Research of the metrological model of optic-thermal method of natural gas flow measurement

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Abstract
The article substantiates the importance of research aimed at the development and study of contactless method of natural gas flow measurement.

On the basis of the developed mathematical model of contactless optic-thermal method of gas flow measurement and key provisions of the uncertainty theory the metrological model analysis is made. The component of the combined standard uncertainty due to the uncertainty of uncorrelated input parameters of the measurement equation is researched and evaluated. The dominant components and the ways of reducing their impact on the combined standard uncertainty are selected. The greatest contribution to combined standard uncertainty of the method makes the uncertainty of interference fringes number measurement, the uncertainty of the distance between the cross-sections of the pipeline measurement and uncertainty of the coefficient determination, which characterizes the velocity distribution of the gas flow.

The components of combined standard uncertainty (thermophysical parameters of the gas and the pipeline material, the geometric characteristics of the pipeline), which are correlated with each other due to the temperature dependence, are identified. The uncertainty budget of correlated measurements is compiled. Quantitative assessment showed that the correlation between certain input parameters does not have large impact on the combined standard uncertainty of the measurement.

Analysis of the metrological model of the contactless optic-thermal method of gas flow measurement allowed estimating the relative combined standard uncertainty of the method and substantiating the perspective applications of the method for measuring gas flow in large diameter pipelines.

Keywords: gas flow; optic-thermal method; standard uncertainty; metrological model; correlated parameters; uncorrelated parameters; uncertainty budget.

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...to analyze and assess the dominant components of uncertainty from the point of view of their origin and ways of reducing their impact on the combined standard uncertainty;

- to analyze and assess the component of combined standard uncertainty, caused by the correlated input parameters of the measurement equation.

### Analysis of the metrological model

The contactless optic-thermal method for measuring gas flow is developed on the basis of optical and thermal methods combination.

The physical essence of the optical method for measuring gas flow is as follows: if there is gas transfer through the pipeline, there will be a pressure drop at two separated sections, which leads to a difference in the pressure drop through the pipeline, there will be a pressure drop at two separated sections, which leads to a difference in the gas refractive indices in these sections. As a result, the phase velocities of the optical rays passing through the studied sections will also differ. The resulting optical path difference is measured by a system consisting of an interferometer and a measuring signal-processing unit. By determining the optical difference in the path of the rays, we can conclude about the pressure difference, that is, about the speed or flow rate of gas in the pipeline.

Increasing in the sensitivity of the optical method is achieved because the optical difference in the path of the rays passing through separated sections of the pipeline increases due to the temperature difference in these sections.

The equation describing the optic-thermal method is [5]

\[ Q = \frac{1}{2} \frac{\mu \cdot l \cdot K}{m} \left( \frac{2\pi}{\beta} \int_0^{R_2} \frac{dr}{T_1(r)} - \frac{2\pi}{\beta} \int_0^{R_1} \frac{dr}{T_2(r)} \right) \left( 1 - \frac{3.75}{\xi} \right) \lambda_0 \cdot m, \]  

(1)

where \( Q \) – the gas flow; \( R \) – the inner radius of the pipeline; \( \mu \) – the gas viscosity coefficient; \( l \) – distance between the researched cross-sections; \( K \) – the coefficient determined as

\[ K = \frac{v_0^2}{m} \sum_{k=1}^{N} \left( \frac{1}{\omega_0_k - \omega_0} \right), \]

from the publication [5]; \( T_1 \) and \( T_2 \) – the absolute temperatures in cross-sections of the pipeline; \( r \) – the current radius; \( \xi \) – the coefficient determined as Lambert function; \( m \) – the number of interference fringes; \( \lambda_0 \) – the wavelength in vacuum.

The metrological model of optic-thermal method of natural gas flow measurement was analyzed based on the developed mathematical model.

A preliminary assessment of the uncertainty components of the optic-thermal method was made in the research, because there are no multiple observations for the study of the systematic and random effects influences. Information for a preliminary assessment was received from the numerical simulation results, natural experiments, the physical properties of the determined values, the passport data of the used equipment and directories.

The uncertainty in the gas flow measurement caused by the inaccuracy of the set uncorrelated input parameters of the measurement equation (1) is determined as [6]:

\[ U_i^2(Q) = \sum_{i=1}^{N} \left( \frac{\partial Q}{\partial x_i} \right)^2 U^2(x_i), \]  

(2)

where \( x_i \) – the input parameters of the measurement equation (1); \( U(x_i) \) – the measurement uncertainty of the \( i \)-th input parameter.

The estimation results of uncorrelated input parameters measurement uncertainty with the assumption of uniform distribution of scattering input values are presented in Table 1.

The uncertainty in the gas flow measurement caused by the inaccuracy of the set uncorrelated input parameters measurement equation (1) is

\[ U_i(Q) = 4.3356 \times 10^{-4} \text{ m}^3/\text{s}. \]

The analysis of uncertainty shows that the dominant components are due to the inaccuracy of number of interference fringes measuring \((\frac{\partial Q}{\partial \ell m}) S'(m) = 6.0035 \times 10^{-4} \text{ m}^3/\text{s})\), the inaccuracy in the cross-sections location \((\frac{\partial Q}{\partial \ell f}) S'(l) = 3.4789 \times 10^{-4} \text{ m}^3/\text{s})\), the inaccuracy in the determination of the gas flow rate type of the distribution \((\frac{\partial Q}{\partial \xi}) S'(\xi) = 1.1686 \times 10^{-4} \text{ m}^3/\text{s})\). Other components in accordance with the criterion of negligible errors can be neglected.

To identify possible ways to improve the accuracy of optical-thermal method, it is necessary to analyze the dominant components of uncertainty from the point of view of their origin and ways of reducing their influence on the combined standard uncertainty.

1. Component of uncertainty due to inaccuracy of the number of interference fringes measuring.

The measurement uncertainty of the interference fringes number associated with the instrumental error of the used interferometer (type B uncertainty). To reduce this component of uncertainty is possible by the use of high-precision laser interferometers.

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The estimation results of measurement uncertainty uncorrelated input quantities

| \( \frac{\partial Q}{\partial P} \), kg | \( \frac{\partial Q}{\partial l} \), s | \( \frac{\partial Q}{\partial R} \), s | \( \frac{\partial Q}{\partial \delta} \), s | \( \frac{\partial Q}{\partial \rho_g} \), s·K | \( \frac{\partial Q}{\partial \lambda} \), s·K
|---|---|---|---|---|---|
| 1.8261×10^{-3} | -2.0167×10^{-2} | 1.2975 | -1.7912×10^{-1} | 5.6263×10^{-3} | |
| \( U_P \), kg/s³ | \( U_1 \), m | \( U_R \), m | \( U_\delta \), m | \( U_{\rho_g} \), W | \( U_{\lambda} \), W·m·K
| 1.1561 | 9.2486×10^{-4} | 2.3124×10^{-4} | 5.7803×10^{-5} | 3.1845×10^{-3} | |
| \( U^2(P) \), m⁶/s² | \( U^2(l) \), m⁶/s² | \( U^2(R) \), m⁶/s² | \( U^2(\delta) \), m⁶/s² | \( U^2(\rho_g) \), m⁶/s² | |
| 4.4562×10^{-10} | 3.4789×10^{-8} | 9.1815×10^{-10} | 1.0720×10^{-10} | 9.6115×10^{-10} | |
| \( \frac{\partial Q}{\partial \lambda_0} \), s | \( \frac{\partial Q}{\partial K} \), kg·m² | \( \frac{\partial Q}{\partial \xi} \), m³/s³ | \( \frac{\partial Q}{\partial \mu_g} \), kg | \( \frac{\partial Q}{\partial \lambda_m} \), m²·s²·K | \( \frac{\partial Q}{\partial \rho_m} \), kg·s
| 214.3595 | -2.2631 | 2.3084×10^{-3} | -3.6514 | -1.7361×10^{-5} | |
| \( U_{\lambda_0} \), m | \( U_K \), K·m·s²/kg | \( U_{\xi} \), kg/m·s | \( U_{\mu_g} \), kg/m·s | \( U_{\lambda_m} \), W/kg·m·K
| 1.0947×10^{-13} | 1.1718×10^{-6} | 4.6810×10^{-2} | 8.3815×10^{-9} | 1.5607 | |
| \( U^2(\lambda_0) \), m⁶/s² | \( U^2(K) \), m⁶/s² | \( U^2(\xi) \), m⁶/s² | \( U^2(P) \), m⁶/s² | \( U^2(\lambda_T) \), m⁶/s² | |
| 5.5065×10^{-20} | 6.9918×10^{-10} | 1.1686×10^{-8} | 9.3662×10^{-12} | 7.3576×10^{-10} | |
| \( \frac{\partial Q}{\partial m} \), m⁶/s | \( \frac{\partial Q}{\partial c_g} \), m⁹·s·K | \( \frac{\partial Q}{\partial \rho_g} \), kg·s | \( \frac{\partial Q}{\partial c_m} \), m⁹·s·K | \( \frac{\partial Q}{\partial \rho_m} \), kg·s | |
| 4.1182×10^{-3} | 2.6484×10^{-7} | 1.0951×10^{-3} | 3.7153×10^{-4} | 1.3147×10^{-4} | |
| \( U_m \) | \( U_{c_g} \), J/kg·K | \( U_{\rho_g} \), kg/m³ | \( U_{c_m} \), J/kg·K | \( U_{\rho_m} \), kg/m³ | |
| 5.9541×10^{-2} | 85.9797 | 7.0953×10^{-2} | 1.1560×10^{-2} | 1.507×10^{-1} | |
| \( U^2(m) \), m⁶/s² | \( U^2(c_g) \), m⁶/s² | \( U^2(\rho_g) \), m⁶/s² | \( U^2(c_m) \), m⁶/s² | \( U^2(\rho_m) \), m⁶/s² | |
| 6.0035×10^{-8} | 5.1863×10^{-10} | 6.0131×10^{-9} | 1.8446×10^{-11} | 3.9254×10^{-10} | |

To improve the accuracy of the interference fringes measuring number to 0.0005 \( \lambda_0 \), it is possible by using a laser interferometer with the score bands based on frequency modulation [7].

2. Component of combined standard uncertainty due to the inaccuracy in the studied cross-sections location.

Component of combined standard uncertainty due to the inaccuracy in the studied cross-sections location has three components:

1) the type B uncertainty caused by the inaccuracy of the used measuring instrument. This component is primarily determined by the technical characteristics of the used radiation source (laser). Most suitable for optical measuring devices are gas lasers, since they provide monochromatic and coherent radiation in a continuous mode in the visible and infrared regions of the spectrum. For preliminary estimation of the optical-thermal method accuracy, the calculations used the technical characteristics of the helium-neon laser LG-55 (\( \lambda_0 = 0.6328 \) μm, beam diameter using a single-mode regime 0.0015 m) [7]. The reducing of the uncertainty component is achieved by pre-adjusting and fine-tune the optical system;

2) the uncertainty caused by the expansion of the pipeline material due to changes in ambient temperature. This component can be reduced by introducing the relevant correction to the measurement result.

The calculation of the input correction in system “pipeline – gas medium” for temperature conditions –70 to +60 °C for the pipeline with a diameter of 142 mm is shown below.
According to the research results [5]:

$$\frac{\partial m}{\partial \theta_c} = 6.6552 \,^\circ C, \quad \frac{\partial \theta_c}{\partial \varepsilon} = 65.8941 \,^\circ C/m.$$  

The uncertainty in the gas flow measurement caused by the availability of uncertainty $\Delta \varepsilon \varepsilon$ with the other fixed parameters is

$$\Delta Q = \frac{\partial Q}{\partial m} \frac{\partial m}{\partial \theta_c} \frac{\partial \theta_c}{\partial \varepsilon} \Delta \varepsilon,$$  

it equals

$$\Delta Q = 0.004118 \cdot 6.6552 \cdot 65.8941 \cdot \Delta \varepsilon = 1.8059 \cdot \Delta \varepsilon.$$  

The change of the distance between the measuring cross-sections depends on temperature in a known way [9]:

$$l = l_0 (1 + \alpha \varepsilon \theta_c),$$  

where $l_0$ – the distance between the measuring cross-sections at $T$; $\alpha \varepsilon$ – coefficient of thermal expansion of the pipe material, for steel $\alpha \varepsilon = 0.9 \times 10^{-5} \, K^{-1}$; $\theta_c$ – the ambient temperature changing $(-70...+60 \, ^\circ C).$

For $l = 2 \, m$, correction will be

$$\Delta Q = 2.1129 \times 10^{-3} \, m^3/s.$$  

3. Component of uncertainty due to inaccuracy in the determination of the gas flow rate type of the distribution.

In accordance with regulatory documentation the volumetric flow rate is defined as [10]

$$Q = K_p \cdot \varphi \cdot S,$$  

where $K_p$ – the ratio of the average flow rate in the cross-section to the flow rate at the measuring point; $\varphi$ – local flow rate; $S$ – the area of the pipeline cross-section.

At the described method, the local flow rate equals the flow velocity at the pipe axis [10]. The coefficient $K_p$ depends on the hydraulic characteristics of pipelines (roughness, Reynolds number) and it must be pre-defined for each measuring cross-section. When a known value of hydraulic friction coefficient, the coefficient $K_p$ is allowed to take in accordance with regulatory documentation [10] from 0.713 to 0.875.

The coefficient $K_p$ uncertainty calculation is:

$$K_p = \frac{\partial Q}{\partial m} \frac{\partial m}{\partial \theta_c} \frac{\partial \theta_c}{\partial \varepsilon} \Delta \varepsilon,$$  

Relative uncertainty is

$$u(K_p) = \frac{1}{K_p} \sqrt{ \left( \frac{1}{\varphi} u^2(\varphi) \right) + \left( \frac{\partial \varphi}{\partial \varphi} \right)^2 u^2(\varphi) } =$$  

$$\frac{u(\varphi)}{\varphi} \sqrt{ \left( \frac{1}{\varphi} u^2(\varphi) \right) + \left( \frac{\partial \varphi}{\partial \varphi} \right)^2 u^2(\varphi) } =$$  

$$\frac{u(\varphi)}{\varphi} \sqrt{ \left( \frac{u(\varphi)}{\varphi} \right)^2 + \left( \frac{\partial \varphi}{\partial \varphi} \right)^2 u^2(\varphi) } =$$  

$$\frac{u(\varphi)}{\varphi} \sqrt{ \left( \frac{u(\varphi)}{\varphi} \right)^2 + \left( \frac{\partial \varphi}{\partial \varphi} \right)^2 u^2(\varphi) } =$$  

$$\frac{u(\varphi)}{\varphi} \sqrt{ \left( \frac{u(\varphi)}{\varphi} \right)^2 + \left( \frac{\partial \varphi}{\partial \varphi} \right)^2 u^2(\varphi) } =$$  

In accordance with [10], the admissible error for measuring the flow velocity by the primary transducer should not exceed ± 3%, therefore, the relative type B uncertainty of velocity measurement, taking into account the 95 percent confidence level with which the error limit was obtained, will be

$$\frac{u(\varphi)}{\varphi} = \frac{u(\varphi)}{\varphi} = 0.03 \frac{2}{2} = 0.015.$$  

Then the coefficient $K_p$ measurement relative uncertainty is

$$\frac{u(K_p)}{K_p} = \frac{u(\varphi)}{\varphi} \sqrt{ \left( \frac{u(\varphi)}{\varphi} \right)^2 + \left( \frac{\partial \varphi}{\partial \varphi} \right)^2 u^2(\varphi) } =$$  

$$\frac{u(\varphi)}{\varphi} \sqrt{ \left( \frac{u(\varphi)}{\varphi} \right)^2 + \left( \frac{\partial \varphi}{\partial \varphi} \right)^2 u^2(\varphi) } =$$  

$$\frac{u(\varphi)}{\varphi} \sqrt{ \left( \frac{u(\varphi)}{\varphi} \right)^2 + \left( \frac{\partial \varphi}{\partial \varphi} \right)^2 u^2(\varphi) } =$$  

Reducing of the combined standard uncertainty component, caused by the inaccuracy of the $K_p$ setting [10], is achieved by prior calibration of the measuring instrument and plotting of gas flow rate for the certain diameter of the pipeline in accordance with the system of equations given in the research [5]. The influence of this component of the combined standard uncertainty is reduced by imposition the correction that calculated for the certain diameter of the pipeline.

The measurement equation (1) contains the parameters that are correlated with each other due to its dependence on the ambient temperature. These include the thermophysical parameters of the gas and the pipeline material, the geometric characteristics of the pipeline.

To estimate the degree of correlation, pairwise estimates of correlation moments are calculated [6]:

$$U(x_i, x_j) = \sum_{i=1}^{q} \frac{\partial x_i}{\partial q_i} \frac{\partial x_i}{\partial q_k} U^2(q_k),$$  

where $x$ – correlated parameters of equation; $q_k$, $k = 1, 2, ..., k$ – independent from each other variables that are dependent on input variables.

For equation (1) $q = T$. The value $U^2(T)$ was determined in accordance with the taken uncertainty of temperature setting ±1.0°C for the uniform distribution of the temperature values.

When determining the sensitivity coefficients $\frac{\partial x}{\partial q}$, it is necessary to have information about the
dependence of each correlated parameter \( x \) from the influencing quantity \( q = T \).

These dependencies have the following form:

1) The dependence of the distance between the measuring cross-sections \( l \), the radius of the pipeline \( R \) and the thickness of the pipe on the temperature \( T \) is determined by the pipeline material, and has the form [9]

\[
l = l_0 (1 + \alpha_m (T - T_0)); \quad (8)
\]

\[
R = R_0 (1 + \alpha_m (T - T_0)); \quad (9)
\]

\[
\delta = \delta_0 (1 + \alpha_m (T - T_0)); \quad (10)
\]

2) The dependence of gas viscosity \( \mu_g \) on temperature \( T \) depends on the molecular composition of the gas and is determined as [9]

\[
\mu_g = \frac{\mu^* \cdot T}{\sqrt{6 \cdot \sigma^*}}, \quad (11)
\]

where \( \mu^* \) – the mass of the gas molecules;

\( \sigma^* \) – the effective sectional area of the gas molecules.

3) Dependence of gas thermal conductivity \( \lambda_g \) on temperature \( T \) has the form [9]

\[
\lambda_g = \frac{i}{2 \sqrt{6} \cdot \sigma_g} \cdot \sqrt{\frac{T}{m_g}}, \quad (12)
\]

where \( i \) – the degrees of freedom of gas molecules.

4) The gas density \( \rho_g \) depends on temperature \( T \) as [9]

\[
\rho_g = \frac{P}{k_b T} \cdot m_g. \quad (13)
\]

5) Thermal conductivity of pipe material \( \lambda_m \) is defined as [9]

\[
\lambda_m = \lambda_{m0} (1 + \alpha_L (T - T_0)), \quad (14)
\]

where \( \lambda_{m0} \) – the thermal conductivity of the pipe material at \( T_0 \); \( \alpha_L \) – constant coefficient for a certain material.

6) The density of the pipe material \( \rho_m \) is defined as [9]

\[
\rho_m = \rho_{m0} (1 + \alpha_r (T - T_0)), \quad (15)
\]

where \( \rho_{m0} \) – the density of the pipe material at \( T_0 \); \( \alpha_r \) – constant coefficient for a certain material.

Based on dependencies (8–13) the measurement uncertainty budget of correlated input parameters of equation (1) was obtained (Table 2).

### Table 2

| \( \frac{\partial Q}{\partial x_i} \) \( S(x_i, x_j) \) | \( \frac{\partial Q}{\partial x_j} \) \( S(x_i, x_j) \) | \( S(l) \) | \( S(R) \) | \( S(\delta) \) | \( S(\mu_g) \) |
|---|---|---|---|---|---|
| \( S(l) \) | 1.3589 \times 10^8 | -3.5322 \times 10^{-9} | 1.2069 \times 10^{-9} | 3.5676 \times 10^{-10} |
| \( S(R) \) | -3.5322 \times 10^{-9} | 9.1815 \times 10^{-10} | 3.1373 \times 10^{-10} | -9.2734 \times 10^{-11} |
| \( S(\delta) \) | 1.2069 \times 10^{-9} | 3.1373 \times 10^{-10} | 1.0720 \times 10^{-10} | -9.2734 \times 10^{-11} |
| \( S(\mu_g) \) | 3.5676 \times 10^{-10} | -9.2734 \times 10^{-11} | 3.1686 \times 10^{-11} | 9.3662 \times 10^{-12} |
| \( S(\lambda_g) \) | -3.6140 \times 10^{-9} | 9.3940 \times 10^{-10} | -3.2099 \times 10^{-10} | -9.4880 \times 10^{-11} |
| \( S(\rho_g) \) | -9.0393 \times 10^{-9} | 2.3496 \times 10^{-9} | -8.0286 \times 10^{-10} | -2.3732 \times 10^{-10} |
| \( S(\lambda_m) \) | 3.1620 \times 10^{-9} | -8.2191 \times 10^{-10} | 2.8084 \times 10^{-10} | 8.3014 \times 10^{-11} |
| \( S(\rho_m) \) | 2.3096 \times 10^{-9} | -6.0034 \times 10^{-10} | 2.0513 \times 10^{-10} | 6.0635 \times 10^{-11} |

| \( \frac{\partial Q}{\partial x_i} \) \( S(x_i, x_j) \) | \( \frac{\partial Q}{\partial x_j} \) \( S(x_i, x_j) \) | \( S(\lambda_m) \) | \( S(\rho_m) \) | \( S(\lambda_g) \) | \( S(\rho_g) \) |
|---|---|---|---|---|---|
| \( S(l) \) | 3.1620 \times 10^{-9} | 2.3096 \times 10^{-9} | -3.6140 \times 10^{-9} | -9.0393 \times 10^{-9} |
| \( S(R) \) | -8.2191 \times 10^{-10} | -6.0034 \times 10^{-10} | 9.3940 \times 10^{-10} | 2.3496 \times 10^{-9} |
| \( S(\delta) \) | 2.8084 \times 10^{-10} | 2.0513 \times 10^{-10} | -3.2099 \times 10^{-10} | -8.0286 \times 10^{-10} |
| \( S(\mu_g) \) | 8.3014 \times 10^{-11} | 6.0635 \times 10^{-11} | -9.4880 \times 10^{-11} | -2.3732 \times 10^{-10} |
| \( S(\lambda_g) \) | -8.4094 \times 10^{-10} | -6.1424 \times 10^{-10} | 9.6115 \times 10^{-10} | 2.4040 \times 10^{-9} |
| \( S(\rho_g) \) | -2.1034 \times 10^{-10} | -1.5363 \times 10^{-9} | 2.4040 \times 10^{-9} | 6.01312 \times 10^{-9} |
| \( S(\lambda_m) \) | 7.3576 \times 10^{-10} | 5.3742 \times 10^{-11} | -8.4094 \times 10^{-10} | -2.1034 \times 10^{-10} |
| \( S(\rho_m) \) | 5.3742 \times 10^{-11} | 3.9254 \times 10^{-10} | -6.1424 \times 10^{-10} | -1.5363 \times 10^{-9} |
Research of the metrological model of optic-thermal method of natural gas flow measurement

Дослідження метрологічної моделі оптико-теплового методу вимірювання витрати природного газу

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Анотація
У статті обґрунтовано важливість проведення досліджень, спрямованих на розробку та вивчення безконтактних методів вимірювання витрати природного газу.

An analysis of the metrological model allows to conclude that the combined standard uncertainty of determining the gas flow by optic-thermal method can be up to ±0.2% for the gas flows more than 0.35 m³/s and reduces with increasing gas flow and pipe diameter.

The combined standard uncertainty of optic-thermal method of natural gas flow measurement is

\[ S(Q) = \sqrt{\sum_{i=1}^{n} \left( \frac{\partial Q}{\partial x_i} S(x_i) \right)^2 + 2 \sum_{i=1}^{n} \sum_{j=i+1}^{n} \frac{\partial Q}{\partial x_i} \frac{\partial Q}{\partial x_j} S(x_i, x_j)} = \sqrt{16.6774 \times 10^{-8} - 1.6683 \times 10^{-8} = 3.8741 \times 10^{-4} \text{ m}^3/\text{s}.} \]
Исследование метрологической модели оптико-теплового метода измерения расхода природного газа

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Аннотация
На базе разработанной математической модели бесконтактного оптико-теплового метода измерения расхода газа и основных положений теории неопределенности проведен анализ метрологической модели метода. Исследована и оценена составляющая суммарной стандартной неопределенности, обусловленная неопределенностью некоррелированных входных параметров уравнения измерения. Выделены доминирующие составляющие и проанализированы пути уменьшения их влияния на суммарную стандартную неопределенность.

Выведены составляющие суммарной стандартной неопределенности, которые коррелированы друг с другом вследствие зависимости от температуры среды. Составлен бюджет неопределенности коррелированных измерений.

Анализ метрологической модели бесконтактного оптико-теплового метода измерения расхода природного газа позволил оценить относительную суммарную стандартную неопределенность метода и обосновать перспективность применения метода для измерения расхода газа в трубопроводах больших диаметров.

Ключевые слова: расход газа; оптико-тепловой метод; стандартная неопределенность; метрологическая модель; коррелированные параметры; некоррелированные параметры; бюджет неопределенностей.

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