Equation uncertainty adjustment of the gas flow measurement results with flowmeters with standard orifice plates

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Abstract

The analysis of the relative uncertainty of the measurement result equation of gas flowrate, using differential pressure flowmeters with standard orifice plates, defined in GOST 8.586.5-2005 and DSTU GOST 8.586.5:2009, is presented. It has been found out that this equation is presented in a simplified form by introducing simplified equations for calculation of relative influence coefficients of input variables upon mass gas flow rate and relative uncertainty of gas expansion factor. New analyticaldependencies for estimation of relative coefficients of influence of differential pressure on orificeplate, of orificeplate hole diameter and measuring pipeline inner diameter on mass gas flow rate. The equation, used to calculate relative uncertainty of gas.expansion factor has been specified. The new equations, used to determine relative influence coefficients of absolute pressure and gas isentropic exponent coefficient on gas expansion factor have been obtained. It has been found out that relative influence coefficients of input variables on mass flow rate of gas and gas expansion factor accept lower values than coefficients of equations, given in Standards. Values of relative influence coefficients obtained from the authors' equations are in good agreement with the results of the calculation of the equations presented in differential form and given in ISO 5168:2005. The analytical dependence reduces relative uncertainty of gas flow rate measurement result.

Keywords: *expansion factor, flow measurement, flowmeter, influence coefficient, mass flow rate, orificeplate, standard primary device, variable differential pressure method, uncertainty.*

Introduction

Differential pressure flowmeters, measuring gas by differential pressure method are widely used for measuring gas or gaseous medium flow rate. Though differential pressure method has been used for a long period of time, it is constantly being improved by input of new analytical dependencies of coefficients which are included into gas-flow equation. Thus, gas flow rate measuring accuracy is also changed. Nowadays in global practice [1–3] in the course of gas flow rate measuring by differential pressure method, the accuracy of its measuring tends to be evaluated due to standard uncertainty of gas flowrate measurement result. Such approach is used in the new International Standards ISO 5168:2005 [4] and ISO 5167:2003 [5–8], as well as the new Interstate Standards GOST 8.586.1,2,3,4,5–2005 [9–11] and in the National Standards DSTU GOST 8.586.1,2,3,4,5:2009 [12–14]. But some standards present simplified algorithms for determination of standard uncertainty of gas flowrate measurement results. Therefore it's necessary to analyze existing techiques of measurement accuracy evaluation as well as equations, used to calculate measurement result uncertainty constituents and if possible to obtain their new analytical dependencies. And this issue is of current importance.

Analysis of modern investigations and publications

On the assumption of uncertainty theory fundamentals, uncertainty is divided into standard uncertainty and expanded uncertainty of coefficient or result of physical variable measurement. While physical variable measuring by indirect method (differential pressure method included) resulting value is obtained by calculating it with the help of equation or algorithm from values of a range of other measured variables $x_i \in X$ (X is multitude of variables, measured or determined by equation). The resulting standard uncertainty $u_c(y)$ is equal to the square root of a sum of squares of components, provided that components are dispersions or covariations of other these variables, evaluated in accordance with the change of measurement result depending on the change of these variables [1, 4, 11, 14], thus

$$u_c(y) = \sqrt{\sum_{i=1}^{n} \left[F_{x_i} u(x_i)\right]^2}\ , \qquad (1)$$

where F_{x_i} is absolute coefficient of influence of i-parameter x_i upon variables y, which value is determined in the following way:

$$F_{x_i} = \frac{\partial y}{\partial x_i}\ . \qquad (2)$$

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If it's impossible to obtain partial initial $\frac{\partial y}{\partial x_i}$ absolute coefficient of influence F_{x_i} is determined as follows:

$$F_{x_i} = \frac{\Delta y}{\Delta x_i}, \qquad (3)$$

where Δy is change of variable y, value of which is calculated by equation $\Delta y = y(x_{i2}) - y(x_{i1})$; Δx_i is change of measured variable x_i, determined by equation $\Delta x_i = x_{i2} - x_{i1}$; x_{i1}, x_{i2} is accordingly the first and the second measured values of x_i.

Such calculation of combined standard uncertainty of measurement result of gas flow rate and its constituents and therefore absolute influence coefficient has been used in ISO 5168:2005 [4].

Relative combined standard uncertainty $u_c'(y)$ is defined as the ratio of combined standard uncertainty of measurement result to evaluation value of measured variable, expressed as a percentage and its value is calculated by the following equation [1, 11, 14]:

$$u_{\mathrm{c}}'(y) = 100\frac{u_{\mathrm{c}}(y)}{y} = \sqrt{u_{\mathrm{FM}}'^2 + \sum_{i=1}^{n}\left[\vartheta_{x_i} u'(x_i)\right]^2}, \qquad (4)$$

where u_{FM}' is relative standard uncertainty, attributed to functional dependence of y determination; ϑ_{x_i} is relative influence coefficient of i-parameter x_i upon y, determined with the help of such equation [1, 11, 14]:

$$\vartheta_{x_i} = \frac{\partial y}{\partial x_i}\frac{x_i}{y} = \frac{\Delta y}{\Delta x_i}\frac{x_i}{y}. \qquad (5)$$

Combined expanded uncertainty defines an interval around measurement result, within the limits of which we will be able to find a large part of the distribution of values that could reasonably be attributed to the measurand. Combined expanded uncertainty U_{cy} of coefficient or measurand y are determined by the following equation [1, 11, 14]:

$$U_{cy} = k u_{cy}, \qquad (6)$$

where k is coverage factor which depends upon probability distribution attributed to measurand and confidence level.

Relative combined expanded uncertainty U_{cy}' is the ratio of combined expanded uncertainty to evaluation value of measureand, expressed as a percentage. Value of relative combined expanded uncertainty U_{cy}' is estimated by the following equation [1, 11, 14]:

$$U_{\mathrm{c}}'(y) = 100\frac{U_{\mathrm{c}}(y)}{y} = \sqrt{U_{\mathrm{FM}}'^2 + \sum_{i=1}^{n}\left[\vartheta_{x_i} U'(x_i)\right]^2}, \qquad (7)$$

where U_{FM}' is relative expanded uncertainty, attributed to functional dependence of variable definition y.

Mass gas flow rate q_m according to [1, 9, 10, 12, 13] is determined as follows:

$$q_m = \frac{\pi}{4} d^2 C E K_a K_n \varepsilon \sqrt{2\Delta p \rho}, \qquad (8)$$

where d is diameter of orifice plate opening at operating gas temperature; C is coefficient of orifice plate outflow; E is inlet velocity coefficient; K_a is adjustment coefficient, accounting for roughness of inner surface of measuring pipeline; K_n is adjustment coefficient, accounting for bluntness of inner edge of orifice plate; Δp is differential pressure on orifice plate; ρ is gas density at operating conditions.

Inlet velocity coefficient E depends on relative diameter β of orifice plate and is determined by equation [6, 10, 13]:

$$E = \frac{1}{\sqrt{1-\beta^4}}, \qquad (9)$$

where relative orifice plate diameter is estimated as [6, 10, 13]

$$\beta = \frac{d}{D}, \qquad (10)$$

where D is inner diameter of measuring pipeline.

Equation for estimation of gas expansion factor ε for an orifice-plate with any type of pressure take-off is as follows [1, 6, 10, 13]:

$$\varepsilon = 1 - \left(0.351 + 0.256\beta^4 + 0.93\beta^8\right)\left(1 - \tau^{\frac{1}{\kappa}}\right), \qquad (11)$$

where

$$\tau = 1 - \frac{\Delta p}{p}. \qquad (12)$$

Having used equations (4), (5) and having considered equation (8) in accordance with [11, 14], the following equation was written down to determine relative combined expanded uncertainty of mass gas flow rate measurement result:

$$u_{q_m}' = \left[\left(\vartheta_C u_C'\right)^2 + \left(\vartheta_d u_d'\right)^2 + \left(\vartheta_D u_D'\right)^2 + \left(\vartheta_{K_a} u_{K_a}'\right)^2 + \left(\vartheta_{K_n} u_{K_n}'\right)^2 + \left(\vartheta_\varepsilon u_\varepsilon'\right)^2 + \left(\vartheta_{\Delta p} u_{\Delta p}'\right)^2 + \left(\vartheta_\rho u_\rho'\right)^2\right]^{0,5}, \qquad (13)$$

where ϑ_C, ϑ_d, ϑ_D, ϑ_{K_a}, ϑ_{K_n}, ϑ_ε, $\vartheta_{\Delta p}$ and ϑ_ρ is influence coefficients of correspondingly coefficient of orifice plate outflow, diameter of orifice plate opening, inner diameter of measuring pipeline, adjustment coefficient, accounting for roughness of inner surface of measuring pipeline, adjustment coefficient, accounting for bluntness of inner edge of orifice plate, gas expansion coefficient, differential pressure on the orifice plate and gas density at operating conditions for mass gas flow rate; u_C', u_d', u_D', u_{K_a}', u_{K_n}', u_ε', $u_{\Delta p}'$ and u_ρ' is relative standard uncertainty of correspondingly coefficient of orifice plate outflow, diameter of orifice plate opening, inner diameter of measuring pipeline, adjustment coefficient, accounting for roughness of inner surface of measuring pipeline, adjustment coefficient, accounting for bluntness of inner edge of orifice plate, gas expansion coefficient, differential pressure on the orifice plate and gas density at operating conditions.

Values of relative coefficients of influence of input variables or flowrate equation coefficients (8) upon mass gas flow rate have been calculated using equation (5) [1, 11, 14] and presented as follows:

ϑ_C , ϑ_{K_a} , ϑ_{K_n} and ϑ_ε ; their values are equal to 1;

$\vartheta_{\Delta p}$ and ϑ_ρ ; their values are equal to 0.5;

ϑ_d , its values are calculated by equation

$$\vartheta_d = \frac{2}{1-\beta^4}\,; \tag{14}$$

ϑ_D , its values are calculated by equation

$$\vartheta_D = \frac{2\beta^4}{1-\beta^4}\,. \tag{15}$$

Relative combined expanded uncertainty u'_ε of gas expansion coefficient ε in accordance with [1, 11, 14] is estimated with the help of the following equation

$$u'_\varepsilon = \left[\frac{1}{4}U'^2_{\varepsilon 0} + \left(\frac{\varepsilon-1}{\varepsilon}\right)^2 \left(u'^2_{\Delta p} + u'^2_p + u'^2_\kappa\right)\right]^{0,5}, \tag{16}$$

where $U'_{\varepsilon 0}$ is relative expanded uncertainty, attributed to functional dependance of estimation of gas expansion coefficient; u'_p is relative standard uncertainty of measurement result of absolute gas pressure; u'_κ is relative standard uncertainty of adiabatic index κ of gas at operating conditions.

Review of unsettled issues of general problem

As it comes from equation (8), considering equations (9), (10) and (11) mass gas flow rate depends upon:

diameter d of orifice plate opening at operating gas temperature;

inner diameter D of measuring pipeline at operating gas temperature;

orifice plate differential pressure.

Values of relative influence coefficients ϑ_d and ϑ_D upon mass gas flowrate according to [1, 13, 18] are calculated by simplified equations (14) and (15).

So far as relative combined standard uncertainty (13) of measurement result of mass gas flow rate and gas expansion coefficient (16) is a function of relative standard uncertainty of measurement result of differential pressure on orifice plate, then influence coefficient of differential pressure upon mass gas flow rate will be estimated by the following equation [1, 11, 14]:

$$\vartheta_{\Delta p\,1} = \sqrt{0.25 + \left(\frac{\varepsilon-1}{\varepsilon}\right)^2}\,. \tag{17}$$

Taking into consideration the above mentioned and equations (4) and (5), it is necessary to determine relative influence coefficients ϑ_d , ϑ_D and $\vartheta_{\Delta p}$ of these parameters upon mass gas flow rate for mass gas flow rate equation (8), leaving them out in equations of relative combined standard uncertainty of mass flow rate equation coefficients (8).

It is also necessary to calculate coefficients of influence of absolute pressure and adiabatic index of gas upon gas expansion coefficient and adjust equation for estimation of relative combined standard uncertainty of gas expansion coefficient.

Paper objectives statement

To adjust equation of relative combined standard uncertainty of gas flowrate measurement result by input of analytical dependencies into this equation to estimate relative coefficients of influence of input values upon mass gas flow rate which in spite of existing dependencies would correspond with requirements to uncertainty of quantity measurement result by indirect method.

Material coverage

Adjustment of equation for calculation of relative combined standard uncertainty of result of gas flow rate measurement, using flowmeters with standard orifice plates has been carried out in accordance with methodology, specified in [15]. To do this, firstly it's necessary to specify influence coefficients of input variables upon mass gas flow rate q_m which are constituents of equation of relative combined standard uncertainty of gas flow rate measurement result.

Using equation (8), equation for estimation of coefficient E inlet velocity (9), gas expansion coefficient ε (11) and considering equation (12), equation for mass gas flow rate estimation q_m can be written down

$$q_m = \frac{K_{q_{m\text{зв}}} d^2}{\sqrt{1-\beta^4}}\left\{1-\left(0.351+0.256\beta^4+0.93\beta^8\right)\times \right.$$
$$\left. \times\left[1-\left(1-\frac{\Delta p}{p}\right)^{\frac{1}{\kappa}}\right]\right\}\sqrt{\Delta p}, \tag{18}$$

where

$$K_{q_{m\text{зв}}} = \frac{\pi}{4} C K_a K_n \sqrt{2\rho}\,.$$

On the basis of equation (5), equations for estimation of relative orifice plate diameter (10) and mass gas flow rate (18) one can obtain equation for estimation of relative coefficient of input variables influence upon mass gas flow rate

$$\vartheta_{\Delta p} = \frac{\partial q_m}{\partial \Delta p}\frac{\Delta p}{q_m} = 0.5 - \frac{1-\tau}{\tau\kappa\varepsilon}\times$$
$$\times\left(0.351 + 0.256\beta^4 + 0.93\beta^8\right)\tau^{\frac{1}{\kappa}}, \tag{19}$$

$$\vartheta_d = \frac{\partial q_m}{\partial d}\frac{d}{q_m} = \frac{2}{1-\beta^4} -$$
$$-\frac{1-\varepsilon}{\varepsilon}\frac{1.024\beta^4 + 7.44\beta^8}{0.351 + 0.256\beta^4 + 0.93\beta^8}, \tag{20}$$

$$\vartheta_D = \frac{\partial q_m}{\partial D}\frac{D}{q_m} = -\frac{2\beta^4}{1-\beta^4} +$$
$$+\frac{1-\varepsilon}{\varepsilon}\frac{1.024\beta^4 + 7.44\beta^8}{0.351 + 0.256\beta^4 + 0.93\beta^8}. \tag{21}$$

It has been specified that values of relative coefficient of influence of :

differential pressure on orifice plate upon mass gas flow rate, calculated by equation (19) decreases with increase of orifice plate relative diameter values or $\frac{\Delta p}{p}$ dependence values and with decrease of gas isentropic exponent coefficient at working conditions. Values of relative influence coefficient $\vartheta_{\Delta p}$, calculated by equation (17), always increase with the change of the above mentioned parameters;

diameter of orifice plate opening at operating gas temperature upon mass gas flow rate, calculated by equation (20) decreases with increase of relative orifice plate diameter values or $\frac{\Delta p}{p}$ dependence values and with decrease of gas isentropic exponent coefficient at operating conditions. Values of relative influence coefficient ϑ_d, calculated by equation (14), always increase with the change of the above mentioned parameters;

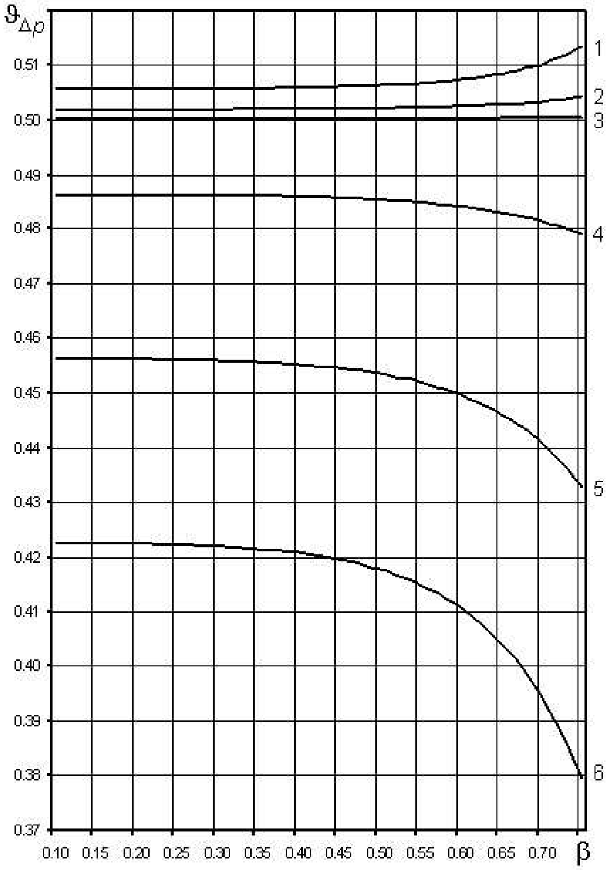
inner diameter of measuring pipeline at operating conditions upon mass gas flow rate, calculated by equation (21) decreases with increase of relative orifice plate diameter values or $\frac{\Delta p}{p}$ dependence values. Values of relative influence coefficient $\vartheta_{\Delta p}$, calculated by equation (15) always increase with the change of the above mentioned parameters.

For example, in Fig. 1 there are values of relative coefficient of influence of differential pressure on orifice plate upon mass gas flow rate for gas adiabatic index, which is equal to 1,3 and is the most common for natural gas.

Values of relative deviation $\delta_{\vartheta_{\Delta p}}$ are calculated by equation

$$\delta_{\vartheta_{\Delta p}} = 100\frac{\left|\vartheta_{\Delta p17} - \vartheta_{\Delta p}\right|}{\vartheta_{\Delta p}}, \tag{22}$$

where $\vartheta_{\Delta p17}$ is relative coefficient of differential pressure influence upon mass gas flow rate of gaseous medium, the value of which is calculated by equation (17); $\vartheta_{\Delta p}$ is relative coefficient of differential pressure influence upon mass gas flow rate of gaseous medium, calculated by equation (19).



1 – equation (17) for $\frac{\Delta p}{p} = 0.25$;

2 – equation (17) for $\frac{\Delta p}{p} = 0.15$;

3 – equation (17) for $\frac{\Delta p}{p} = 0.05$;

4 – equation (19) for $\frac{\Delta p}{p} = 0.05$;

5 – equation (19) for $\frac{\Delta p}{p} = 0.15$;

6 – equation (19) for $\frac{\Delta p}{p} = 0.25$

Figure 1 — Relative coefficient of orifice plate differential pressure influence upon mass flow rate of gaseous medium

Maximum value of relative deviation $\delta_{\vartheta_{\Delta p}}$ between values of relative influence coefficient $\vartheta_{\Delta p18} = 0.513$ and $\vartheta_{\Delta p} = 0.380$ for an orifice plate is 35 %.

Let's compare values of relative influence coefficients $\vartheta_{\Delta p}$, ϑ_d, ϑ_D, calculated by equations (5), (14), (15), (17), (19), (20) and (21) for values of input variables, presented in Table 1. Equation (5) in differential form is used to estimate relative influence coefficients in ISO 5168:2005 [4]. The results of comparison of relative influence coefficients $\vartheta_{\Delta p}$, ϑ_d , ϑ_D are presented in Table 1.

Table 1 – Comparative analysis of values of relative coefficient of input variables influence upon mass gas flow rate

Variable	Unit	Value	Equation
t	°C	20	–
p_1	MPa	0.252	–
Δp_1	kPa	63	–
ρ_c	kg/m³	0.696	–
ρ	kg/m³	1.73569	–
μ	mkPa·s	11.094	–
κ_1	1	1.3	–
D_1	m	0.4	–
d_1	m	0.3	–
q_{m1}	kg/s	21.2474	–
ε_1	1	0.895757	–
E_1	1	1.20949	–
$d_1^2 E_1 \varepsilon_1$	m²	0.0975068	–
$E_1 \varepsilon_1$	1	1.083409	–
$\vartheta_{\Delta p1}$	1	0.513	(17)
$\vartheta_{\Delta p}$	1	0.380	(19)
Δp_2	kPa	62.9	–
q_{m2}	kg/s	21.2346	–
$\vartheta_{\Delta p}$	1	0.379	(5)
ϑ_d	1	2.926	(14)
ϑ_d	1	2.689	(20)
d_2	m	0.299	–
$d_2^2 E_2 \varepsilon_2$	m²	0.096637	–
ϑ_d	1	2.691	(5)
ϑ_D	1	-0.926	(15)
ϑ_D	1	-0.689	(21)
D_2	m	0.401	–
$E_2 \varepsilon_2$	1	1.081552	–
ϑ_D	1	-0.688	(5)

As it's clear from Table 1 values of relative coefficient of influence of input quantities upon mass gaseous medium flowrate, calculated by equations (19)–(21) almost correspond with values of relative coefficient of influence of input quantities upon mass gas flowrate, calculated by equation (5) in differential form. Thus, equations (19)–(21) are estimated correctly but this is not to say about equations (14), (15) or (17). Values of relative influence coefficients $\vartheta_{\Delta p}$, ϑ_d , ϑ_D , estimated by equations (19), (20) i (21) are smaller than values of the same relative influence coefficients but which are calculated by equations (17), (14) and (15). Thus this doesn't decrease values of relative combined standard uncertainty of gas flow rate measurement result.

Now let's be more specific about equation for estimation of relative standard uncertainty u'_ε of gas expansion coefficient.

As far as coefficient of gaseous medium expansion depends on differential pressure Δp on tapered flange, opening diameter or tapered flange neck, inner diameter of measuring pipeline and relative influence coefficients $\vartheta_{\Delta p}$, ϑ_d , ϑ_D were accounted for by equations (19), (20) and (21) correspondingly, then combined uncertainties $u'_{\Delta p}$, u'_d and u'_D won't be considered in uncertainty u'_ε .

Considering the fact that expansion coefficient ε of gaseous medium depends upon both gas qbsolute pressure p and adiabatic index κ at operating conditions, then general equation for estimation of relative standard uncertainty values u'_ε of gas expansion coefficient will be as follows:

$$u'_\varepsilon = \sqrt{\frac{U_{\varepsilon 0}}{4} + \left(\vartheta_{p\varepsilon} u'_p\right)^2 + \left(\vartheta_{\kappa\varepsilon} u'_\kappa\right)^2}\ , \tag{23}$$

where $\vartheta_{p\varepsilon}$, $\vartheta_{\kappa\varepsilon}$ is relative coefficients of influence of correspondingly absolute pressure p of gas and adiabatic index κ of gas upon gas expansion coefficient ε .

Values of relative influence coefficients $\vartheta_{p\varepsilon}$ and $\vartheta_{\kappa\varepsilon}$ in accordance with standards [11, 14] are estimated by simplified equation

$$\vartheta_{p\varepsilon} = \vartheta_{\kappa\varepsilon} = \frac{\varepsilon - 1}{\varepsilon} . \tag{24}$$

Equations for estimation of relative expanded uncertainty $U'_{\varepsilon 0}$ [1, 10, 13] and new equations which have been developed to estimate relative influence coefficients $\vartheta_{p\varepsilon}$ and $\vartheta_{\kappa\varepsilon}$ will be as follows:

$$U'_{\varepsilon 0} = 3.5 \frac{1 - \tau}{\kappa} , \tag{25}$$

$$\vartheta_{p\varepsilon} = \frac{\partial \varepsilon}{\partial p} \frac{p}{\varepsilon} = \frac{1 - \tau}{\tau} \tau^{\frac{1}{\kappa}} \frac{0.351 + 0.256\beta^4 + 0.93\beta^8}{\kappa\varepsilon} , \tag{26}$$

$$\vartheta_{\kappa\varepsilon} = \frac{\partial \varepsilon}{\partial \kappa} \frac{\kappa}{\varepsilon} = -\tau^{\frac{1}{\kappa}} \ln(\tau) \frac{0.351 + 0.256\beta^4 + 0.93\beta^8}{\kappa\varepsilon} . \tag{27}$$

Let's compare values of relative coefficient of input variables influence upon gas expansion coefficient which were estimated by equations (5), (24), (26) and (27) for input variables values, presented in Table 1. The results of comparison of relative influence coefficients ($\vartheta_{p\varepsilon}$ and $\vartheta_{\kappa\varepsilon}$) values can be found in Table 2.

As we see from Table 2 values of relative influence coefficients $\vartheta_{p\varepsilon}$ and $\vartheta_{\kappa\varepsilon}$ upon gas expansion coefficient, estimated by equations (26) and

(27), correspond with the values of the same relative influence coefficients upon gas expansion coefficient which were calculated by equation (5) in differential form. Thus equations (26) and (27) are defined correctly what cannot be said about equation (24). Though value of relative influence coefficient $\vartheta_{p\varepsilon}$, calculated by equation (26) is bigger than its value, calculated by equation (24), but relative standard uncertainty of measurement result of absolute gas pressure is significantly smaller than relative standard uncertainty of gas adiabatic index. That's why the main influence upon relative combined standard uncertainty u_{ε}' will have relative influence coefficient $\vartheta_{\kappa\varepsilon}$. Considering that value of relative influence coefficient $\vartheta_{\kappa\varepsilon}$ by absolute value is smaller than the value of the same relative influence coefficient, calculated by equation (24), then it decreases value of relative standard uncertainty of gas expansion coefficient as well as value of relative combined standard uncertainty of gas flow rate measurement result.

Table 2 — Comparative analysis of values of relative coefficients of influence ($\vartheta_{p\varepsilon}$ and $\vartheta_{\kappa\varepsilon}$) upon gaseous medium expansion coefficient

Variable	Unit	Value	Equation
$\vartheta_{p\varepsilon}$	1	-0.116	(24)
$\vartheta_{p\varepsilon}$	1	0.120	(26)
p_2	MPa	0.255	–
ε_2	1	0.897026	–
$\vartheta_{p\varepsilon}$	1	0.120	(5)
$\vartheta_{\kappa\varepsilon}$	1	-0.116	(24)
$\vartheta_{\kappa\varepsilon}$	1	0.104	(27)
κ_2	1	1.29	–
ε_2	1	0.895035	–
$\vartheta_{\kappa\varepsilon}$	1	0.104	(5)

Substituting equations (19)–(21) into equation (13), we will get the following adjusted equation for estimation of relative combined standard uncertainty of gas measurement result:

$$u'_{q_m} = \Big\{ u'^2_C + u'^2_{K_{\text{ш}}} + u'^2_{K_{\text{п}}} + u'^2_{\varepsilon} + u'^2_{\rho} + \\ + \left[0.5 - \frac{1-\tau}{\tau\kappa\varepsilon} \left(0.351 + 0.256\beta^4 + 0.93\beta^8 \right) \tau^{\frac{1}{\kappa}} \right]^2 u'^2_{\Delta p} + \\ + \left(\frac{2}{1-\beta^4} - \frac{1.024\beta^4 + 7.44\beta^8}{0.351 + 0.256\beta^4 + 0.93\beta^8} \frac{1-\varepsilon}{\varepsilon} \right)^2 u'^2_d + \\ + \left(\frac{2\beta^4}{1-\beta^4} - \frac{1-\varepsilon}{\varepsilon} \frac{1.024\beta^4 + 7.44\beta^8}{0.351 + 0.256\beta^4 + 0.93\beta^8} \right)^2 u'^2_D \Big\}^{0,5}, \tag{28}$$

in which value of relative combined standard uncertainty u_{ε}' of gas expansion coefficient is calculated by such an equation:

$$u'_{\varepsilon} = (1-\tau)\tau^{\frac{1}{\kappa}} \left\{ \left(\frac{1.75}{\tau^{\frac{1}{\kappa}}\kappa} \right)^2 + \left(\frac{0.351 + 0.256\beta^4 + 0.93\beta^8}{\tau\kappa\varepsilon} \right)^2 u'^2_p + \\ + \left[\ln(\tau) \frac{0.351 + 0.256\beta^4 + 0.93\beta^8}{(1-\tau)\kappa\varepsilon} \right]^2 u'^2_{\kappa} \right\}^{0.5}. \tag{29}$$

CONCLUSIONS

1. The conducted analysis has shown that in the Interstate Standard GOST 8.586.5-2005 [11] and in the National Standard DSTU GOST 8.586.5:2009 [14] simplified equations for estimation of relative combined standard uncertainty of gas flow rate measurement result are presented, which usesimplified equations of relative coefficients of influence of input quantities upon mass gas flow rate and gaseous medium expansion coefficient which enhances relative combined standard uncertainty of gas flow rate measurement result.

2. New obtained equations (19)–(21) for estimation of relative coefficients of influence of differential pressure on orifice plate, relative diameter of orifice plate opening at operating gas temperature and inner diameter of measuring pipeline at operating gas temperature upon mass gas flow rate accept smaller values than simplified equations, given in Standards [11, 14]. This decreases also relative combined standard uncertainty of gas flow rate measurement result.

3. Equation for calculation of relative combined standard uncertainty of gas expansion coefficient has been adjusted by input of new equations (26) and (27) for calculation of relative coefficients of influence of absolute gas pressure and gas adiabatic index upon coefficient of its exapsion. The latter decreases this uncertainty and correspondingly decreases also relative combined standard uncertainty of gas flow rate measurement result.

4. Obtained equations of relative coefficients of input variables influence upon mass gas flow rate or upon gas expansion coefficient completely correspond with relative influence coefficients, calculated by equations in differential form, presented in ISO 5168:2005 [4], which confirms truthfulness of obtaining of these equations.

5. Adjusted equation of calculation of relative combined standard uncertainty (28) of gas flowrate measurement result with consideration of equation for calculation of relative combined standard uncertainty (29) of gas expansion coefficient, will enhance accuracy of gas flow rate measurement result.

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Коригування рівняння невизначеності результатів вимірювання витрати газу витратомірами зі стандартними діафрагмами

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Здійснено аналіз рівняння відносної невизначеності результату вимірювання витрати газу витратомірами змінного перепаду тиску із застосуванням стандартних діафрагм, наведеного у стандартах ГОСТ 8.586.5–2005 та ДСТУ ГОСТ 8.586.5:2009. Встановлено, що це рівняння представлено у спрощеному вигляді шляхом введення у нього спрощених рівнянь для розрахунку відносних коефіцієнтів впливу вхідних величин на масову витрату газу і відносної невизначеності коефіцієнта розширення газу. Розроблено нові аналітичні залежності для розрахунку відносних коефіцієнтів впливу перепаду тиску на діафрагмі, діаметра отвору діафрагми та внутрішнього діаметра вимірювального трубопроводу на масову витрату газу. Уточнено рівняння для розрахунку відносної невизначеності коефіцієнта розширення газу. Одержано нові рівняння для визначення відносних коефіцієнтів впливу абсолютного тиску та показника адіабати газу на коефіцієнт розширення газу. Встановлено, що відносні коефіцієнти впливу вхідних величин на масову витрату газу та на коефіцієнт розширення газу приймають менші значення ніж коефіцієнти, рівняння яких наведені у стандартах. Значення коефіцієнтів впливу, одержані за розробленими авторами рівняннями, добре узгоджуються із результатами їх розрахунку за рівняннями, які представлені у різницевому вигляді і наведені в ISO 5168:2005. Одержані аналітичні залежності зменшують відносну невизначеність результату вимірювання витрати газу.

Ключові слова: *вимірювання витрати, витратомір, діафрагма, коефіцієнт впливу, коефіцієнт розширення, масова витрата, метод змінного перепаду тиску, невизначеність, стандартний звужувальний пристрій.*