



Influence of the Variable Geometry of the Diverter Nozzle on the Metrological Characteristics of a Calibration Unit with Weighing Devices

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Abstract

The rationale for the expediency of using a diverter with a variable geometry of the nozzle exit in a calibration unit with weighing devices (hereinafter – Unit) is presented for the first time in this paper. The design, operating principle and timing diagram of a diverter with a variable geometry of the nozzle exit are described in this. The local hydrodynamic characteristics of the water flow in the nozzle exit of the diverter are made by a Pitot probe. The cut-off width of the diverter nozzle was changed at fixed values of the water flow rate. The metrological characteristics of the Unit are determined by the comparison method using a comparison standard. The effect of the width of the nozzle cut on the metrological characteristics of the Unit in the investigated range of the liquid flow rate has been established. The graphical dependencies of type $\tau = f(U(Q_M))$ and $Q_M = f(U(Q_M))$ of the expanded measurement uncertainty of the Unit when reproducing the unit of the mass flow rate of the liquid on the time interval of measurements and on the mass flow rate of the liquid are presented ($k = 2, P = 0.95$). Based on the research results, the optimal values of the nozzle exit width and measurement time intervals were determined depending on the values of the mass flow rate of the liquid when using a diverter with a variable geometry of the nozzle exit. Expansion of the range of operation of weighing devices included in Unit is justified.

1. Introduction

The principle of operation of the Unit is based on the gravimetric method for determining the final mass (volume) of the liquid contained in the weighing device, referred to the time of filling the weighing device with the liquid flow. The liquid flow is directed into the weighing device through the cut of the diverter nozzle. According to the best practices of foreign [1-5] and Russian [6-7] researchers, the nozzle section of the diverter should be filled with a liquid flow. This recommendation is fulfilled when using in the Unit: a) a set of diverters with flat nozzles with fixed geometry; b) a diverter with a variable geometry of the nozzle exit over the entire range of fluid flow. A diverter with a flat nozzle of constant geometry is designed for the ratio of the reproducible flow rate range $Q_{min} : Q_{max} = 1 : 10$ for one weighing device.

The Unit with a set of diverters with flat nozzles of constant geometry has a common outlet manifold with additional pipe fittings. This increases the likelihood of uncontrolled leaks through the valves

between the outlet manifold elbows, creates free space for air pockets, complicates the control system and the maintenance procedure. The Unit costs increase.

The Unit with a diverter with a variable geometry of the nozzle exit looks preferable [1]. This design solution made it possible to expand the ratio of the reproducible fluid flow range to $Q_{min} : Q_{max} = 1 : 22$ for one weighing device. The cut of the nozzle of the diverter is filled with a fluid flow. There is no manifold with shut-off valves. The weight and dimensions of the Unit have been reduced. The Unit's costs have dropped.

2. Characteristics of the diverter with a variable geometry of the nozzle exit

2.1 The design of the diverter with a variable geometry of the nozzle exit.

The liquid flow enters the diverter nozzle from the vertical pressure pipeline A (Fig. 1) through the end hole B. The profile of the expanding part of the



nozzle is formed by the inlet planes *C* and *D*. The formation of a thin flat jet of liquid flow occurs in the converging part of the nozzle, which is a slotted nozzle, whose generators are arcs *E* and *F*.

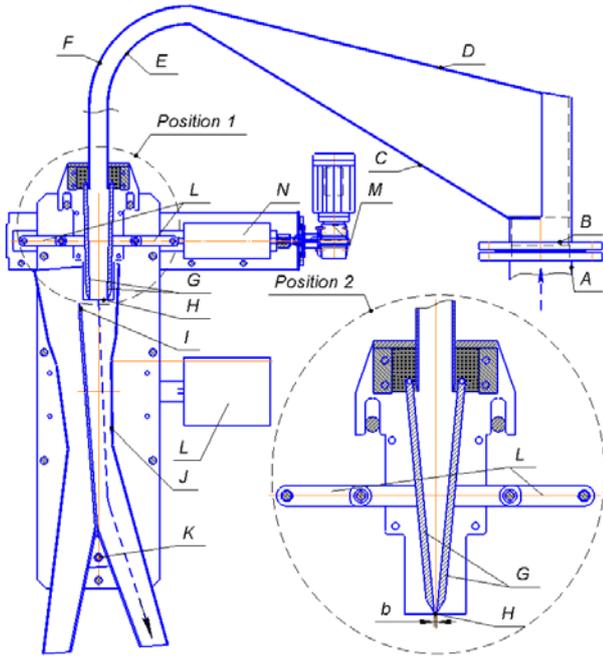


Figure 1: Cross-section of a diverter with variable geometry of the nozzle exit.

The change in the geometry (width *b*) of the nozzle exit, from where the flat jet of the liquid flow enters the actuator of the diverter *J*, is provided by the movement of the movable walls *G*. The maximum width of the nozzle exit is achieved at $b = 0.085 \text{ m}$ (*Position 1*, see Fig. 1). With a decrease in the value of the liquid flow rate *Q*, the nozzle exit is not completely filled with water. Regions are formed in the nozzle exit, which are occupied by air at atmospheric pressure. To eliminate this phenomenon, the walls of the nozzle *G* move from *Position 1* to meet each other (Fig. 1). The walls of the nozzle *G* are translationally moved by the rods *L* from *Position 1* (Fig. 1), which are driven by the drive *M* through the screw mechanism *N*. The nozzle cut width decreases. The stream of water fills the nozzle exit. The minimum width of the nozzle exit reaches $b = 0.001 \text{ m}$ (*Position 2*, see Fig. 1).

The diverter actuator *J* is a double chute. The tray is open at the top and bottom, divided in the middle by a partition – knife *I*. The rotation of the diverter actuator *J* around the *K*-axis is carried out by the servo drive *L* (Fig. 1). The stream of water directs a flat stream to either the weighing device or the storage tank. The knife edge *I* of actuator *J* is profiled to provide a flat jet of fluid flow at a constant, reproducible flow rate without splashing. The diverter sensors record the values of the

measurement time interval. The diverter sensors are oriented at the center of the nozzle *H*.

2.2 Diverter timing diagram

The countdown of the measurement time interval $\tau = IL$ (“start” command) begins at point *I* and ends – at point *L* (“stop” command) (Fig. 2). This makes it possible to minimize the influence of the source of uncertainty due to the difference in the times of the forward τ_{AF} and reverse τ_{HD} of the diverter moves (the difference in the mass $M_{AEF} - M_{DGH}$). Under ideal conditions, the mass of liquid M_{IJKL} is supplied to the weighing device for the time interval τ , which is equivalent to the mass of liquid in the flow *M* with density ρ passed at the average flow rate *w* per unit time through the cross-section *F* of the meter under test (MUT), kg:

$$M_{IJE'F} + M_{FE'GH} + M_{HGK'L} = M_{IJKL} \equiv M = (\rho \cdot w \cdot F) \cdot \tau. \quad (1)$$

where M_{IJKL} – the mass according to the readings of the measuring channel of the liquid mass, kg; *M* – the mass of liquid in the flow according to the MUT, kg; ρ – density of the liquid at absolute pressure in the pipeline, kg/m^3 ; *F* – cross-section of the MUT, m^2 ; *w* – average flow rate of the fluid flow in the cross-section *F*, m/s ; τ – the time interval according to the readings of the measuring channel of the measurement time intervals, s.

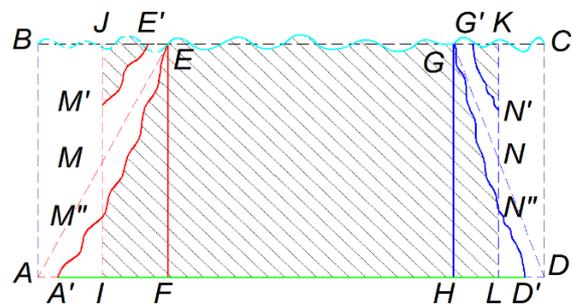


Figure 2: Diverter timing diagram.

In real operating conditions of the diverter, the mass equivalence condition (1) is not satisfied. The reasons for this are sources of uncertainty due to dynamic factors [1,6-7]. These are fluctuations in the liquid flow rate, turbulent pulsations, irregularity of the velocity profile in the nozzle exit of the diverter, and the fragmented filling of the nozzle exit of the diverter by the liquid flow. Fragmentation – the cut of the diverter nozzle is partially filled with liquid, and the space free from liquid is occupied by air at atmospheric pressure. Thus, the actual time interval for the forward stroke of the diverter $\tau_{A1} = A'I$ (Fig. 2) is less than the time interval $\tau_{AI} = AI$, which is recorded by the diverter sensors. Likewise for the reverse stroke of the diverter. The actual time interval $\tau_{HD'} = HD'$ is less than the time interval



$\tau_{HD} = HD$, which is recorded by the diverter sensors. The area of the right-angled triangle AMI (Fig. 2) is equivalent to the mass of liquid poured into the weighing device during the time interval $\tau_{AI} = \frac{1}{2} AF$ under ideal conditions. The area of the figure with the tops $A'M'I$ is equivalent to the mass of liquid that got into the weighing device during the time interval $\tau_{AI} = A'I$ in real conditions (Fig. 2). The areas of the figures are not equal to $AMI \neq A'M'I$. Similarly, the areas of the figures are not equal to $LND \neq LN'D'$. It is necessary to exclude the source of uncertainty due to the fragmentation of the filling of the diverter nozzle cut by the liquid flow. Within the framework of this study, the design of a diverter with a variable nozzle exit geometry is considered. The liquid fills the nozzle exit with a decrease in its width b (Fig. 1).

3. Object of research

The Unit, certified as the Secondary standard of units of mass and volume of liquid in the flow, mass and volumetric liquid flow rates, was chosen as the object of research. The Secondary standard is traceable to the State primary special standard GET 63-2019 [8] (hereinafter – GET 63-2019) according to the State verification scheme for measuring instruments of mass and volume of liquid in the flow, liquid volume and capacity during static measurements, mass and volumetric liquid flow rates approved by the Order of Rosstandart No. 256 dated February 07, 2018 (hereinafter – SVS). The secondary standard transmits units of mass and volume of liquid in the flow, mass and volumetric liquid flow rates in the range from 0.01 to 2000 t/h (m^3/h) according to SVS. Expanded measurement uncertainty of the Secondary standard when reproducing the unit of liquid flow rates $U(Q_M) = 0.055\%$ ($k = 2$, $P = 0.95$) according to SVS.

The mass flow rate of liquid is calculated using the measurement equation, kg/s (t/h):

$$Q_M = \frac{M_{wd}}{\tau} \cdot \frac{1 - \frac{\rho_{air}}{\rho_{sw}}}{1 - \frac{\rho_{air}}{\rho_{liqatp}}} = \frac{M_{MCH}}{\tau} \quad (2)$$

where M_{wd} - mass of the liquid according to the readings of the weighing device, excluding the air buoyancy correction, kg ; ρ_{air} - density of air, kg/m^3 ; ρ_{sw} - density of standard weights, kg/m^3 ; ρ_{liqatp} - density of liquid at atmospheric pressure, kg/m^3 ; M_{MCH} - mass according to the readings of the liquid mass measuring channel, including the air buoyancy correction, kg ; τ - measurement time interval, s .

4. Experimental research

4.1 Investigation of the local characteristics of the fluid flow in the nozzle exit of the diverter

The local characteristics of the liquid flow in the diverter nozzle exit were measured with a Pitot probe in the mass flow rate range $Q_M = 25 - 550$ t/h. The flow velocity $w_i = \gamma \sqrt{2(p_i^* - p_{st}) / \rho_{liqatp}}$ at the studied nozzle exit point was determined by the Pitot probe on the basis of stagnation pressure p_i^* , static pressure p_{st} and water density ρ_{liqatp} . The Pitot probe was moved in the nozzle exit plane on a coordinate device.

The diverter nozzle has a rectangular cut. The length of the nozzle exit has a constant value $l = 0.772$ m. The nozzle exit width varies in the range $b = 0.085 - 0.001$ m (Fig. 1) depending on the value of the mass flow rate of water Q_M . The geometry of the flow path of the nozzle is calculated for the maximum value of the mass flow rate of water $Q_{M \max} = 550$ t/h. The filling of the investigated section of the nozzle with water was carried out at a minimum value of the mass flow rate of water $Q_{M \min} = 25$ t/h. The ratio of the reproducible water flow rate range for the investigated diverter nozzle is $Q_{M \min} : Q_{M \max} = 1 : 22$ for one weighing device, as compared to a diverter with a fixed nozzle exit geometry ($Q_{M \min} : Q_{M \max} = 1 : 10$).

It was found that with the maximum width of the nozzle exit $b = 0.085$ m, the nozzle exit is not filled with water at the values of the mass flow rate of water $Q_M = 300$ t/h. It was determined that the local values of the velocity in the nozzle exit do not exceed 1.3 m/s at $b = 0.085$ m. By reducing the width to the value $b = 0.045$ m, it was possible to fill the nozzle exit with water, while the local values of the velocity in the nozzle exit reached 2.43 m/s. At a mass flow rate $Q_M = 200$ t/h ($b = 0.085$ m), the nozzle exit is also not filled with water. Local values of velocity in the nozzle exit do not exceed 0.7 m/s. The nozzle exit is filled with water at a width of $b = 0.036$ m. The local values of the velocity in the nozzle exit reached 1.98 m/s. At a mass flow rate $Q_M = 100$ t/h ($b = 0.085$ m), the nozzle exit is also not filled with water. Local values of velocity in the nozzle exit do not exceed 0.42 m/s. The nozzle exit is filled with water at a width of $b = 0.021$ m. Local values of the velocity in the nozzle exit reached 1.71 m/s. A similar situation was observed in the mass flow rate range $Q_M = 25 - 300$ t/h. It can be concluded that with a decrease in the mass flow rate of water Q_M , it is necessary to decrease the value of the nozzle exit width b to fill it with water. In the course of



research, it was found that the profile of the water velocity in the nozzle exit is uneven. There are pulsations in the flow rate of the water, recorded by the oscillations of the pressure sensor connected to the Pitot probe. A quantitative assessment of the sources of uncertainty for the metrological characteristics of the Unit was carried out by the comparison method using a comparison standard.

4.2 A method of transferring units of quantities by comparison using a comparison standard

The reliability of the method of transferring units of quantities using a comparison standard has been repeatedly confirmed by theoretical and experimental studies in the Russian Federation and in foreign scientific and metrological institutes [8]. The set of comparison standards used in this study is part of the GET 63-2019 in accordance with the SVS.

The method of comparison using a comparison standard includes:

- determination of metrological characteristics: study of the reference standard; comparisons with the investigated Unit; re-examination of the reference standard.
- calculation of expanded uncertainty.

5. Research results

The dependence $\tau = f(U(Q_M))$ of the expanded measurement uncertainty of the Unit when reproducing the unit of mass flow of water ($k = 2$, $P = 0.95$) on the measurement time interval τ is shown in Figure 3. The studies were carried out at the point of mass flow of water $Q_M = 100$ t/h for two fixed values of the width nozzle exit $b = 0.085$ m (\square) and $b = 0.021$ m (\blacksquare).

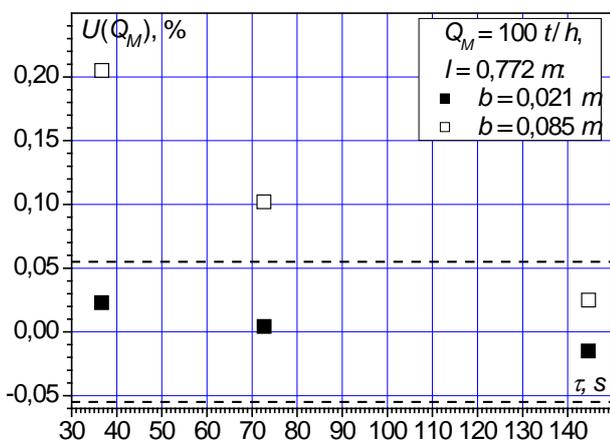


Figure 3: The dependence of the expanded measurement uncertainty of the Unit when reproducing the unit of mass flow of water ($k = 2$, $P = 0.95$) on the measurement time interval τ .

The value of the expanded measurement uncertainty of the unit when reproducing the unit of mass flow rate of liquid is $U(Q_M) = 0.015\%$ ($k = 2$, $P = 0.95$) with the value of the nozzle exit width $b = 0.085$ m and the value of the measurement time interval $\tau = 144.6$ s (Fig. 3), for which water enters the weighing device at a mass flow rate $Q_M = 100$ t/h. In this case, the measurement time interval τ significantly exceeds the total time interval of the forward and reverse strokes of the diverter $\tau_{AF} + \tau_{HD}$, i.e. mass ratio $(M_{IJEF} + M_{HGKL})/M_{IJKL} \rightarrow 0$ (Fig. 2). The influence of the transient process during the operation of the diverter, caused by the fragmented filling of the nozzle exit with water, on the metrological characteristics of the Unit is negligible. It can be argued that the resulting mass flow rate Q_M tends to the true value $Q_{M\ true}$. However, the total time to study the MUT increases due to the large value of the measurement time interval τ with multiple measurements (at least 5 times) at a given mass flow point Q_M . In addition, the total time is added to the time interval for emptying the storage tank, the time interval for stabilization of the weighing device readings and the time interval for the stabilization of the water flow rate Q_M . Therefore, it is necessary to reduce the value of the measurement time interval τ while maintaining the actual metrological characteristics of the Unit. This will reduce the economic and material costs of the Unit owners.

If we reduce the measurement time interval at the maximum width of the nozzle exit $b = 0.085$ m to values $\tau = 72.7$ s and $\tau = 36.6$ s at the point of mass flow rate $Q_M = 100$ t/h, this will lead to a significant increase in the values of the expanded measurement uncertainty of the Unit at reproducing the unit of mass flow to the values $U(Q_M) = 0.101\%$ and $U(Q_M) = 0.205\%$, respectively ($k = 2$, $P = 0.95$) (Fig. 4). The obtained values of the expanded measurement uncertainty exceed the value of the expanded measurement uncertainty for the secondary standard when reproducing the unit of liquid mass flow rate $U(Q_M) = 0.055\%$ ($k = 2$, $P = 0.95$) according to SVS. This is explained by an increase in the influence of the source of uncertainty due to the fragmented filling of the nozzle exit with water.

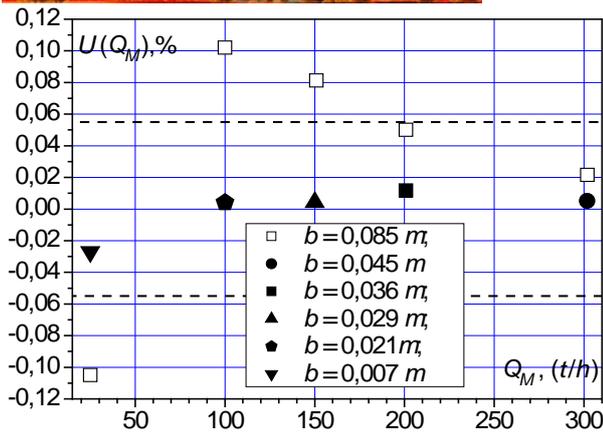


Figure 4: The dependence of the expanded measurement uncertainty of the Unit when reproducing the unit of mass flow of water ($k = 2, P = 0.95$) on the measurement time interval τ . The solution was obtained by reducing the value of the width to $b = 0.021 \text{ m}$ at the point of mass flow rate $Q_M = 100 \text{ t/h}$ (Fig. 3). This made it possible to reduce the value of the measurement time interval from $\tau = 140 \text{ s}$ to $\tau = 36.6 \text{ s}$ while maintaining the value of the expanded measurement uncertainty of the Unit when reproducing the unit of mass flow to the value $U(Q_M) = 0.0231\%$ ($k = 2, P = 0.95$). Similar results were obtained for other mass flow points (Fig. 4) of the investigated diverter with a variable geometry of the nozzle exit.

The graphical dependence of type $Q_M = f(U(Q_M))$ of the expanded measurement uncertainty of the Unit when reproducing the unit of the mass flow rate of the liquid ($k = 2, P = 0.95$) on the mass flow rate of the liquid is shown in Figure 5. It was found that at the maximum value of the nozzle exit width $b = 0.085 \text{ m}$ at the values of $Q_M \leq 200 \text{ t/h}$, the values $U(Q_M)$ increase over the entire range of the investigated water flow rate Q_M . The obtained values of the expanded measurement uncertainty of the Unit exceed the value of the expanded measurement uncertainty for the secondary standard when reproducing the unit of mass flow rate of liquid $U(Q_M) = 0.055\%$ ($k = 2, P = 0.95$) according to SVS. By reducing the nozzle exit width $b < 0.085 \text{ m}$, the value can be significantly reduced $U(Q_M)$. For example, for the mass flow point $Q_M = 200 \text{ t/h}$ at $b = 0.045 \text{ m}$ the value $U(Q_M) = 0.012\%$, and for $Q_M = 150 \text{ t/h}$ – $U(Q_M) = 0.004\%$. A significant decrease in the value of the $U(Q_M)$ in the investigated range of mass flow rate Q_M with a decrease in the nozzle exit width b is explained by the minimization of the influence of the source of uncertainty due to the fragmentation of water filling the diverter nozzle exit. This was achieved in the entire range of the investigated mass flow rate Q_M by reducing the width of the nozzle exit b . In this case, the time intervals of the transient process are reduced for

the forward $\tau_{AF} = A'F$ and reverse $\tau_{HD'} = HD'$ diverter strokes (Fig. 2).

It should be noted that the use of a diverter with a variable geometry of the nozzle exit made it possible to shorten the measurement time interval depending on the value of the mass flow rate Q_M . For example, for the values of the mass flow rate $Q_M = 25 \text{ t/h}$, the shortening of the measurement time interval τ reached 2 times, for the value $Q_M = 300 \text{ t/h}$ – 0.4 times. This significantly shortens the MUT calibration process by direct comparison with the setup in multiple measurements. Reducing the number of diverters and weighing devices, reducing metal consumption and dimensions will reduce the final cost of the Unit. This will improve the competitiveness of the Unit in the world market.

6. Conclusion

For the first time in the world hydrometric practice, the Unit with a diverter with a variable geometry of the nozzle exit has been developed, manufactured and investigated. The optimal values of the width of the diverter nozzle cut are experimentally determined depending on the value of the mass flow rate of water at which it is completely filled with water. It was found that a decrease in the nozzle exit width with a decrease in the value of the mass flow rate of water improves the metrological characteristics of the Unit. The reduction of the measurement time interval is substantiated when the actual metrological characteristics of the Unit are maintained. The design of the outlet manifold, the control system of the shut-off valves and the maintenance procedure of the Unit have been simplified. Improved weight and size and technical and economic characteristics of the Unit.

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