Measurement Uncertainties Estimation Introduced by the Diverter Into the Budget of Standard Uncertainties

R.A. Korneev[1], A.R. Tukhvatullin[1], V.A. Fafurin[1], A.V. Shchelchkov[1,2], A.I. Ataeva[1]

[1]*Federal State Unitary Enterprise «All-Russian Research Institute of Flow Metering»,*
St. 2nd Azinskaya, 7a, Kazan, Republic of Tatarstan, Russian Federation, 420088
[2]*Kazan National Research Technical University named after A. N. Tupolev - KAI,*
Karl Marx Street, 10, Kazan, Republic of Tatarstan, Russian Federation, 420011
E-mail (corresponding author): lexa_kzn@mail.ru

Abstract

An indirect method is presented for estimation standard measurement uncertainties included into a standard uncertainty budget by the diverter, reproducing units of mass and volume of fluid in a stream, mass and volumetric flow rates of a fluid.

1. Introduction

The review of literature sources on the actual topic of transferring units of mass and volume of liquid in the flow, mass and volume flow of liquid to the working standards of the 1st, 2nd and 3rd categories, which are used as calibration units with weighing devices, allowed to determine the list of main influencing factors on the budget of uncertainties. According to the recommendations of the standards [1-3], the accuracy of the static weighing method when calibrating the flow and quantity measuring instruments depends on the determination of water and air densities.

It is also necessary to pay attention that the pipeline and shut-off valves must be completely filled with a flow of moving liquid, and there must be no air or gas bubbles in the measuring line [3,4]. Not unimportant factor in the quality of the standard is a part of the measuring system that ensures the stability of the flow rate of liquid in the pipeline, for example, by maintaining a constant level in the pressure tank, or the use of proportional-integral-differential control, etc. V.P. Kargapoltsev recommends in article [4] to complete the system that circulates the working fluid with low-noise circulation pumps with a low level of vibration threshold values. As a reference, it is recommended to use flow meters produced by the world's leading manufacturers, one of the functional advantages of which can be attributed to the stability of the readings in time. These recommendations will ensure satisfactory long-term operation of the standard, and the transition process will fade over time.

It is necessary to discuss one of the requirements imposed on the calibration facilities, formulated in the article [4]: «... an important requirement is the compactness of the installation to exclude significant costs for the construction of new premises». This requirement enters into serious disagreement with the recommendations in the articles by W. Nunner [5], R. Koch [6], R.L. Webb [7], A. Shchelchkov [8] and monographs of L. Loitsyansky et al. [9], I. Idelchik [10] on the length of sections of hydrodynamic stabilization of fluid flow, on which the velocity profile after local resistance gradually changes to the normal stabilized flow profile. For example, in turbulent flow, the relative length of the rectilinear section is not less than 35-130 calibers, depending on the Reynolds number [9].

It should be noted that the requirement for compactness of installations mentioned in article [4] requires deep theoretical and empirical study. Consideration of this issue has a practical aspect. One of the requirements to ensure the declared metrological characteristics of the measuring instrument during the installation of the pipeline is the presence of straight sections of the pipeline of a certain length, in order to eliminate the factors that cause a change in the normal profile of the speed of the stabilized fluid flow.

Influential factor on the budget of uncertainty of the standard in transferring units of mass and volume of

fluid in the stream, the mass and volumetric flow of the fluid is the function of the diverter. When assessing the metrological characteristics of the majority of high-precision standards in the Russian Federation, only the time difference of the diverter operation is taken into account. Meanwhile, the researchers T. Shimada [11] and Rainer Engel [12], based on the results of optical Particle Image Velocimetry (PIV) experiments, demonstrated the presence of irregularity of the velocity profile and turbulent pulsations on the nozzle section of the diverter. The experimental studies of V. Fafurin, R. Korneev, A. Shchelchkov, etc., presented in the article [13], performed using the pneumometric method, also recorded significant differences in the profile of the liquid flow rates at the nozzle section of the diverter from the «ideal», determined by the average flow rate (Figure 1-2). For this reason, the mass $M = M_{f2} + M' + M_{r2}$ (Figure 2), which differs from the calculated the mass $M_{calc} = M_{f1} + M' + M_{r1}$ (Figure 1) by the magnitude of the mass M_d gets on the weight device for the time τ. Here, M_{f1} and M_{r1} are the calculated masses of the fluid at the forward $\tau_{forward}$ and reverse τ_{revers} the diverter stroke times. M_{f2} and M_{r2} are the experimental masses of the fluid at the forward $\tau_{forward}$ and reverse τ_{revers} the diverter stroke times.
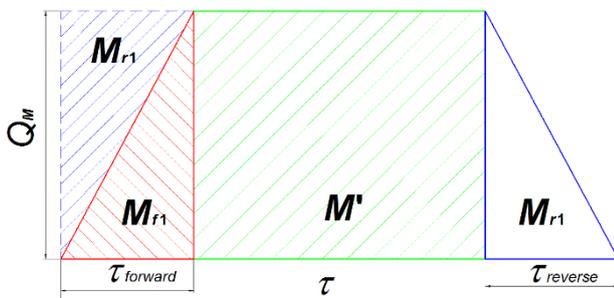
Figure 1: Theoretical timing diagram of the diverter operation.
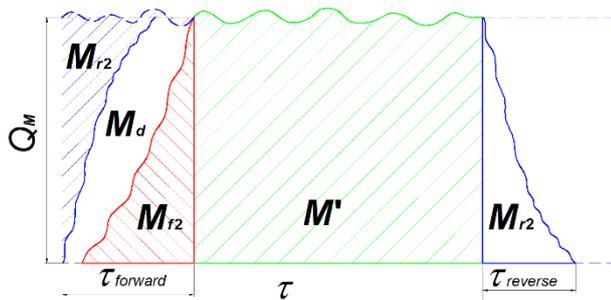
Figure 2: Experimental timing diagram of the diverter operation.

It should be noted that due to the design features of the diverter real standards, optical and pneumatic methods do not always allow to determine the local values of flow rates in the nozzle section. In this

regard, there is a need to determine engineering approaches to assess the impact of factors introduced by the diverter in the budget of uncertainty of the standard in a wide range of design and operating parameters.

The purpose of this article is to test an indirect method for estimating standard measurement uncertainties introduced by the diverter to a standard uncertainty budget when reproducing units of mass and volume of liquid in a stream, mass and volume flow rates of a liquid.

2. Features of the method for conducting experiments to evaluate

Reproduction of units of mass and volume of liquid in the flow, mass and volume flow rate of the standard liquid is based on the static measurement of the mass of the working fluid entering the weighing device for a fixed interval of time, followed by the ejection force.

Filling degree and distribution of flow velocities (flow velocity profile) of the fluid in the slice (plane) of the diverter nozzle are factors that affect the metrological characteristics of the entire standard. It should be noted that the evaluation of standard measurement uncertainties caused by the operation of the standard diverter is also influenced by the following factors: asynchronous signals «start» – «stop» between the measuring controller of the standard and the testing flow meter; the difference in time and irregularity in the operation of the actuators of the diverter in «direct» and "reverse" strokes; pulsations (instability) fluid flow rate; leakage (overflow) and splashing of a jet of liquid when switching to the opposite drain [1-4,11-14].

Experimental studies for evaluation the standard uncertainty of the measurements made by the diverter, are made in the range of liquid mass flow rate $Q_M = 11,1-83,3$ kg/s (40-300 t/h) for weighting device, part of the experimental standard, the description of which is presented in [13]. Before starting the research, visually make sure that there are no effects in the diverter associated with splashing and overflowing.

According to the indirect method, to estimate the standard measurement uncertainties introduced by the reference diverter, it is necessary to select at least three points (modes) of mass flow Q, kg/s (t/h): Q_{Mmin}, Q_{Mmax}, and the arithmetic mean of the sum of the largest and minimum mass $Q_{Mavg} = 0,5 \cdot (Q_{Mmin} + Q_{Mmax})$. It is allowed to increase the number of flow points in the range. In studies,

the authors chose 8 mass flow points for a more complete and thorough study of the characteristics of the flow switch standard.

For each point (mode) of the mass flow, it is necessary to select at least five values of the measurement time interval τ (s), during which the liquid enters the weighing device. Maximum value of τ_1 can be limited by the volume of the storage tank. Minimum value τ_5 is determined, including the lower range of sensitivity and discreteness of the weighing device, as well as due to the quality of the flow switch, and for each standard individually. It should be noted that in GOST R 8.909 - 2016 [1] and international standard ISO 4185 [3], minimum value of the measurement time interval is recommended $\tau_5 \geq 30$ s. Intermediate values of time intervals are calculated in equal time intervals $\tau_3 = 0,5 \cdot (\tau_1 + \tau_5)$, $\tau_2 = 0,5 \cdot (\tau_1 + \tau_3)$, $\tau_4 = 0,5 \cdot (\tau_3 + \tau_5)$. For each value of the time interval τ_i at a fixed flow rate mode is carried out at least eleven measurements. For each point weighing i write values measurement time τ_i, mass of fluid M_i received in the storage container and liquid mass flow rate Q_{Mi}.

3. Features of the experimental data processing methodology

The initial data for processing measurement results are: a) density of the driving fluid ρ_f, kg/m^3; b) the mass of the liquid according to the indications of the weighing device M, kg; the density of the environment ρ_a, kg/m^3; the measurement time τ, s.
For one of the studied flow points (modes):
1) The arithmetic mean values of the basic values of the measurement equation are determined:

$$\overline{M}_j = \frac{1}{n}\sum_{i=1}^{n} M_{ji} \qquad (1)$$

where M_{ji} – the mass value according to the weights, kg; $\overline{M}_j$ – average mass value for 2, 3 , …, 10 and n measurements according to the weight device, kg; n – number of measurements (n≥11); i, j – indices of weighing point and series of measurements. The obtained data are used in the construction of graphical dependencies of the form M_{ji}=f(n) and $\overline{M}_j$ =f(n) (example $\overline{Q}_{Mj}$=250 t/h – Figure 3).

$$\overline{\tau}_j = \frac{1}{n}\sum_{i=1}^{n} \tau_{j,i} \qquad (2)$$

where τ_{ji} – the value of time according to indications of the channel, s; $\overline{\tau}_j$ – the arithmetic average of the time for 2, 3,…, 10 and n measurements according to indications of the channel, s. The obtained data are used in the construction of graphic

dependencies τ_{ji}=f(n) and $\overline{\tau}_j$ =f(n) (example $\overline{Q}_{Mj}$ =250 t/h – Figure 4).
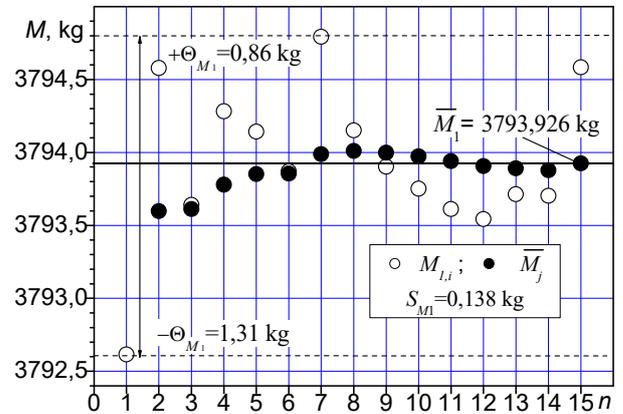
Figure 3: Graphic dependences of measurements quantities n on the basic value of the equation of measurement of mass values M according to the readings of the weighing device.
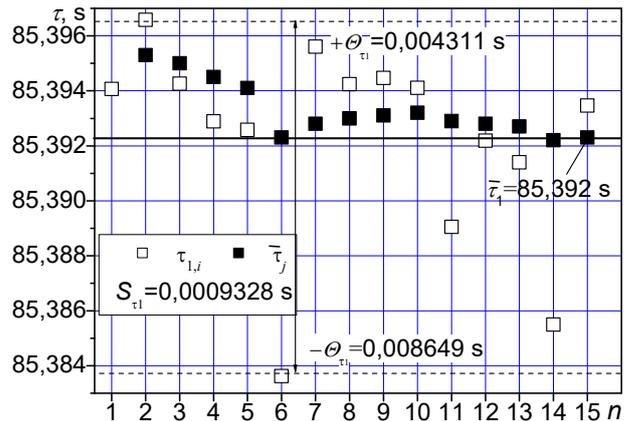
Figure 3: Graphic dependences of measurements quantities n on the basic value of the equation of measurement of time values of measurements according to the time channel τ.

$$\overline{Q}_{Mj} = \frac{1}{n}\sum_{i=1}^{n} Q_{Mji} \qquad (3)$$

where Q_{Mji} – the value of the mass flow, kg/s; $\overline{Q}_{Mj}$ – the arithmetic mean value of the mass flow rate of at least 11 measurements, kg/s.

Graphic dependencies (Fig. 3-4) allow you visually justify the required number of measurements of basic quantities M_{ji} and τ_{ji}. Further increase in the number of measurements of n, from the metrological and economic points of view is impractical, because the increase in the number of measurements of n>11 is self-similar.

2) For the set point (mode) of flow we determine (Q_{Mmin}, Q_{Mavg}, Q_{Mmax}), the value of the liquid mass M_d that did not fall into the weight device due to the functional features by the diverter, flow control and automated system of measurement and control standard [1], kg:

a) we assume that value of the liquid mass for the first $\bar{\tau}_{j1}$, second $\bar{\tau}_{j2}$, ..., fifth $\bar{\tau}_{j5}$ time values are $M_{dji} = M_{d1j} = M_{d2j} = M_{d3j} = M_{d4j} = M_{d5j}$;

b) we assume that in the systems of equations (4-7) the mass flow value $\bar{Q}_{M1}$ is «true».

$$1\text{-}2 \begin{cases} \overline{M}_{1j} = \overline{Q}_{M1j} \cdot \bar{\tau}_{1j} - M_{d1j} \\ \overline{M}_{2j} = \overline{Q}_{M2j} \cdot \bar{\tau}_{2j} - M_{d2j} \end{cases} \quad (4)$$

$$1\text{-}3 \begin{cases} \overline{M}_{1j} = \overline{Q}_{M1j} \cdot \bar{\tau}_{1j} - M_{d1j} \\ \overline{M}_{3j} = \overline{Q}_{M3j} \cdot \bar{\tau}_{3j} - M_{d3j} \end{cases} \quad (5)$$

$$1\text{-}4 \begin{cases} \overline{M}_{1j} = \overline{Q}_{M1j} \cdot \bar{\tau}_{1j} - M_{d1j} \\ \overline{M}_{4j} = \overline{Q}_{M4j} \cdot \bar{\tau}_{4j} - M_{d4j} \end{cases} \quad (6)$$

$$1\text{-}5 \begin{cases} \overline{M}_{1j} = \overline{Q}_{M1j} \cdot \bar{\tau}_{1j} - M_{d1j} \\ \overline{M}_{5j} = \overline{Q}_{M5j} \cdot \bar{\tau}_{5j} - M_{d5j} \end{cases} \quad (7)$$

The required value M_{dji} (8-11) is determined by substituting the mass flow $\overline{Q}_{M1}$ into the second equation of system (4-7):

$$M_{d(1\text{-}2)j} = \overline{Q}_{M1j} \cdot \bar{\tau}_{2j} - \overline{M}_{2j} \quad (8)$$

$$M_{d(1\text{-}3)j} = \overline{Q}_{M1j} \cdot \bar{\tau}_{3j} - \overline{M}_{3j} \quad (9)$$

$$M_{d(1\text{-}4)j} = \overline{Q}_{M1j} \cdot \bar{\tau}_{4j} - \overline{M}_{4j} \quad (10)$$

$$M_{d(1\text{-}5)j} = \overline{Q}_{M1j} \cdot \bar{\tau}_{5j} - \overline{M}_{5j} \quad (11)$$

Similar actions are performed for systems of equations.

$$2\text{-}3 \begin{cases} \overline{M}_{2j} = \overline{Q}_{M2j} \cdot \bar{\tau}_{2j} - M_{d2j} \\ \overline{M}_{3j} = \overline{Q}_{M3j} \cdot \bar{\tau}_{3j} - M_{d3j} \end{cases} \quad (12)$$

$$2\text{-}4 \begin{cases} \overline{M}_{2j} = \overline{Q}_{M2j} \cdot \bar{\tau}_{2j} - M_{d2j} \\ \overline{M}_{4j} = \overline{Q}_{M4j} \cdot \bar{\tau}_{4j} - M_{d4j} \end{cases} \quad (13)$$

$$2\text{-}5 \begin{cases} \overline{M}_{2j} = \overline{Q}_{M2j} \cdot \bar{\tau}_{2j} - M_{d2j} \\ \overline{M}_{5j} = \overline{Q}_{M5j} \cdot \bar{\tau}_{5j} - M_{d5j} \end{cases} \quad (14)$$

$$3\text{-}4 \begin{cases} \overline{M}_{3j} = \overline{Q}_{M3j} \cdot \bar{\tau}_{3j} - M_{d3j} \\ \overline{M}_{4j} = \overline{Q}_{M4j} \cdot \bar{\tau}_{4j} - M_{d4j} \end{cases} \quad (15)$$

$$3\text{-}5 \begin{cases} \overline{M}_{3j} = \overline{Q}_{M3j} \cdot \bar{\tau}_{3j} - M_{d3j} \\ \overline{M}_{5j} = \overline{Q}_{M5j} \cdot \bar{\tau}_{5j} - M_{d5j} \end{cases} \quad (16)$$

$$4\text{-}5 \begin{cases} \overline{M}_{4j} = \overline{Q}_{M4j} \cdot \bar{\tau}_{3j} - M_{d4j} \\ \overline{M}_{5j} = \overline{Q}_{M5j} \cdot \bar{\tau}_{5j} - M_{d5j} \end{cases} \quad (17)$$

We assume that in systems of equations (12-14) «true» mass flow value – $\overline{Q}_{M2}$, for systems of equations (15-16) «true» mass flow value – $\overline{Q}_{M3}$ and for (17) «true» mass flow value – $\overline{Q}_{M4}$.

$$M_{d(2\text{-}3)j} = \overline{Q}_{M2j} \cdot \bar{\tau}_{3j} - \overline{M}_{3j} \quad (18)$$

$$M_{d(2\text{-}4)j} = \overline{Q}_{M2j} \cdot \bar{\tau}_{4j} - \overline{M}_{4j} \quad (19)$$

$$M_{d(2\text{-}5)j} = \overline{Q}_{M2j} \cdot \bar{\tau}_{5j} - \overline{M}_{5j} \quad (20)$$

Unknown quantity M_{dji} (18-20) for other systems of equations are determined by substituting the second equation of each mass flow system $\overline{Q}_{M_{2j}}$ in (12-14).

$$M_{d(3\text{-}4)j} = \overline{Q}_{M3j} \cdot \bar{\tau}_{4j} - \overline{M}_{4j} \quad (21)$$

$$M_{d(3\text{-}5)j} = \overline{Q}_{M3j} \cdot \bar{\tau}_{5j} - \overline{M}_{5j} \quad (22)$$

Unknown quantity M_{dji} (21-22) for other systems of equations are determined by substituting the second equation of each mass flow system $\overline{Q}_{M_{3j}}$ in (15-16).

$$M_{d(4\text{-}5)j} = \overline{Q}_{M4j} \cdot \bar{\tau}_{5j} - \overline{M}_{5j} \quad (23)$$

Unknown quantity M_{dji} (23) for other systems of equations are determined by substituting the

second equation of each mass flow system and $\overline{Q}_{M_{4j}}$ in (17).

3) Non-excluded systematic error of liquid mass which did not get into the weighing device, due to the functional features by the diverter, flow control and automated system of measurement and control of the standard [1], in j - point $\Theta (M_d)_j$, кг, determine:

$$\Theta\left(M_d\right)_j = \overline{M}_{dj} \qquad (6)$$

where $\overline{M}_{dj} = \dfrac{M_{d(1\text{-}2)j} + \ldots + M_{d(2\text{-}3)j} + \ldots + M_{d(4\text{-}5)j}}{10}$.

4) Standard deviation of liquid mass that did not get into the weighing device, due to the functional features by the diverter, flow control and automated system of measurement and control of the standard [1], in j – point $S(M_d)_j$, кг, determine:

$$S(M_d)_j = \sqrt{\dfrac{\left(M_{d(1\text{-}2)j} - \overline{M}_{dj}\right)^2 + \ldots + \left(M_{d(4\text{-}5)j} - \overline{M}_{dj}\right)^2}{n \cdot (n-1)}}$$
$$(7)$$

Next, a quantitative comparison of non-excluded systematic error of liquid mass that did not fall into the weighing device due to the functional features of the diverter and flow control systems of the medium, as well as an automated system of measurement, control of the standard is made [1] $\Theta (M_d)_j$ obtained by indirect method and experimental data of the authors [13], defined with the use of pneumometric method (Figure 5).
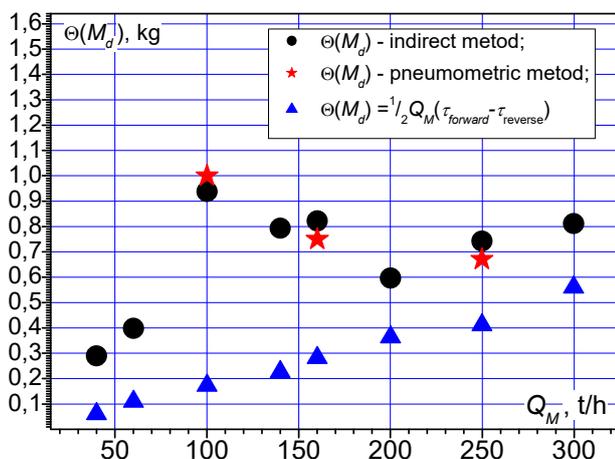
Figure 5: Non-excluded systematic error of missing liquid mass in the weighing device, determined by various methods.

Field research by an indirect method is presented in the range of fluid mass flow Q_M=11,1-83,3 kg/s (40-300 t/h) for the weight device which is a part of the standard (with fixed geometry diverter nozzle). It should be noted that the results of the pneumometric method are obtained on the basis of measurements of flow velocity profiles on the nozzle section in the range of the mass flow rate Q_M=27,7-69,4 kg/s (100-250 t/h). The results of the pneumometric method are indicated in the form of stars «★» (Figure 5). This method is difficult for wide application in real-life standards due to the design features of the diverters. The results of the indirect method are indicated in the form of circles «●» (Figure 5). There is a satisfactory agreement of results obtained by direct and indirect methods, which led to the conclusion about their reliability.

It should be recalled that in existing methods, the only influencing factor determining the characteristics of the diverter operation is the difference in the operation of the diverter actuators. Component values of non-excluded systematic error of liquid mass that did not get into the weighing device, due only to the time difference in the «forward» and «reverse» moves are indicated in the form of triangles «▲»(Figure 5), significantly lower than the values taking into account other influencing factors.

7. Conclusion

1) overall estimate of contributing factors of diverter on metrological characteristics of the standard by indirect method was conducted; 2) verification of the results of pneumometric and indirect methods, allowed to determine a rational method for assessing the impact of the diverter on the metrological characteristics of the standard units of liquid mass and volume in the flow, mass and volume flow rates; 3) testing of a rational method for assessing the contributing factors of the diverter (evaluation of standard measurement uncertainties).

It is necessary to take into account all standard uncertainty budget components introduced by the diverter, including the degree of filling and the distribution of flow rates of the fluid in the nozzle section (plane), asynchronous signals "start" – "stop" between the measuring controller of the standard with the flow meter under study, ripple fluid flow rate; as well as leaks (overflow) and splashing of a jet of liquid when switching to the opposite drain [1]. Therefore, the authors included in the developed standard method of transferring units of mass and volume of fluid in the flow, mass and

volumetric flow rates of liquid, indirect measurement method, developed for the first time an indirect method for estimating the maximum number of standard measurement uncertainties introduced by the standard of the diverter. This method does not require additional expensive equipment, performing complex numerical and experimental procedures, and is made without the involvement of well qualified personnel.

At present, the specialists of FGUP "VNIIR" are testing the standard method of transferring units of mass and volume of liquid in the flow, mass and volume flow of liquid on the standards located in Kazan, in order to determine the possibility of its wide application in the certification of working standards.

References

[1] GOST P 8.909-2016: State system for insuring the uniformity of measurements. Secondary standards of units of mass and volumetric flow rate, mass and volume of fluid. General metrological and technical requirements, 2016.

[2] GOST R 8.608-2004 GSI: State system for ensuring the uniformity of measurements. Mountings for verification of instruments measuring the expenditure and volume of water by calibrating with transformers (meters) of expenditure and (or) volume of water. General metrological and technical requirements, 2004.

[3] ISO 4185:1980: Measurement of liquid flow in closed conduits. Weighing method, 1980.

[4] Kargapoltsev V P, «Requirements for pouring installations for flow meters - water meters and process fluids», *Oil and Gas Business*, **Vol.** 1, pp. 1-6, 2004.

[5] Nunner W., «Warmeubergang und Druckabfall in rauchen Rohren», *VDI-Forschungscheft*, **Vol.** 455, pp. 5-39, 1956.

[6] Koch R, «Druckverlust und Warmeubergang bei verwirbelter Stromung», *VDI-Forschungscheft*, **Vol.** 469, pp. 44-49, 1958.

[7] Webb R L, «Generalized heat transfer and friction correlations for tubes with repeated-rib roughness», *Int. J. of Heat and Mass Transfer*, **Vol.** 15, pp. 180-184, 1972.

[8] Shchelchkov A, «Thermohydraulic characteristics of discretely rough tubes for the transitional flow regime», *Heat Transfer Research*, **Vol. 47**, pp. 545-557, 2016.

[9] Loitsyansky L G, *Fluid and gas mechanics*, (Moscow, State. ed. Technical and theoretical lit.), 1950.

[10] Idelchik I, *Handbook of hydraulic resistance* (Moscow, Mashinostroenie), 1992.

[11] Shimada T, Oda S, Terao Y, Takamoto M, «Development of a new diverter system for liquid flow calibration facilities», *Flow Measurement and Instrumentation*, **Vol. 14**, pp. 89–96, 2003.

[12] Rainer Engel, «Liquid Flowmeter Characteristics, Meter Calibration, Measurement Uncertainty and Traceability», *Conference Proc. COOMET comparison of National Standards for Liquid Flow* (PTB Braunschweig, Germany, 24 – 25 February), 2009.

[13] .Korneev R A, Tukhvatullin A R, Fafurin V A, Shchelchkov AV, «Impact assessment of the flow switch on the metrological characteristics of the standard units of mass and liquid volume in the flow, mass and volume liquid flow», *Measurement Techniques*, **Vol. 4**, pp. 42–47, 2019.

[14] Kosach N I, «Estimation of measurement uncertainty of fluid flow on standards», *Information processing systems*, **Vol. 6 (64)**, pp. 47-50, 2007.