose, automatic drain trap, quick coupler, desiccant filter, isolating valve, filter/regulator/lubricator assembly, control valve, filter/regulator/coalescent filter assembly, coil hose, pressure regulator, pneumatic cylinder.

There are many various ways of determining or measuring the quantity of compressed air leaking out [4-6]. For compressors that have on/off controls or load/unload controls, there is an easy way to estimate the amount of leakage in the system. This method involves starting the compressor when there are no demands on the system (when all the air-operated end-use equipment is turned off). A number of measurements are taken to determine the average time it takes to load and unload the compressor. The compressor will load and unload because the air leaks will cause the compressor to cycle on and off as the pressure drops due to air escaping through the leaks. Leakage can be estimated in compressed air pipelines by emptying the compressed air receiver. This method requires an estimate of total system volume, including any downstream secondary air receivers, air mains and piping. The system is started and brought to the normal operating pressure (p1). Measurements should then be taken of the time (t) it takes for the system to drop to a lower pressure (p2), which should be a point equal to about one-half the operating pressure.

2. Determine the of leakage flow rate by indirect method

The new measurement method of compressed air leakage flow rate in compressed air pipeline based on the controlled flow in branch line is proposed. In this method, the automatic measuring device is connected to a branch of the pipeline. The measurement method consists in determining the relation between air leakage flow rate in pipeline and the controlled air flow rate through control valve. Compressed air leakage flow rate in pipeline is calculated on the basis of pressure ratio measurements in two time periods - during leakage with or without the controlled flow in branch line. The proposed measurement methods of compressed air leakage in pipeline are independent of receiver and compressor parameters, which is not the case with traditional method measuring leaks by emptying the receiver. Branch connections of measurement device in compressed air pipeline do not require pipeline disassembly or modification. The methods can be used to measure compressed air leakage in any place of compressed air pipeline: in main line, distribution line and connection line.

A new measurement method of compressed air leakage in pipelines based on the controlled flow consists in determining the relation between air leakage flow rate qL in leak point of pipeline and the controlled air flow rate qvc directly measured by flow meter in branch line [3]. Practical formula for calculating the total volume leakage rate in the compressed air system using the indirect method with controlled flow in branch line then has the form [4]:

\[
q_L = K K_T q_{vc} \frac{\ln \left( \frac{P_{Lu}}{P_{Ld}} \right) t_{Lc}}{\ln \left( \frac{P_{Lcu}}{P_{Lcd}} \right) t_{Lc} - \ln \left( \frac{P_{Lcu}}{P_{Lcd}} \right) t_{Lc}}
\]

(1)

where:
qL – total leakage volume flow rate by the leak points in pipeline,
PLu, Plu – upstream and downstream absolute pressure during leakage without the controlled flow,
tL – measuring time during air leakage without the controlled flow,
PLu, Pld – upstream and downstream absolute pressure during leakage with the controlled flow,
\[ t_{Lc} \] - measuring time during air leakage with the controlled flow,

\[ q_{vc} \] - volumetric air flow rate measured by flow meter,

\[ K_K \] - calibration factor dependent on the measurement conditions,

\[ K_T \] - correction factor dependent on the temperature measurement,

\[ K_T = \frac{T_i}{T_N} \]  \hspace{1cm} \text{(2)}

where:

\[ T_i \] - temperature recorded during the measurement,

\[ T_N \] - temperature at conditions of reference ANR.

With a new indirect method compressed air leakage is estimated by measurement of pressure ratio in a two time intervals (Figure 1):

1. For the air leakage without the controlled flow the pressure drop ratio \( \frac{dp_{L}i}{dp_{L}d} \) in time intervals \( t_{L} \) is measured.

2. For the air leakage with the controlled flow the pressure drop ratio \( \frac{dp_{Lc}u}{dp_{Lc}d} \) in time intervals \( t_{Lc} \) is measured.

**Figure 1.** Pressure change in two time intervals in compressed air pipelines during the air leakage measurement based on the controlled flow in branch line.

The diagram of the air leakage measuring circuit in compressed air pipelines based on the controlled flow in branch line is shown in Figure 2. The measurement system MS is designed to work with a measuring device MD that reads the voltage input signals of the measuring transducer 1 \( (u_T, u_p) \) and the thermal flow meter 2 \( (u_q) \), and also generates a voltage output signal \( (u_k) \) to the proportional flow control 2/2 valve 3. The measuring system MS consists of a calculation block of leakage 4, a block forming the reference signal 5 a calculation block of flow rate 6, the feedback block 7, the controller block 8, and a block 9 that limits the set signal \( t_{Lc} \). The way of measuring leakages that uses the measuring system MS includes: calibration, measurement without controlled flow and measurement of controlled flow. During the calibration of the measurement path of constant time of \( t_{Lc} \) of polytropic pressure drop through the control valve 3 is defined. On the basis of the measurement the pressure \( p_i \) in the pipeline, the critical pressure \( p_{cr} \) to the limit range of critical flow is determined. It is reasonable to agree the critical flow in the throttle valve 3, because the air flows into the atmosphere. By measuring the time constant \( \tau \), the pressure \( p_i \) in the pneumatic system and the critical pressure \( p_{cr} \), selected measurement time \( t_{Lc} \) controlled. Block 6 determines the flow rate \( q_{Lc} \) through the control valve 3 on the base of \( p_i \) measurement. It is possible to determine the flow rate \( q_{Lc} \) through the control valve 3 on the base of the measurement using the thermal flow meter 2.
Figure 2. The schematic diagram of a measurement system connection to branch of compressed air pipeline: DL – distribution line, BL – branch line, BV – ball valve, LP – leak point, MD - measuring device, MS - measuring system, 1 - measuring transducer p/T, 2 - thermal flow meter, 3 - proportional flow control valve, 4 - calculation block of leakage, 5 - block forming the reference signal, 6 - calculation block of flow rate, 7 - feedback block, 8 - controller block, 9 - set signal block.

During measurements leakage without the controlled flow, when the control valve 3 is closed, the block 4 record the pressure \( p_{Lu} \) upper and lower pressure \( p_{Ld} \) during \( t_L \), and on this basis the pressure drop ratio \( \ln(p_{Lu}/p_{Ld}) \) is determined caused by the leakage \( q_L \) of compressed air in the pipeline. Then during measurements leakage with the controlled flow, when the control valve 3 is opened, the block 4 record the pressure \( p_{Lcu} \) upper and lower pressure \( p_{Lcd} \) during \( t_{Lc} \), and on this basis pressure drop ratio \( \ln(p_{Lcu}/p_{Lcd}) \) is determined due to leakage in the pipeline as well as the flow to the atmosphere. To carry out controlled flow, there was a block forming the reference signal 5, that generates a voltage of limited duration at the control valve input 3. To keep the measuring time a constant flow rate \( q_{Le} \) by the control valve 3, feedback block 7 determines the adjustment error, the controller 8 generates a voltage signal limited to the value of by the block 9. Time pulse voltage into the control valve 3 is determined in the range of \( t_{Le} = 5 - 50 \) s.

3. Test of automatic measurement device

The view of portable compact measurement device type LT-I 200 for automatic measurement of leakage flow rate in compressed air pipeline is shown in Figure 3. This measuring procedure makes it possible to measure the determination of leakage flow rate in the test pipeline in a fully automatic way.

Standard features:
- automatic measurement of the leakage flow rate according to dedicated calculation procedure,
- measurement of the air pressure \( p(t) \) to 0.8 MPa (8 bar),
- testing of pressure drops \( \Delta p(t) \),
- measurement of volumetric flow rate of compressed air to 200 l/min.
Advanced features:

- compact device size 330x230x180 mm,
- integrated colour touch display WVGA (800x480), with a high-resolution resistive touch screen (16-bit colours),
- dual 10/100 Ethernet for Factory and World-wide Networking - supporting Modbus/TCP Master/Slave, FTP and HTTP,
- two RS232/RS-485 termination,
- USB 2.0 FLASH drive support - transfer files between the internal micro SD and the USB flash drive, USB Port for easy programming and application loading,
- 1MB memory, 32GB flash memory storage,
- power 230 V AC (24-30 VDC).

The device is configured with membrane keyboard and touch screen 1 on the front panel. The touch screen device has the basic functions for measuring the leakage in compressed air systems: F1 - measuring the flow rate, F2 - measuring the pressure, F3 - measuring the leakage in the pipeline. Pneumatic connection 2 allows direct measurement of leakage flow rate of compressed air in pipeline. Connection 3 is used for automatic measurement of the indirect method of leakage flow rate of compressed air in pipeline. Pneumatic control valve 5 is used to determine the controlled leakage flow rate \( q_v \). This measurement instrument after introducing the initial operating parameters such as: times \( t_1, t_{Lc} \), the intensity of the controlled leakage flow rate \( q_v \) performs automatic procedure for measuring and computing. As a result, we obtain automatic measurement the value of leakage flow rate \( q_L \) in compressed air pipeline.

![Figure 3. View of the device type LT-I 200 for automatic measurement of leakage flow rate in compressed air pipeline: 1 – touch panel, 2 - pneumatic connector for direct measurements of the air flow rate, 3 - pneumatic connector for indirect measurements of the leakage flow rate, 4 - output of pneumatic line, 5 - control valve.](image)

After testing the portable measurement device type LT-I 200 two example of the measurement results of flow rate \( q_v(t) \) and pressure drop \( p(t) \) on graph Figure 4 is show. During the measurements it was observed that after the operation of control valve, at the transition from the first to the second measuring interval, the pressure disturbances take place. Panel of the LT-I 200 device display measurement results of pressure \( p \) change in time intervals (according to Figure 1) and flow rate \( q_{vc} \), and also calculation results of air leakage flow rate \( q_{Lc} \) in compressed air pipeline. After completing the measurements parameters the leakage flow rate \( q_L \) was calculated automatically according to Equation (1).
Figure 4. Graph of the measurement results of flow rate $q_v(t)$ and pressure drop $p(t)$.

The results of the measurements of parameters $p(t)$, $q_v(t)$ and calculations of leakage flow rate $q_L$ for the analyzed example are summarized in Table 2.

**Table 2.** The results of the measurements and calculations.

| Ex. | Pressure $p_{Lu}$ [bar] | Time interval $t_L$ [s] | Pressure $p_{Lcu}$ [bar] | Time interval $t_{Lc}$ [s] | Controlled flow rate $q_n$ [l/min] | Leakage flow rate $q_L$ [l/min] |
|-----|-------------------------|------------------------|--------------------------|---------------------------|-----------------------------------|-------------------------------|
| 1.  | 6.8                     | 8                      | 4.7                      | 2                         | 100                               | 7.1                           |
|     | 6.6                     |                         | 4.2                      |                           |                                   |                               |
| 2.  | 6.7                     | 8                      | 5.7                      | 2                         | 100                               | 26                            |
|     | 6.3                     |                         | 5.3                      |                           |                                   |                               |
The demonstrative portable measurement device type LT-I 200 was honoured the medal for the innovative product on the 8th Exhibition of Pneumatics, Hydraulics, Drives and Controls PNEUMATICON’2015 in Kielce Trade Fairs (Figure 5).

![Image](HERVICON+PUMPS-2017) IOP Publishing
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Figure 5. The demonstrative portable measurement device type LT-I 200 in test pipeline.

4. Conclusions
The paper deals with the new automatic indirect measurement method of air leakage flow rate in compressed air system. Compressed air leakage flow rate in the pipeline is calculated automatically on the basis of pressure drop ratio measurements in two time periods - during leakage with and without the controlled flow. A portable measurement device for automatic measurement of leakage flow rate in compressed air pipeline is presented. With the use of this method, the leakages might be measured at any time and in any place of the pipeline: in the main pipeline, distribution line or connecting line the receivers (machines, equipment, tools).

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