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The effect of changes in the surface roughness of the inflow section of a sharp-edged orifice on the flow coefficient

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ABSTRACT

This article examines the effect of changes in the roughness of the inflow part of a sharp-edged orifice on the value of the flow coefficient. During prolonged operation of orifices, the roughness of their inflow surface changes as a result of phenomena such as erosion, abrasion or cavitation, which may affect the value of the flow coefficient. Changes in the value of this coefficient should be taken into account in the equation for the flow rate characteristic; otherwise, the error in flow rate measurement will increase. This article demonstrates the effect of changes in the roughness parameter R_a on the flow coefficient values for a sharp-edged orifice, as well as the R_a value at which it becomes necessary to correct the flow characteristic equation to account for this new value, in order to reduce flow measurement errors. Ten sharp-edged orifices with different R_a roughness parameters were used in the study, and measurements were taken at the maximum flow rate achievable in the measurement setup.

Keywords: surface roughness, flow measurement, flow coefficient, orifice plate, sharp-edged orifice

INTRODUCTION

Continuous flow rate measurement using orifice plates remains one of the most widely used techniques in industrial flow processes. As reported by Kabza [1], orifice plates (primary devices) with various design and metrological parameters account for approximately 50–60% of all flow rate measurements. The main advantage of a flow measurement system based on an orifice plate is its relatively low cost compared to alternative flow measurement methods. Furthermore, in a properly installed system, flow rate measurement errors across a wide operating range do not significantly deviate from those of flow meters operating on other physical principles, such as vortex, ultrasonic, or thermal flow meters. During extended operation of primary devices, mechanisms such as contamination deposition, erosion, abrasion, or cavitation lead to an increase in upstream surface roughness. This alteration in surface roughness can affect the flow coefficient C, thereby increasing flow rate measurement errors. This paper represents a continuation of the authors' research into the impact of upstream surface roughness on the metrological properties of primary elements. In the first study, a segmental orifice plate was investigated [2], whereas the second focused on an ISA orifice plate with corner pressure tappings [3]. Other notable investigations regarding the determination of flow coefficients C for various primary elements include the work of Golijanek-Jędrzejczyk et al. [4–6], who evaluated flow coefficients C across various orifice types in both turbulent and laminar flows, as well as studies by Hieronimczak [7] and Kasprzak [8]. Issues surrounding the determination of actual characteristics of primary flow elements, measurement uncertainty estimation, CFD modeling of meter responses, and geometric optimization

have been extensively addressed by international researchers [9–15].

The primary objective of this paper is to determine the effect of upstream surface roughness changes on the flow coefficient C of a sharp-edged orifice plate resulting from long-term operation. The selection of a sharp-edged orifice plate was motivated by its simple construction – specifically the absence of outlet bevels – which simplifies manufacturing and installation, thereby reducing production costs compared to other primary devices such as classical ISA orifice plates, Venturi tubes, or ISA nozzles. Consequently, it offers a viable alternative for continuous flow rate measurements, while the absence of bevels contributes to greater stability of the flow coefficient C over its operational lifespan.

The secondary objective of this study was to identify which pressure tapping arrangement – corner or flange tappings – results in a smaller flow coefficient error during long-term operation under varying surface roughness conditions. This topic is of significant practical relevance, as it directly impacts installation costs and the application of orifice plates in fluid flow balance calculations.

METHOD OF CARRYING OUT THE MEASUREMENTS

The measurements were carried out on an experimental test rig, a section of which is shown in Figure 1. The sharp-edged orifice plate was mounted in a housing within a DN50 flow line, positioned between two long, straight pipe sections. The upstream distance from the nearest flow disturbance was 46 pipe diameters (approximately 2.3 m), whereas the downstream straight pipe length was 36 pipe diameters (approximately 1.8 m).

A photograph of the orifice, together with its main parameters and the R_a roughness parameter measurement, is shown in Figure 2a and Figure 2b.

Ten sharp-edged orifice plates with a bore diameter of d_o = 20 mm, a thickness of g = 2.5 mm, and surface roughness values ranging from Ra = 1.38 μm to Ra = 20.76 μm were used in the study. The plates were manufactured from PA6 aluminum alloy via face turning. The varying upstream surface roughness levels were obtained by altering the cutting parameters, the cutting insert corner radius, and the tool cutting edge angle. These orifice plates were utilized over an extended operational period in continuous water flow rate measurements, during which their upstream surface roughness underwent changes. Four of the tested orifice plates exhibited a roughness parameter Ra below the threshold specified in PN-EN ISO 5167 [16]. For d_o = *20* mm, the recommended maximum roughness criterion is $Ra < 2\ \mu$m ($Ra < 10^{-4}\ d_o$).

Surface roughness measurements of the orifice plates were performed using the contact method with a Nanoscan 855 profiler equipped with a WCN1T KE 2/60 diamond stylus over a sampling length of l_r = 0.8 mm, which is equal to the evaluation cut-off wavelength ($l_c = l_r$ = 0.8 mm). For each orifice plate, the roughness measurements were conducted along the axis of symmetry on the upstream surface at a distance of approximately 2.5 mm from the orifice bore. Under this instrument setup, the expanded uncertainty for straightness measurement, as stated in the calibration certificate, is U = 0.07 μm.

PROMAG 30AT15 electromagnetic flowmeter from Endress+Hauser was installed in a pipe with an internal diameter of D = 15 mm such that the upstream straight pipe length was 1.5 m (100D) and the downstream length was 0.75 m (50D). The electromagnetic flowmeter was programmed for a range of q_{vz} = (0 ÷ 1.2) dm^3/s, and the maximum permissible error of the flow rate measurement is expressed by the Equation 1:

$$\Delta q_v = \pm(0.2\% \cdot q_{vm} \pm 0.05\% \cdot q_{vz}) \quad (1)$$

where: Δq_v – maximum permissible error of the flow rate measurement, dm^3 /s; q_{vm} – measured flow rate value, dm^3 /s; q_{vz} – programmed range of the flowmeter, dm^3 /s.

A centrifugal pump installed in the flow loop maintains the water flow by generating a volumetric flow rate of q_v < 1.2 dm^3 /s, which corresponds to a Reynolds number of Re < 35,000. The static pressure difference across the tested orifice plate was measured using both flange and corner tappings with APR-2000/ALW differential pressure transmitters featuring a 4–20 mA current output signal, corresponding to a differential pressure range of Δp = 0 ÷ 20.0 kPa. Within this range, the maximum permissible measurement error of the transmitter does not exceed 0.1% of the indicated differential pressure value.

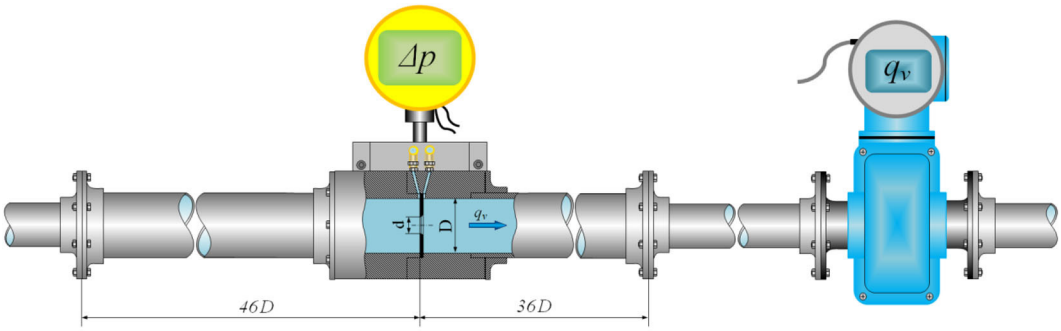


Figure 1. Detail of the measuring station: orifice plate and electromagnetic flowmeter [3]

a b

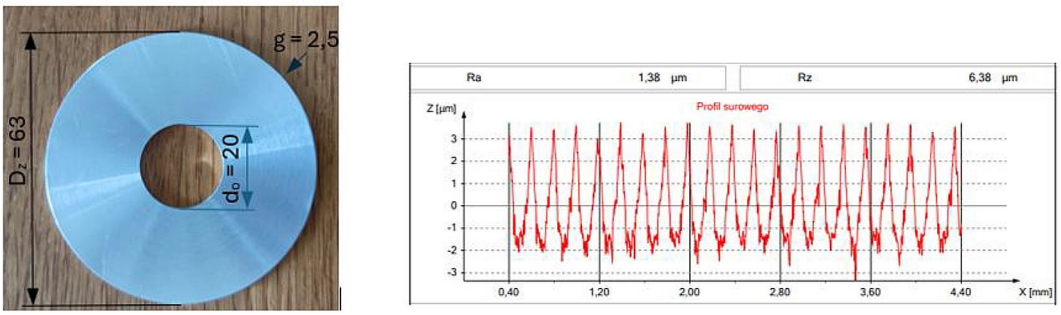


Figure 2. a. Photograph of a sample sharp-edged orifice plate with indicated characteristic dimensions; D_z – outer diameter of the orifice plate, d_o – orifice bore diameter, g – thickness of the orifice plate. b. Surface roughness profile plot presenting parameters *Ra* and *Rz* of the orifice plate

Flow parameters represented by signals from the differential pressure transmitter and reference flowmeter were measured using SANWA 5000 digital multimeters connected to a PC via an RS-232 interface. Data acquisition and communication with the multimeters were handled by dedicated PC Link Plus software configured with a sampling interval of Δt = 2 s. The data acquisition process involved real-time recording of current signals corresponding to the volumetric flow rate q_v and the differential pressure Δp across the orifice plate. The recording duration for each tested orifice plate was set to 30 min, yielding 900 independent measurement samples for analysis.

To demonstrate the impact of upstream surface roughness variations on the discharge coefficient, measurements were performed at a single, maximum flow rate achievable in the system. This choice was justified firstly by the high Reynolds number, which reached nearly 34,000, ensuring a fully developed turbulent flow typical of industrial applications. Secondly, primary flow elements are fundamentally designed for a single nominal flow rate. At flow rates below nominal, variations in the flow coefficient C for the baseline orifice plate (Ra = 1.38 μm) would need to be accounted for first, as the coefficient depends on the flow rate magnitude, particularly in lower ranges.

To determine the flow coefficient C of the orifice plate, the following Equation 2 was used:

$$q_v = C \cdot \frac{\pi \cdot d_o^2}{4} \frac{1}{\sqrt{1-\beta^4}} \cdot \varepsilon \cdot \sqrt{\frac{2 \cdot \Delta p}{\rho}} \qquad (2)$$

where: q_v – volumetric flow rate, $\frac{m^3}{s}$; Δp – static differential pressure across the orifice plate, Pa; ρ – water density, $\frac{kg}{m^3}$; d_o – orifice bore diameter, m; $\in$ – expansibility factor ($\in$ = 1 for water), – ; β – diameter ratio ($\beta = d_o/D$), -.

For each selected orifice plate, measurements were carried out after steady-state operating conditions of the experimental rig were established. Table 1 presents the average physical properties of the working fluid and the primary parameters of the sharp-edged orifice plate. The data show that a temperature variation of approximately 1 °C results in a water density change of roughly 0.3%. These conditions were deemed to be steady-state.

Table 1. Physical properties of the fluid and selected parameters of the baseline sharp-edged orifice plate (i.e., for Ra = 1.38 μm)

Type of fluid	Avg. temperature t, °C	Density ρ, kg/m³	Kinematic viscosity v, m²/s	Internal diameter of the pipeline D, mm	Flow coefficient C, -	Expansibility factor $\in$, -	Internal diameter of the orifice d, mm
Water	24.8 ±0.9	997.1 ±0.3	(0.903± 0.018) · 10^{-6}	50.35	C_k= 0.6048 C_p= 0.6060	1	20

EXPERIMENTAL RESULTS AND DISCUSSION

Figure 3 presents representative results of flow rate distributions measured by the electromagnetic flowmeter. They clearly demonstrate that these distributions are narrow, with a width not exceeding 1% of the mean flow rate. Furthermore, the calculated standard deviations exhibit very low values, reaching at most 0.25% of the mean flow rate. This confirms that steady-state measurement conditions were achieved. Based on these exceptionally low standard deviation values, it was concluded that this flowmeter can serve as a reference standard for the continuous determination of the actual flow rate.

The flow coefficient values C were calculated by rearranging Equation 2.

As previously noted, the measurements were carried out at a single, maximum volumetric water flow rate q_v. The mean value of this flow rate across all tested orifice plates was q_v = (4.325 ± 0.020) m³ /h, and the dispersion of its values is illustrated in Figure 3.

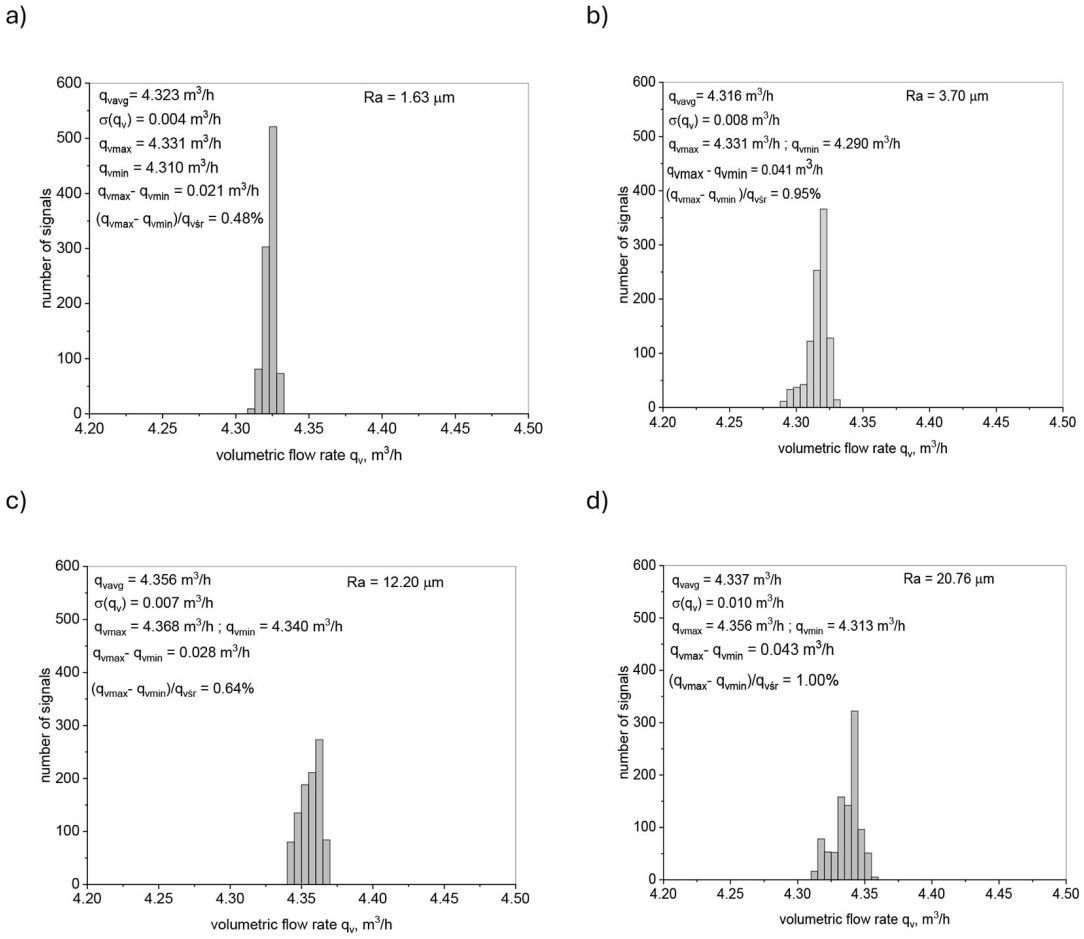


Figure 3. Selected distributions of the volumetric water flow rate measured by the electromagnetic flowmeter for orifice plates with surface roughness: a) Ra=1.63 μm, b) Ra=3.70 μm, c) Ra=12.20 μm, d) Ra=20.76 μm

An analysis of Figure 4 indicates that for the last two surface roughness parameters *Ra* – namely 12.20 μm, and 20.76 μm – the avarage flow rates are higher than for the remaining plates. This suggests that an increase in upstream surface roughness may lead to a reduction in flow resistance across the entire installation, associated with a lower permanent pressure loss downstream of the orifice plate. Consequently, the measured differential pressure values across the orifice plate for these higher roughness levels are lower than those observed for the other surfaces.

Figure 5 shows representative distributions of the differential pressures measured using both flange and corner tappings for selected surface roughness parameters *Ra*.

The distributions presented in Figure 5 indicate that for the highest values of the surface roughness parameter *Ra*, the mean recorded differential pressure values can be lower than those observed for smaller roughness parameters. A decrease in differential pressure, accompanied by a simultaneous increase in flow rate, leads to an increase in the discharge coefficient *C* of the orifice plate. Figure 5 also demonstrates that the differential pressure distributions resemble a normal distribution, indicating that an increase in upstream surface roughness does not affect the profile of the pressure difference distribution. Therefore, the shape of the differential pressure distribution alone cannot serve as a basis to definitively judge whether an orifice plate remains suitable for continued operation or requires replacement.

Figure 6 displays the calculated values of the flow coefficient *C* and the relative errors resulting from roughness variations compared to the baseline orifice plate, plotted against the roughness parameter *Ra*. Table 2 summarizes the complete measurement and calculation results for all orifice plates evaluated in the study.

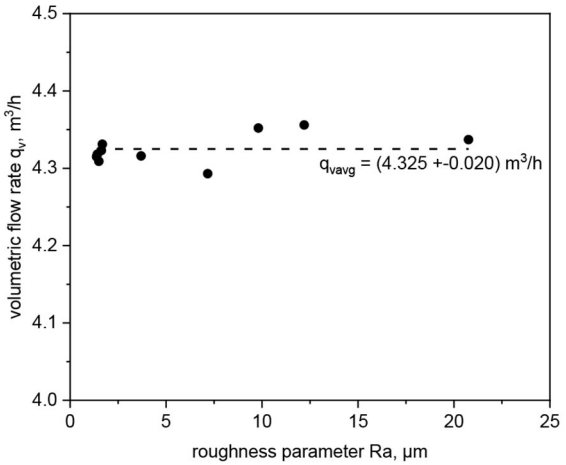


Figure 4. Distribution of the calculated average flow rate values depending on the R_a roughness parameter

As shown in Figure 4 and Table 2, a distinct increase in the flow coefficients C – for both corner and flange pressure tappings – occurs at surface roughness values exceeding *Ra* = 9.81 μm, specifically at *Ra* = 12.20 μm and *Ra* = 20.76 μm. The relative errors of the flow coefficient C compared to the baseline values reach their maximum at *Ra* = 20.76 μm, exceeding 1%. For a roughness parameter of *Ra* = 12.20 μm, the relative error for flange tappings is 0.99%, whereas for corner tappings it is 0.87%. For lower surface roughness levels, the relative errors of the flow coefficients C do not exceed 0.41%.

Up to a roughness parameter of *Ra* = 9.81 μm, the orifice plate can continue to be used in measurements without applying any correction to the flow coefficient C. Notably, this roughness threshold is nearly five times higher than the limit recommended by the standard. Conversely, for roughness values exceeding 9.81 μm (i.e., the two highest roughness levels evaluated), the flow coefficient *C* in Equation (2) should be adjusted. If such calibration is not feasible, its associated uncertainty must be expanded beyond the values prescribed in standard specifications. Naturally, this increases the overall measurement uncertainty of the differential pressure flow system. To remain within acceptable error limits, replacing the degraded primary element with a new one should also be considered.

The rationale for establishing the 0.41% error threshold – corresponding to *Ra* = 9.81 μm, below which no correction to the flow coefficient C is required – warrants further explanation. According to PN-EN ISO 5167, the relative uncertainty of the flow coefficient C for an orifice plate with a diameter ratio of $\beta < 0.6$ is 0.5%. Because the 0.41% error falls within this standard uncertainty margin for flow coefficient *C*, correcting the coefficient C is unnecessary within this range.

The contribution of other error sources in Equation 2 – most notably the differential pressure Δp, given the large sample size of independent readings – will not exceed 1%. Consequently, the relative combined uncertainty of the volumetric flow rate remains under 2%, a level widely accepted for differential pressure flow

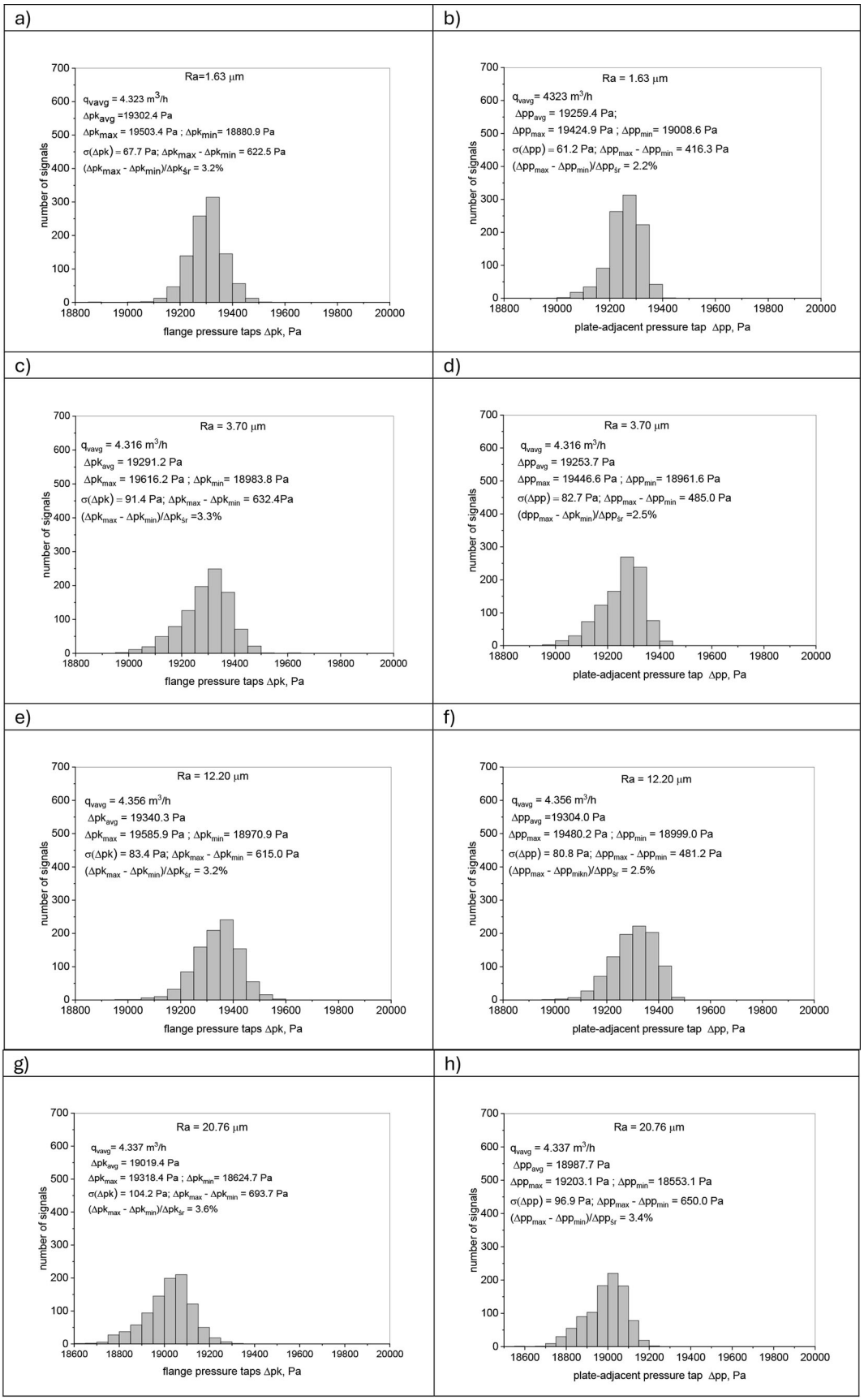


Figure 5. Examples of pressure difference distributions across the orifice in a corner and a flange system for orifice plates with surface roughness: a) flange tappings Ra=1.63 μm, b) corner tappings Ra=1.63 μm, c) flange tappings Ra=3.70 μm, d) corner tappings Ra=3.70 μm, e) flange tappings Ra=12.20 μm, f) corner tappings Ra=12.20 μm, g) flange tappings Ra=20.76 μm, h) corner tappings Ra=20.76 μm

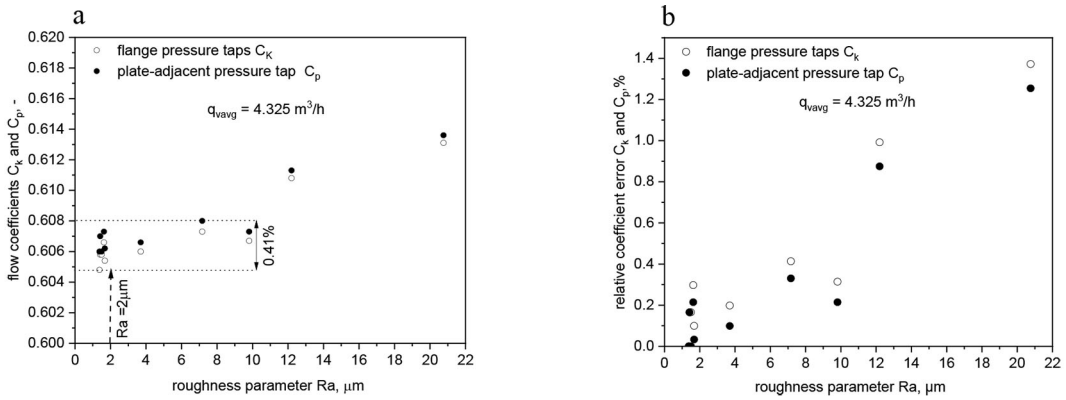


Figure 6 a. Plot of the discharge coefficient C as a function of the surface roughness parameter Ra for sharp-edged orifice plates. b. Plot of the relative error of the discharge coefficient C as a function of the surface roughness parameter Ra for sharp-edged orifice plates

Table 2. Summary of experimental measurements and calculations: $q_{v,avg}$ – mean volumetric flow rate, m³/h; Re_{avg} – Reynolds number, – ; Δp_k, Δp_p – differential pressure across the orifice plate for flange and corner tappings, respectively, Pa ; $\sigma(\Delta p_k)$, $\sigma(\Delta p_p)$ – standard deviation of differential pressure, Pa; C_k, C_p – flow coefficients for flange and corner tappings, -

R_a, µm	q_{vavg}, m³/h	Re_{avg}, -	Δpk±σ(Δpk), Pa	Δpp±σ(Δpp), Pa	Ck, -	Cp, -	Error Ck, %	Error Cp, %
1.38	(4.325 ±0.020)	(339±7) · 10²	19358±98	19283±106	0.6048	0.6060	0,00	0,00
1.42			19323±94	19234±105	0.6056	0.6070	0.17	0.17
1.50			19234±102	19197±100	0.6058	0.6060	0.17	0,00
1.63			19503±68	19259±62	0.6066	0.6073	0.30	0.21
1.68			19452±84	193400±83	0.6054	0.6062	0.10	0.03
3.70			19616±92	19447±83	0.6060	0.6066	0.20	0.10
7.17			19184±69	19098±62	0.6073	0.6080	0.41	0.33
9.81			19587±88	19544±87	0.6067	0.6073	0.30	0.21
12.20			19340±84	19304±81	0.6108	0.6113	0.99	0.87
20.76			19019±105	18987±97	0.6131	0.6136	1.37	1.25

measurement in practical industrial applications. However, for the two highest roughness parameters (Ra = 12.20 μm and Ra = 20.76 μm), the relative combined flow rate uncertainty inevitably exceeds 2%. Thus, the discharge coefficient value must either be adjusted during continued operation or explicitly factored into the expanded flow measurement uncertainty budget.

Additionally, while the calculated flow coefficients C for flange pressure tappings are systematically lower than those for corner tappings, the relative errors with respect to the baseline orifice plate are smaller when using corner tappings. Therefore, when specifying orifice plates for long-term continuous operation without scheduled plant maintenance shutdowns, corner pressure tappings should be preferred to minimize measurement errors over time.

CONCLUSIONS

The main conclusions drawn from the experimental investigations and calculations are as follows:

1. Measurements and calculations demonstrated that even when exceeding the maximum permissible roughness parameter Ra specified in PN-EN ISO 5167-1:2005 by a factor of five, the flow coefficient C values for both flange and corner pressure tappings remain practically unchanged, with maximum relative errors compared to the baseline orifice plate staying below 0.41%.
2. A significant increase in the discharge coefficient occurs only when the roughness parameter increases by a factor of six; specifically, for Ra = 20.76 μm, the increase in the flow coefficient C exceeds 1%.

3. Increased upstream surface roughness of the orifice plate causes the fluid jet to pass through a larger effective cross-sectional area compared to smoother surfaces. Consequently, the flow velocity is lower and the downstream pressure is higher, resulting in a reduced differential pressure across the orifice plate and a corresponding increase in the flow coefficient C.
4. Recorded differential pressure signal distributions revealed that all pressure profiles, regardless of the roughness parameter *Ra*, closely resembled a normal distribution. This confirms that differential pressure probability distributions alone cannot serve as a conclusive diagnostic indicator for deciding whether an orifice plate should be replaced or kept in service.
5. Relative errors in the flow coefficients C compared to the baseline orifice plate were systematically smaller when using corner pressure tappings. Although these differences are minor (on the order of 0.1%), corner tappings should be preferred for differential pressure acquisition in long-term, continuous flow metering installations to minimize long-term measurement error.

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