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Automation of the Measurement Process of the Parameters of the Sensitive Elements of the Gas Flow Rate Sensors

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Abstract—The study of the characteristics and errors of sensors is as difficult as designing and manufacturing them. The operation of sensors needs to be accurately studied in order to correct the design of sensor models accurately carry out the initial calibration of the ready-made sensors. The stand for investigating the sensitive elements of the gas flow rate sensors, in which the hot-wire anemometric and the calorimetric measurement modes are used, is described. It is shown that the facilities of the automatic control of the gas flow rate and dynamic recording of the measurement results make it possible to process and record the results in millisecond time intervals, investigate the operation of sensitive elements in the pulse mode, and simulate the operation of a microprocessor-based signal processing circuit at the hardware and software levels. The proposed stand makes it possible to take measurements at different gas temperatures and ambient temperatures ranging from –40 to 60°C and control the atmospheric pressure, and it makes it possible to specify the gas flow rate within 0–119 L/min. The considered stand is designed to develop compact sensors of the natural gas flow rate, which could replace the diaphragm flowmeters of the G1.6, G2.5, and G4 series. The stand makes it possible to carry out the comprehensive measurements of sensors in one place and considerably reduces the time of testing the developed converters.

Keywords: automated stand, MEMS, gas flow rate, flowmeter

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INTRODUCTION

The diaphragm flowmeters of the G1.6, G2.5, and G4 series [1], which are commonly used to measure the amount of gas consumed in domestic and industrial objectives have relatively large dimensions, which limit their application. The proposed stand is designed for the research and development of compact sensors of the natural gas flow rate, which is capable of replacing the flowmeters.

The MEMS-based thermal primary converters serve as the foundation for the development of compact sensors (meters) of the gas flow rate. Unlike the flowmeters, they can accurately measure the gas mass flow rate, they are small and highly reliable, they do not have movable parts, they can simultaneously measure several parameters of the gas flow, and they have low production costs due to their group treatment. However, they require the power supply of a heater and measuring circuits and are characterized by a relatively narrow range of gas flow to be measured. The dynamic operation mode of the converter when heating is carried out with short current pulses of a specific pulse ratio can reduce energy consumption.

DESCRIPTION OF SPECIMENS

A silicon chip, the topology of which is shown in Fig. 1, is a specimen of MEMS-based converters. The methods of arranging a specimen in the gas flow and some investigation results are presented in [2].

The MEMS-based converters are measured in two modes: the calorimetric mode and hot-wire anemometric mode. The calorimetric mode of the flow rate measurement is implemented if the current pulse is fed to the heater. The magnitude of the flow velocity is defined by the temperature difference of measuring thermal resistors (see Fig. 1). The hot-wire anemometer mode records the temperature drop of the heater due to the heat, which is removed with the gas flow, depending on its velocity [3–5]. The measuring thermal resistors can also be used as heaters [6].

STAND DESCRIPTION

The automated stand for the research of sensitive elements is designed to solve the problem of optimizing the structure of MEMS-based converters, to develop the circuits of the preliminary analog signal processing of the sensitive element and the algorithms

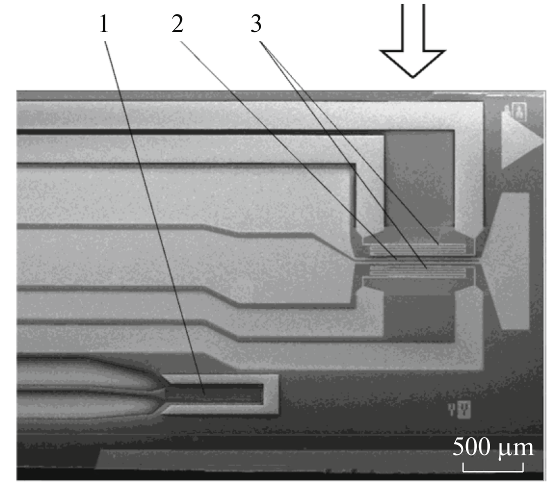

Fig. 1. Sensitive element topology (MEMS converter) of the gas flow rate meter: (*1*) thermal resistor of environment control; (*2*) heater; (*3*) two thermal resistors.

of their subsequent digital processing with the meter. A distinctive feature of the stand is its full automation of the study of heat exchange processes and the ability to automatically record the results to a file in millisecond time intervals. For this, in addition to a pneumatic system, the stand is equipped with an instrumental industrial PC with the devices of digital and analog input/output, and with software written in the LabVIEW environment. The set of special hardware matchers ensures coupling a computer with the MEMS-based converter. The matchers form the computer-controlled continuous and pulse power supply of the thermal resistors of the converter and match (in terms of the level) the signals taken from them with the facilities of the analog input. The pneumatic circuit of the stand with an indication of the controlled and monitored signals is shown in Fig. 2.

The compressed air (gas simulator) is fed through receiver RSV, dehumidifier DRY, and reducer RD into two installed in-parallel gas flow rate regulators RRG1 and RRG2 produced by Massflow. They are controlled by a computer with the control analog signals au_RRG1 and au_RRG2 and ensure the gas supply up to 5 L/min and up to 117 L/min, respectively. The actual gas flow rate is controlled by analog control signals ac_RRG1 and ac_RRG2. These regulators are certified in Russia as measurement instrumentation and have a relative error of not more than (±0.5 + 0.1)% of the scale. Two in-parallel regulators are used to increase the accuracy of the assignment and measurement of the flow within the region of low gas flow rates. The gas flow rate regulators make it possible to automatically control the gas flow rate up to 123 L/min (ANR), which covers with a margin the nominal flow ranges of the G1–G4 series of meters.

In order to investigate the meters with a fast gas flow rate, manual control of the flow is provided. Moreover, the ball valve KV3 is opened and the adjust-

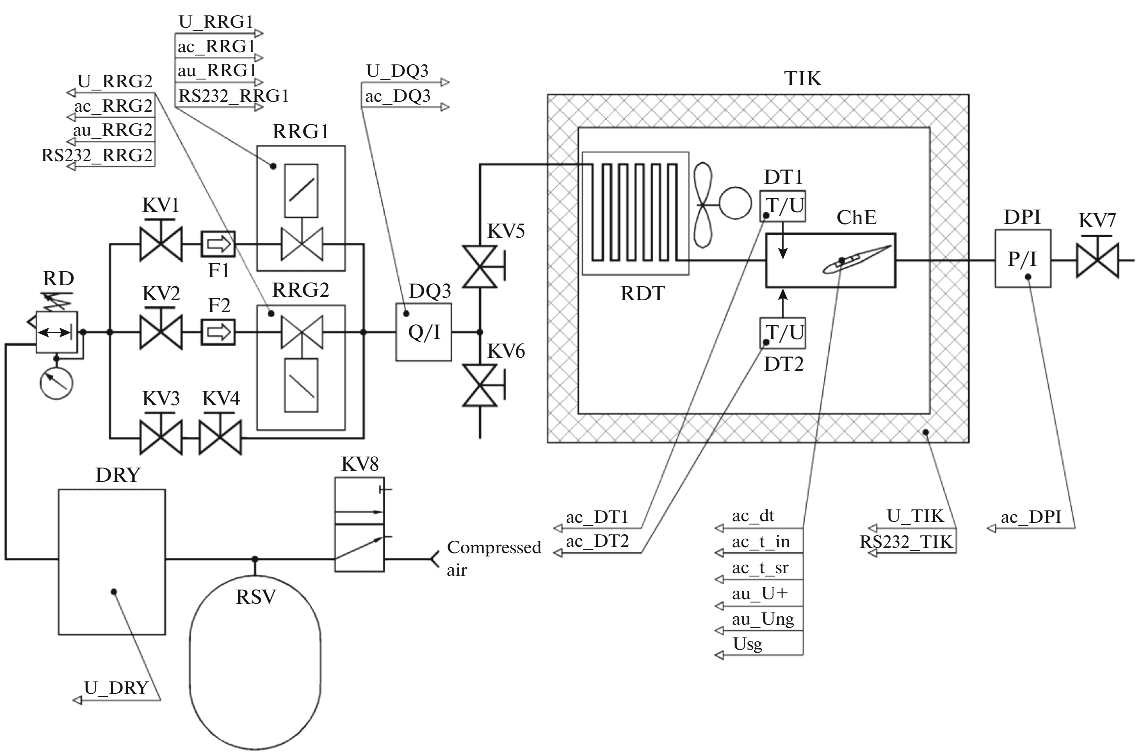

Fig. 2. Pneumatic circuit of the stand.

ment is made by valve KV4. The gas flow rate is controlled by the flowmeter DQ3 of the FMT400-VTS-DN25 type produced by ABB. In this case, the maximum gas flow rate will be up to 120 L/min. Then the flow is bifurcated. Through valve KV5 it feeds into radiator RDT located in the temperature test chamber of the T-70/100 type, then it feeds into the measuring channel in which the MEMS-based converter ChE being tested is installed on a special wing [2]. The temperature of the gas flow and of the case of the measuring channel is controlled with the thermoelectric converters of the DTPL 021-0.5/1.5 type and normalizing converters of the NTP-1.00.1.1 type (DT1 and DT2, respectively) manufactured by OVEN. The output signals ac_DT1 and ac_DT2 (current signals within 4–20 mA) ensure that the error does not exceed ±0.5°C within the specified range from –40 to +60°C.

As the investigations have revealed, radiator RDT and the fan, which is part of the chamber, provide the gas flow temperature setting from the normal temperature (+20°C) to the minimum (–40°C) or maximum (+60°C) temperature for not more than one hour over the whole range of automatically set flows. Moreover, the preset chamber temperature, its actual temperature, which is measured by a built-in sensor, and the temperature recorded using the additional thermal resistor converter placed in the chamber (not shown in Fig. 2), as well as with sensors DT1 and DT2, do not differ by more than by 1°C. The overpressure meter DPI is arranged at the outlet of the gas flow, generating the current signal ac_DPI, which is recorded by the informational and control system of the stand. Valve KV7 is used to manually control the overpressure inside the measuring channel.

The MEMS-based converter ChE being studied is connected through hardware matchers with the information and control system of the stand with signals ac_dt, ac_t_In and ac_t_sr. They record the temperature difference of the thermal resistors, as well as the temperature of the heater and of the chip. The analog command signals au_U+ and au_Ung control the currents of the thermal resistor and heater of the MEMS-based converter, while the voltage Usg is used to form these currents. The external auxiliary devices for the thermal stabilization of the gas flow when the gas flow rates exceed 123 L/min (ANR) (not shown in Fig. 2) are connected with valve KV6.

The foundation of the control system of the stand is the station of the technological control of the IPC-SYS2-1-A5 model (WS computing station) produced by Fastwel, which contains the circuit board of the MOXA CP-118U type to create up to eight duplex channels of the RS-232 type, the circuit board of the analog output of the PCI-1720U-AE type, the multifunction input/output board of the PCI-1741S-AE type, and the circuit board of relay outputs of the PCL-735 AE type. One of the RS-232 channels connects the computing station with the test chamber TIK and makes it possible to remotely control it. Two channels are used to remotely adjust the gas flow rate regulators RRG1 and RRG 2 (see Fig. 2). The RS-232_VM channel is intended for communication with the universal voltmeter of the GW Instek GDM-8246/RS type, which makes it possible to additionally check the control and monitoring channels of the station. The circuit board of the analog output of the PCI-1720U-AE type produced by Advantech contains four 12-bit channels of the digital-to-analog converter and generates the analog control signals which are fed to the RRG (au_RRG1, au_RRG2) and the matcher of the MEMS-based converter (au_U+au_Ung). The multifunction circuit board of thew PCI-1741S-AE type produced by the same company, in addition to 16 channels of analog monitoring and one channel of analog control, contains 16 channels of discrete control and discrete monitoring. In the informational and control system of the stand only 9 of the 16 channels of analog monitoring are used. It uses 16-bit conversion and the digitization frequency is up to 200 kHz. The circuit board of the relay outputs of the PCL-735 type is used to remotely open and close the built-in valves of the gas flow rate regulators (not shown in Figs. 2 and 3).

The stand's software is developed in the LabVIEW environment. For writing it, the basic Advantech drivers, which are supplied with the PCI-1720, PCI-1741, and PCL-735 circuit boards, are used. In the analog-to-digital conversion, a duration of 50 μs turns out to be sufficient; therefore the drivers with software detection of the end of the conversion are used. The library of devices was created to structure and unify the software development for operation with different matchers, with gas flow rate regulators, and other elements of the stand. The results of the software operation are written in the standardized text files, which are opened directly in Excel.

Figure 3 shows the screenshot of the test program of the sensitive element, combining the hot-wire anemometric mode and the calorimetric mode of the flow rate measurement, which makes it possible to extend the measuring range. Moreover, the heater located in the center of membrane (see Fig. 1) is not used. The thermal resistors arranged sequentially over the flow are used as the heater, on which the temperature difference and the temperature drop of the thermal resistor–heater placed first in the flow are measured.

The operator enters the designations of the sensitive elements of the MEMS-based converter. All of them are previously measured and the resistance of thermal resistors R_InOut, the resistance of the environment R_sr, and the coefficient of the temperature resistance are recorded in the database. The measuring channels of the PCI-1741 circuit board are adjusted automatically and the operator merely visually controls the adjustment of Config Ch1 and Config Ch2 (see Fig. 3).

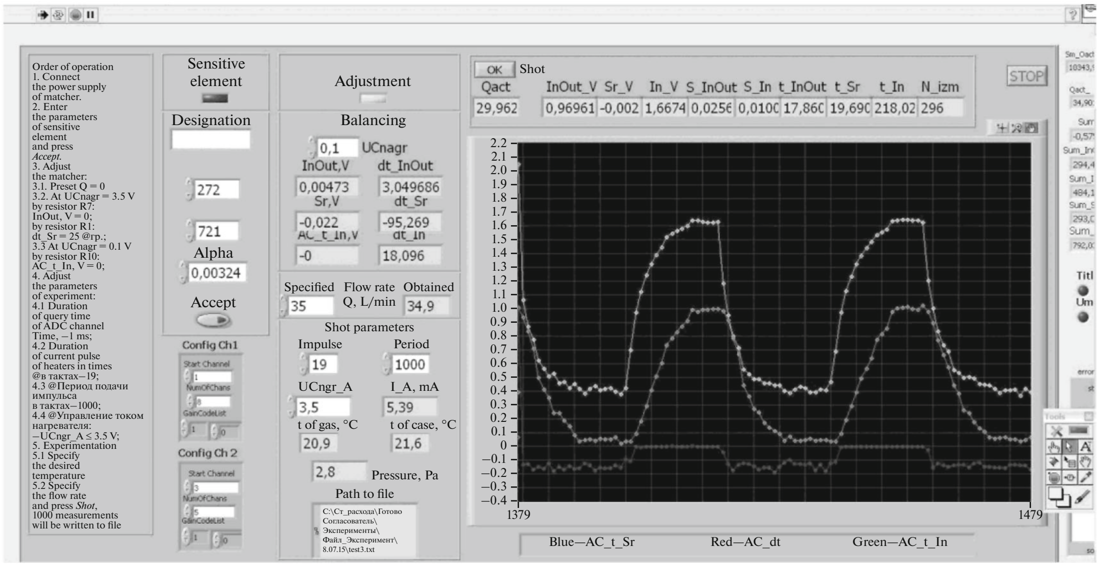

Fig. 3. Screenshot of research program of MEMS-based converter combining the calorimetric and the thermo-anemometric methods of measurement.

Balancing is carried out once under the normal temperature (20°C). After balancing, the parameters of the shot of measurements are set. The temperature shot contains 1000 measurements at each of the gas flow rates set further. The period, the pulse duration, and the control voltage UCngr_A defining the pulse current of the heater–resistor I_A, mA are preset in advance.

When clicking the "Shot" button, the shot photograph is carried out; moreover, the software scans the current pulses which are fed to the heater. Figure 3 displays the signal which is read from the resistor of the environment AC_t_Sr (blue), the signal of the temperature difference AC_dt (red), and the signal from the resistor–heater AC_t_In (green). The oscillograms are synchronized by the current pulse with a duration of 19 μs, after the completion of which the cooling of heater is fixed for 21 μs. The duration of the transition process when applying the pulse to the heater of the sensitive element under study does not exceed 11–12 μs, 19 μs is sufficient to record the steady-state temperature pulse, and the heater cools on the membrane for 13–15 μs.

The program registers the version, the date, the test time, the designation of the MEMS-based converter and its parameters, and the following parameters of the temperature shot: the temperature of gas t_g and of the converter channel t_k; the overpressure in the channel P_g; the heater current I_ng; and the duration of the pulse and of the cycle. The test of the MEMS-based converter is recorded at different gas flow rates, one row for the set flow rate is formed for 2 min. Moreover, 1000 measurements are conducted and the average actual flow rate Qact and the signals from the temperature difference of the thermal resistors InOut, as well as from the thermal resistors of environment Sr and heater In, are recorded. Then the standard deviations of the parameters and the design values of the temperatures corresponding to the measured signals from the thermal resistors are recorded. Photographing the full temperature shot for 10 different flow rates takes about 25 min.

The set of temperature shots taken at various temperatures makes it possible to study the parameters of the sensitive element depending on the gas temperature to be measured. Figure 4 graphically illustrates the processing results of the temperature shots taken at –40, 0, 20, and 50°C.

The flow temperature significantly influences both the temperature difference of the thermal resistors-heaters t_InOut and the temperature drop of the heater. It is seen from Fig. 4 that when changing the gas temperature by 90°C (from –40 to +50°C) a relative error of about 35% arises. To reduce the temperature errors, hardware or algorithmic thermal compensation of the signal of the MEMS-based converter should be used.

Apart from the research of the dependences of the parameters of the thermal resistors of MEMS-based converters on the flow, on the temperature, and on the gas pressure, the stand makes it possible to prototype the flow rate meters and refine the circuits of analog preprocessing of the converter signals and the algorithms of their subsequent digital processing. Figure 5 shows the screenshot of the program which simulates the meter's operation that uses only the calorimetric mode of measurement of the gas flow rate in the range up to 42 L/min.

The analog circuit of the primary processing of the signal of the sensitive element of the meter is simple.

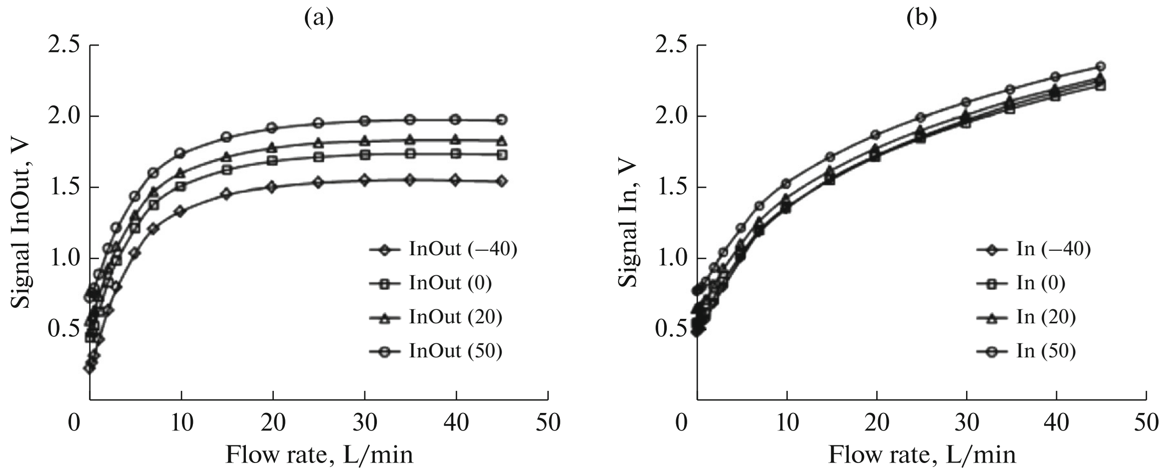

Fig. 4. Dependence of the signal of temperature difference InOut (a) and the signal of heater's temperature drop In (b) on the gas flow rate in different ambient temperatures.

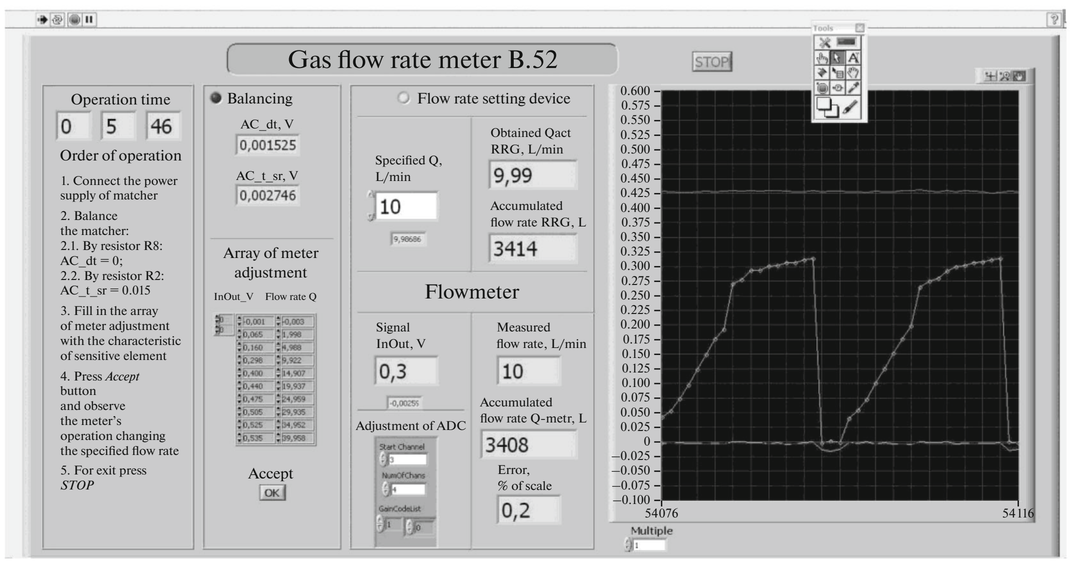

Fig. 5. Screenshot of the flow meter's simulation program with MEMS transducer.

First the analog signal processing circuit is balanced in the pulsed at the zero flow rate. In order to calculate the flow rate, depending on the drop in the temperature of the InOut resistors, the approximation of the dependences taken at the automated stand with a cubic spline is used. For a MEMS-based converter over the test shot, a two-dimensional array of the meter's adjustment is formed (see Fig. 5), which is then entered into the program of the simulator. After pressing the ACCEPT button, the test starts; during the test, we can change the preset flow rate (the analog control signal at RRG). Moreover, the actual flow rate (the analog control signal from RRG) is integrated per second, summarizing the accumulated flow rate. Simultaneously the flow rate computed by the spline table of the MEMS-based converter is measured, processed, and summed. The accumulated flow rates of the signal from the RRG and converter are compared, and the relative error is calculated (in %) with respect to the accumulated flow rate from the RRG.

ANALYSIS OF THE OBTAINED RESULTS

In the range of 10 to 15 L/min, the calorimetric measurement mode gives good results. The sensitivity threshold is 0.1 L/min, the errors with respect to the RRG-based meter do not exceed 1%. However, the errors at the flow rates faster than 20–25 L/min exceed the normative values specified with the standard [1] for a meter of the G1 size standard.

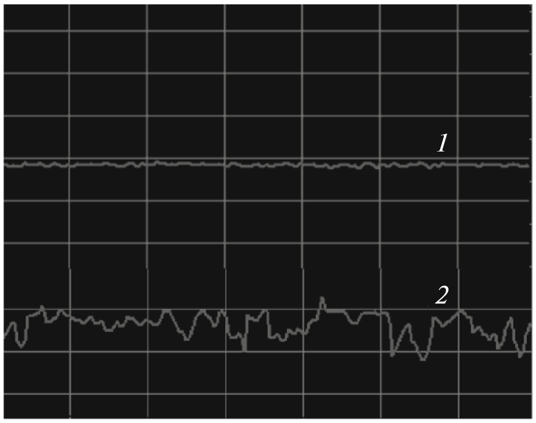

Fig. 6. Oscillograms of the signal of temperature difference at resistors InOut at different flow rates: (*1*) 2 L/min; (*2*) 20 L/min.

We can extend the measurement range of the flow of a MEMS-based converter, if in order to measure the low flows, we apply the calorimetric mode, in which the temperature difference between the thermal resistors connected in-series over the gas flow is the flow indicator. For large flows it is advisable to use the hot-wire anemometric mode, in which the gas flow is related to the temperature drop of heater Δ t_In. For the converter under study, if the flow is less than 10 L/min, the calorimetric mode should be used, and if the flow exceeds 10 L/min, the hot-wire anemometric mode should be used; moreover, the upper limit of the measurement of flow rate exceeds the maximum flow of the G4 size standard.

If the flow rate exceeds 10 L/min, noticeable distortions appear in the signals registering the temperature difference of the InOut resistors and the temperature drop at the input resistor Δt_In. Figure 6 shows the signals from the bridge of InOut resistors during the gas flow rates of 2 and 20 L/min. Obviously, the membrane vibrations of the MEMS-based converter are the cause of these distortions. The period of signal digitization InOut is 1 ms, and the frequency of the natural vibrations of the membrane is 30 kHz. This explains the fact that the signal is of the form of a polygonal line.

The membrane's vibrations arising if the gas flow rate exceeds 10 L/min noticeably increase the random measurement errors during the pulse; however, they are averaged over time. Therefore, either the signals should be integrated by hardware or digitized 8–10 times per pulse for effective averaging. It is advisable to provide the facilities for the damping vibration which do not significantly increase the heat removal from the heaters on the chip package. The sorption processes of the moisture contained in the air between the pulses and desorption during the pulse also significantly distort the measurement results. If the compressed air is used for tests, it should be dried beforehand. This can be implemented by cooling the flow to temperatures lower than the temperature of the flow which is used to study the MEMS-based converter. Therefore, the pneumatic circuit of the stand contains a moisture freezer (see Fig. 2).

CONCLUSIONS

The presented automated stand for the study of the sensitive elements of the sensors of the gas flow rate can be effectively used not only in development but also during their serial production (1) to form a batch of devices and for selective correction of the array of meter settings, and (2) to define and correct the coefficients of algorithmic compensation of the temperature errors. The stand makes it possible to measure the specimens within the range of flow rates of 0 to 119 L/min.

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