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Methodology for Developing an Automated Adaptive System for Measuring Fluid Volume based on Gas Meter

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Abstract

The paper analyses the dependencies for estimating the uncertainty of the gas volume under base conditions measured with application of an automated system based on a gas meter and volume corrector. The authors propose using the absolute uncertainty of the gas volume for a certain time period as an indicator of the measurement system's accuracy. In order to calculate this uncertainty the dependencies of the gas meter error on the gas flow rate through the meter have been developed based on the statistical processing of the results of the metrological verification of gas meters for industrial rotary and turbine gas meters. Correcting the measured gas volume under operating conditions, with taking into account the unexcluded systematic error calculated according to the developed dependencies, will ensure the adaptation of the measuring system to the application conditions and the flow rate changes in the measuring pipeline. A methodology for development of automated adaptive systems for measuring the gas volume has been created on the basis of the adaptive algorithm for correcting the measured gas volume under operating conditions, the analytical dependencies for calculating the absolute uncertainty of the measured gas volume under base conditions during a certain time period, and the analytical dependencies for monitoring the variation of the main error of the gas meter.

Keywords: gas volume measurement; automated system; adaptive algorithm; gas meter; gas volume uncertainty.

1. Introduction

Nowadays, measuring the natural gas flow rate and volume is carried out using automated systems. Such systems include a primary flow rate transducer or gas meter, measuring transducers of gas parameters (pressure, temperature, pressure drop, density), and a microprocessor calculator (corrector) of gas volume. Such systems measure the flow parameters, flow rate and volume of natural gas, bring the gas volume to base conditions, form archives of gas parameters, flow and volume, exchange data with dispatching systems and other functions. Gas flow rate and volume measurement systems have a fixed structure and configuration parameters, determined by the project and technical documentation.

However, during the operation of automated systems for measuring the flow and volume of natural gas, the technical and metrological characteristics of individual system components may change because of many operational factors. For example, when the gas temperature and pressure change, the measuring pipeline's internal diameter also changes. Operational factors also lead to blunting of the orifice edge of the variable pressure differential flowmeter, which is the cause of the change in the blunting coefficient and, accordingly, the measured gas flow rate, as well as a change in the calibration characteristic of gas meters.

The goal of developers of gas flow rate and volume measurement systems is to implement such hardware or software solutions that consider the impact of operational factors, i.e., the system is adapted to operating conditions. For example, in systems based on standard constriction devices, algorithms have been implemented that take into

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account the change in the diameter of the orifice plate and the internal diameter of the pipeline when the temperature of the fluid changes, as well as the change in the sharpness of the orifice edge and its impact on the measured flow value. The dependencies for considering these influences are standardized by the DSTU GOST 8.586.1-5:2009.

However, for gas meters of different types, many factors have been identified that lead to changes in the metrological characteristics of the gas meter and, therefore, in the entire measuring system. The regulations and software of measurement systems based on gas meters do not consider these factors' impact. The authors have studied and estimated the effect of individual factors. This work aims to develop a methodology for considering the studied impacts for the development of adaptive gas flow rate and quantity measurement systems based on gas meters.

2. Analysis of the recent publications and research works on the problem

The development of adaptive volume measurement systems is an urgent task for systems based on flow meters, as well as gas meters, and makes it possible to improve the technical and metrological characteristics of these systems. For example, in [1], a system for measuring non-stationary air flow with an adaptive differentiator is presented. Introduction of this adaptive element made it possible to simplify the scheme and reduce the cost of the system while at the same time expanding the dynamic range of flow rate measurement. In [2], the author presented an adaptive measurement system based on an ultrasonic flow meter. Thanks to improving the algorithms for calculating the fluid flow rate, the author considered the effects of changing the pipeline's internal diameter, fluid temperature and density.

Modern industrial gas volume measurement systems based on gas meters, which contain gas volume correctors, bring the gas volume measured under operating conditions to base conditions by implementing equations [3], [4]

$$V_{bc}=V_r\cdot(P\cdot T_{bc}\,)\,/\,(\,T\cdot P_{bc}\cdot K\,), \tag{1}$$

where V_{bc}, V_r are the gas volume under base conditions and under real (operating) conditions, respectively; P, T are the gas absolute pressure and temperature under real measuring conditions; P_{bc}, T_{bc} are the gas absolute pressure and temperature under base conditions; K is the gas compressibility coefficient.

Considering formula (1) as a functional dependence $V_{bc}= f(V_r,\ P,\ T,\ K)$ and applying to it the rule for determining the combined standard uncertainty [5], [6], we obtain the equation of the combined relative uncertainty of the gas volume measured by the metering system with flow computer

$$u'_{Vbc}=\sqrt{u'^2_{V_r}+u'^2_{p}+u'^2_{T}+u'^2_{K}+u'^2_{fc}}\;, \tag{2}$$

where u'_{V_p} is the relative standard uncertainty (from now on uncertainty) of the volume measured by the gas meter under operating conditions; u'_p is the uncertainty of the measured gas absolute pressure; u'_T is the uncertainty of the measured gas absolute temperature; u'_K is the uncertainty of calculating the gas compressibility coefficient; u'_{fc} is the uncertainty of calculating the gas volume under base conditions by the flow computer.

Regulatory and methodological documents in Ukraine provide several methods for normalizing the error of gas volume correctors [4]. There are two main methods among them [3], [4]:

- Normalizing the error of the calculator, pressure measuring transducer, temperature measuring transducer as separate devices and calculating the error of the corrector by quadratic dependence based on the errors of individual components;
- Normalizing the error of the corrector as a complete device, which includes a calculator, pressure measuring transducer, temperature measuring transducer.

With the first method of normalization, the uncertainty of the volume measurement system is calculated by formula (2), and with the second method by the following formula

$$u'_{Vbc}=\sqrt{u'^2_{V_r}+u'^2_{cor}}\;, \tag{3}$$

where u'_{cor} is the uncertainty of gas volume caused by the gas meter signal transforming, gas pressure and temperature measurement and the calculation of the gas volume reduced to standard conditions.

Each uncertainty component in formulas (2) and (3) may contain additional components:

$$u'_x = \sqrt{u'^2_{mx} + u'^2_{adx}} \ , \tag{4}$$

where u'_{mx} is the main component of the uncertainty of the result of determining the quantity x; u'_{adx} is the total additional component of the uncertainty of the quantity *x*, *x* =[V_r, *P*, *T*, *K*].

Then, considering the additional components, formulas (2) and (3) will have the form:

$$u'_{V_{bc}} = \sqrt{u'^2_{mV_r} + u'^2_{mp} + u'^2_{mT} + u'^2_{mK} + u'^2_{fc} + \sum_{i=1}^{m} u'^2_{ad\,i}} \ ; \tag{5}$$

$$u'_{V_{bc}} = \sqrt{u'^2_{mV_r} + u'^2_{cor} + \sum_{i=1}^{m} u'^2_{ad\,i}} \ , \tag{6}$$

where *m* is the number of identified additional uncertainty components of the quantities V_r, *p, T, K*. It should be noted that the quadratic summation of additional uncertainty components is valid if these components are random.

The main uncertainty components included in formulas (5) and (6) can be determined based on the errors of the gas meter, measuring transducers of gas pressure and temperature, and calculator, which are provided by manufacturers in the technical documentation. Particularly, the uncertainties of the measured values of gas pressure and temperature should be determined based on the limits of the main error determined for the measurement range of each transducer. However, the main component of the uncertainty of the measured gas volume under operating conditions also requires specific investigation, since it depends on the gas flow rate and measured gas volume.

Separate additional uncertainty components can also be calculated based on manufacturers' data. However, many additional uncertainty components of the measured gas volume should be identified based on the results of additional studies. The authors have studied the main and additional components of the error in measuring gas volume using gas meters, the results of which are presented in [7]-[9]. In this research, the authors obtained the dependence of rotary gas meters error on the measured gas volume [7], as well as the dependence of rotary gas meters error on the measured gas flow rate [9], which are proposed to be used for the development of adaptive gas flow rate and volume measurement systems.

3. Formulation of the goal of the paper

This paper aims to form a methodology for developing an automated adaptive system for measuring fluid volume using gas meters. Applying this methodology will make it possible to design automated adaptive systems for measuring fluid volume that will consider changes in the metrological characteristics of a gas meter caused by the impact of certain operational factors.

4. Methodology for developing an automated adaptive system for measuring fluid volume

The methodology for developing an automated adaptive system for measuring fluid volume is based on algorithmic methods for adapting the system to the application conditions. The criterion for forming adapting algorithms is the minimum absolute uncertainty of the measured gas volume over a fixed time.

Formulas (5) and (6) make it possible to estimate the uncertainty of the measured gas volume under fixed conditions when all uncertainty components are constant. However, the gas volume uncertainty components depend on the measured flow rate. The flow rate can vary during the operation of volume measurement systems within wide limits, which must be considered when estimating the uncertainty of the measured gas volume value.

The absolute uncertainty $u_{V_{bc}}$ of the gas volume measured by the instrument system over a certain time period under conditions of variable flow can be estimated by the formula

$$u_{V_{bc}} = \int_0^{\tau} V_Q(t) \cdot u'_{V_{bc}}(t) dt \ , \tag{7}$$

where $u_{V_{bc}}$ is the absolute standard uncertainty of the measured gas volume (under the base conditions); $V_Q(t)$ is the dependence of the gas volume, accounted for by the system per unit of time on time;

$u'_{V_{bc}}(t)$ is the dependence of the relative standard uncertainty of the measured value of the gas volume on time.

To implement formula (7), it is necessary to have information about the change in the gas volume $V_Q(t)$, accounted for by the system during the studied time, and about the change in uncertainty $u'_{V_{bc}}(t)$ over time, which complicates the practical application of this formula. Particularly, estimating the uncertainty $u'_{V_{bc}}(t)$ at each fixed point in time can be made by formulas (5), (6). Most of the uncertainty components included in these formulas can be considered constants in the conditions of applying natural gas metering systems. So, the uncertainty of the measured absolute gas pressure u'_p, the uncertainty of the measured absolute gas temperature u'_T, the uncertainty of calculating the gas compressibility coefficient u'_K, the uncertainty u'_{fc} of calculating the gas volume under base conditions by the microprocessor calculator of the corrector are, as a rule, constant during the operation of gas metering systems. However, the relative standard uncertainty of the gas volume u'_{V_r} measured by the meter depends on the gas flow rate through the meter [9]. Since the gas flow rate in the measuring pipelines changes over time, the uncertainty $u'_{V_{bc}}(t)$ will also change.

The error of rotary, turbine-type, and ultrasonic gas meters are normalized during production according to the requirements of regulatory documents [10]-[12] and during periodic verification according to the standard [13] in two flow rate ranges: $Q_{min} \le Q < Q_t$, $Q_t \le Q < Q_{max}$. If, during the determination time of $u_{V_{bc}}$ the gas flow rate does not belong to one of the specified ranges, then the limit of the basic error of the gas meter is constant. Therefore, the main component of the uncertainty u'_{mV_r} of the measured volume under operating conditions based on this error is also constant. Then, provided that the additional uncertainty components are independent of the flow rate and constant, it follows from (5) and (6) that the uncertainty $u'_{V_{bc}}$ is also constant. Under the above conditions, we obtain:

$$u'_{V_{bc}} = \begin{cases} u'_{V_{bc}}(u'_{mV_{r1}}),\ Q_t \le Q \le Q_{\max}; \\ u'_{V_{bc}}(u'_{mV_{r2}}),\ Q_{\min} \le Q < Q_t. \end{cases} \quad (8)$$

Therefore, in the absence of additional research results and the dependence of uncertainty $u'_{Vbc}(t)$ on time, the absolute uncertainty $u_{V_{bc}}$ of the gas volume measured over time τ can be calculated by the formula (7) for the conditions when the gas flow rate varies within wide limits, taking into account expression (8) and the normalized values of the gas meter error in individual flow rate ranges. The gas flow rate can be assigned to one of the subranges in real-time in the gas volume corrector algorithms or in the dispatching system based on the archive of the gas flow parameters.

As indicated above, regardless of the normalizing method of the gas volume corrector errors, the uncertainty of the measured gas volume value under operating conditions u'_{V_r} depends on the gas flow rate. This was shown in [7], [9]. It is well known that this uncertainty is based on the gas meter error. Additional uncertainty components included in equations (5) and (6) are complex functions of many parameters, and each of these components requires separate consideration.

In [7], the authors performed statistical processing of the results of metrological verification of industrial rotary gas meters of the RG, RG-K type and developed the dependences of the main error of rotary gas meters on gas flow rate. Fig.1 shows these dependencies.

The authors performed the same studies for the LG and LG-K type industrial turbine gas meters. The dependences of the basic error of turbine gas meters on gas flow are presented in Fig.2.

We should emphasize that the dependencies presented in Fig.1 and Fig.2 were developed based on many metrological verification results for industrial gas meters. The authors collected and processed 545 metrological verification protocols for industrial rotary and turbine gas meters. Therefore, the dependencies presented in Fig.1 and Fig.2 can be reasonably used to calculate the main error of the gas meter depending on the relative gas flow rate $Q_{rel} = Q / Q_{\max}$.

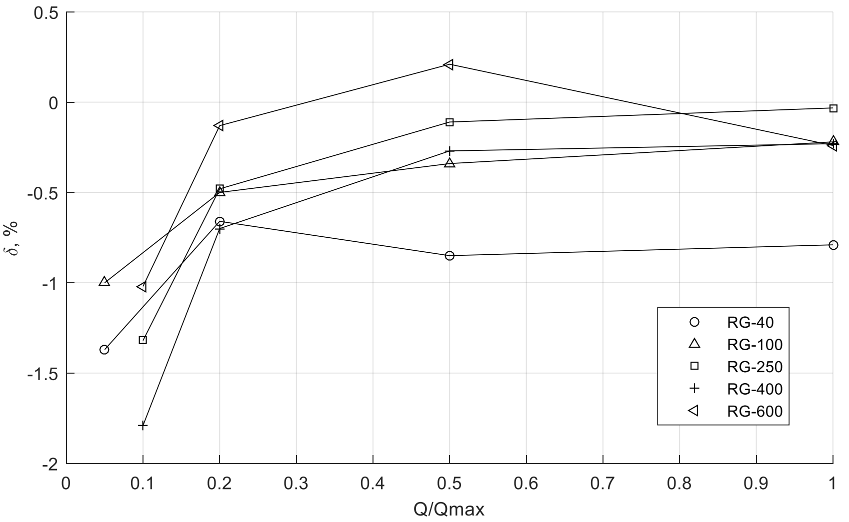

Fig.1. Dependence of the average error of RG-type rotary meters on the measured flowrate.

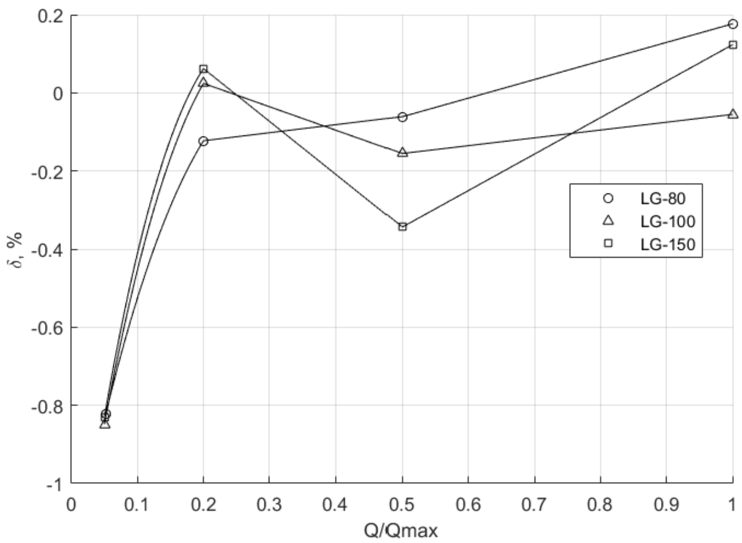

Fig.2. Dependence of the average error of LG-type turbine meters on the measured flowrate.

The dependencies of the gas meter error, and accordingly, the uncertainty of the measured value of the gas volume under operating conditions on the relative flow rate $u'_{V_r} = f(Q_{rel})$ make it possible to transform formula (7) to the form

$$u_{V_{bc}} = \int_0^{\tau} V_{bc}(t) \cdot u'_{V_{bc}}(Q_{rel})dt\,, \tag{9}$$

where Q_{rel} is the relative gas flow rate through the meter.

Equation (9) can be implemented based on the known values of gas volume, gas pressure and temperature. Flow calculators designed for commercial gas metering store archives of changes in these parameters over time. Dispatching systems ensure their transfer from calculators to dispatching centres of gas transportation and gas distribution organizations. Therefore, equation (9) can be implemented in the correctors' algorithms and the dispatching system of a gas transportation or gas distribution network.

The authors propose to apply one of the numerical integration methods and implement the dependence (9) in the gas volume corrector algorithm in a recurrent form. For the rectangle integration method, we obtain the following recurrent equation (10) in which dependence (9) for the absolute standard uncertainty of the measured gas volume is implemented:

$$u_{V_{bc(i)}} = u_{V_{bc(i-1)}} + V_{Q(i)} \cdot u'_{V_C}(Q_{rel(i)}) \cdot \Delta t \,, \tag{10}$$

$$V_{Q(i)} = \frac{V_{bc(i)} - V_{bc(i-1)}}{\Delta t} \,, \tag{11}$$

$$Q_{rel(i)} = \frac{V_{r(i)} - V_{r(i-1)}}{\Delta t \cdot Q_{\max}} \,, \tag{12}$$

where $u_{V_{bc(i)}}$, $u_{V_{bc(i-1)}}$ are the absolute uncertainties of gas volume under base conditions determined for the i-th and (i-1)-th records in the corrector archive; $V_{bc(i)}$, $V_{bc(i-1)}$ are the values of the gas volume under base conditions stored in the i-th and (i-1)-th records of the corrector archive; $u'_{V_C}(Q_{r(i)})$ is the relative standard uncertainty of the gas volume under base conditions calculated considering the dependence $u'_{V_r} = f(Q_{rel})$; $Q_{rel(i)}$ is the relative gas flow rate based on current $V_{r(i)}$ and previous $V_{r(i-1)}$ values of the gas volume under operating conditions, stored in the gas volume corrector; Δt is the interval for forming the records in the gas volume corrector archive; Q_{max} is the maximum measured gas flow rate for the corresponding gas meter.

The methodology for developing an automated adaptive system for measuring the volume of fluid energy carriers using a gas volume meter involves the following stages:

- Analysis of the main and additional uncertainty of the measured parameters V_p, p, T, based on the manufacturer's technical documentation for gas meters and pressure and temperature measuring transducers; analysis of the main and additional uncertainty of the compressibility coefficient K based on data from standards and methodological documents for calculating this parameter; determining the list of additional uncertainties that have a significant impact on the measurement results when using a specific gas volume measurement system;
- Experimental investigation or statistical processing of the results of metrological verification of gas meters to develop the dependencies of the gas meter main error on the relative gas flow rate $\delta_{V_r} = f(Q_{rel})$; the technique for processing the results of metrological verification of gas meters and developing the dependencies $\delta_{V_r} = f(Q_{rel})$ is presented by the authors in [9]; estimation of the main uncertainty of the measured gas volume under operating conditions using the obtained dependencies $\delta_{V_r} = f(Q_{rel})$;
- Developing the algorithm for correcting the measured gas volume under operating conditions, taking into account the unexcluded systematic error calculated according to the dependence $\delta_{V_r} = f(Q_{rel})$ for each measured gas flow rate; thus, we provide the adapting the measuring system to the application conditions and the flow rate changes in the measuring pipeline, considering the dependence $\delta_{V_r} = f(Q_{rel})$ individual for a specific gas meter type;
- Statistical processing of the results of metrological verification of gas meters to develop the dependence of the main error of the average statistical meter on the measured gas volume; estimating the unexcluded systematic error, its constant and progressive component; the methodology for such investigation and its application for rotary gas meters is presented by the authors in [7];
- Experimental investigation of the additional uncertainties of the measured gas volume and determine the possibilities for improving the measurement system to minimize these additional components;
- Developing the algorithm for calculating the relative uncertainty of the measured gas volume under base conditions according to formulas (4), (5) considering the dependence $u'_{V_r} = f(Q_{rel})$;
- Developing the algorithm for calculating the absolute uncertainty $u_{V_{bc}}$ of the measured value of the gas volume under base conditions during a certain time according to the recurrent equation (10) based on the gas volume under operating conditions and the gas volume under base conditions stored in the archive of the gas volume corrector; application of the absolute uncertainty $u_{V_{bc}}$ to estimate the probable value of the gas volume imbalance in the gas pipeline system;

- Developing the algorithm for monitoring the change in the main error of the gas meter based on the dependences of the main error of an average statistical meter on the measured gas volume; particularly for industrial rotary gas meters RGK-250, the authors have developed the following dependencies [7]:

$$\delta_1 = -1.931 \cdot 10^{-5} \cdot V + 0.097 \text{ for } Q_{max}, \tag{13}$$

$$\delta_2 = -8.309 \cdot 10^{-5} \cdot V + 0.2192 \text{ for } 0.5Q_{max}, \tag{14}$$

$$\delta_3 = -0.407 \cdot 10^{-5} \cdot V - 0.4592 \text{ for } 0.2\, Q_{max}, \tag{15}$$

$$\delta_4 = -1.875 \cdot 10^{-5} \cdot V - 1.2268 \text{ for } Q_{min}, \tag{16}$$

where $V = v/Q_{nom}$; v is the measured volume, m^3; Q_{nom} is the nominal flow rate for the corresponding type of gas meter (Q_{nom} = 250 m^3/h); if the main error exceeds the permissible value specified for the corresponding type of gas meter by regulatory documents, a diagnostic message from the corrector is formed about the necessity for an extraordinary verification of the meter and this message is recorded into the accident archive;

- Implementing the adaptive algorithm for correcting the measured gas volume under operating conditions considering the dependence $\delta_{V_r} = f(Q_{rel})$, the algorithm for calculating the uncertainty of the measured gas volume under base conditions $u'_{V_{bc}}(Q_{rel(i)})$, the algorithm for calculating the absolute uncertainty $u_{V_{bc}}$ of the measured gas volume under base conditions during a specified time and the algorithm for monitoring the change in the main error of the gas meter in the software of gas volume microprocessor corrector;
- Improving the software for forming the gas volume corrector archive to store the values of uncertainties $u'_{V_{bc}}(Q_{rel(i)})$ and $u_{V_{bc}}$.

The application of this methodology makes it possible to develop automated adaptive gas volume measurement systems that correct the measured gas volume under operating conditions, considering the unexcluded systematic error of the gas meter, determined by the individual dependence $\delta_{V_r} = f(Q_{rel})$ for a specific gas meter type.

5. Conclusion

The following results and conclusions were obtained in the paper:

1) Statistical processing of the results of metrological verification of gas meters makes it possible to develop the dependencies of the main error of the gas meter on the relative gas flow rate $\delta_{V_r} = f(Q_{rel})$. Such dependences were obtained by the authors for industrial rotary and turbine gas meters; the authors are developing an algorithm for correcting the value of the measured gas volume under operating conditions, considering the unexcluded systematic error calculated according to the developed dependencies, which will ensure the adaptation of the measuring system to the application conditions and the flow rate changes in the measuring pipeline;

2) The authors propose to implement an algorithm for monitoring the change in the gas meter main error based on analytical dependencies of the main error of the average statistical meter on the measured gas volume into the automated flow rate measurement system; such dependencies were developed by the authors for rotary gas meters of the RGK-100, RGK-250 type; if the main error exceeds the permissible value specified for the corresponding type of gas meter by regulatory documents, the algorithm generates a diagnostic message from the corrector about the necessity for an extraordinary verification of the meter and records this message into the accident archive;

3) The proposed approaches to correcting the measured gas volume under operating conditions, considering the dependence $\delta_{V_r} = f(Q_{rel})$, the analytical dependencies for calculating the absolute uncertainty of the measured gas volume under base conditions during a specified time, and the analytical dependencies for monitoring the change in the main error of the gas meter in the software of the gas volume microprocessor corrector serve as the basis for the methodology for developing automated adaptive systems for measuring fluid volume based on gas meters.

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Методологія розроблення автоматизованої адаптивної системи вимірювання об'єму плинного середовища із застосуванням лічильника газу

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Анотація

У статті виконано аналіз залежностей для оцінювання невизначеності об'єму газу за стандартних умов, вимірюваного за допомогою автоматизованої системи на основі лічильника та коректора об'єму газу. Як інтегральний показник точності системи вимірювання запропоновано застосовувати абсолютну невизначеність об'єму газу за визначений інтервал часу. Для обчислення цієї невизначеності розроблено залежності похибки лічильника газу від витрати газу через лічильник на основі статистичного опрацювання результатів метрологічної перевірки промислових роторних та турбінних лічильників газу. Запропоновано виконувати коректування значення вимірюваного об'єму газу за робочих умов із врахуванням невилученої систематичної похибки, обчисленої за розробленими залежностями, що забезпечить адаптацію вимірювальної системи до умов застосування та зміни витрати газу у вимірювальному трубопроводі. Сформовано методологію розроблення автоматизованих адаптивних систем вимірювання об'єму газу, яка базується на застосуванні адаптивного алгоритму коректування вимірюваного об'єму газу за робочих умов, аналітичних залежностей для обчислення абсолютної невизначеності вимірюваного значення об'єму газу за стандартних умов протягом визначеного інтервалу часу та аналітичних залежностей для контролю зміни основної похибки лічильника газу.

Ключові слова: вимірювання об'єму газу; автоматизована система; адаптивний алгоритм; лічильник газу; невизначеність об'єму газу.