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Effect of Changes in the Roughness of the Inflow Surface of a Sloping Segmental Orifice with Point Pressure Reception on its Characteristics

Andrzej Mrowiec[1], Artur Andruszkiewicz[2], Piotr Piechota[2*]

[1] Polytechnic Faculty, Calisia University, ul. Nowy Świat 4, 62-800 Kalisz, Poland

[2] Faculty of Mechanical and Power Engineering, Department of Thermal Science, Wrocław University of Science and Technology, ul. Wybrzeże Wyspianskiego 27, 50-370 Wrocław, Poland

* Corresponding author's e-mail: piotr.piechota@pwr.edu.pl

ABSTRACT

The subject of this paper is the effect of changing the roughness of the inflow surface of an orifice on its characteristics. A sloping segmental orifice was chosen as the reducer and its surface roughness was changed by lining its inflow surface with sandpaper of different roughness parameters. In such a system, the dependence of the flow stream on the differential pressure at the orifice was measured on a test stand in the range of Reynolds numbers 4110–17000, the flow coefficient C was calculated and flow characteristics were prepared. The study was carried out for a selected segmental orifice with flow coefficient $C = 0.723$ installed in a pipeline with diameter $Dw = 50.35$ mm. The roughness of the inflow surface was changed by sticking sandpaper with a gradation of P120 ÷ P1200 to its surface. The roughness parameter Ra was in the range $Ra = 5.69–25.85$ µm and $Rz = 43.84–164.83$ µm. The dependence of the variation of the coefficient C on the roughness parameter Ra is then presented and the relative errors of the flow stream measurements were calculated. The paper also presents distributions of the differential pressure measured at the orifice for different flow streams depending on the roughness parameter.

Keywords: flow stream, measurement orifice, surface roughness.

INTRODUCTION

In the measurement of flow streams, the reducer method is very often used. According to estimates, about 50% of all flow stream measuring devices installed in flow systems are various types of reducers or orifices [1]. In pipelines with diameters in the range of 50 mm to 1000 mm, standard reducers can be used, for example orifice plates with by disc pressure receiver, ISA 1932 nozzles or Venturi reducers.

All types of standard reducers along with the conditions for their use and the relation for calculating the flow coefficient, are presented in ISO 5167-1 [2]. In cases where the flow conditions for fluids included in the above-mentioned standard cannot be met, such as with a pipeline diameter of less than 50 mm, non-standard orifices are used to measure flow streams. Among them can be: quadrant orifice, cylindrical orifice, multi-hole orifice, eccentric orifice and segmental orifice [3-6]. The latter two types of orifices are used mainly for liquids contaminated with solids or for dusty gases [7÷12]. In the measurement of flow streams, it is very important to install the orifice appropriately to the direction of fluid flow, at a distance of at least several diameters from system components that change the distribution of velocity in the cross-section of the pipeline [13, 14]. It is also important to check the condition of its surface after a long period of operation.

During long operation orifices wear over time: when centric orifices are used, it is very common for the orifice's inlet sharp edge to wear out and for dirt particles from the flowing fluid to be deposited in the orifice hole or just behind

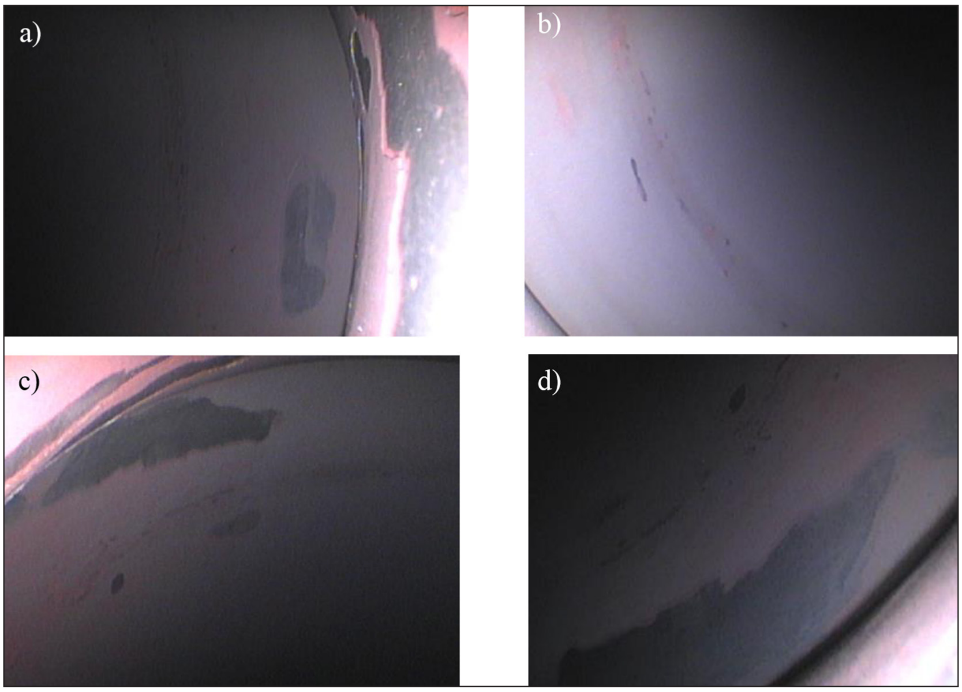

Fig. 1. The inner surface of the ISA 1932 nozzle after a long period of operation

it [15, 16]. This causes a change in the geometry of the orifice itself, as well as the flow kinematics, including a gradual change in the value of the flow coefficient. The photos in Figure 1 show the inner surface of an ISA 1932 nozzle, which is used to measure the mass stream of superheated steam from a steam boiler after its long operation [17]. The illustrations clearly show material loss on the inflow surface of the orifice. The surface roughness and the value of the flow coefficient C are changed, resulting in an increase in the error in the measurement of the fluid stream rate.

The works on the effect of roughness changes on the values of the flow coefficient C for an orifice is mainly concerned with the analysis of changes in the roughness of the pipeline inner walls on the values of this coefficient. As Turkowski [18] states in his book, the effect of roughness on the change in flow coefficient is taken into account by measuring the pressure drop across the pipeline and determining the linear loss coefficient, in the form of the equation:

$$\Delta C = \beta^{3,5} \cdot \Delta\lambda \tag{1}$$

where: β – orifice narrowing;
$\Delta\lambda$ – change in the linear loss coefficient λ relative to a smooth pipeline.

This form of the equation can also be found in ISI/TR 12767 [19] and in the work of Reader-Hariris [20], who determined the relative change in flow coefficient C of a reducer in 10-inch pipes lined with P80 and P240 sandpaper, in the lower part of the pipe, in the ¼ and ½ lining and over the entire inner surface. Calculated from equation (1), the value of the relative change in flow coefficient was for the ¼ lining about 0.6%, for the ½ lining about 1.1% and for the whole lining about 2%. Determining the value of the flow coefficient from equation (1) requires the calculation of the linear loss coefficient λ by measuring the pressure drop across a section of pipeline and this is not possible in some cases. Furthermore, such a measurement is characterised by a large dispersion in the results, which significantly affects the error in the relative value of the flow coefficient ΔC. In order to eliminate this error, Tomasik et al. in their article [21] compared the percentage changes in the flow coefficient C for pipelines lined with sandpaper of different granularity in dependence of the roughness parameters Ra and Rz related to the actual diameter of the pipeline. Carried out studies have shown that it is not possible to introduce a uniform correction formula for the value of C as a result of changes in pipeline roughness, and that even with corrections, the added uncertainty in the flow factor C could be about 0.7% for an orifice narrowing of β = 0.5. Publications related to the influence of wear of the inlet part of the orifice or changes in the sharpness of its edge on changes in the value of the flow coefficient and resulting from long-term operation are practically not encountered. Only Turkowski in the paper [18] gives the value of an additional correction factor to be taken into account in the case of changes in the sharpness of the orifice inlet edge. However, the calculation of this coefficient is inaccurate and the reason is the difficulty in correctly determining the radius of the orifice inlet edge. The lack of work related to the influence of changes in the roughness of the inflow surface of the orifice itself on changes in the values of flow coefficients led the authors of the publication to address this issue.

The subject of the article is the effect of changing the roughness of the inflow surface of a selected orifice on its characteristics. A sloping segmental orifice was selected as a reducer, the surface roughness of which was changed by lining its inflow surface with sandpaper of different roughness parameters Ra and Rz, (marked P1200, P800, P500, P320, P220, P120 respectively). For the roughnesses modelled in this way, the dependence of the flow stream on the differential pressure at the orifice was measured on the measurement stand, the flow coefficient C was calculated and flow characteristics were prepared. Then the dependence of the changes in the C-factor on the roughness parameter Ra was shown, and the errors of the flow stream measurements were calculated. Also shown are the changes in the differential pressure measured at the orifice depending on the roughness parameter.

Method of measurement

A photograph of the sloping segmental orifice selected for testing is shown in Figure 2. Compared to the typical segmental orifice described in standard [2], the inflow plane of the tested orifice was bent at an angle consistent with the direction of fluid movement by 30°.

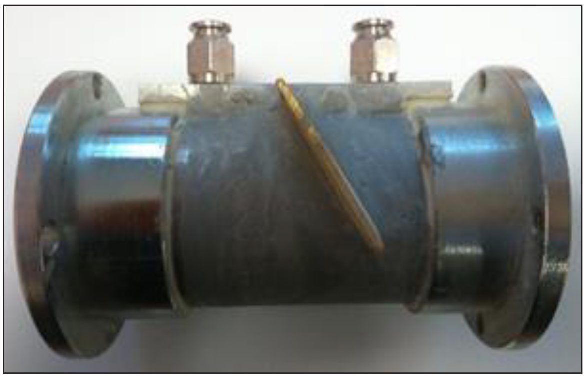

Fig. 2. Photograph of a segmental orifice

A simplified diagram of the flow measurement system in the test stand is shown in Figure 3. The entire test stand was constructed using a 0.35 m^3 tank in a closed system. The flow hydraulic system consists of two parallel pipelines connected to each other by an arc. In the upper pipeline, the so-called measuring pipeline with a diameter of DN 50, a sloping segmental orifice with places for collecting stagnation pressure was mounted. The rectilinear sections in this pipeline are 2.3 m before the orifice (46.D) and 1.8 m behind the orifice (36.D), respectively. In the lower parallel pipeline DN 15, an electromagnetic reference flow meter is installed so that the rectilinear section is 1.5 m before (100.D) and 0.75 m behind (50.D).

A centrifugal pump installed in the flow system of a DN 50 pipeline ensures the flow of water by generating in it a volume flow $qv < 0.75$ dm^3/s, which corresponds to the Reynolds number $Re <$ 20,000. The static pressure difference at the tested orifice was measured in a point manner with an intelligent differential pressure transducer type APR-2000/ALW with an output current signal of 4–20 mA. For the carried out measurements, it was programmed with a time constant $t = 5$ s for the differential pressure measurement range $\Delta p =$ 0...10.4 kPa. In this measuring range the limiting

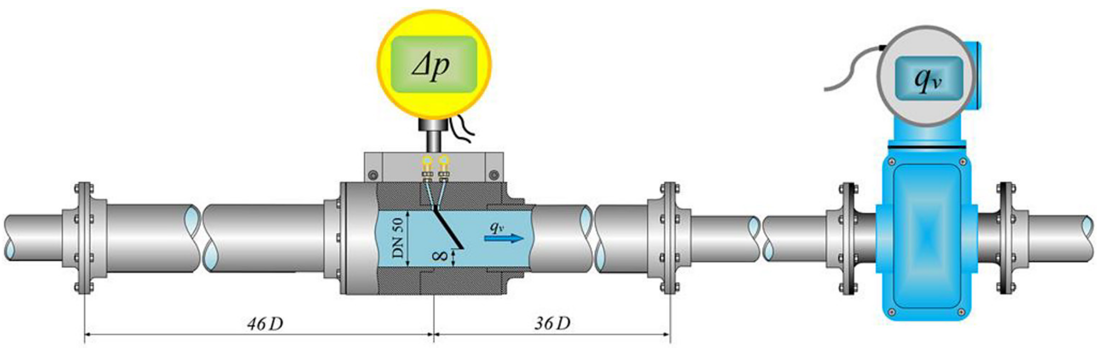

Fig. 3. Flow measurement system

error of measurement with the transducer does not exceed 0.1%.

A PROMAG 30AT15 electromagnetic flow meter from Endress+Hauser with an output current signal of 0–20 mA was used as a reference flow meter to measure the volume stream. It was programmed for the flowing volume stream with a time constant $t = 5$ s at a measuring range of qv = 0–1.0 dm^3/s with a measurement error of Δqv = ±(0.2%-qv-measured ± 0.05%-qv). Flow characterisation parameters in the form of signals from the differential pressure transducer and reference flow meter were measured with SANWA 5000 multimeters, which were connected via an RS232 interface to a computer. Communication with the multimeters and measurement data acquisition is enabled by PC Link Plus specialised software installed on a PC with a set sampling time of $\Delta t = 3$ s. Measurement data acquisition consisted of recording current values from transducers measuring: volume stream *qv* and stagnation pressure difference Δp at the orifice in real time.

Measurements were made for 11 water flow streams in the range corresponding to Reynolds numbers in the interval $4100 < Re < 17000$. For each series of measurements, the lining of the sloping inflow surface of the orifice was changed with sandpaper with a gradation of P1200 to P120. The equation used to determine the flow coefficient C for the sloping standard orifice was (1). Table 1 shows the average physical properties of the flowing fluid in the installation and the basic parameters of the segmental orifice.

$$q_v = C \cdot \frac{F_h}{\sqrt{1-\left(\frac{F_h}{F_D}\right)^2}} \cdot \varepsilon \cdot \sqrt{\frac{2 \cdot \Delta p}{\rho}} \tag{2}$$

where: Δp – static pressure difference at the orifice;
ρ – density of water;
F_h – hole area of the orifice narrowing;
F_D – cross-sectional area of the pipeline;
ε – expansion factor (for water ε = 1).

The roughness parameters *Ra* and *Rz* were determined according to the illustrative Figure 4.

The parameter *Ra* is the arithmetic mean of the deviation of the absolute values of the ordinates z(x) from the mean line inside the elementary section le, while the parameter *Rz* is the sum of the height of the highest rise and the largest indentation of the profile inside the elementary section le. A profilometer Nanoscan 855 from Jenoptik (Hommel-Etamic) was used to test the surface of the used segmental orifice for measurements of: roughness, surface topography or contours. During the passage of the diamond measuring tip along the adopted elementary section, graphs were generated and roughness parameters calculated with a straightness measurement accuracy for this device of less than 0.4 µm/200 mm. Example printouts showing the generated graph together with the roughness parameters for P200 and P1200 – are shown in Figure 5.

Table 1. Physical properties of the flowing fluid and selected parameters of the segmental orifice

Kind of factor	*t*, °C	*ρ*, kg/m^3	*v*, m^2/s	*d*, mm	*C*, -	*ε*, -	F_h, mm^2
Water	23.06	997.7	0.935 10^{-6}	50.35	0.723	1	203.6

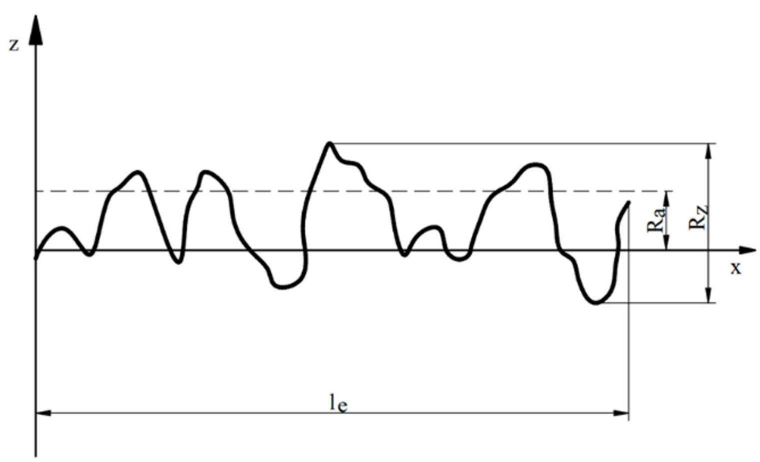

Fig. 4. Illustrative diagram for the determination of Ra and Rz roughness parameters

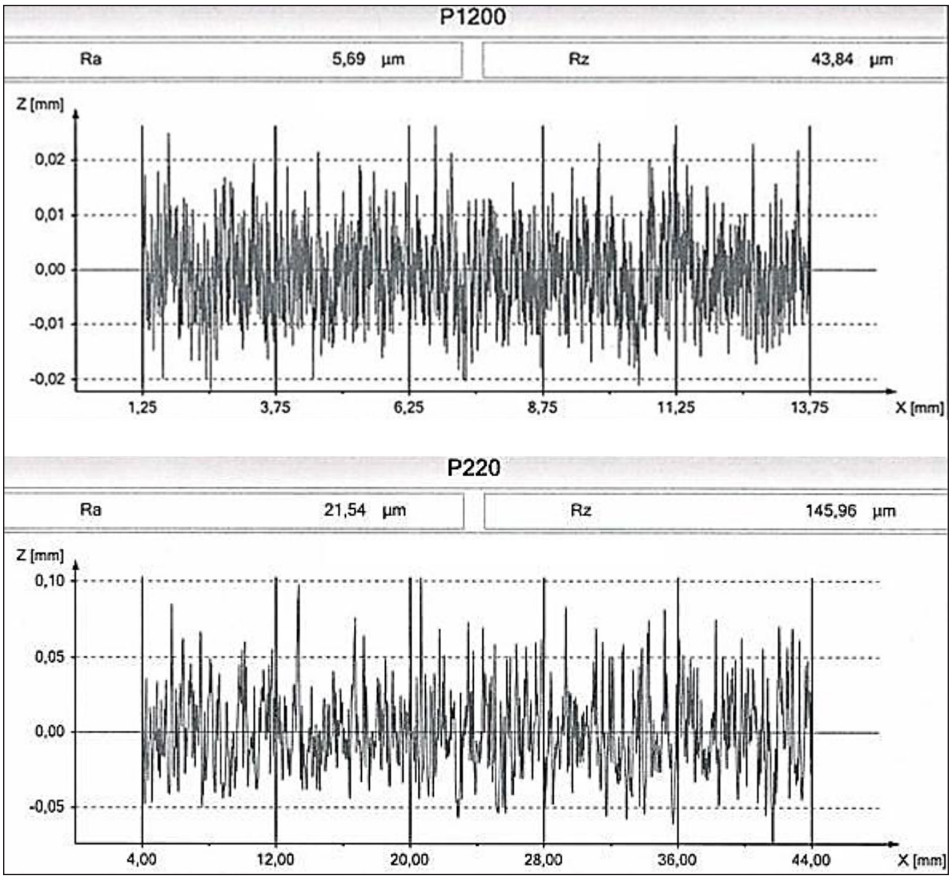

Fig. 5. Example of roughness measurement for (a) P1200 and (b) P220

EXPERIMENTAL RESULTS

Flow characteristics at different inflow surface roughnesses

Figure 6 shows an example of the measurement signals, i.e. the dependence of the pressure difference at the reducer on the measurement number.

Figure 7 shows the actual flow characteristics of the tested sloping segmental orifice for different roughness coefficients *Ra* and *Rz* obtained on the test stand. It also gives the equations of the fitting functions in the form (3):

$$q_v = k \cdot \sqrt[n]{\Delta p} \tag{3}$$

And the coefficient of determination *R*2. Note that the values of the coefficient of determination *R*2 for all cases are equal to 1, which indicates that the measurement points lie exactly on the fitting curve. The presented relations show that in the case of roughness *Ra* = 7.51µm and *Rz* = 53.94 µm (for

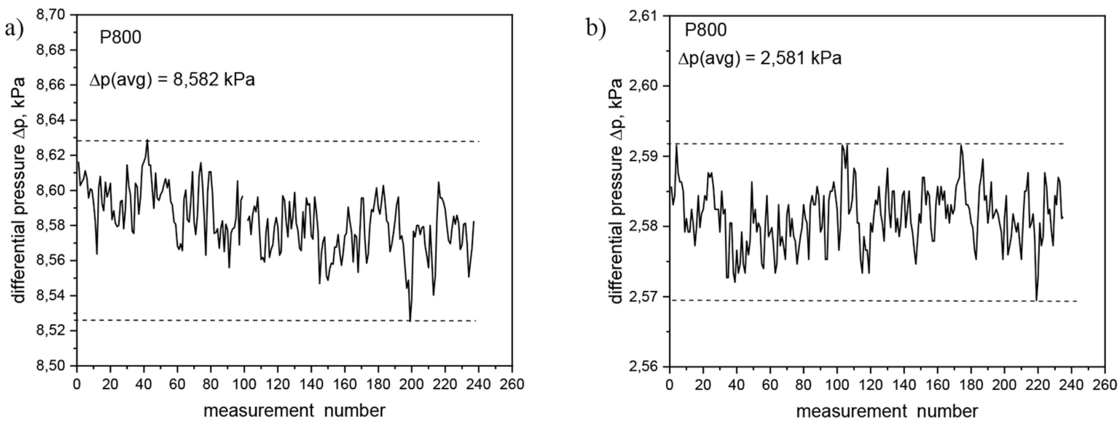

Fig. 6. Example of the measurement signals for (a) P800

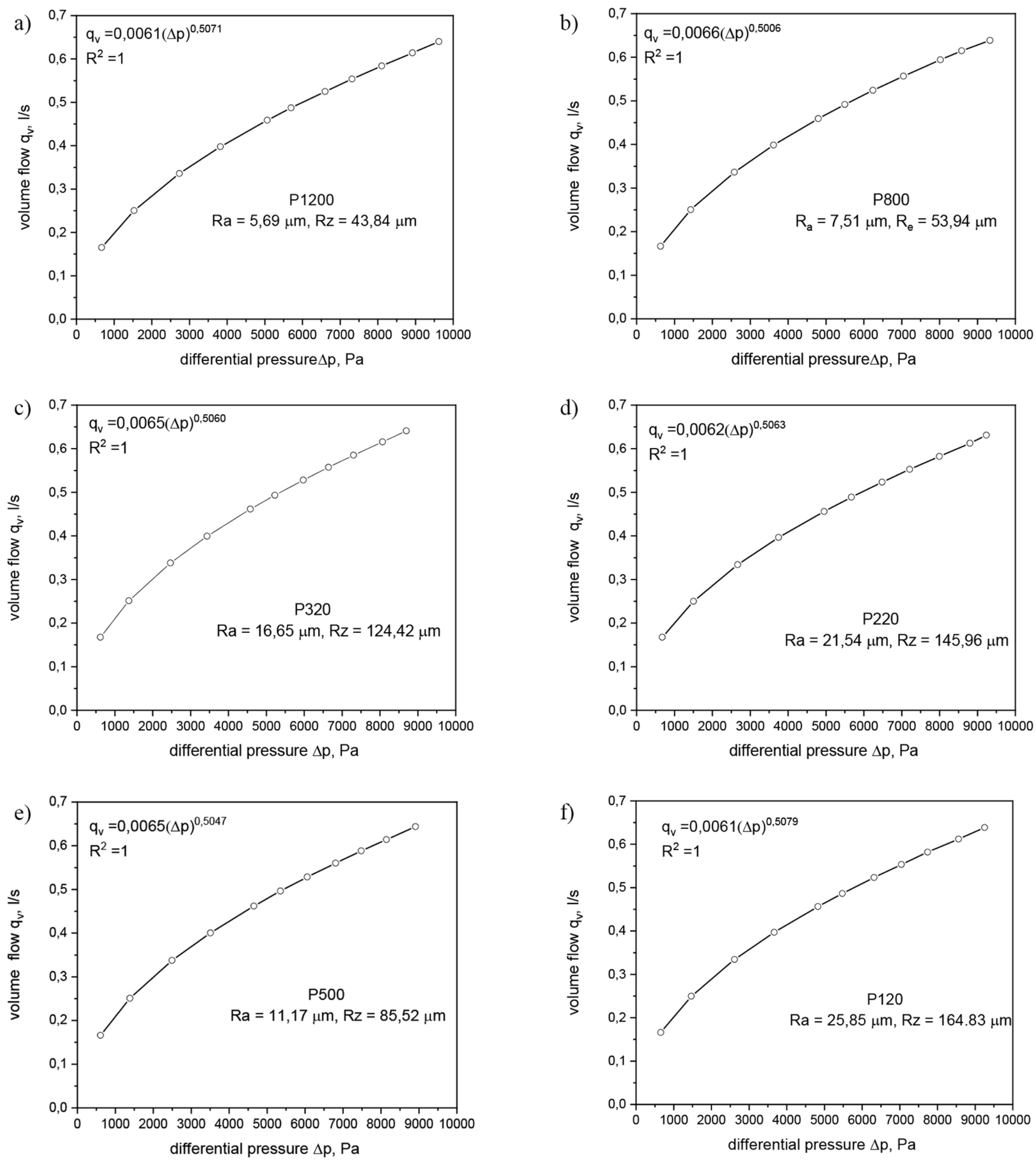

Fig. 7. Actual flow characteristics for a sloping segmental orifice at different roughness coefficient values (a) P1200 (b) P800 (c) P320 (d) P220 (e) P500 (f) P120

P = 800), the volume stream is practically a function of the square root of the orifice pressure difference $\sqrt{\Delta p}$, which corresponds to the characteristics of the actual orifice, i.e. without sandpaper lining.

In other cases, the values of the coefficient n vary from a value of 0.5, ranging from a minimum value of n = 0.5047 to a maximum value of n = 0.5071. On the other hand the values of the coefficient k vary from 0.0061 to 0.0066, which means that individual flow characteristics should be used to determine the volume stream values when measuring with an orifice, as the surface roughness of the inflow surface changes. Otherwise, a correction related to the change in roughness of its surface should be taken into account. Figure 8 shows the dependence of the relative error in water volume stream (compared to orifice P800) on the measured differential pressure Δp.

This figure shows that, for a given orifice inflow surface roughness, these errors are systematic errors. For roughnesses Ra = 5.49 μm (P1200), Ra = 21.54 μm (P220) and Ra = 25.85 μm (P120) they are negative errors, and for the other two roughnesses they are positive errors. There is therefore no unambiguity in the nature of these errors, which proves that in the case of roughness changes associated with orifice long time using, flow streams should be determined according to individual flow characteristics. It can also be seen, that in the case of the roughnesses Ra = 5.49 μm, Ra = 21.54 μm and Ra = 25.85 μm the systematic error values increase with increasing

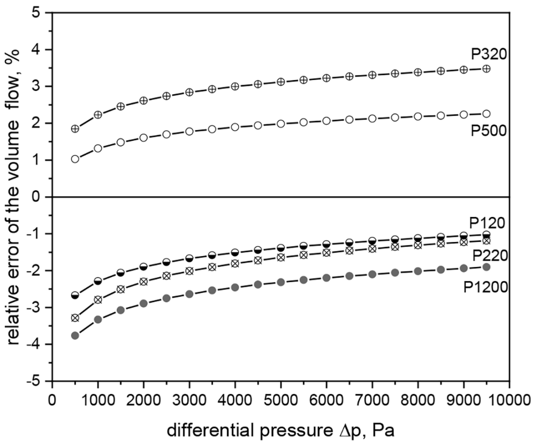

Fig. 8. Relative error in volume stream depending on pressure difference at the orifice Δp at different values of inflow surface roughness

differential pressure at the orifice Δp approaching a value of -1%, while in the other two cases they increase, reaching a value of approximately +3.5% in the case of Ra = 16.65 µm (P320) for Δp = 9500 Pa. In an attempt to explain the reason for the change in systematic error signs and values of n coefficients from the theoretical value of 0.5, it is necessary to calculate the C coefficient for this orifice at different roughness values.

Values of flow coefficient C

For a sloping segmental orifice in normal operation, the value of the flow coefficient C was C = 0.723. Figure 9 shows the dependence of the variation of this coefficient on the Reynolds

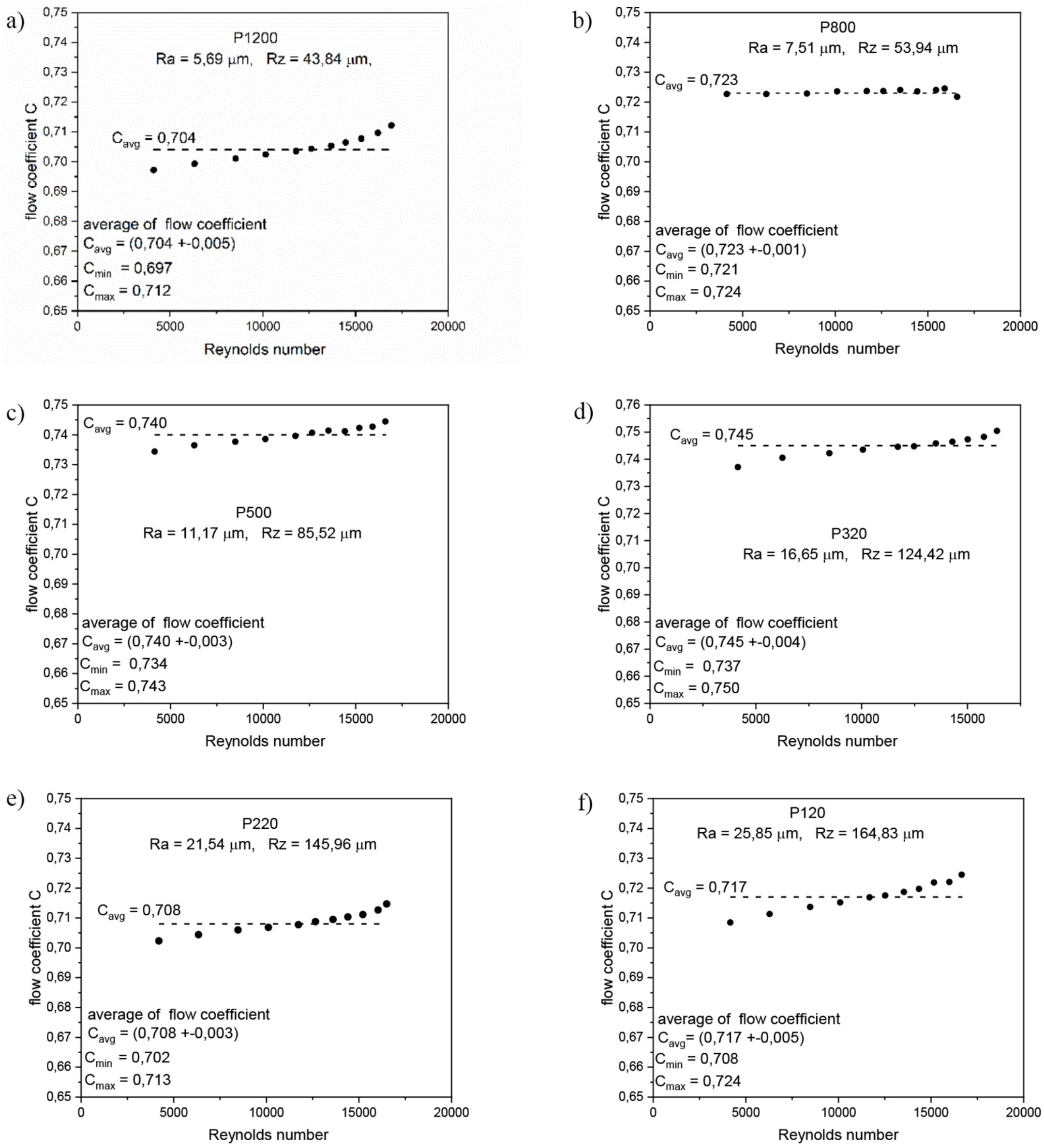

Fig. 9. Variation of flow coefficient C depending on Reynolds number with different inflow surface roughness (a) P1200, (b) P800, (c) P500, (d) P320, (e) P220, (f) P120

number for different roughness values, and was calculated by transforming equation 1. The calculated mean values and ranges of variation of the coefficient C are also marked.

It is easy to see that for a roughness of *Ra* = 7.51 µm (P800), the coefficient C characteristic is practically constant and it does not depend on the Reynolds number. This figure correlates with Figure 5 for roughness P800, the volume stream is then a function of the square root of the pressure difference at the orifice $\sqrt{\Delta p}$. The average value of the coefficient is *C* = 0.723 and is the same as for the unlined orifice.

In other cases, the values of the C coefficient increase with increasing Reynolds number, and the variation between the minimum and maximum values in the investigated range of Reynolds numbers can reach about 3%. It is also worth noting that the average values of the *C* coefficient are both higher and lower than for a real sloping orifice, i.e. without lining.

The dependence of the mean values of the flow coefficient C on the roughness parameter Ra is shown in Figure 10. Table 2 presents the summary results from the calculation of the mean value of the coefficient together with the relative error of this coefficient.

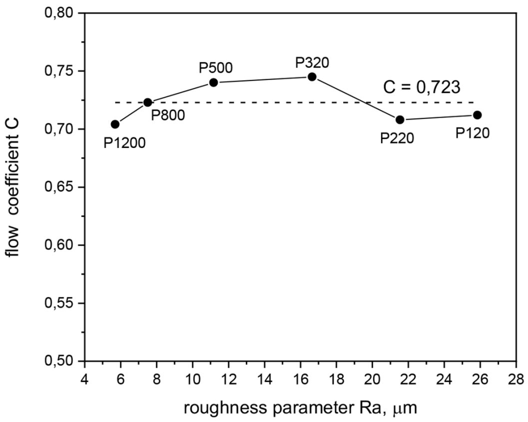

Fig. 10. Changes of the average coefficient C value from the roughness parameter Ra

This figure (Figure 10) correlates very well with Figure 8. For the lining of the orifice with P1200, P220 and P120 paper, the values of the average flow coefficients are smaller than for the unlined orifice, so the committed systematic errors of the flow stream will be negative and in accordance with this figure. In contrast, for the other two roughnesses, the opposite situation occurs, also consistent with the error patterns according to Figure 8. Also characteristic is the 5% decrease in the value of the flow coefficient between roughness *Ra* = 16.65 µm (P320) and *Ra* = 21.54 µm (P200) after an increase in this coefficient for the first four roughness values. The changes in the value of the flow coefficient therefore do not show unambiguity with an increase in the roughness parameter Ra. An increase in the roughness Ra with a constant value of the contraction coefficient is responsible for the increase in the flow coefficient value, which causes a change in the inflow velocity distribution on the orifice.

In contrast, the sudden drop in flow coefficient *C* is caused by a decrease in the cross-sectional area of the stream and thus an increase in velocity behind the orifice. The increase in velocity corresponds to a decrease in pressure behind the reducer which results in a higher pressure difference Δp and thus a decrease in the value of the flow coefficient *C*. Table 2 shows that the maximum error of the coefficient *C* is +-3% for the parameter *Ra* = 16.65 µm. This value can be considered as the limiting error of the flow coefficient and included in the error analysis of the mass/volume stream measured with the segmental orifice.

Distribution of differential pressure at the orifice

Figure 11 shows a typical distribution of differential pressure at the orifice during normal operation, i.e. in the absence of changes in wall roughness.

The measured pressure differences completely fill the measurement range and their distributions

Table 2. Values of flow coefficient C for the investigated sloping segmental orifice at different inflow surface roughness

Gradation	Roughness parameter Ra, µm	Roughness parameter Rz, µm	Reynolds number range Re	Value of the coeficcient C	Relative error of the coeficcient C, %
P1200	5.69	43.84	4116÷16936	0.704	-2.6
P800	7.51	53.94	4150÷ 16584	0.723	0.0
P500	11.17	85.52	4142÷16509	0.740	+2.3
P320	16.65	124.42	4158÷16393	0.745	+3.0
P220	21.54	145.96	4196÷16506	0.708	-2.1
P120	25.85	164.83	4161÷16653	0.712	-1.5

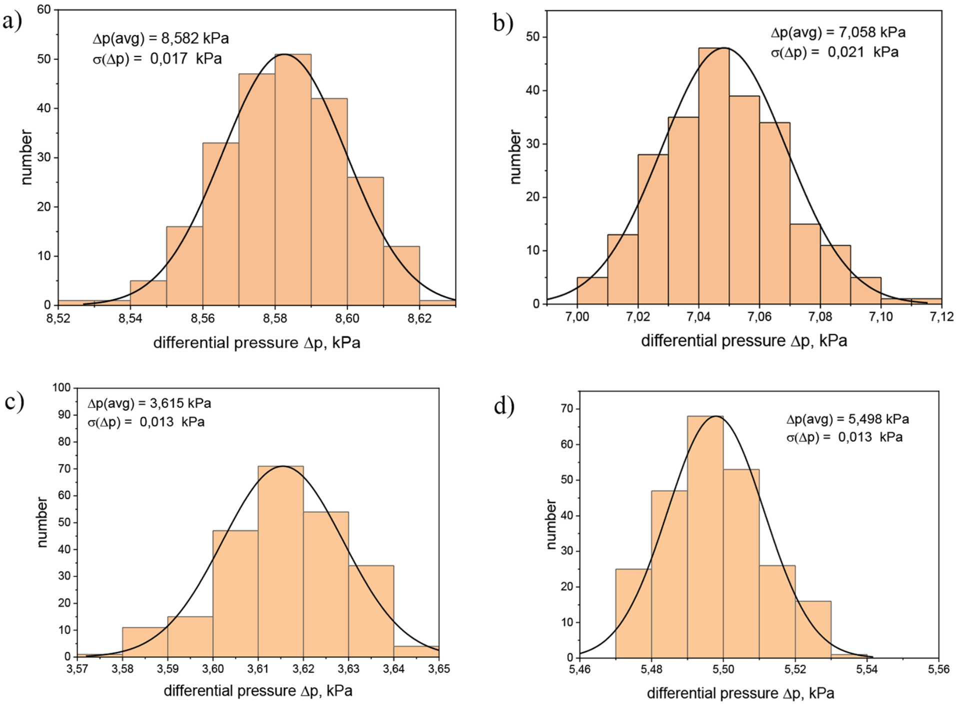

Fig. 11. Distributions of pressure differences at the orifice in the absence of changes in wall roughness related to its operation

looks like normal distributions. In the case of roughness changes, the pressure distributions are shown in Figure 12.

Characteristic for these diagrams is the appearance of blank spots, i.e. areas where there are no or only single signals from differential pressure. Further behind these spots, groups of signals appear at the edges of the distributions. The pressure distributions differ from Gaussian curves. However, the graphs show a lack of systematicity in the variation in the pressure difference - for example, for the roughness parameters Ra = 5.69 μm and Rz = 43.84 μm (P1200), for Δp(avg.) = 5.147 Pa and Δp(avg.) = 6.484 Pa, additional signals with smaller values can be seen on the left side of the Gauss curve, while for Δp(avg.) = 8.563 Pa, signals with larger values occur on its right side.

Smaller values of the registered differential pressure at the orifice result in a momentary, visible decrease in velocity during the water flow. If the pressure difference Δp increases, the process is reversed. It is also possible, as in the case of the P120 paper gradation, that there are additional signals from the pressure difference Δp at both the left and right ends of the Gaussian curve.

Increasing the roughness of the orifice wall therefore causes the velocity to oscillate around its average value. Changes in the roughness of the inflow surface of the orifice cause changes in the velocity of the flowing water, but with a constant value of the roughness parameters as the flow stream changes, the directions of these changes can vary. It is also possible for the velocity to oscillate around its average value.

Changes in velocity values also affect the flow coefficients calculated from Equation 2, which can be both under- and overestimated. The lack of systematicity of velocity changes casues that the pressure distributions shown in Figure 12 only provide information about changes in the roughness of the reducer walls during operation. This information can be used as a basis for determining the individual flow characteristics for the orifice used in the measurements and, if the system is stopped, for replacing it.

It is therefore not possible to make unambiguous corrections to the value of the flow coefficient C for the orifice used in the measurements, resulting from changes in roughness. The pressure distributions shown in Figure 12 correlate very well with the steam stream flow distribution curves determined by the authors for the ISA 1932 nozzle shown in Figure 13.

According to Equation 2, the flow stream depends on the root of the pressure difference, so the pressure difference distributions will take on an analogous shape to the flow streams distributions.

They clearly show the appearance of recorded signals on the right side of the Gaussian distributions, as well as a reduced number of recorded signals in the middle part of the curve similarly to the gradation of paper P220 and pressure difference Δp(avg.)= 7.994 kPa.

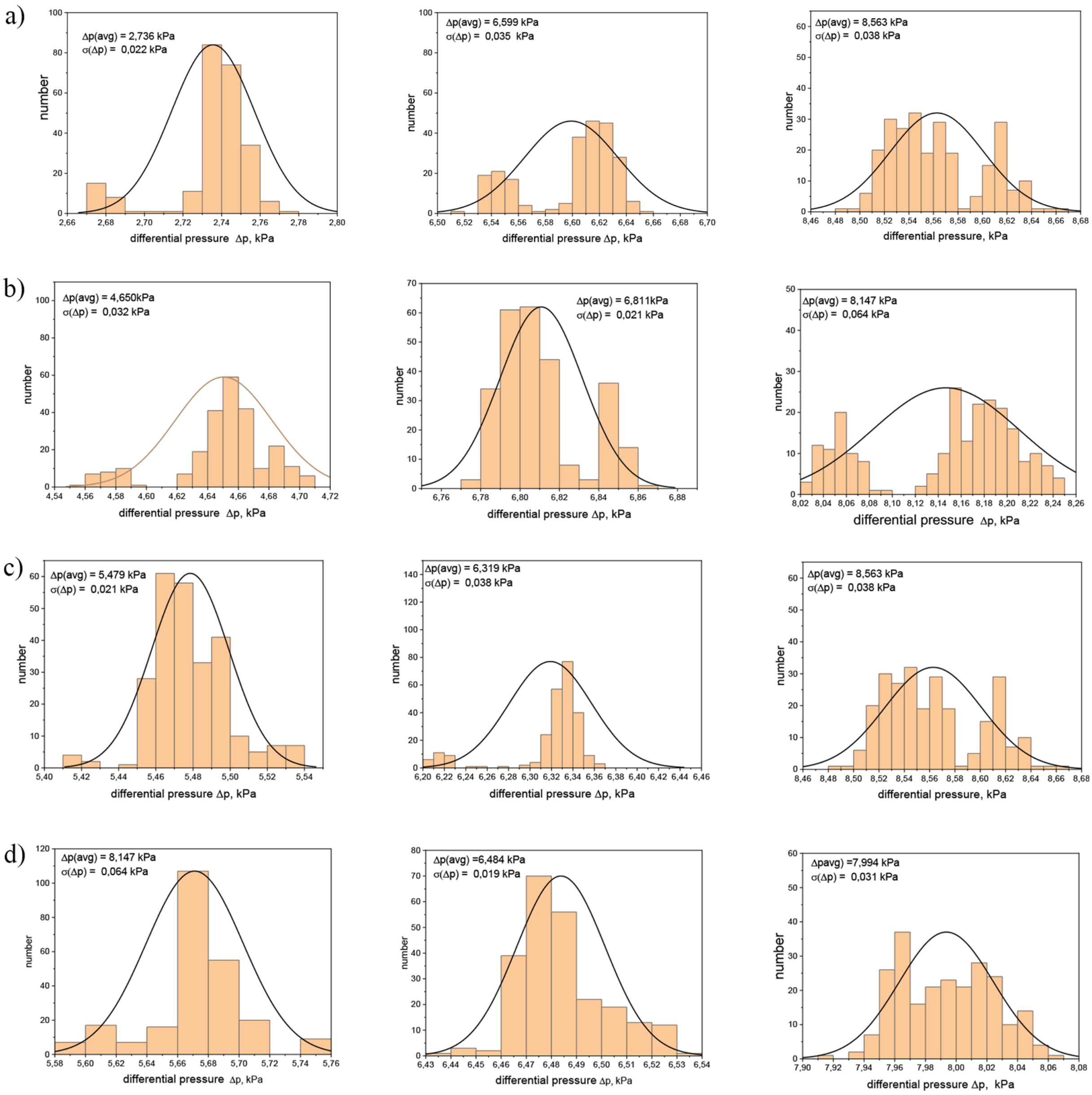

Figure 12. Examples of static pressure distributions at the orifice when its roughness changes (a) P1200, (b) P500, (c) P120, (d) P220

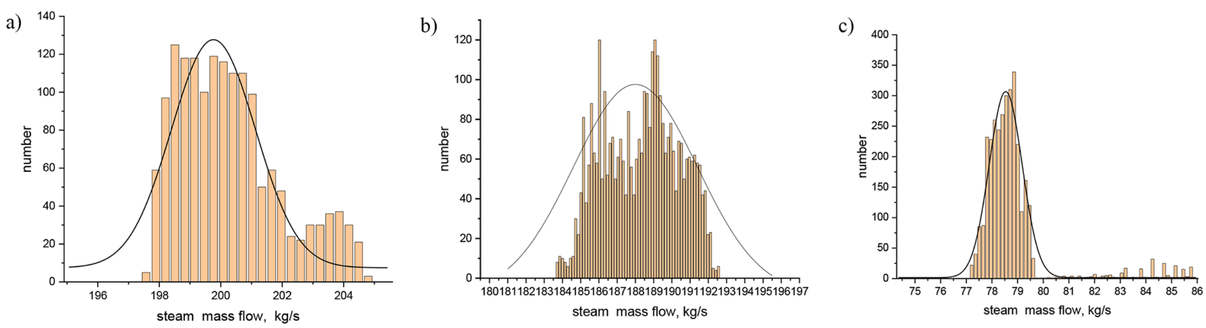

Figure 13. Examples of steam stream flow distributions for the ISA1932 nozzle [17]

CONCLUSIONS

Carried out measurements of water stream flows at different values of roughness parameters showed that an increase in the roughness parameter Ra (Rz) causes changes in the value of the flow coefficient C; the values of this coefficient for the first three roughness parameters (P1200, P500, P320) increase, then for the next roughness parameter P320 the value of the C coefficient decreases by about 5%, followed by a slight increase again. The calculated values of the coefficient C are both lower (P1200, P220, P120), and higher (P500, P320) than the values of this factor for normal operation of the orifice, i.e. without changes in roughness, and there is no unambiguousness in the direction of these changes. The relative errors of the coefficient C related to the change in roughness of the inflow surface are in the range of +-3%. The distributions of the measured static pressure drops at the orifices for changes in the roughness of the inflow surfaces deviate from Gaussian distributions. Additional distinct signals appear at both ends of the curves, causing a decrease or increase in velocity. The nature of these changes is also not unambiguous - when changing flow streams for a given roughness, additional signals may appear at one end of the normal distribution and then at the next. It is also characteristic that there are areas where there are no recorded pressures. The nature of the variations in the measured pressure differences indicates changes in the roughness of the inflow side results from its using time, and also indicates the replacement of the orifice, the recalculation of its flow coefficient or the determination of individual characteristics.

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