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Metrological studies of a reference installation for reproducing the mass flow of humid air

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Abstract

The relevance of the development and metrological studies of reference installations when working in a humid gas medium is considered. The concept of creating a reference installation for reproducing the mass flow of humid air is outlined. An algorithm for the operation of a reference installation has been developed, which provides for the generation of water vapour as a component of the gas flow. Based on the algorithm and operation features of a reference installation, a list of the considered type A uncertainties, which relate to the estimation of the air volume measured by a reference meter, duration of the control volume reproduction, mass of generated water vapour during the period of reproduction of the volume, and relative humidity of the ambient air, was formulated. Type B uncertainties are considered, which are determined by metrological characteristics of the used measuring equipment: reference gas meter, chronometer, hygrometer, manometer, thermometer, and instruments for measuring the mass of generated moisture. Algorithms for evaluating the standard uncertainty by using the standard reference data are given: pressure and density of saturated water vapours, and air density under standard conditions. The formula and algorithm for its metrological evaluation based on the uncertainty theory for determining the compressibility coefficient of the ambient air used during the operation of the installation, taking into account its relative humidity, are also presented. The expressions for evaluating the combined and extended uncertainties of the developed installation are given.

The developed model relates to the mass measurement of wet gas and allows assessing the influence of operating conditions of the installation on the indications of the mass flow measuring equipment of various operating principles, for example, thermo-anemometric, ultrasonic.

The developed metrological model can be used to estimate metrological characteristics of reference installations operating in different types of gaseous medium, including natural gas.

Keywords: reference installation; air; humidity; compressibility coefficient; mass flow; reference gas meter; thermo-anemometer; uncertainty.

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Introduction

At present, the accuracy and reproducibility of physical quantities are relevant in the field of accounting for gas-fluid medium. Metrological studies of flow measurements taking into account various physical and chemical characteristics of the working medium, which are carried out with the help of reference installations for reproducing the volume and flow of gas media, require sufficient attention. They realise the scientific and methodological basis for determining the metrological characteristics of such measuring instruments as flow meters and gas meters.

As it is known [1], most reference instruments and installations for determining the metrological characteristics of instruments in the field of flowmetry of gaseous media operate on dry air or dry natural gas. This is caused primarily by technical requirements for the quality characteristics of natural gas (for example, the molar fraction of water should not exceed 0.00015 [2]), which is transported by gas networks. In addition, the current regulatory documents that regulate the conditions of verification of domestic and industrial gas meters [3—5] provide for the operation of reference installations in air under conditions when the moisture content in it practically does not affect the change of metrological characteristics of the gas meters under consideration. This approach is justified by the fact that moisture reduces the calorific value of natural gas while simultaneously increasing its volume, and at the same time, the possibility of hydrate formations in low-pressure gas networks increases. The presence of moisture in natural gas at the stage of extraction is related to the origin and operation modes of gas fields, and at the stage of delivery to the final consumer, it depends on the level of drying at industrial complexes and directly on the condition of the gas transportation system and the conditions in which it functions.

Along with this, when producing gas, which is usually wet, new measurement technologies, can be used for its metering, for example, using the thermo-anemometric method [6]. Measuring instruments of this type are relatively simple in design and are characterized by sufficient accuracy and sensitivity of measuring the multicomponent flows, and have a small inertia. In addition, from the point of view of the authors, in the future they can be used as moisture meters of gaseous media.

The theoretical aspects of the influence of humidity on the operation of thermo-anemometric converters are described in [7], which determines the need for practical confirmation of theoretical studies. Therefore, the development and metrological studies of reference installations for reproducing the mass flow of humid air are relevant, which is the purpose of highlighting the research results of this publication.

Main part

With the participation of the authors, a schematic diagram of the installation was developed, which provides for the generation of a range of air flows with different degrees of humidity. The installation includes a flow source (blower), which can provide different air flow modes by throttling the flow with a choke mounted at its outlet. The flow source is connected in series to the reference gas meter, which, complete with a chronometer, allows determining the volume flow of air in the installation. The output from the reference meter is connected in series to the ultrasonic humid generator, which saturates the air passing through the gas fraction of the water container with moisture. The humidified air stream enters the test instrument of the measuring equipment, for example, a thermo-anemometer. The installation measures the pressure and temperature of the working medium at its inlet and outlet, as well as the relative humidity of the medium entering the installation inlet. The mass value of moisture, which is added to the air flow in the installation, is determined with the help of a microprocessor-based tensor-resistive scale.

The algorithm of the operation of the installation, taking into account known physical patterns of changes in the density and partial pressure of the water vapour of the gas mixture, involves the implementation of such an algorithm proposed by the authors [8]:

$$q_m = \frac{V}{\tau}\left(2.89\cdot 10^{-3}\cdot \rho_S \frac{P-\varphi\cdot P_{W\max}}{T\cdot K_W}+\varphi\cdot\rho_{W\max}\right)+\frac{m}{\tau}, \quad (1)$$

where q_m is the mass flow of generated humid air, kg/s; V is the volume of air measured by the reference meter over time τ, m^3; φ, P, T are relative humidity, absolute pressure and absolute air temperature under operating conditions of the installation (after the air flow generator) (φ is a dimensionless unit; P – Pa; T – K); $P_{W\max}$, $\rho_{W\max}$ are the partial pressure and density of saturated water vapour under operating conditions of the installation (Pa, kg/m^3 accordingly); K_W is the compressibility coefficient of humid air (ambient medium) at the inlet of the installation (dimensionless unit); ρ_S is the air density under standard conditions, kg/m^3; m is the mass of generated humid per time τ, kg.

To calculate the compressibility coefficient of humid air K_W, one can use a calculation method that takes into account the water vapour content in the gas accounting for the methodology [9] and its specification, taking into account that the compressibility coefficient of water vapour at low working pressures $K_{WV}=1$ [10]:

$$K_W = K_D + \frac{\varphi\cdot P_{W\max}}{100\cdot P}\left(1-K_D\right), \quad (2)$$

where K_D is the compressibility coefficient of dry air under operating conditions of the installation.

The relative error of the studied flowmeter δ can be experimentally calculated using the formula:

$$\delta = \frac{(q-q_m)}{q_m}\cdot 100\%, \quad (3)$$

where q is the flow, which is measured by the flowmeter under consideration.

To evaluate the uncertainty of the compressibility coefficient of humid air, the following expressions can be used to estimate the weighting coefficients of the influence of the components included in formula (2):

$$\frac{\partial K_W}{\partial K_D} = 1-\frac{P_{W\max}\cdot\varphi}{100\cdot P}, \quad (4)$$

$$\frac{\partial K_W}{\partial\varphi} = -\frac{P_{W\max}\cdot\left(K_D-1\right)}{100\cdot P}, \quad (5)$$

$$\frac{\partial K_{WV}}{P_{W\max}} = -\frac{\varphi\cdot\left(K_D-1\right)}{100\cdot P}, \quad (6)$$

$$\frac{\partial K_W}{\partial P} = \frac{P_{W\max}\cdot\varphi\cdot\left(K_D-1\right)}{100\cdot P^2}. \quad (7)$$

According to [11], the combined uncertainty for estimating the humid gas compressibility coefficient can be written as the following expression, since the table data and the error of the manometer and hygrometer are characterized by type B uncertainties, and the experimental data (measurements of operating pressure and relative humidity) will be characterized by type A uncertainty:

$$u_C(K_W)=\sqrt{\begin{aligned}&\left(\frac{\partial K_W}{\partial K_D}\cdot u_B(K_D)\right)^2+\left(\frac{\partial K_W}{\partial P}\cdot u_A(P)\right)^2+\left(\frac{\partial K_W}{\partial P}\cdot u_B(P)\right)^2+\\&+\left(\frac{\partial K_W}{\varphi}\cdot u_B(\varphi)\right)^2+\left(\frac{\partial K_W}{\varphi}\cdot u_A(\varphi)\right)^2+\left(\frac{\partial K_W}{\partial P_{W\max}}\cdot u_B(P_{W\max})\right)^2\end{aligned}}. \quad (8)$$

Since the metrological model of the reference installation is built on the theory of uncertainty and contains standard uncertainties of type A and B, which in their combination form the combined and extended uncertainty of the installation, which is methodically explained in [11].

Uncertainties of type A are determined by parameters that are subject to experimental study during metrological studies. These are the uncertainties of the volume of air measured by the reference meter $u_A(V)$, duration of reproduction of the control volume $u_A(\tau)$, mass of generated water vapour during the volume reproduction period $u_A(m)$, relative humidity of the ambient air $u_A(\varphi)$. These uncertainties are evaluated according to the known formula:

$$u_A(F)=\sqrt{\frac{\sum_{i=1}^{n}\left(F_i-\bar{F}\right)^2}{n(n-1)}}, \quad (9)$$

where the letter F_i refers to the parameters of the volume of measured air V_i, the duration of reproduction of the volume of the working medium τ_i, the mass of generated water vapour m_i, the relative humidity of the ambient air φ_i at the i-th measurements, accordingly; and $\bar{F}$ is the average arithmetic value of the parameters listed above; n is the number of repeated measurements (n = 13).

Uncertainties of type B are formed by the standard uncertainties of the used measuring instruments $u_B(V)$, $u_B(\tau)$, $u_B(m)$, $u_B(\varphi)$, $u_B(T)$, $u_B(P)$, as well as metrological characteristics of the reference data, which relate to the determination of the partial pressure of water vapour $u_B(P_{W\max})$, its density in the saturation state $u_B(\rho_{W\max})$, and air density under standard conditions $u_B(\rho_S)$. Taking into account the adopted uniform law of distribution of measured and table values, the specified uncertainties can be evaluated as:

$$u_B(E)=\frac{E}{\sqrt{3}}, \quad (10)$$

where the letter E refers to the values of the maximum basic permissible error of the instruments to measure volume δ_V, time δ_τ, mass δ_m, relative humidity δ_φ, temperature δ_T, pressure δ_P, the maximum basic permissible error of the partial pressure of water vapour $\delta_{Pw\max}$, density in the state of saturated water vapour $\delta_{\rho w\max}$, and air density under standard conditions $\delta_{\rho s}$.

The combined uncertainty $u_C(q_m)$ during the operation of the installation in the flow reproduction mode, taking into account the main provisions of the theory of uncertainty in measurements, is evaluated by the formula:

$$u_C(q_m)=\sqrt{\begin{aligned}&\left(\frac{\partial q_m}{\partial V}\cdot u_C(V)\right)^2+\left(\frac{\partial q_m}{\partial \tau}\cdot u_C(\tau)\right)^2+\left(\frac{\partial q_m}{\partial \rho_S}\cdot u_B(\rho_S)\right)^2+\left(\frac{\partial q_m}{\partial P}\cdot u_B(P)\right)^2+\\&+\left(\frac{\partial q_m}{\partial \varphi}\cdot u_C(\varphi)\right)^2+\left(\frac{\partial q_m}{\partial P_{W\max}}\cdot u_B(P_{W\max})\right)^2+\left(\frac{\partial q_m}{\partial T}\cdot u_B(T)\right)^2+\\&+\left(\frac{\partial q_m}{\partial K_W}\cdot u_C(K_W)\right)^2+\left(\frac{\partial q_m}{\partial \rho_{W\max}}\cdot u_B(\rho_{W\max})\right)^2+\left(\frac{\partial q_m}{\partial m}\cdot u_C(m)\right)^2\end{aligned}}. \quad (11)$$

Combined uncertainties $u_C(V)$, $u_C(\tau)$, $u_C(\varphi)$, $u_C(m)$ of the estimation of parameters V, τ, φ, m are evaluated according to the formula:

$$u_C(D)=\sqrt{u_B^2(D)+u_A^2(D)}, \quad (12)$$

where D is the conditional designation of each of the four parameters indicated above.

To evaluate the combined uncertainty of the mass flow of humid air q_m, which passed through the device under consideration, we present the following expressions for estimating the weighting coefficients of the influence of the components included in formula (1):

$$\frac{\partial q_m}{\partial V}=\frac{\varphi\cdot\rho_{W\max}+\dfrac{2.89\cdot10^{-3}\cdot\rho_S\cdot(P-P_{W\max}\cdot\varphi)}{K_W\cdot T}}{\tau}, \quad (13)$$

$$\frac{\partial q_m}{\partial \tau}=-\frac{m}{\tau^2}-\frac{V\cdot\left[\varphi\cdot\rho_{W\max}+\dfrac{2.89\cdot10^{-3}\cdot\rho_S\cdot(P-P_{W\max}\cdot\varphi)}{K_W\cdot T}\right]}{\tau^2}, \quad (14)$$

$$\frac{\partial q_m}{\partial \rho_S}=\frac{2.89\cdot10^{-3}\cdot V\cdot(P-P_{W\max}\cdot\varphi)}{K_W\cdot T\cdot\tau}, \quad (15)$$

$$\frac{\partial q_m}{\partial P}=\frac{2.89\cdot10^{-3}\cdot V\cdot\rho_S}{K_W\cdot T\cdot\tau}, \quad (16)$$

$$\frac{\partial q_m}{\partial \varphi}=\frac{V\cdot\left(\rho_{W\max}-\dfrac{2.89\cdot10^{-3}\cdot P_{W\max}\cdot\rho_S}{K_W\cdot T}\right)}{\tau}, \quad (17)$$

$$\frac{\partial q_m}{\partial P_{W\max}}=-\frac{2.89\cdot10^{-3}\cdot V\cdot\varphi\cdot\rho_S}{K_W\cdot T\cdot\tau}, \quad (18)$$

Table 1

Uncertainty budget of the installation for reproducing the mass flow of humid air

Measured quantity x_i and its dimension	Estimated value	Value of type A uncertainty, $u_A(x_i)$	Sensitivity coefficient, $\partial q_m/\partial x_i$		Value of type B uncertainty, $u_B(x_i)$	Measurement uncertainty contributions, $u_C(x_i)$
			Calculation algorithm formula	Result		
V, m^3	5.5×10^{-2} m^3	2.44×10^{-5} m^3	(13)	6.09×10^{-3} kg/(s·m^3)	1.16×10^{-4} m^3	1.18×10^{-4} m^3
τ, s	200 s	7.05×10^{-2} s	(14)	-1.75×10^{-6} kg/(s^2)	5.77×10^{-2} s	9.11×10^{-2} s
ρ_S, kg/m^3	1.20 kg/m^3	–	(15)	2.76×10^{-4} m^3/s	5.77×10^{-6} kg/m^3	–
P, Pa	1.03×10^{5} Pa	39.01 Pa	(16)	3.27×10^{-9} kg/(s·Pa)	57.74 Pa	–
φ	0.5	1.98×10^{-4}	(17)	-2.88×10^{-6} kg/s	2.89×10^{-3}	2.89×10^{-3}
$P_{W\max}$, Pa	2335.34 Pa	–	(18)	-1.63×10^{-9} kg/(s·Pa)	5.66×10^{-1} Pa	–
T, K	293 K	–	(19)	-1.14×10^{-6} kg/(s·K)	5.77×10^{-2} K	–
K_W	0.9996	–	(20)	-3.33×10^{-4} kg/s	–	5.77×10^{-5}
$\rho_{W\max}$, kg/m^3	17.29×10^{-3} kg/m^3	–	(21)	1.38×10^{-4} m^3/s	5.77×10^{-6} kg/m^3	–
m, kg	3×10^{-3} kg	9.94×10^{-7} kg	(22)	5×10^{-3} s^{-1}	5.77×10^{-7} kg	1.15×10^{-6} kg

$$\frac{\partial q_m}{\partial T} = -\frac{2.89\cdot10^{-3}\cdot V\cdot\rho_S\cdot(P-P_{W\max}\cdot\varphi)}{K_W\cdot T^2\cdot\tau}, \quad (19)$$

$$\frac{\partial q_m}{\partial K_W} = -\frac{2.89\cdot10^{-3}\cdot V\cdot\rho_S\cdot(P-P_{W\max}\cdot\varphi)}{K_W{}^2\cdot T\cdot\tau}, \quad (20)$$

$$\frac{\partial q_m}{\partial \rho_{W\max}} = \frac{V\cdot\varphi}{\tau}, \quad (21)$$

$$\frac{\partial q_m}{\partial m} = \frac{1}{\tau}. \quad (22)$$

The extended uncertainty of the installation is evaluated by the formula:

$$U = k_0\cdot u_C\left(q_m\right), \quad (23)$$

where k_0 is the coverage factor, which forms the numerical value of the expanded uncertainty for the corresponding confidence level, which for 95% in the absence of correlations between measurement parameters can be taken equal to two.

The calculation of the uncertainty budget of the developed installation is given in Table 1.

Taking into account that the combined uncertainty according to (11) is $u_C(q_m)$ = 7.64×10^{-7} kg/s, the calculated value of the absolute expanded uncertainty according to (23) will be U = 1.53×10^{-6} kg/s. At the same time, the relative extended uncertainty (in percent) according to the selected calculated values given in the Table 1 is quantified as Ur = ±0.44% provided that q_m = 3.502×10^{-4} kg/s is calculated according to (1).

Conclusion

Based on the results of theoretical studies, algorithms for evaluating the standard uncertainties of measurements of the control volume of the reference installation, its reproduction time, the mass of generated moisture, the relative humidity of the working medium and operating parameters of the installation were developed, as well as the algorithm for calculating the compressibility coefficient of humid air, which is necessary for metrological assessment of reference installations for reproduction of mass flows of humid air. Expressions for evaluating combined and extended uncertainties during the operation of the installation under consideration are given.

The developed model concerns the mass measurements of humid gas and allows estimating the influence of operating conditions of the installation on the indications of mass flow measuring equipment of various principles of operation, for example, thermo-anemometric, ultrasonic. The use of numerical modelling characterizes that the extended uncertainty of the installation with the correct selection of reference instruments and measuring transducers can be within $\pm(0.4-0.5)\,\%$, which justifies the possibility of its use as a working standard.

The developed metrological model can be used to assess metrological characteristics of reference installations operating on different types of gaseous media, including natural gas.

Метрологічні дослідження еталонної установки для відтворення масових витрат вологого повітря

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Анотація

Розглянуто актуальність розроблення та метрологічних досліджень еталонних установок при роботі на вологому газоплинному середовищі. Викладено концепцію створення еталонної установки для відтворення масових витрат вологого повітря. Розроблено алгоритм функціонування еталонної установки, що передбачає генерування водяної пари як компонента газоплинного потоку. На основі алгоритму та особливостей функціонування еталонної установки сформульовано перелік досліджуваних невизначеностей типу А, що стосуються оцінювання об'єму виміряного повітря еталонним лічильником, тривалості відтворення контрольного об'єму, маси генерованої водяної пари за період відтворення об'єму та відносної вологості повітря навколишнього середовища. Розглянуто невизначеності типу В, що визначаються метрологічними характеристиками використаних засобів вимірювальної техніки: еталонного лічильника газу, хронометра, вологоміра, манометра, термометра та засобу вимірювання маси генерованої вологи. Наведено алгоритми оцінювання стандартної невизначеності від використання стандартних референтних даних: тиску та густини насиченої водяної пари та густини повітря за стандартних умов. Також подано формулу та алгоритм її метрологічного оцінювання на базі теорії невизначеності для визначення коефіцієнта стисливості, використовуваного при роботі установки навколишнього повітря з врахуванням його відносної вологості. Наведено вирази для обчислення сумарної та розширеної невизначеностей розробленої установки.

Розроблена модель стосується масового вимірювання вологого газу та дозволяє оцінювати вплив робочих умов установки на покази засобів масової витратовимірювальної техніки різних принципів дії, наприклад, термоанемометричних, ультразвукових.

Розроблену метрологічну модель може бути застосовано для оцінювання метрологічних характеристик еталонних установок із функціонуванням на різних видах газоплинних середовищ, у тому числі природного газу.

Ключові слова: еталонна установка; повітря; вологість; коефіцієнт стисливості; масова витрата; еталонний лічильник газу; термоанемометр; невизначеність.

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