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GAS FLOW MEASURING SYSTEM USING SIGNAL PROCESSING ON THE BASIS OF ENTROPY ESTIMATIONS

Purpose. To increase the accuracy of gas flow measurement in tachometric transducers based on the improvement of structural, hardware and algorithmic support of information and measuring systems.

Methodology. The gas consumption value is determined by the parameters of information and measurement signals. Sensor signals interacting with the environment are traditionally processed on the basis of amplitude and frequency methods. The research methodology is based on the information theory, methods of statistical and spectral analysis, digital signal processing, the theory of gas dynamics, based on mathematical modeling in a computational experiment, as well as the theory of errors and measurement results uncertainty. The statistical characteristics of the measuring signals of the converter presented in the unitary basis are studied.

Findings. The conducted research resulted in development of an information-measuring system to control the sensitivity threshold of the transducers of the primary volume and the volume of gas consumption based on the developed primary transducer, which allows providing relative standard uncertainty of cost determination within $\pm 0.5 \%$. A special processor has been developed to calculate the entropy estimates of signal information.

Originality. For the first time, a method for the formation and processing of information-measuring signals, which is based on the use of pressure pulsations due to the movement of the measuring element of the converter in the toroidal measuring cell, is proposed. Implementation of the measuring element of a spherical converter, whose density is almost commensurable with the density of the controlled medium is offered.

Practical value. The proposed method allows providing a lower sensitivity threshold compared to the industrial implementation of tachometric type transducers.

Keywords: *information measuring system, information entropy estimation, measuring signals, gas flow, primary converter*

Introduction. At the present stage of development of computer information-measuring systems, cost converters are the primary link of measurement channels. The rapid development of these devices leads to the need to improve the methods for processing the measurement signals. In the implementation of information measuring channels in computer verification systems, certification and control parameters of the gas volume conversion are most often used by primary converters of tachometric type [1, 2].

Practical problems of accuracy of such converters are caused by their design. In particular, the density of the material of the measuring element is several orders of magnitude greater than the density of the flow medium. As a result, the inertness of the measuring element does not allow measurements at low flow rates. In addition, the use of only the parameter of the amplitude of the measuring signal causes low resistance to noise and distortion.

Literature review. Information and measurement systems are widely used in drilling [3], production [4], storage and transportation of hydrocarbons [5] and their accounting. The significant effect is achieved by a combination of monitoring [6], control and measurement [7].

The widest application in industrial implementations of information and measuring channels is observed for primary transducers with a mechanical measuring element, which are characterized by simplicity of design, reliability, maintainability. Comparison (by sensitivity and accuracy) of the most common tachometric volume transducers and volume flow of gas, in particular rotary Novator G2.5, drum GSB-400, diaphragm MGM-UA G1.6, G2.5, turbine LIS-1 G2.5, rotameter P-1, PE-1, are shown in Fig.1.

Thus, common disadvantages also include the significant inertia of the sensor measure element. This is due to the use of materials with a density, which is several orders of magnitude higher than the gas flow density of the measured medium. In fact, the movement of a measured element requires the creation of a corresponding effort, in particular for tachometric type converters. As a result, due to the gas leaks, accuracy decreases in the field of low gas flow value.

Traditionally, transducers are additionally equipped with specialized technical means for the formation of information-measuring signals. The transducers' operation, as part of the information-measuring channels of accounting energy consumption systems, is characterized by the signal distortions presence. Such creation is conditioned by the unevenness of the measured element movement. It is also necessary to take into account the influence of communication interruptions
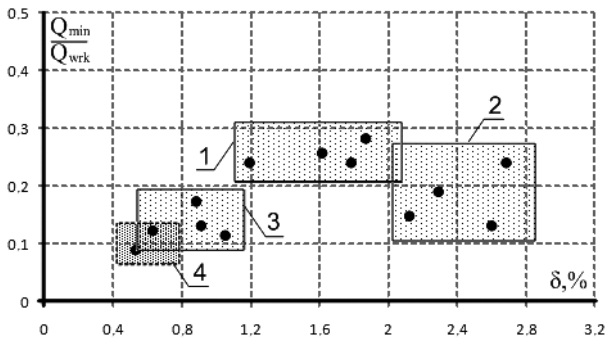
Fig. 1. Comparison of different flow transducers types by sensitivity and the value of the relative error:

1 − rotary and turbine; 2 − rotameters; 3 − chamber; 4 − predicted characteristics of the developed device

that arise with an increasing length of the data exchange channel [7, 8].

Unsolved aspects of the problem. Existing information and measurement channels based on tachometric flow transducers have design shortcomings. In particular, sensor elements made of high-density materials are the cause of low sensitivity. When processing measurement signals, one does not use probabilistic characteristics, which are an additional informative component and also reduces the impact of noise on the measurement results.

The current state of implementation of information-measuring channels and tachometric flow transducers, as a source of information about the measuring parameter, shows possible options for their improvement. In particular, the possibility of creating a measuring element from materials having a density close to the flux density of the measured medium should be considered. This approach can improve sensitivity. Another option is to involve the probabilistic characteristics of the measurement signals, which may reduce the impact of noise interference on the measurement results [9].

One of the promising options for solving these problems is to improve existing and to find new constructive implementations of measured components for primary gas flow measurement devices. In the long run, improvement of methods for forming and digital processing of measuring signals will reduce the information loss and measurement uncertainty. It is also expected to reduce computing and hardware complexity of digital signal processing tools.

Purpose. The aim of the study is to increase the accuracy of gas flow measurement in tachometric transducers based on the improvement of structural, hardware and algorithmic support of information and measuring systems. The article is devoted to the implementation of modern information technologies to improve the existing and develop new methods and tools for digital signal processing.

One of the promising options for solving these problems is to improve existing and develop new designs of measured components for gas flow transducers as well as to use probabilistic characteristics in the formation and digital processing of measuring signals. This approach will reduce information loss and, as a consequence, the uncertainty of measurements. In addition, the computational and hardware complexity of digital signal processing facilities is expected to be reduced.

Methodology. The research methodology is based on the information theory, methods of statistical and spectral analysis, digital signal processing, the theory of gas dynamics, use mathematical modeling in a computational experiment, as well as the theory of errors and measurement results uncertainty. A mathematical model of the dependence flow speed at the measuring cell and parameters of the measuring element which forms the measuring signals is obtained. The statistical

characteristics of the measuring signals of the converter presented in the unitary basis are studied.

Results. On the basis of the conducted research, the measuring signal generate method and flow value measurement based on digital sensor signal processing according to information entropy estimations are offered. The method indicated differs in the fact that the change in time intervals of the passage of the spherical label in the toroidal measurement cell is used to determine the gas flow rate.

In the measuring signal formation, due to the gas pressure fluctuations $P(t)$, distortions $n_f(t)$ arise due to the measured element's movement and the influence of flow fluctuation and the noise of data transmission channel $n_k(t)$ [12].

The structural scheme of the converter and the system for processing its signals (Fig. 2) are developed by the authors. The proposed method can reduce the uncertainty of gas flow measurements within the range of the converter sensitivity threshold.

The result obtained is due to the fact that the density of the measured medium is practically the same as the density of the measuring element.

That is, the measuring element can be considered as a signal shaper (marker). The characteristics of the movement of such a marker will be proportional to the measured parameter value.

On the basis of the gas dynamics theory [10], a mathematical model for the displacement of a measuring element in a toroidal cell is proposed.

The model describes the dependence of the dynamic pressure force on cell parameters and the measuring element's parameters. The measuring element can be made both solid and hollow. In addition, the model allows determining the threshold of sensitivity of the signal shaper

$$Q_{\min 1} = \pi \cdot r_0^2 \cdot 1.5 \sqrt{\frac{5}{42} \cdot \frac{\mu_{rest} \cdot r_0 \cdot \rho_m \cdot d^{0.5} \cdot g}{\mu^{0.5} \cdot \rho^{0.5}}},$$

where r_0, d are the signal forming radius and the measuring cell diameter, respectively; ρ, ρ_m are the density of the medium and the signal forming material, respectively; μ_{rest} is the rest friction coefficient; μ is dynamic viscosity; $g = 9.81$ m/s².

In the investigations on the signal shaper as a signal waveform generator, the numerical experiment found that, starting with a wall thickness of 0.001 m or more, the gas velocity (flow rate) practically does not change.

In fact, this allows you to determine the optimal thickness parameter for a given marker radius.

Also, the dependence of the minimum flow speed on the parameters of the measuring cell and the measuring element (Fig. 3), in which the measuring signals are formed, is obtained.

The consumption $Q_{\min 1}$ (applique axis) depends on r_0 (abscissa axis) − the radius of the dimensional element (where 0.00195 m $< r_0 < 0.02$ m) and (ordinate axis) − the radius of the sphere carved inside the measuring element 0.0 m $< r < 0.02$ m.

According to the proposed scheme (Fig. 1), the input of the flow is carried out at a tangent, output flow − on the inner
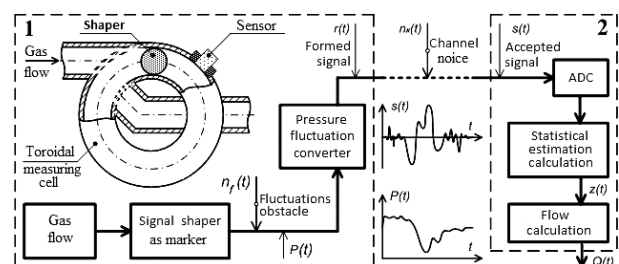

Fig. 2. The block diagram of the gas consumption flow transducers:

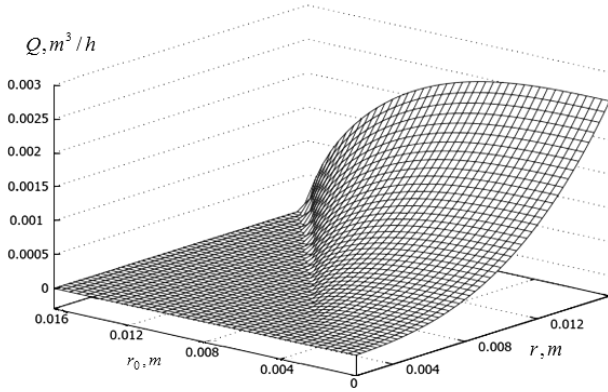*1 − PMC; 2 − a system of measuring signals digital processing*

Fig. 3. Dependence of the minimum gas consumption on the converter shaper component parameters

average radius of the toroidal cell in the opposite direction. This allows for the signal shaper movement by flow in a circle and, as result, the formation of periodic pressure pulsations. These pulsations $P(t)$ are fixed by the sensor. However, there is a problem of distortions. The pressure sensor signal is distorted by the flow unevenness due to local flow vortices and fluctuations caused by a measuring element $n_f(t)$.

In addition, the signal is influenced by the pulse characteristic $h_c(t)$ of the data transmission channel [11]. And with an increase in its length, additional industrial noise and switching noise arise

$$s(t) = r(t) \cdot h_s(t) + n_k(t),$$

where $r(t) = f(P(t), h_f(t))$ is the pressure sensor signal, which reduces the efficiency of the signal allocation without prior processing.

According to the experimental results of studies on the primary converter prototype, (carried out for a range of costs from 0.078 to 1.014 m³/h), it was found that for $Q > 0.3$ m³/h, distortions practically do not affect the information-measuring signals. At $Q < 0.3$ m³/h, obstacles are characterized by greater spectral energy. This make measuring signals distortion. For the sensitivity threshold range, the shape of the measuring signal undergoes significant changes. As a result, redundant signals are generated, which prevents the selection of informative signal constituents based on hardware filters uses. Hence the need arises to proceed to the analysis of the time characteristics of the signal.

At the next stage of the research, the method for processing measuring signals of tachometric primary converters was improved. In particular, it was proposed to use statistical characteristics estimates of measuring signal fragments $z(S)$ [11, 12].

For a 16-bit analog-to-digital converter, the PMC signals are represented by a vector $S = (s_1, s_2, ..., s_n) \in [-32\,768; 32\,767]^n$, that is, for $z(S):[-32768;32767]^n \rightarrow [0;16]^{\left[\frac{n}{w}\right]}$, where $\left[\frac{n}{w}\right]$ is rounding to a smaller whole, we obtain

$$z(S) = (\hat{Z}(s_1, s_2, ..., s_w), \hat{Z}(s_{w+1}, s_{w+2}, ..., s_{w+w}),$$
$$..., \hat{Z}(s_{w+...+w+1}, ..., s_n)),$$

where $\hat{Z}$ is the function of statistical estimation calculation; s_i is an element of the signal S is a fragment vector; w is the size of the signal fragment on which it is calculated $\hat{Z}$.

Thus, a statistical estimate vector is placed on each fragment of the measuring signal. The measuring signal realization with appropriately calculated statistical characteristics, for example, the informational entropy of Shannon $\hat{H}_x$, is presented in Fig. 4, *a*. So, the basis of the method is the fact that the value $z(S)$ is used to select the signals informative components.
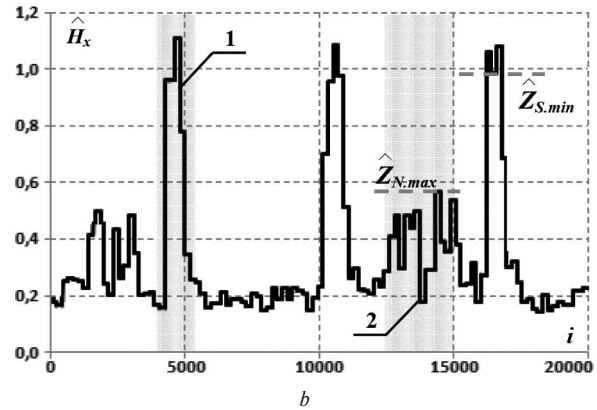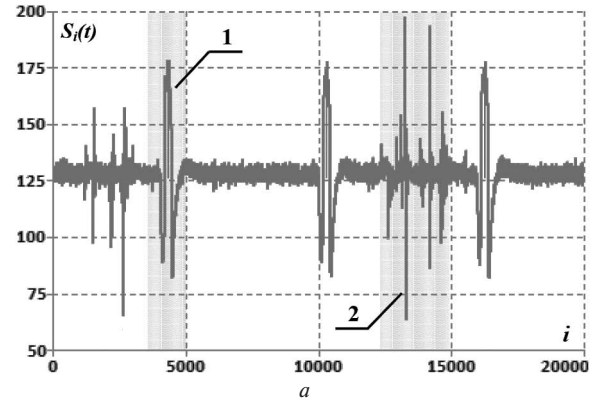

Fig. 4. Fragments of a) measurement signal − 1, noise − 2; b) the information entropy evaluation of multistate signal realization: signal − 1, noise − 2

Moreover, according to these signals, the time intervals are fixed, with the subsequent calculation of the measured parameter value.

The effectiveness of the use of various statistical estimates (Fig. 5), in particular, was considered: mathematical expectation M_x, dispersion D_x, STD, higher orders central moments, entropy according to [12, 13]:

C. Shannon

$$H_x = -k \sum_{i=1}^{n} p_i \log p_i;$$

B. Oliver

$$H_o = \lim_{n \to \infty} \frac{\log N}{n};$$

Y. Nikolaichuk

$$H_N = n\hat{E}\left[\frac{1}{2}\log_2 \frac{1}{m}\sum_{j=1}^{m}\left(D_x^2 - R_{xx}^2(j)\right)\right];$$

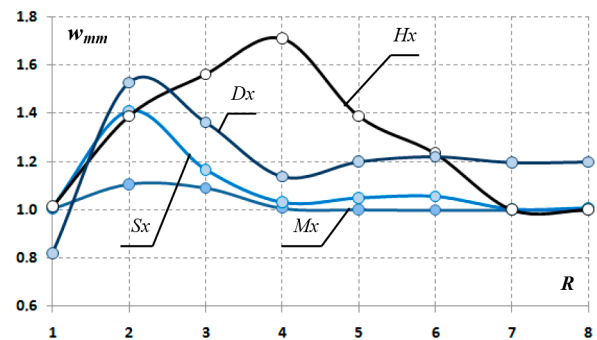Fig. 5. Dependence w_{mm} on the bit ADC R for different statistical characteristics with sample size $n = 185$

R. Hartley

$$H_h = \log_2(N) \; H_h = \log_2(N) \; ;$$

C. Kramp

$$H_k = \log_2 \sqrt{2\pi e D_x^2},$$

as well as R (ADC) ratings on the adequacy of measuring signals selection informative components.

In the research, the ratio of the statistical estimation minimum value of the signal amplitude fragment to the maximum statistical estimation value of the distorted signal amplitudes is analyzed (Fig. 4, b)

$$w_{mm} = Z_{S.\min}/Z_{N.\max}.$$

Using the Kramp entropy (Fig. 5) gives results that are consistent with D_x and STD; however, it has low efficiency due to the additional calculation of the logarithm function.

When using Hartley's measure, for the case of binary implementations, the score becomes non-informative because the number of states is unchanged.

Information measures H_O and H_N are characterized by a considerable amount of computations, in particular for the autocorrelation function R_{xx}. This situation is unacceptable for computing platforms with limited resources.

So, $\hat{H}_x$ according to Shannon formula, with using a comparator, has to ensure a sufficient probability of unambiguous signal allocation.

Hardware implementation on FPGA. Modern technologies for designing digital devices are based on the use of programmable logic integrated circuits. Use of direct interface circuits for the conversion of a sensor's signals value to digital information provides a simple and low-cost solution that is valid for virtually any programmable digital device [14, 15].

On the basis of the results obtained, the structure and circuitry of the specialized processor components were developed (Fig. 6).

The device processes the sensor information-measuring signals represented by binary realizations [14].

Sensor analog signals are formed by the measure element of the PMC. Such signals are fed to a comparator that generates the corresponding binary sequences. Then, these sequences are sent to the counter CntS through the logical element And.

In parallel, signals from the generator of reference pulses, which specify the frequency of digits, are fed to the same element and the counter CntG. The CntG counter is also used to block CntControl for sample control.

After completing the loop in the CntG calculation, you will get a CntControl ready-to-date output signal. After the signal is generated on the block HTable100 which calculates $\hat{H}_x$, a signal is made to correct the CntG and CntS counters and the cycle is repeated (Fig. 7).

The entropy calculating block of the signal sampling HTable100, is realized on the basis of pre-calculated entropy values by the measure of C. Shannon, multiplied by 10^6.

This representation allows you to go to integer operations. Simplification is expedient, since the set of possible values is
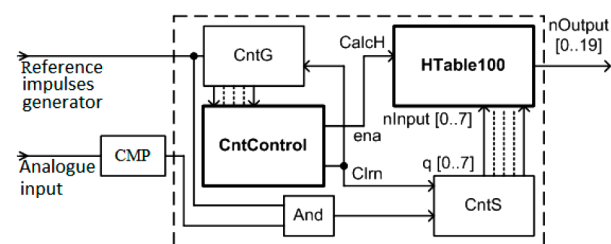

Fig. 6. Block diagram of a specialized processor for calculating the information entropy estimation of PMC binary signals
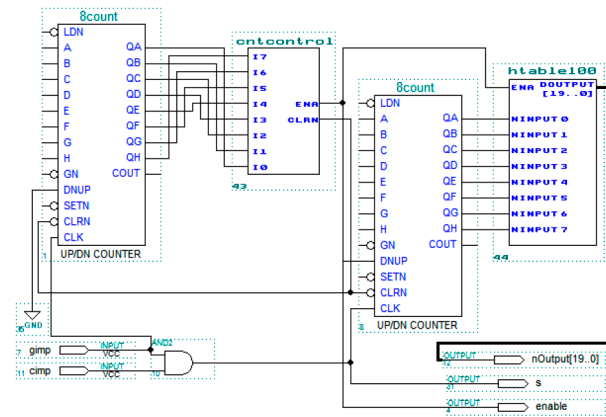

Fig. 7. Functional diagram of a specialized processor based on two 8-bit counters and components CntControl and hTable100

discrete and, for $n = 200$ elements, is 100, which is explained by the symmetry of the characteristic [16, 17].

The choice of the corresponding entropy value is carried out in the presence of a logic zero signal on the CntControl block ENA line.

The signal goes to CalcH — the permission to start the calculation line of the formation block of the result HTable100. The received number of individual states from CntS is applied to the nInput {7..0} data bus of the HTable100 block.

The result is formed on the original 20-bit bus nOutput {19..0}, which represents $\hat{H}_x$, for the corresponding correlation of the probabilities of occurrence of the null and one states of the signal fragment. According to the results of functional modeling, negative and positive absolute error values of calculation do not go beyond $5 \cdot 10^{-7}$.

According to the results of experimental studies on the developed PMC, an empirical dependence was obtained on the basis of which the model was developed. The model describes the relationship between the mediated signal duration parameter $1/l$ (l — momentum interval) and the gas consumption value

$$Q(1/l) = \begin{cases} 0.0023 < 1/l \le 0.1442; \quad a_0(1/l)^2 + b_0(1/l) + c_0 \\ 0.1442 < 1/l \le 0,2287; \quad a_1(1/l)^2 + b_1(1/l) + c_1 \end{cases},$$

where

$$a_0 = -1.709; \quad b_0 = 3.949; \quad c_0 = 0.069;$$
$$a_1 = -6.985; \quad b_1 = 7.469; \quad c_1 = -0.329.$$

The conducted research on this model showed that the obtained dependence is characterized by the relative error of the transformation, which is five orders of magnitude smaller, compared with the measurement errors of the existing model converters. Consequently, the effect of model error on the signals processing result can be considered non-essential.

Appropriate algorithms and programs for gas consumption calculation for the information-measuring system were developed.

Experimental studies on the developed system were carried out on the basis of the etalon of the EIF "TEMPO" bell type installation (medium — air, control volume 0.005 m³, pressure 113 mm.w.col., temperature stabilization 20 °C ± 0.5 %, limit of permissible basic relative error installation ± 0.33 %).

The research results showed that the relative standard uncertainty of the developed system does not exceed ± 0.5 % (Fig. 8).

As a result, improved accuracy at low gas consumption was established. This advantage stipulated the expediency of using the developed PMC gas flow in the measuring channel of sen-
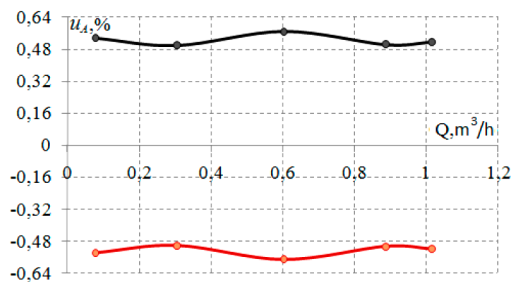
Fig. 8. Dependence of the relative standard uncertainty on measurements on gas consumption
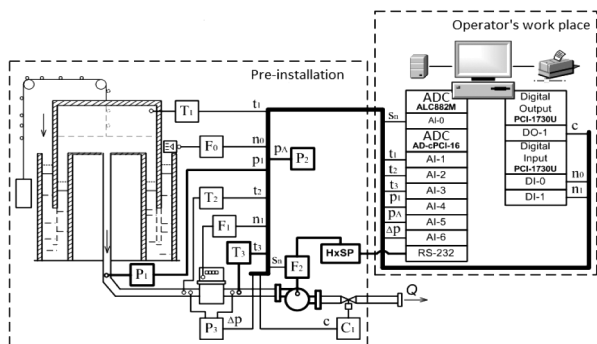

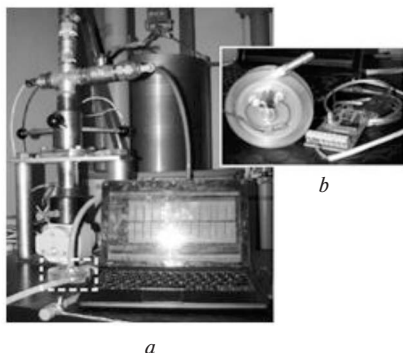Fig. 9. The verification installation block diagram; implementation as part of the TEMPO-3 installation

Fig. 10. Developed system implementation as part of TEMPO-3 installation (a), toroidal measuring cell (b)

sitivity threshold control as part of the "TEMPO-3" installation (Figs. 9, 10).

The threaded connections with self-locking from unscrewing are used to maintain the tightness of the installations [18].

The developed software of the computer information and measurement system for monitoring the threshold of sensitivity, allows us to quickly investigate domestic gas meters of membrane and rotary types during the carrying out of certification, calibration and calibration procedures.

Conclusions. As a result of the scientific research, the actual task of realization of the gas consumption information-measuring system is solved on the basis of application of modern information technologies for the measuring signals processing. This approach is aimed at reducing the standard relative measurement uncertainty and simplifying the hardware complexity of digital processing tools.

Based on the analysis of existing primary gas converters used in the information-measuring systems, a new method is proposed for the formation and processing of information-measuring signals according to entropy estimates. This method is based on using the pressure pulsations, which are formed with the converter component moving in a toroidal measuring cell.

The proposed solution allowed reducing the influence of non-informative components of random signals. On the basis of the above method, a mathematical model describing the process of moving the signal shaper is developed. A study on influence of the dynamic pressure on the flow movement when measurement element is moving into a measuring cell was carried out. As a research result, it was found that for expenses $Q_{min\,2} = 0.00536$ m^3/h the average speed is $\upsilon_2 = 0.12475$ m/s. According to the model, the proposed method provides a lower threshold of sensitivity compared with industrial converters of tachometric type. In addition, a study on the measuring signals spectral and statistical characteristics of the gas consumption primary measuring transducer was carried out.

According to the analysis results, a method for processing signals is proposed. The indicated method is based on the estimation of the signals information entropy of binary realizations obtained from the comparator. The proposed method provides the best probability of selecting the signal informative components. Modified algorithms of information entropy estimation for working out of binary and multistate signals are developed. Such algorithms serve as symmetric entropy characteristics and do not require the use of a Taylor series expansion procedure.

As a result, the number of operations is reduced by two orders of magnitude, the absolute error of calculation (for binary signals) does not exceed $\pm 0.5 \cdot 10^{-2}$, (for multistate) — $\pm 0.68 \cdot 10^{-2}$. A specialized processor for estimating the binary signals information entropy has been developed. Such a processor includes a counters block, a sample data control block and a result formation block.

The developed device allows you to extend the functionality and reduce the time expenditures when calculating the entropy of signals. Absolute error of calculation does not exceed $\pm 5 \cdot 10^{-7}$. In addition, circuit design solutions for signal processing systems for various sensor types based on the use of a serial microcontroller have been developed. The information-measuring system of sensitivity threshold control, functioning in the structure of the bell type etalon verification device, is developed.

The specified system provides a relative measurement standard uncertainty of ± 0.5 % with a confidence probability of 0.95. In addition, the software for processing signals of the primary converter is developed.

The proposed solutions allowed expanding the functional capabilities of the computer information and measuring system, which is part of the etalon installation of volume unit control and gas volume consumption.

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Інформаційно-вимірювальна система витрати газу на основі опрацювання сигналів за оцінками ентропії

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Мета. Підвищення точності вимірювання витрати газу в тахометричних перетворювачах на основі вдосконалення структурного, апаратного та алгоритмічного забезпечення інформаційно-вимірювальних систем.

Методика. Визначення величини витрати газових середовищ ґрунтується на параметрах інформаційно-вимірювальних сигналів. Сигнали сенсора, що взаємодіють із середовищем, традиційно опрацьовують на основі амплітудних і частотних методів. Проведення досліджень базується на теорії інформації, методах статистичного та спектрального аналізу, цифрового опрацювання сигналів, теорії газової динаміки, заснованій на математичному моделюванні в обчислювальному експерименті, а також на теорії похибок і невизначеності результатів вимірювань. Досліджувались статистичні характеристики вимірювальних сигналів перетворювача, представлені в унітарному базисі.

Результати. Результатом проведених досліджень є розробка інформаційно-вимірювальної системи для контролю порогу чутливості перетворювачів первинного об'єму та обсягу споживання газу на основі розробленого первинного перетворювача, що дозволяє забезпечити відносну стандартну невизначеність визначення витрат у межах $\pm 0,5$ %. Розроблено спецпроцесор для розрахунку оцінок ентропії інформації про сигнал.

Наукова новизна. Полягає в тому, що вперше запропоновано метод формування та опрацювання інформаційно-вимірювальних сигналів, який базується на використанні пульсацій тиску внаслідок переміщення мірного елемента перетворювача в торовидній мірній камері. Запропонована реалізація мірного елемента сферичного перетворювача, густина якого практично співрозмірна з густиною контрольованого середовища.

Практична значимість. Полягає в тому, що запропонований метод дозволяє забезпечити нижчий поріг чутливості у порівнянні із промисловою реалізацією перетворювачів тахометричного типу.

Ключові слова: *інформаційно-вимірювальна система, оцінки інформаційної ентропії, вимірювальні сигнали, витрата газу, первинний перетворювач*