Estimation of the accuracy of measurements of oil mass in fiscal metering

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Abstract. In modern metrology, two approaches to assessing the accuracy of measurement results have been formed: the traditional approach using errors and a relatively new approach based on the concept of uncertainty. The question of which of them to use in a specific metrological situation is not idle and is of great practical importance. In particular, this applies to the commercial accounting of marketable oil, especially when it is supplied abroad. In Russia, at the level of state accounting policy, an estimate is made based on the error, and in most other countries - according to uncertainty, which causes discrepancies in the mass of oil exported. The article analyzes both approaches and, on the basis of a comparative calculation of both estimates for several systems for measuring the quantity and quality of oil (OQMS), through which commercial accounting is conducted, the expediency of switching to an estimate through expanded uncertainty is shown.

1. Introduction

The production, transport and processing of liquid and gaseous hydrocarbons is a fundamental branch of the Russian economy. Considering the volumes of hydrocarbons produced and processed or sold abroad and their cost, one can easily conclude about the importance of metrological support for their accounting, especially commercial accounting.

Oil is accounted for by weight. Oil produced from the reservoir is essentially a so-called borehole fluid, or gas-oil-oil emulsion. In addition to oil itself, it includes formation water with mineral salts, dissolved and free gas, and various mechanical impurities. In the oil field, the primary preparation of oil necessarily takes place, preparing it for long-distance transport, but even in the marketable oil corresponding to GOST R 51858-2002, a certain amount of impurities still remains. Therefore, commercial accounting includes the measurement of gross oil mass and the calculation of net mass, which are carried out in accordance with approved state standards and measurement techniques (methods). Methods (methods) of measurements represent a clear algorithm, step by step and with maximum detail, regulating the process of determining the specified parameters of a particular object with the required accuracy.

In Russia, in accordance with GOST R 8.595-2004, oil accounting is carried out both by direct (static and dynamic) and indirect (volume-mass static, volume-mass dynamic and hydrostatic) methods. Limiting values of errors for all methods are regulated in the same document. In addition, all large oil producing and transporting companies develop local regulatory documents (LD) to ensure the reliability of the measurements.
Despite this, due to the fact that accounting during the movement of oil from the well to the consumer is performed repeatedly (wellhead - delivery from the field to the main oil pipeline (MP) - transfer between production sections of the MP - delivery to the consumer), the error in measuring the mass of oil increases from regulated by 0.35% to 3% [1]. Therefore, any research aimed at increasing the reliability of measurements or simplifying calculations without loss of accuracy is an urgent scientific and practical task.

2. Materials and methods

2.1. Theory

The dynamic method is used to measure the mass of oil transported or pumped through a pipeline, and the static method is used when measuring in terms of capacity and total capacity.

The main accounting scheme in Russia, as a rule, is the oil quantity and quality indicators measurement system (OQMS) [2]. Measurement of any technological parameters or indicators of oil quality occurs in all components of the OQMS, which makes it possible to consider it as a measuring system intended for direct or indirect dynamic measurements of the mass and quality indicators of oil, corresponding to GOST R 51858-2002, and oil products.

Depending on the implemented measurement method, OQMS solves different problems (figure 1).

![Figure 1. Measuring instruments used to account for gross oil mass.](image)

For the direct dynamic measurement method, they are as follows:

- measurement of the gross weight of oil with a mass flow transducer (MFT) for each measuring line (IL);
- calculation of gross and net weight of oil according to OQMS as a whole;
- measurement of oil pressure and temperature with appropriate transducers.

For the indirect method of dynamic measurements, the range of tasks increases:

- measurement of oil volume by volumetric PR;
- measurement of oil density with flow density converters;
- measurement of oil pressure and temperature with appropriate transducers;
- calculation of the gross weight of oil for each test line based on the results of measurements of the oil volume for each test line and the oil density reduced to standard conditions or to the conditions for volume measurements;
- Calculation of the gross and net weight of oil according to OQMS as a whole.

The total error in determining the mass of oil includes many components. If, when determining the gross oil mass, these are errors of all used measuring instruments (MI) and errors of data processing in the information processing system (IPS), then when calculating the net weight, errors of sampling, errors
of laboratory analysis results (determination of the mass fraction of water, solids and chlorides salts), etc.

In the general case, the relative error \( \delta_{M_{pr}} \) for measuring the net mass for the direct dynamic method is determined by the formula given in GOST R 8.595-2004:

\[
\delta_{M_{pr}} = \pm 1.1 \sqrt{\delta_m^2 + \frac{\Delta W_{MB}^2 + \Delta W_{MII}^2 + \Delta W_{XC}^2}{\left(1 - \frac{W_{MB} + W_{MII} + W_{XC}}{100}\right)^2}},
\]

where: \( W_{MB} \) – mass fraction of water in oil,%; \( W_{MII} \) – mass fraction of mechanical impurities in oil,%; \( W_{XC} \) – mass fraction of chloride salts in oil,%; \( \Delta W_{MB} \) – absolute error in measuring the mass fraction of water in oil,%; \( \Delta W_{MII} \) – absolute error in measuring the mass fraction of mechanical impurities in oil,%; \( \Delta W_{XC} \) – absolute error in measuring the mass fraction of chloride salts in oil,%; \( \delta_m \) – relative error in measuring gross oil mass, %.

When using the indirect method when measuring the net mass of oil, the fraction \( \frac{\delta_m}{1.1} \) is introduced into the expression under the square root sign, and the expression for the error \( \delta_{M_{косв}} \) takes the form:

\[
\delta_{M_{косв}} = \pm 1.1 \sqrt{\left(\frac{\delta_m}{1.1}\right)^2 + \frac{\Delta W_{MB}^2 + \Delta W_{MII}^2 + \Delta W_{XC}^2}{\left(\frac{W_{MB} + W_{MII} + W_{XC}}{100}\right)^2}}.
\]

The use of a coefficient equal to 1.1 before and below the square root sign is regulated by GOST 8.736-2011, according to which this coefficient (denoted by the symbol \( k \) in the standard) is determined by the level of confidence, the number of non-excluded components of the systematic error and their relationship to each other. For the probability \( P = 0.95 \), the coefficient \( k \) depends negligibly on the number of components of the non-excluded systematic error and their ratio; therefore, for a given probability, the coefficient \( k \) for a uniform distribution law is taken to be 1.1.

The error in the measurement result is not the only estimate of their reliability. Although the measurement error is interpreted as the difference between the measured and the true (instead of which, in practice, the real is usually used) value of the quantity, in practice, all experts in the field of measurement consider it to be some uncertainty of this difference, as evidenced by the presence of the sign "±" in front of the numerical value of the error when presenting measurement result. The true value of the quantity remains unknown in all cases. Therefore, a theory of measurement, based on what is never known and in principle indefinable, is always vulnerable. Basically, measurement uncertainty is reflected in two main measures of measurement accuracy:

- Systematic measurement error (evaluating the effect of systematic influence on the measured value).
- Random measurement error (reflecting the degree of dispersion of the measured values under the influence of random factors on the measuring instrument).

To link these concepts, the International Organization for Standardization (ISO) in 1991 introduced a special parameter called "uncertainty", disclosed in GOST R 54500.3.1–2011/ISO/IEC Guide 98–3: 2008.

To date, for calculating the characteristics of the measurement result, Recommendations R 50.2.038-2004 provide for both approaches: the traditional one used in the Russian Federation for metrological purposes, and the European one, covered in GOST R 54500.3.1–2011. In the traditional approach, measurement uncertainty plays a central role, in the European approach, measurement uncertainty.

It should be noted that in many countries, with the exception of Russia, it is the uncertainty that is mainly used to assess the reliability of both the measurement results and the measuring instruments themselves. The error as a criterion of reliability is used much less frequently [3]. Many leading vendors of measuring instruments are actively switching to their standardization using uncertainty. In the
descriptions of the type (DT) of Russian measuring instruments (MI), one can also find the standardization of metrological characteristics by means of expanded uncertainty.

The concept of uncertainty is given in two normative documents: RMG 29-13 and GOST 34100.3-2017/Guide ISO/IEC 98-3: 2008. In accordance with these documents, uncertainty means the following, respectively:

- A non-negative parameter characterizing the dispersion of the values of the quantity, assigned to the measured value based on the measurement information.
- Parameter related to the measurement result and characterizing the spread values that could reasonably be attributed to the measurand.

In fact, uncertainty is a measure of the scattering of the measurement results.

The emergence of the concept of uncertainty was a consequence of the change in the very concept of "measurement". The measurement process is traditionally understood as comparing the measured value with its unit, that is, with the standard. However, in today's reality, when measurable quantities have appeared that, in principle, cannot have a standard, these are information or transport streams, for example, measurement in accordance with GOST R 54500.3.1–2011 is understood as the totality of any operations that lead to some then the value of this quantity [4].

Then the measurement uncertainty can be considered as a parameter linking the measurement result and the spread of values into a whole, - this is how it is interpreted in GOST 34100.3-2017. As such, the measurement uncertainty is denoted by the letter $U$ (Uncertainty).

The following characteristics of measurement uncertainty exist:

- $u_A$ – Type A standard uncertainty is the standard deviation that characterizes the random error.
- $u_B$ – Type B standard uncertainty is the standard deviation of the non-excluded bias.
- $U_C$ – the total uncertainty is the standard deviation characterizing total error.
- $U_P$ – expanded uncertainty - confidence limits of error.

The Type A standard uncertainty applies only to static methods when the number of measurements exceeds 30.

For single measurements, the Type B standard uncertainty is calculated.

It is estimated on the basis of one of three prior distribution laws: normal, triangular or uniform. The rationale for the choice of the distribution law is given in ISO/IEC Guide 98-3: 2008. In accordance with it, if the limits are known, then it is believed that the result can be obtained with equal probability at any point of the segment, and therefore it is a uniform distribution law for which the uncertainty of type B is found by the formula:

$$ u_B = \frac{b-a}{2\sqrt{3}}, $$(3)

where: $b$ and $a$ – lower and upper limits, between which the measured value can be.

2.2. Statement of the research problem

Analysis of the regulatory framework concerning the issues of metrological support for measuring the mass of commercial oil shows that in Russia uncertainty is much less often used in comparison with the metrological services of foreign countries as an assessment of measurement results, which is inconvenient from the point of view of international partnership [5]. The basic principle in metrology is to ensure the uniformity of measurements. Therefore, in order to avoid an imbalance in the measurement of the mass of commercial oil during commercial operations, especially export-import, it is advisable to move to assess the accuracy to uncertainty [6, 7].

The aim of the study is to analyze the possibility of such a transition and compare the results of the traditional estimation method using errors and the so-called European estimation method using expanded uncertainty.
3. Results and discussion

3.1. Algorithms for calculating the relative error and expanded uncertainty of measuring the mass of oil by the dynamic method of indirect measurements

The volume of oil varies depending on its temperature. Therefore, commercial transactions take into account the mass of oil, not its volume. In the indirect method, the mass of oil is determined by measuring the volume, temperature and density of the product. There are no results of measuring the mass of oil, therefore, the calculation of the uncertainty is carried out in accordance with type B, when the general values of the MI characteristic (from the description of the MI type) are used as the initial data.

The most common way to formalize incomplete knowledge about quantity values is to assume a symmetric uniform distribution law for quantity values. Then the type B standard uncertainty is:

$$u_B(x_i) = \frac{b_i}{\sqrt{3}}$$  \hspace{1cm} (4)

where:  $x_i$ – measured value;  $b_i$ – symmetric boundaries of the MI error indicated in the passport data.

The total uncertainty is calculated by the formula:

$$u_c(y) = \sqrt{\sum_{i=1}^{m} \left( \frac{\partial f}{\partial x_i} \right)^2 u^2(x_i)}.$$  \hspace{1cm} (5)

The expanded uncertainty is calculated as:

$$U_p = k \cdot u_c(y),$$ \hspace{1cm} (6)

where:  $k$ – coverage ratio.

The coverage factor $k$ is selected by the formula:

$$k = t_p(\nu_{eff}),$$ \hspace{1cm} (7)

where:  $t_p(\nu_{eff})$ – quantile of the Student's distribution with effective number of degrees of freedom $\nu_{eff}$ and confidence probability $p$.

Effective degrees of freedom:

$$\nu_{eff} = \frac{u_c^4}{\sum_{i=1}^{m} \frac{\nu_i u^2(x_i)}{u_i (\frac{\partial f}{\partial x_i})^4}}.$$ \hspace{1cm} (8)

where:  $\nu_i$ – the number of degrees of freedom.

For calculations of standard uncertainties of type B, all $\nu_i = \infty$, respectively $\nu_{eff} = \infty$.

To ensure comparability with the estimation of the accuracy of the results by means of the error in which the value of $P = 0.95$ is used in calculating the confidence intervals of the systematic measurement error, as noted above, the same level of confidence is chosen to calculate the expanded uncertainty.

Quantile of the Student's distribution for the effective degree of freedom $\nu_{eff} = \infty$ and confidence probability $P = 0.95$ $t_p(\nu_{eff}) = 1.96$ [8]. Thus, in accordance with formula (7), the coverage factor $k = t_p(\nu_{eff}) = 1.96$.

GOST 34100.1-2017 introduces the concept of an uncertainty budget, which is understood as “a formalized presentation of a complete list of sources of measurement uncertainty for each input quantity, indicating their standard uncertainty and their contribution to the total standard uncertainty of the measurement result.”

Table 1 shows the relative error budget compiled by analogy, and table 2 shows the expanded uncertainty budget for net oil mass.
Table 1. Budget of net weight relative error.

| Characteristic                                         | Source                                                                 |
|--------------------------------------------------------|------------------------------------------------------------------------|
| Measured value evaluation                              | $m = \rho_0 \cdot V_0$                                                |
| Measured values                                        | $\rho, \ T, \ V$                                                      |
| Estimation of the density measurement error, $\Delta \rho$, kg/m$^3$ | Specified in the MI type description                                  |
| Estimation of the temperature measurement error, $\Delta T$, °C | Specified in the MI type description                                  |
| Estimation of the volume measurement error, $\Delta V$, m$^3$ | Installed by GOST 8.595                                               |
| Confidence probability $P$                              | $\delta_m = 1.96 \sqrt{\delta_T^2 + \delta_T^2 + \delta_N^2}$     |
| Limit of permissible relative error of gross oil mass measurement | for $P=0.95$                                                          |

To calculate the relative standard uncertainty for gross mass, the following relationship is used:

$$U_m = 1.96 \sqrt{U_N^2 + U_T^2 + U_V^2 + U_T},$$  \hspace{1cm} (9)$$

where: $U_N$ – standard uncertainty of the measuring and computational complex (MCC), which is part of the OQMS; $U_T$ – standard uncertainty of the volume measurement result; $U_V$ – standard uncertainty of the density measurement result; $U_T$ – standard uncertainty of the temperature measurement result.

Expanded uncertainty in net oil mass:

$$U_M = 1.96 \sqrt{U_m^2 + U_{WB}^2 + U_{WXC}^2 + U_{WMP}^2},$$  \hspace{1cm} (10)$$

where: $U_{WB}$ – standard uncertainty of the result of determining the mass fraction of water; $U_{WXC}$ – standard uncertainty of the result of determining the mass fraction of chloride salts; $U_{WMP}$ – standard uncertainty of the result of determining the mass fraction of mechanical impurities.

Table 2. Expanded uncertainty budget for net mass.

| Characteristic                                         | Source                                                                 |
|--------------------------------------------------------|------------------------------------------------------------------------|
| Measured value evaluation                              | $m = \rho_0 \cdot V_0$                                                |
| Measured values                                        | $\rho, \ T, \ V$                                                      |
| Standard uncertainty of density measurement, kg/m$^3$ | $u_B(\rho) = \frac{\Delta \rho}{\sqrt{3}}$                            |
| Standard uncertainty of temperature measurement, °C   | $u_B(T) = \frac{\Delta T}{\sqrt{3}}$                                  |
| Standard uncertainty of volume measurement, m$^3$     | $u_B(V) = \frac{\Delta V}{\sqrt{3}}$                                  |
| Confidence probability $P$                              | Selected equal to the value for calculating the error                 |
| Total standard uncertainty                             | $u_c(y) = \sqrt{\sum_{i=1}^{m} \left( \frac{\partial f}{\partial x_i} \right)^2 u^2(x_i)}$ |
| Effective number of degrees of freedom                 | $U_{eff} = \frac{u_c^2}{\sum_{i=1}^{m} \frac{u^4(x_i)}{v_i} \left( \frac{\partial f}{\partial x_i} \right)^2}$ |
| Coverage ratio                                         | $k = t_p(U_{eff})$                                                     |
| Expanded uncertainty                                   | $U_p = k \cdot u_c(y)$                                                |
3.2. An example of calculating the relative error and expanded uncertainty of measuring the mass of oil by the dynamic method of indirect measurements.

To carry out a comparative analysis of the assessment of the accuracy of the results of measuring the net oil mass by the indirect dynamic method according to the formulas given in tables 1 and 2 for five conditional OQMS, the relative error and expanded uncertainty were calculated. The initial data for the calculation are shown in table 3.

Table 3. Initial data for calculating the relative error and expanded uncertainty.

| Characteristic                                      | OQMS   |
|-----------------------------------------------------|--------|
| Density of oil, kg/m³                                | 781    |
| Absolute measurement error of oil density, kg/m³    | 0.3    |
| Oil temperature in the flow transducer, °C           | 30     |
| Oil temperature in the density converter, °C         | 32     |
| Absolute error of oil temperature measurements when measuring its volume and density, °C | 0.1    |
| Mass fraction of water, %                            | 0.7    |
| Absolute error in measuring the mass fraction of water, % | 0.7    |
| Mass fraction of mechanical impurities, %            | 0.05   |
| Absolute error in measuring the mass fraction of mechanical impurities, % | 0.5    |
| The content of chloride salts, %                    | 0.005  |
| Absolute error in measuring the mass fraction of chloride salts, % | 0.5    |
| Absolute error in measuring the volume of oil, m³    | 0.15   |
| Relative error in measuring the volume of oil, %     | 0.23   |

The calculation results for gross and net weights for OQMS 1 are shown in table 4, and for all OQMS for gross weights in figure 2.

As you can see, the calculations turned out to be comparable.

The results obtained prove that the assessment of the reliability of measurement results can be carried out not only with the help of relative errors, but also through expanded uncertainties.

Table 4. Results of calculating the relative error and expanded uncertainty.

| Oil mass   | Relative error | Expanded uncertainty |
|------------|----------------|----------------------|
| Gross      | $\delta_m = \pm 0.28 \%$ | $U_m = \pm 0.29 \%$  |
| Net        | $\delta_M = \pm 0.32 \%$ | $U_M = \pm 0.33 \%$  |

Figure 2. Comparative analysis of the results of calculating the relative error and expanded uncertainty for five OQMS.
3.3. Discussion of the results

Naturally, the question arises about the expediency of using each of the measurement accuracy assessment tools in specific metrological situations. In the order of the Ministry of Energy No. 179 dated 03.15.2016, in effect until 01.01.2021, which approved the list of measurement accuracy indicators, they operate only with the concept of the relative measurement error, which limits the practical application of the uncertainty calculation, in particular, in commodity accounting operations with oil.

When to use uncertainty? First of all, this is advisable for full-scale measurements, when the result obtained is a characteristic not of a measured value, but of a realized value, i.e. it was obtained on a real object in the presence of various interference. Accounting for differences between the realized quantity and the quantity to be measured is more conveniently estimated by means of uncertainty. In contrast to the inaccuracy of field measurements, which cannot be calculated, since the exact value of the interference is unknown, the components of the uncertainty (deviations of the realized value from the measured value, errors of measuring instruments, etc.) can be estimated. This makes it possible, with some probability, to expect that the results of subsequent measurements will be within the range of values, the dimensions of which are characterized by the calculated uncertainty. For many practical applications, this is quite sufficient, since it allows one to compare the measurement results of different laboratories and use them in technical calculations [9].

Measurement errors must be used when checking or calibrating a measuring instrument, as well as when standardizing the metrological characteristics of measuring instruments. In this case, the characteristics of the error are used as the limits of the permissible errors of measuring instruments of this type (when compiling a description of the type MI).

As for the already mentioned modern trend towards standardization of uncertainty in descriptions of the MI type, this seems to be a fundamentally wrong approach. Uncertainty is a characteristic of the measurement quality under specific conditions, which may differ from those indicated in the type description. Therefore, it can in no way be normalized in it. In addition, the register includes MI intended for work in the field of state regulation of ensuring the uniformity of measurements (SREUM). For them, verification is mandatory in order to confirm their compliance with the established metrological requirements, based on the concept of error.

Measurement uncertainty is a parameter that is associated with a measurement result and which characterizes the spread of values that could reasonably be attributed to the measured quantity, i.e. MI has no measurement uncertainty by definition. Uncertainty has a measurement result for a specific MI.

4. Conclusions

The studies carried out allow us to draw the following conclusions:

In modern metrology, two approaches are used to assess the accuracy of measurements: the traditional one, based on the concept of measurement error, and a relatively new one, which is based on the concept of uncertainty. In many countries, the second approach prevails, and the concept of uncertainty is used both to characterize the accuracy of any measurements and to standardize the metrological characteristics of the measuring instruments themselves.

In Russia, the current regulatory documents allow the use of uncertainty. In particular, with regard to the commercial accounting of commercial oil, the state standards stipulate that the measurement error of the oil mass can be estimated by calculating the measurement uncertainty of the oil mass, as well as determining the accuracy for all significant oil quality indicators that are used in calculating their mass. However, the documents do not provide a single expression for their calculation, while the expressions for calculating the limits of relative errors are described in detail.

Specific measurement results in any metrological situations can and should be unambiguously characterized by uncertainty. The undoubted advantage of this concept is the general approach to calculating the standard uncertainty for all error components, which is of interest for practical use.

When determining or normalizing the metrological characteristics of measuring instruments, the uncertainty is not suitable, since it characterizes the measurement process, and not the instrument. Accordingly, in this case, it is necessary to use the concept of error.
Hence follows the main conclusion - in the commercial accounting of commercial oil, the transition to the assessment by uncertainty is quite justified, since quantitatively, these estimates - relative error and expanded uncertainty - are practically the same, but on the international market, greater confidence in the results is provided precisely by uncertainty, allowing the main purpose of metrology to be fulfilled - to ensure the uniformity of measurements.

References
[1] Nemirov M S 2013 State and prospects of improving the accuracy of measurements and accounting of oil Automation, telemechanization and communication in the oil industry 6 8-11
[2] Prakhova M Yu, Krasnov A N, Khoroshavina E A and Emets S V 2019 Automation systems in the oil industry (Moscow Vologda: Infra-Engineering) p 242
[3] Barash V. Ya and Tretyakova O Yu 2009 Uncertainty and error in modern metrology Legal and applied metrology 5 (105) 15–20
[4] Bogdan S N, Kovalevich O M, Kozlova N A, Shevchenko SA and Yashnikov D A 2017 On the assessment of errors in calculations performed when justifying the safety of using atomic energy facilities Nuclear and radiation safety 2(84) 1-16
[5] Doinikov A S 2006 Guidelines for the application of the concepts "error" and "uncertainty" in various metrological problems Legal and applied metrology 1 43–6
[6] Mironchuk B V and Fatkullin A A 2012 On the error in measuring net weight of crude oil Measuring equipment 1 16-25
[7] Bashevskaya O S, Denis Yu A and Romash E V 2012 Automated method for calculating the mass of petroleum products using the concept of uncertainty Vestnik MGTU "Stankin" 4 (23) 113–8
[8] Pustylnik E I 1968 Statistical Methods for the Analysis and Processing of Measurements (Moscow: Nauka) p 273
[9] Issues of accounting for measurement uncertainty 2019 Explanations of experts of the Russian Accreditation Agency