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Use of the theory of measurement uncertainty in procedures for data processing and results obtained by checking-calibration gas flow meters

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Abstract: The work is dedicated to the certification of natural gas consumption meters – calibration methods for processing, which meets the requirements of modern international standards. This article discusses the rules for the processing of measurement data and the correct formatting of the obtained results. An illustrative example of a real practical measurement is highlighted in the article.

Keywords: checking-calibration, gas flow, Standard totals, expanded uncertainties, uncertainty of budget.

1. Introduction

In the realm of gas flow meter calibration, ensuring precision and reliability is paramount. The accurate measurement of gas flow rates is critical across various industries, from energy production to environmental monitoring. However, achieving this accuracy hinges not only on the meticulousness of the instruments but also on a nuanced understanding of measurement uncertainty (Castrup, 2007) (Salicone, 2023).

Measurement uncertainty, a concept rooted in statistical analysis, acknowledges the inevitable imprecision inherent in any measurement process. Yet, rather than viewing uncertainty as a limitation, modern calibration procedures embrace it as a tool for refining accuracy. By incorporating the theory of measurement uncertainty into calibration methodologies, practitioners can not only quantify the reliability of their measurements but also optimize processes to minimize errors and enhance precision (Joint Committee for Guides in Metrology, 2020) (White, 2008), (Aaron N., 2004).

In this article, we delve into the application of the theory of measurement uncertainty in the calibration and verification of gas flow meters. From establishing uncertainty budgets to implementing rigorous data processing techniques, we explore how a comprehensive understanding of uncertainty empowers calibration procedures to deliver results that meet the highest standards of accuracy and reliability (Chkheidze, Otkhozoria, & Narchemashvili, 2021).

2. Object and subject of research

The primary object of research is the calibration and verification of gas flow meters. This encompasses understanding the intricacies of gas flow measurement, the instruments involved, and the methodologies employed to ensure accurate readings.

The subject of research is the theory of measurement uncertainty and its application in the procedures for processing data and results obtained during the calibration and verification of gas flow meters. This involves a detailed examination of how uncertainty is quantified, analyzed, and accounted for in the calibration process.

3. Target of research

In the "Target of research" section, on the basis of the identified shortcomings of the object of research, it is necessary to formulate the goal of the research and the tasks by which this goal can be achieved. In this section, you can give examples of tasks, with the help of which you can improve, update and describe the new work of the object.

4. Literature analysis

In particular, the main relative error, based on the analysis of which the metrological verification of the calibratable natural gas consumption meters (hereinafter - CM) is performed, is expressed as follows:

$$\delta = \left[\frac{v}{v_0}\left(1 - \frac{\Delta p}{p}\right) - 1\right] 100\% \quad (1)$$

Where v (m^3) is the volume of air measured by CM, v_0 (m^3) is the corrected reading of the reference meter (hereinafter - RM) included in the proposed calibration stand device when passing the same V volume of air, P-absolute pressure in the stand device, ΔP - difference of absolute pressures in CM and RM, (1) is actually the measurement equation, and v, v_0, ΔP and P are the input quantities (Abelashvili & Abelashvili, 2021), (Johnson, 2003).

During the measurement process, we pass the volume of air V_{RM}= Q_t (2) during the time t (s), where Q (m3/h) is the given (pre-set on the stand) air flow, and t is the corresponding time calculated by the stopwatch, display V_{CM} .

The corrected volume is $V_0 = V_{RM}\left(1 + \frac{F}{100}\right)$ (3). The error F can be found depending on the cost Q and the type of CM [1]. The main purpose of calibration is to determine the total measurement uncertainty of δ.

$$U_c(\delta) = \sqrt{[C_v U(v)]^2 - \left[C_{v_0} U(v)\right]^2 + \left[C_{\Delta p} U(\Delta p)\right]^2 + [C_p U(p)]^2} \quad (4)$$

For the sensitivity coefficients involved in the fourth, we have [1]:

$$\begin{cases} C_v = \dfrac{\partial \delta}{\partial V} = \dfrac{100}{V_0}(1 - \dfrac{\Delta p}{p}) = LM & (5) \\ C_{v0} = \dfrac{\partial \delta}{\partial V_0} = \dfrac{-100}{{V_0}^2}\left(1 - \dfrac{\Delta p}{p}\right) = -LMN & (6) \\ C_{\Delta_p} = \dfrac{\partial \delta}{\partial \Delta p} = -\dfrac{100V}{V_0 p} = LR & (7) \\ C_p = \dfrac{\partial \delta}{\partial p} = \dfrac{100V\Delta p}{V_0 P^2} = C_{\Delta p}(M-1) & (8) \end{cases}$$

Where $L = \frac{100}{V_0}$; $M = 1 - \frac{\Delta p}{p}$; $N = \frac{V}{V_0}$; $R = V(P)$ are constants for the calculation of which it is sufficient to know the estimated average values of the input quantities, as for the standard uncertainties, Among them, - $U(v)$ and $U(V_0)$ are determined according to type A, while the arithmetic averages of v and v_0 are considered as estimates for the values of $\bar{v}$ and $\overline{v_0}$ [1]:

$$U(v) = U(\bar{v}) = \sqrt{\sum_{i=1}^{n} \frac{(v_i - \bar{v})^2}{n(n-1)}} \quad (9)$$

$$U(v_0) = U(\bar{v}_0) = \sqrt{\sum_{i=1}^{n} \frac{(v_{0i} - \overline{v_0})^2}{n(n-1)}} \quad (10)$$

As usually, according to the recommendation given in n<10 [2], it is appropriate to multiply the numbers U(v) and U(v_0) calculated by formulas (9) and (10) by a correction multiplier. K_n=(4_n-3)(4_n-4) (11) U_p and U_Δp uncertainty is calculated according to type B. This issue will be discussed in detail in the main part of the article.

5. Research methods

This part of the article highlights a specific example from the practical field of verification and calibration of natural gas flow (Taylor, 1994). Table 1 shows the main fragments of the actual table, which was compiled in the Mechanics Department of the Institute of Metrology during the process of calibrating a residential gas turbine meter (Kayl, Johnson, & . Kline, 2009).

Table 1. Process of calibrating a residential gas turbine meter

Type of model	time, minutes seconds	gas meter Indicator, m3/h		value of reference counter	calibration gas flow meter				The flow rate of the meter to be calibrated.m3	Pressure difference ΔP, mbar
		starting	ending		Average pressure drop	Absolute pressure mbar	Indications, m3 starting	ending		
G250	11:30	6050.3	6060.3	10	0.000	965	0214089.7	0214099.96	10.26	0.00
	11:30	6060.8	6070.8	10			021410048.48	0214110.72	10.25	
	11:30	6071.3	6081.3	10			0214111.24	0214121.5	10.26	
	11:30	6081.8	6091.8	10			0214121.98	0214132.23	10.26	
	11:30	6092.2	6102.2	10			0214132.66	0.214142.89	10.22	
G1000	11:44	94718.0	94768.0	50	0.002	957	0213816.26	0213866.46	50.20	2
	11:42	94771.0	94821.0	50			0213869.46	0213919.64	50.18	
	11:43	94823.0	94873.0	50			0213921.64	0213971.80	50.16	
	11:42	94875.0	94925.0	50			0213973.80	0214023.96	50.16	
	11:43	94927.0	94977.0	50			0214025.96	0214076.14	50.18	

Continued table 1

G1000	11:49	94280.0	94360.0	80	0.006	953	0213378.95	0213458.86	79.91	7
	11:57	94365.0	94445.0	80			0213463.85	0213543.66	79.81	
	12:00	94451.0	94531.0	80			0213549.65	0213629.54	79.89	
	12:03	94535.0	94615.0	80			0213633.50	0213713.40	79.90	
	12:04	94619.0	94699.0	80			0213717.40	0213797.30	79.90	

The already described calibration stand was used for calibration. As can be seen in the table, the first 5 tests of the series of control measurements were carried out for values of $V_{RM} = 10\ m^3$. A stopwatch was used to record the time interval, after which the difference between the final and initial readings of the reference meter (G250 type) became equal to $10m^3$. By this time, the stopwatch was being turned off (Azmaiparashvili & Otkhozoria, 2016).

Stopwatch readings are recorded in column II of table 2, and in column $V - V_{RM} = 10\ m^3$ values.

The following five sets of control measurements are carried out using the same method, with the difference that at this time the second channel of the calibration stand is working, in which the 1000-type sample counter is turned on, and the stopwatch is turned off at the moment when the difference between the final and initial values of the sample counter reaches 50 m^3 (for the second five tests). , or $80m^3$ (for the third five tests).

In the same way, the final readings of the counter to be verified for the moments of stopwatch shutdown and, accordingly, the gas volumes measured by it are recorded (see Table 2).

Table 2. Final readings of the counter

N	V m^3	Evaluation m3	U()x10^{-3} m^3	ΔP mbar	U(ΔP)x10^{-2} mbar	P mbar	U(P) mbar	Δ (Evaluat) %	$U_c(\delta)x10^{-2}$ %	U(δ) %
1	10.26	10.25	8.230	0	5.66187	965	2.22857	1.875	8.20	0.16
2	10.25									
3	10.26									
4	10.26									
5	10.22									
6	50.20	50.176	7.951	-2	5.66187	957	2.21010	0.721	1.70	0.03
7	50.18									
8	50.16									
9	50.16									
10	50.18									
11	79.91	79.882	19.418	-7	5.66187	953	2.20086	0.678	2.53	0.05
12	79.81									
13	79.89									
14	79.90									
15	79.90									

The table covers the values of the absolute pressures measured by the stand manometer P in the test meter and the difference Δ P of the absolute pressures measured by the U-shaped water manometer between the test meter and the sample meter (millimeters of the water column in the table are converted to millibars) for all three fives of control measurement trials.

The results of mathematical processing of data from Table 1 are shown in Table 2, in column II of which the time intervals calculated in minutes and seconds are converted into hours.

This conversion is necessary to calculate the current flow rate Q (column III), which in turn is the main parameter in the F coefficient formula (see (4) in 1) by multiplying which the corrected (V_0) value of the volume carried by the sample meter is determined (column V).

Table 2 also demonstrates the standard deviations of all input quantities.

We have already mentioned that the uncertainties $U(v)$ and $U(v_0)$ are calculated using formulas (11) and (12) (based on the value of n=5 and the data in Table 1).

The obtained results are multiplied by the correction factor K_n=K_5=17/16=1.0625 [see (II)] Considering that the error of Δp -s measurement (it is measured by a U-shaped water manometer) does not exceed ± 1mm.Hg=±9.80665 ·10-2 mbar and in this interval we considered it as a uniformly distributed random variable $U(\Delta p) = 9.80665 \cdot 10^{-2}/\sqrt{3} \cong 5.66187 \cdot 10^{-2}$ mbar. The pressure P is measured by a manometer, the relative error of which does not exceed 0.4%, so $U(P) = \frac{0.4P}{100\sqrt{3}}$ and it changes with the pressure P, when moving from one quintet of measurements to another, which is also reflected in Table 3.

Thus, it is already possible to draw up an uncertainty budget by means of formulas (6)÷(9) needed to calculate the sensitivity coefficients, multiply them by the corresponding standard uncertainties and calculate the contribution of each input quantity to the total $U_c(\delta)$ uncertainty (Coleman, 1999).

In order to facilitate the corresponding calculations and checking the correctness of the report separately for each of the above-mentioned five sets of measurement trials, it is appropriate to separately calculate those constants that participate in the expressions of sensitivity C_J coefficients [(2)... (3).] and which maintain constant values in the above-mentioned five sets of measurement trials.The results of these calculations are shown in Table 3.

Table 3. The results of calculations

N	Constanta	1 quintile of control trials	II quintile of control trials	III quintile of control trials
1		9.93727	2.00316	1.25114
2		1	1.00209	1.00735
3		1.01857	1.00511	0.99944
4		0.01062	0.05243	0.08382

Column II of the present table and the symbols $\overline{V_0}$ and $\bar{V}$ indicate the average arithmetic values of $V_0$and V, which are calculated for the corresponding quintiles according to the formulas in Table 1 $\overline{V_0} = \frac{\sum_{i=1}^{5} V_{0i}}{5}$ and $\bar{V} = \frac{\sum_{i=1}^{5} V_i}{5}$As for the ΔP and P values, each of them is the same for all measurement trials included in the given quintile, which is also reflected in Table 2.

According to the data in Tables 2 and 3, an uncertainty budget was drawn up (Fig. 4), from which it is clear that the standard uncertainty of the meter to be tested is dominated by the standard uncertainty U(V), which allows us to use the criterion of negligible error ($U_c(\delta)$ to not take into account the relevant uncertainty when calculating the total uncertainty Small uncertainty of input size.

Table 4. Unlimited budget

N	Input value X_i	Estimated value $\bar{X_i}$	type of uncertainty	standard uncertainty $U(X_i)$	Sensitivity coefficient C_i	Contribution to total uncertainty $U_i(\delta) \cdot 10^{-2}\%$
1	V (m^3)	10.25 50.176 79.882	A	8.230 7.951 19.418	9.93727 2.00735 1.26034	8.17837 1.59604 2.44733
2	V_0 (m^3)	10.06313 49.92107 79.92689	A	2.125 1.164 73.385	-10.12181 -2.01761 -1.25963	0.02151 0.00235 0.09243
3	Δ (mbar)	0 -2 -7	B	5.66187x10^2 mbar	-0.10553 -0.10503 -0.10487	0.59750 0.59467 0.59376
4	P (mbar)	965 957 953	B	2.2286 2.2101 mbar 2.009	0 -0.00022 -0.00077	0 0.04862 0.16947

Considering (11), we have ($n = 5 => K_n = 1{,}0625$)

$$U_c(\delta) = \begin{cases} 8.2 \cdot 10^{-2}\,\% \\ 1.7 \cdot 10^{-2}\,\% \\ 2.53 \cdot 10^{-2}\,\% \end{cases} \qquad (12)$$

Let's choose the confidence level P=95%, which corresponds to the coefficient K=1, 96 in the normal law distribution.

Therefore, according to the equation ($1U = KU_c$) in extended uncertainty we have:

$$U = \begin{cases} 0.16\,\% \\ 0.03\,\% \\ 0.05\,\% \end{cases} \qquad (13)$$

Which gives us the final result of the measurement (rounded to the nearest hundredth):

$$\begin{cases} 1.7 \le \delta\% \le 2.02 \\ 0.69 \le \delta\% \le 0.75 \\ 0.63 \le \delta\% \le 0.73 \end{cases} \qquad (14)$$

(13) Recorded for quintiles 1, 2 and 3 of measurement trials.

8. Conclusions

A practical illustrative example is discussed for the proposed testing scheme and methodology for natural gas consumption meters, the basic error and its expanded uncertainty are calculated, which is the basis for expanding the measurement results according to modern requirements.

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