Szacowanie niepewności ilości energii cieplnej w układach pomiarowych z przepływomierzami zwężkowymi

Evaluating the uncertainty of the amount of thermal energy for metering systems with differential pressure flowmeters

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Abstract: *In commercial metering systems of thermal energy it is important to obtain not only the measured value of the amount of thermal energy, but also the characteristic of the uncertainty of this value. The paper presents the developed technique for evaluating the uncertainty of the measurement result of the amount of thermal energy for metering systems with differential pressure flowmeters used for metering the heat carrier flowrate. The technique uses the dependencies developed by the authors for calculating the relative standard uncertainty of the amount of thermal energy, enthalpy and flowrate of heat carrier. The equation for calculating the uncertainty of heat carrier enthalpy was developed by applying the dependencies of the technique IAPWS IF 97. The approaches proposed by the authors make it possible to develop dependencies for evaluating the uncertainty of the measurement result of the amount of thermal energy for systems of different configurations and systems with different types of flowmeters.*

Keywords: uncertainty of the measurement result, amount of thermal energy, flowrate of heat carrier, enthalpy, differential pressure flowmeter

Streszczenie: Dla systemów komercyjnego rozliczania energii cieplnej ważne jest uzyskanie nie tylko zmierzonej ilości energii cieplnej, ale również charakterystyki niepewności tej ilości. W artykule opracowano technikę oceny niepewności wyniku pomiaru energii cieplnej dla systemów pomiarowych, w których do pomiaru przepływu nośnika ciepła stosowane są przepływomierze zwężkowe. Opracowana technika polega na wykorzystaniu opracowanych przez autorów zależności do obliczenia względnej standardowej niepewności ilości energii cieplnej, entalpii i przepływu nośnika ciepła. Zależność do obliczania niepewności entalpii nośnika ciepła opracowano przy użyciu zależności metody IAPWS IF 97. Podejścia zaproponowane przez autorów umożliwiają opracowanie zależności do szacowania niepewności zmierzonej wartości ilości energii cieplnej dla układów o różnej konfiguracji, a także układów wykorzystujących przepływomierze różnych typów.

Słowa kluczowe: niepewność wyniku pomiaru, ilość energii cieplnej, przepływ nośnika ciepła, entalpia, przepływomierz zwężkowy

Introduction

Accurate metering of thermal energy is a necessary condition for its efficient and economical use, as well as allows to identify and to eliminate the disadvantages of heat generating facilities and thermal networks. Automated systems based on microprocessor calculators are used for accurate metering the amount of thermal energy. Such systems realize the calculation of the amount of thermal energy in real time, taking into account changes in the thermo-physical parameters of the heat carrier.

The measuring transducers of heat carrier flowrate are the important components of thermal energy metering systems. The differential pressure flowmeters on the basis of standard primary devices are often used to meter the heat carrier flowrate in pipelines of large diameters.

The measurement results of the amount of thermal energy are the subject of commercial calculations between its supplier and the consumer. Therefore, it is important not only to obtain the measured value of the amount of thermal energy, but also to characterize the uncertainty (error) of this value. Therefore, developing dependencies for evaluating the uncertainty of thermal energy is an important task to be solved for organizing accurate metering of thermal energy, in particular for metering systems based on differential pressure flowmeters.

Analysis of the recent publications and research works on the problem

According to the normative documents defining the rules of metrological activity (in particular, in Ukraine the Law „On metrology and metrological activity" [1]), thermal energy metering refers to the sphere of legislatively regulated metrology. This type of activity is the subject of state regulation regarding the measuring procedure, units of measurement and characteristics of measuring equipment. According to the requirements of the Law [1], the measurement results can be used in the field of legislatively regulated metrology, provided that the corresponding error characteristics or uncertainty of the measurement result is known for such results.

The technical and metrological characteristics of thermal energy meters are normalized in accordance with the requirements of the „Technical Regulation of Measuring Equipment" [2], developed on the basis of Directive 2014/32/EC of the European Parliament and the Council [3]. In particular, the metrological characteristics of measuring equipment that are the part of a commercial meter of thermal energy must meet the requirements of DSTU EN 1434-1: 2019 (EN 1434-1: 2015 + A1: 2018, IDT) [4]. According to [4], the limits of the permissible values of the relative error of the thermal energy meters are defined as the sum of the limits of the permissible relative errors of their components (calculator, flowrate transducer and a pair of temperature transducers). However, there is no methodology in [4] for evaluating the uncertainty of the measured value of the amount of thermal energy.

The standard DSTU GOST 8.586.5: 2009 [5] regulates the technique for evaluating the uncertainty of the measurement result of the flowrate for the automated systems of thermal energy metering, in which the differential pressure flowmeters are used for metering the mass or volume of the heat carrier. The technique, presented in standard [5], is based on the guidelines of the international standard ISO 5168 [6]. However, there isn't any technique for evaluating the uncertainty of the measurement result of the amount of thermal energy by such systems in the sources known to the authors. So developing the technique for evaluating the uncertainty of the measurement result of the amount of thermal energy by automated metering systems is the subject of research in this paper.

Theoretical material and research

Metering the amount of thermal energy is carried out by the indirect method based on the calculated values of the heat carrier parameters (in particular enthalpy) and the measured values of the flow parameters. Therefore, in order to evaluate the uncertainty of the amount of thermal energy, first of all it is necessary to evaluate the uncertainty of the methods used to calculate the heat carrier parameters and the uncertainty of the measured values of the flow parameters (temperature, pressure, flowrate). The resulting dependence for evaluating the uncertainty of the measured value of the amount of thermal energy should be based on the equation for calculating the amount of thermal energy that is implemented in the automated metering system, and also should take into account the uncertainties of all components of this equation.

The amount of thermal energy flowing through the section of the pipeline over a period of time is determined by integrating the product of the heat carrier flowrate and enthalpy. In the metering system with two flowmeters installed in the supply and return pipelines, the amount of thermal energy transmitted to the consumer or received from the source during this time interval, is calculated as the difference between the amount of energy transmitted by the supply pipeline and returned by the return pipeline [7]:

$$W = \int_{t_0}^{t_k} q_{m1} h_1 dt - \int_{t_0}^{t_k} q_{m2} h_2 dt \qquad (1)$$

where W is the amount of thermal energy transmitted from the source or received by the consumer; q_{m1}, q_{m2} are the mass flowrates of the heat carrier in the supply and return pipelines respectively; h_1, h_2 are the specific enthalpies of the heat carrier in the supply and return pipelines; $t = t_k - t_0$ is the time interval for calculating the amount of thermal energy.

If we consider metering the amount of thermal energy over a short time interval during which the heat carrier flowrates and enthalpies can be considered conditionally constant, then we obtain a simplified dependence for calculating the amount of thermal energy:

$$W = M_1 h_1 - M_2 h_2 \qquad (2)$$

where M_1, M_2 are the masses of the heat carrier passed over the analyzed time interval through the cross section of the supply and return pipelines respectively.

A simplified approach is often used to calculate the measuring error of the amount of thermal energy by equation (2) (see [7], [8]), which is to differentiate the dependence of the amount of thermal energy from the input parameters. Applying this approach to dependence (2), we obtain:

$$\delta_W = \frac{dW}{W} = \frac{dM_1 h_1 + M_1 dh_1 - (dM_2 h_2 + M_2 dh_2)}{M_1 h_1 - M_2 h_2} = = \frac{\delta_{M1} + \delta_{h1} - \alpha\beta\delta_{M2} - \alpha\beta\delta_{h2}}{1 - \alpha\beta} \qquad (3)$$

where $\alpha = \frac{M_2}{M_1}$, $\beta = \frac{h_2}{h_1}$.

Formula (3), as well as formulas for calculating the measuring errors of the amount of thermal energy obtained for the other equations for calculating the amount of thermal energy using such simplified approach, is presented in documents [7], [8].

The current methodology for evaluating the accuracy of a measurement result involves evaluating the uncertainty of this result [9]. When evaluating uncertainties, information about the main and additional components of the measurement error, or the main and additional components of the uncertainty caused by the appropriate measuring equipment, should be provided, as well as information on the distribution of the external impact values. However, it is often necessary to evaluate the uncertainty of a measurement result without some components of this information. In particular, such situation is common when evaluating the uncertainty of the measured value of thermal energy. Therefore, in this work, dependencies for calculating the uncertainty of the amount of thermal energy and dependencies for evaluating the uncertainty of its arguments are obtained using the following assumptions:

- all significant systematic phenomena are taken into account in the measurement results;
- the mathematical expectation of the sensitivity factor is its normalized maximum allowable value;
- there is no correlation between the input variables of the flow equation and the equation of the amount of thermal energy;
- the probability distribution of the measured values corresponds to the normal Gauss law.

As it is shown above, the amount of thermal energy is a function of the flowrate of the heat carrier and its enthalpy, which are the functions of the measured parameters of the heat carrier (pressure, temperature). So, in order to evaluate the resulting uncertainty of the amount of thermal energy it is necessary to evaluate the impact of the uncertainties of the measured parameters of the heat carrier and the characteristics of the measuring equipment on the resulting uncertainty. For this purpose it is necessary to analyze the functional dependences of the heat carrier flowrate and enthalpy on heat carrier parameters.

In thermal energy metering systems based on differential pressure flowmeters with standard primary devices used to measure the heat carrier flowrate, the mass flowrate of the fluid is calculated by the formula [5]:

$$q_m = 0,25\pi d^2 CEK_R K_{es}\varepsilon(2\Delta p\rho)^{0,5} \tag{4}$$

where d is the diameter of the opening of primary device at the operating temperature of the fluid; C is the leakage factor; E is the coefficient of entry speed; K_R is the correction factor that takes into account the roughness of the inner surface of the measuring pipeline; K_{es} is the correction factor that takes into account the inlet edge sharpness of the orifice plate; ε is the expansion factor; Δp is the differential pressure on the primary device; ρ is the density of the fluid.

The known approaches described in ISO 5168 are used in order to obtain the uncertainty of the measured value of flowrate [6]. In particular, the impact factors of the uncertainties of the input parameters on the combined uncertainty of the measured flowrate can be found according to [6] by the formula:

$$C_i^* = \frac{\partial y}{\partial x_i} \cdot \frac{x_i}{y} \tag{5}$$

where C_i^* is the dimensionless impact factor of uncertainty of parameter x_i on uncertainty of output value y.

Then, provided that impact factors of all input parameters are known and input parameters are uncorrelated, the relative total uncertainty of the output value $u'_c(y)$ can be calculated by

$$u'_c(y) = \sqrt{\sum_{i=1}^{N} [C_i^* u'(x_i)]^2} \tag{6}$$

where $u'(x_i)$ is the relative uncertainty of the input parameter x_i.

Applying the approaches of ISO 5168 [6] to evaluating the combined standard uncertainty of flowrate calculated by equation (4), we obtain the following uncertainty equation of the measurement result of the fluid flowrate [5]:

$$u'_q = \left\{ u'^2_{fc} + u'^2_C + u'^2_{K_R} + u'^2_{K_{es}} + \left(\frac{2\beta^4}{1-\beta^4}\right)^2 u'^2_D + \left(\frac{2}{1-\beta^4}\right)^2 u'^2_d + 0,25\left(u'^2_{\Delta p} + u'^2_\rho\right) \right\}^{0,5} \tag{7}$$

where u'_{fc} is the relative standard uncertainty (below – uncertainty) of the implementing of dependence (4) by the flowrate calculator; u'_c – uncertainty of measurement result of leakage coefficient; u'_{K_R} is the uncertainty of the measurement result of the correction factor, which takes into account the roughness of the inner surface of measuring pipeline; $u'_{K_{es}}$ is the uncertainty of the measurement result of the correction factor, which takes into account the inlet edge sharpness of the orifice plate; β is the relative diameter of the opening of primary device; u'_D is the uncertainty of the measurement result of the internal diameter of the measuring pipeline or the inlet of the Venturi pipe at the operating temperature of the fluid; u'_d is the uncertainty of the measurement result of the diameter of the opening of the orifice plate at the operating temperature of the fluid; $u'_{\Delta p}$ is the uncertainty of the measurement result of the differential pressure on the primary device; u'_p is the uncertainty of the measurement result of the fluid density.

The equations presented in the IAPWS report [10] or simplified equations (for example in [11]) are often used to calculate the enthalpy of a heat carrier in thermal energy metering systems and for the automated design of such systems. The deviations between the enthalpy values calculated by equations [10] and [11] are inconsiderable.

The equation for evaluating the enthalpy uncertainty is obtained by considering the enthalpy as a value (y), which is determined by the indirect method and related functionally $y = F(y_1, y_2, \ldots, y_3)$ to the measured parameters (y_i) (for example, temperature and pressure):

$$u'_y = \left[u'^2_{MF} + \sum_i^n C^{*\,2}_{y_i} u'^2_{y_i} \right]^{0,5} \tag{8}$$

where u'_{MF} is the relative methodical uncertainty of functional dependence; u'_{y_i} is the uncertainty of the measurement result of the i-th parameter; $C^*_{y_i}$ is the relative impact factor of change of the i-th measured parameter on the value (y), which should also be determined by the formula (5).

Applying the equation (8) to the dependence of the enthalpy on the pressure and temperature of the water (steam) $h = F(p, T)$) the equation of the relative uncertainty of the enthalpy is obtained:

$$u'_h = \left[u'^2_{Mh} + \left(C_{hT} u'_T \right)^2 + \left(C_{hp} u'_p \right)^2 \right]^{0,5} \tag{9}$$

where u'_{Mh} is the methodical uncertainty of the dependence $h = F(p, T)$; $u'_{Mh} = 0{,}15\%$ [12]; C_{hT} is the relative impact factor of the uncertainty of the measured value of the water (water vapor) temperature on the enthalpy uncertainty; C_{hp} is the relative factor of the uncertainty of water (water vapor) pressure on the enthalpy uncertainty; u'_T is the relative standard uncertainty of water (water vapor) temperature; u'_p is the relative standard uncertainty of measurement result of water (water vapor) pressure.

The authors analyzed the dependencies $C_{hT} = F_1(p, T)$ and $C_{hp} = F_2(p, T)$ [12] and found that the dependence $C_{hT} = F_1(p, T)$ with accuracy sufficient for practical problems can be reproduced only as a function of temperature, and the dependence $C_{hp} = F_2(p, T)$ must take into account the changes of temperature and pressure of the heat carrier. The simplified dependences $C_{hT} = F_1(T)$ and $C_{hp} = F_2(p, T)$ were developed by approximating the values of C_{hT}, C_{hp}, calculated using the equations [10]. A cubic polynomial was used as an approximating function. Simplified dependencies look like:

$$C_{hT} = 1.3471\Theta^3 - 19.8754\Theta^2 + 96.8585\Theta - 158.4162 \tag{10}$$

$$\begin{aligned} C_{hp} &= 0.06p(-0.0265\Theta^3 + 0.3695\Theta^2 - \\ &-1.7163\Theta - 2.6647), \Theta = T/100, K \end{aligned} \tag{11}$$

The simplified dependencies, developed by the authors, are proposed to be used to determine the impact factors of the uncertainties on the temperature and pressure of water (water vapor) on the uncertainty of enthalpy for the pressure range from 0 to 5 MPa and temperature range from 300 to 550 K. Relative deviations of values C_{hT}, C_{hp} obtained by (10), (11) from the values obtained by the formulas [10] are respectively 0,48% and 0,56% for the temperature changes from 300 K to 550 K.

Applying the formulas (5) and (6) to evaluate the combined standard uncertainty of the amount of thermal energy calculated by equation (1), we obtain the following equation

$$u'_W = \sqrt{u'^2_\tau + C_1^2 u'^{\,2}_{q1} + C_2^2 u'^{\,2}_{h1} + C_3^2 u'^{\,2}_{q2} + C_4^2 u'^{\,2}_{h2}} \tag{12}$$

where u'_τ is the uncertainty of the measured value of the time interval during which the amount of thermal energy is calculated; u'_{q1}, u'_{q2} are the uncertainties of the measurement results of the flowrate of heat carrier in the supply and return pipelines, respectively; u'_{h1}, u'_{h2} are the uncertainties of measurement results of enthalpy of the heat carrier in the supply and return pipelines, respectively; C_1, C_2, C_3, C_4 are the impact factors to be calculated from the formulas:

$$\begin{aligned} C_1 &= \frac{\partial f}{\partial q_1}\frac{q_1}{W} = \frac{h_1 q_1}{W}; \quad C_2 = \frac{\partial f}{\partial h_1}\frac{h_1}{W} = \frac{q_1 h_1}{W} \\ C_3 &= \frac{\partial f}{\partial q_2}\frac{q_2}{W} = -\frac{h_2 q_2}{W}; \quad C_4 = \frac{\partial f}{\partial h_2}\frac{h_2}{W} = -\frac{q_2 h_2}{W} \end{aligned} \tag{13}$$

The relative expanded uncertainty of the measurement result of the amount of thermal energy at 95% confidence level should be calculated by the formulas [5], [9], [13]:

$$U'_W = 2u'_W \tag{14}$$

It is advisable to compare the value of the relative error of the amount of thermal energy calculated by formula (3) and the value of the relative expanded uncertainty of the amount of thermal energy U'_W calculated by (14). We have made the following comparing for a thermal energy metering system that implements equation (1) for the average-hour values of the heat carrier parameters presented in Table 1.

Table 1. Heat carrier parameters in the pipelines of the acting metering system

No	Parameter	Value
1	The heat carrier temperature in the supply pipeline T_1, °C	92,7
2	The heat carrier temperature in the return pipeline T_2, °C	54,8
3	The heat carrier pressure in the supply pipeline p_1, MPa	0,8306
4	The heat carrier pressure in the return pipeline p_2, MPa	0,5374
5	The heat carrier flowrate in the supply pipeline q_1, t/h	204,813
6	The heat carrier flowrate in the return pipeline q_2, t/h	200,00

The uncertainties in equation (12) are calculated as follows: uncertainty of the heat carrier flowrate – according to equation (7), uncertainty of enthalpy – according to equation (9). The values of the relative error of enthalpy calculating and the error of flowrate measuring are assumed to be equal in modulus to the corresponding expanded uncertainty values, calculated using standard uncertainty values by formulas similar to (14): $|\delta_{M1}| = U'_{M1}$; $|\delta_{h1}| = U'_{h1}$; $|\delta_{M2}| = U'_{M2}$; $|\delta_{h2}| = U'_{h2}$.

However, the relative error value can be both positive and negative, so we compared the sets of the error components with positive and negative values.

The comparing results are presented in table 2.

The relative errors of all components in the first set have are positive. The relative error of the amount of thermal energy δ_w is minimal for such a set of input parameter errors, since compensation for the impact of errors of individual parameters is achieved, in particular, errors of flowrate and enthalpy in the supply pipeline are compensated by the errors of these parameters in the return pipeline (see the formula (3)). In the second set the relative errors of the return flow parameters are negative. This leads to a significant increase in the relative error of the amount of thermal energy δ_w calculated by formula (3). The same increase in the modulus of energy error δ_w is observed for the third set of errors, in which the errors of the direct flow

Table 2. Comparison of the relative error and the uncertainty of the measured value of thermal energy

No	The value of the relative error of the input parameters, %				The relative error of the amount of thermal energy δ_W, %	The expanded relative uncertainty of the amount of thermal energy U_W, %
	δ_{M_1}	δ_{h_1}	δ_{M_2}	δ_{h_2}		
1	+ 1	+ 0,85	+ 1	+ 1,23	1,32	3,11
2	+ 1	+ 0,85	– 1	– 1,23	7,41	3,11
3	– 1	– 0,85	+ 1	+ 1,23	–7,41	3,11
4	+ 1	+ 0,85	– 1	+ 1,23	4,05	3,11
5	– 1	+ 0,85	+ 1	+ 1,23	–3,41	3,11

parameters are negative. In the fourth and fifth sets, the thermocouples have well-matched characteristics, so the enthalpy errors have the same sign, the heat carrier flowrate errors have different signs. Here, the resulting error δ_w becomes intermediate.

Therefore, the value of the relative error of the amount of thermal energy δ_w calculated by (3) depends on the sign of the relative errors of the input parameters. It is not possible to determine the sign of relative errors in practical application of formula (3), since the manufacturers give the accuracy (the ranges of the reduced error) for most measuring transducers of pressure, temperature, flowrate. The sign of relative error for each individual measurement cannot be determined. Therefore, it is very difficult to apply formula (3) for calculating the measurement error of the amount of thermal energy in acting metering systems.

The common practice for evaluating the combined standard uncertainty of the amount of thermal energy was applied to obtain formula (12), which meets the recommendations [6, 9]. Using the dependence (12) makes it possible to evaluate the uncertainty of the amount of thermal energy, taking into account the uncertainties of the input parameters. Therefore, in our opinion, dependence (12) should be used to characterize the measurement result of the amount of thermal energy in metering systems that realize the equation (1).

Conclusions

Therefore, evaluating the uncertainty of the measurement result of the amount of thermal energy by means of a metering system based on differential pressure flowmeters, which implements the equation (1), is proposed to be carried out by the following method:

1) to calculate the uncertainty of the flowrate of the heat carrier in the supply u'_{q1} and return u'_{q2} pipelines, respectively, according to the equation (7);
2) to calculate the uncertainty of the enthalpy of the heat carrier in the supply u'_{h1} and return u'_{h2} pipelines, respectively, by the formulas (9), (10), (11);
3) to calculate the value of the combined standard uncertainty of the amount of thermal energy by equation (12); it is proposed to calculate the values of the impact factors according to formulas (13) based on the nominal values of the heat carrier parameters;
4) to calculate the value of the relative expanded uncertainty of the amount of thermal energy by formula (14).

The approaches proposed by the authors make it possible to develop dependencies for evaluating the uncertainty of the measured value of the amount of thermal energy for systems of different configuration that implement the measuring equations different from equation (1).

Equations (9)–(11), (12), developed in this work, can be used to evaluate the uncertainty of the measurement result of the amount of thermal energy for systems with different types of flowmeters.

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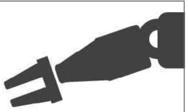

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WYDARZENIA

● **Przyszłością kolejnictwa jest wodór. Pierwsze polskie pociągi na paliwo wodorowe mogą się pojawić już w 2021 r.**

Wodór to ekologiczne i wydajne paliwo. Idealnie wpisuje się także w plany Unii Europejskiej dotyczące redukcji poziomu emisji gazów cieplarnianych w gospodarce. Transport obecnie odpowiada za 25 proc. emisji w UE, dlatego wprowadzenie paliwa, którego jedyną pochodną jest woda, jest tak istotne. W planach polskich producentów są już także pierwsze pociągi zasilane wodorem. Choć udział transportu kolejowego w emisji CO_2 jest marginalny, to plan Unii do 2050 roku zakłada osiągnięcie zeroemisyjności.

– Przewagi wodoru są oczywiste. Efektem jego spalania jest woda, co jest jego główną zaletą. Choć teraz trudno to przewidzieć, to wodór zmieni polską kolej. Jesteśmy na samym początku drogi, jednak wodór może dać kolei szansę na bardzo duży skok – podkreśla w rozmowie z agencją informacyjną Newseria Innowacje Robert Mikulski, członek zarządu Stowarzyszenia Polski Wodór.

Eksperci podkreślają, że wodór nie zastąpi całkowicie pojazdów elektrycznych. Jednak w tych miejscach, w których dalej są używane napędy spalinowe w lokomotywach, już teraz można zastosować napędy wodorowe.

Polskie firmy nie chcą pozostawać w tyle. W grudniu bydgoska PESA zadeklarowała, że do połowy 2020 roku planuje opracować etapy rozwoju technologii napędu wodorowego dla kolei. Przy realizacji tego celu będzie współpracować z PKN Orlen. W 2021 roku wraz z koncernem paliwowym chce rozpocząć pierwsze próby tych pojazdów. Według zapowiedzi przedstawicieli polskiego producenta w planach jest już budowa pasażerskiego pociągu z napędem wodorowym. Tymczasem PKN Orlen już teraz otwiera wodorowe stacje tankowania dla samochodów.

Źródło: Newseria