Volume 8, Number 1, 2022 57

Analysis of Influence of Pipeline Internal Surface Roughness on Flow Rate Measured by Means of Standard Pressure Differential Devices

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Received: May 06, 2022. Revised: June 22, 2022. Accepted: June 29, 2022.

Abstract

The paper presents the analysis of scientific and technical sources on the influence of constructive features of pressure differential flowmeters on flow rate measurement error. According to the research results, the significant surface roughness of pipe sections downstream of the orifice plate does not significantly affect the flow measurement result. The influence of the pipe roughness upstream of the orifice plate depends on geometric characteristics of roughness, the pipe diameter, the relative area of the orifice plate throat, and the Reynolds number. The change in the uncertainty of the orifice discharge coefficient under conditions of inhomogeneous measuring pipe roughness in the pipe section with a length of 10*D* upstream of the orifice plate is analyzed. The authors have determined that even a pipe section length of 1.5*D* with high roughness might be enough to change the flowmeter readings by more than 1% at a large orifice diameter ratio.

Keywords: pressure differential flowmeter; standard primary device; roughness; orifice plate discharge coefficient; measurement error.

1. Analysis of recent publications and definition of problem to be solved

Measuring natural gas flow rate at gas transmission companies and in large gas pipelines of distribution networks is carried out by means of variable pressure differential flowmeters based on standard primary devices [1]. Good regulatory support is necessary for achieving the high accuracy of natural gas metering using these flowmeters [2].

According to the goals of Ukraine's integration into the European Union, the Ukrainian regulatory documents on natural gas metering must be harmonized with the regulatory documents of European countries.

Taking into account these requirements, as well as eliminating some shortcomings of old documents on measuring the flow rate and quantity of fluids, a set of interstate standards GOST 8.586.1-5: 2005 was developed with the participation of the Lviv Polytechnic National University in 2005. These standards came into force in Ukraine on April 1, 2010 by order of the State Committee of Ukraine for Technical Regulation and Consumer Policy No. 486 of December 30, 2009, as National Standards DSTU GOST 8.586.1-5: 2009 "Measurement of fluid flow rate and quantity of liquid and gas using standard primary devices" [3] – [7]. The developed standards are based on the international ISO 5167: 2003 [8] – [12]. They are as close as possible to these standards, and the differences are only in expanding the measurement method, particularly for application conditions in Ukraine.

Full implementation of standards DSTU GOST 8.586.1-5:2009 makes it possible to increase the accuracy of natural gas metering and reduce the current imbalances in gas volume. However, the influence of deviations of specific geometrical characteristics of pipelines from the values determined by the requirements of DSTU GOST

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This paper should be cited as: F. Matiko, V. Roman, H. Matiko, L. Lesovoi. Analysis of influence of pipeline internal surface roughness on flow rate measured by means of standard pressure differential devices. Energy Engineering and Control System, 2022, Vol. 8, No. 1, pp. 57 – 63. https://doi.org/10.23939/jeecs2022.01.057

8.586.1–5: 2009 remains unexplored. Therefore, it is important to carry out research to determine the influence of geometric characteristics of measuring pipelines and orifice plates on the measured value of gas flow rate and volume. Particularly, it is necessary to investigate the effect of pipe internal surface roughness on the measured flow rate, especially the influence of the sections with inhomogeneous roughness within the pipe section length $10D$ (D is internal pipe diameter) upstream of the orifice plate.

2. Formulation of the goal of the paper

The paper aims to analyze the influence of pipe internal surface roughness on a measurement result of gas flow rate by means of standard pressure differential devices in order to estimate the flow rate uncertainty and to expand the application area of such devices.

3. Analysis of influence of pipeline internal surface roughness on flow rate measurement result

The equation for determining the discharge coefficient of the orifice plate [4], [9] is obtained for the conditions of experimental studies of smooth pipes. The use of rough pipes leads to a change in the discharge coefficient because the discharge coefficient of the primary device (PD) depends on the internal surface roughness of the measuring pipe (MP). It is described by a relative equivalent roughness R_r/D. An increase in the equivalent roughness R_r/D leads to an increase in the discharge coefficient of PD. The larger the diameter ratio β of the orifice plate and the Reynolds number Re are, the greater the discharge coefficient C is. The influence of the pipe internal surface roughness in standards [3] – [7] is taken into account by a correction factor, which requires information on the value of the equivalent roughness of the MP internal surface R_r.

The discharge coefficient C was experimentally determined for pipes with a specific internal surface roughness, characterized by the equivalent roughness R_r or the arithmetic mean deviation of the roughness profile R_a. The ranges of change of these parameters were limited by minimum and maximum values. Therefore, the value of the orifice plate discharge coefficient calculated by the equation in [4], [9] will be correct only for the condition that the value of R_a is in a given range, i.e. between the minimum and maximum allowable values of internal surface relative roughness of the pipe $10^4R_{a\ min}/D$ and $10^4R_{a\ max}/D$, respectively [1], [13].

We should note that the pipe's internal wall roughness affects the fluid velocity distribution in its cross-section. If the value of R_a exceeds the above limits, it leads to distortion of the velocity distribution of the fluid in its cross-section and, accordingly, to a change in the value of the discharge coefficient C [1], [14].

Standard [8] does not allow using variable pressure flowmeters in pipelines with the value of R_a outside the permissible limits. Some other standards, in particular [3] – [7], allow the use of variable pressure differential flowmeters in pipes with the value of R_a above these limits. Still, the appropriate correction factor should be used. This means that the influence of the pipe internal surface roughness on the primary device discharge coefficient will be corrected by the correction coefficient K_r for the pipe internal surface roughness. The correction factor K_r depends on the pipe equivalent roughness R_r.

One of the following methods can be used to determine R_r:

- direct measurement of the arithmetic mean deviation of the roughness profile R_a and calculation of correction factor R_r according to DSTU GOST 8.586.1 [3];
- experimental determination of MP hydraulic friction factor λ and calculation of correction factor R_r according to DSTU GOST 8.586.1 [3];
- application of tabular values of MP equivalent roughness according to DSTU GOST 8.586.1 [3].

Based on experimental data obtained by German scientists and given in DIN1952 [15], the values of the maximum allowable pipe relative roughness $(10^4R_r/D)_{al}$ were obtained, above which it is necessary to take into account the correction factor K_r when calculating the flow rate. Fig. 1 shows the range of values of $10^4R_r/D$ for determining the application conditions of orifice plates according to [15].

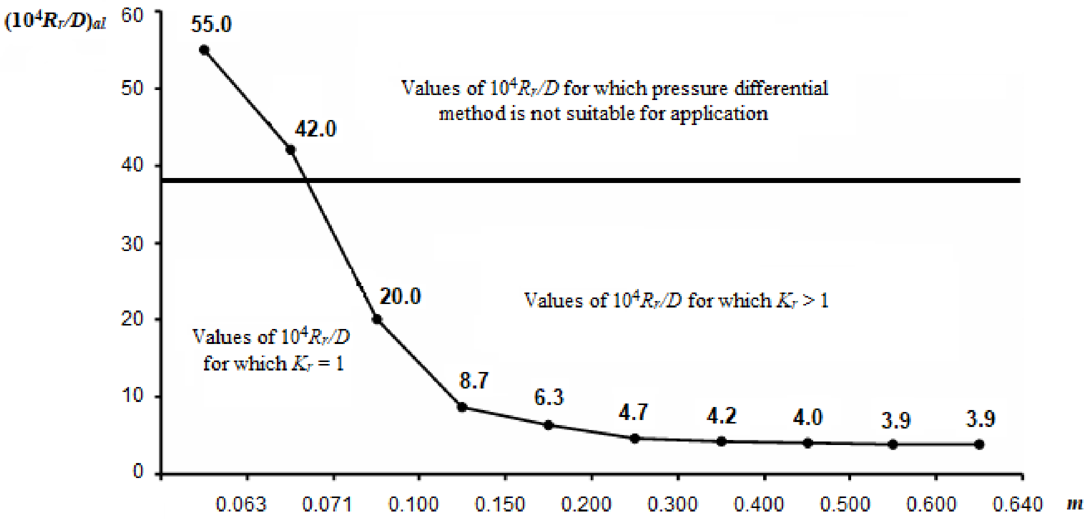

Fig. 1. Values of $10^4R_r/D$ for determining the application conditions for orifice plates.

Considering ISO 5167–1: 2003 [8], a new roughness equivalent called the arithmetic mean deviation of the roughness profile R_a for determining the correction factor for pipe internal surface roughness was included in standard DSTU GOST 8.586.2: 2009 [4]. The dependence of the equivalent roughness R_r on the arithmetic mean deviation of the roughness profile R_a is determined by a simplified equation

$$R_r = \pi \cdot R_a . \tag{1}$$

As mentioned above, the discharge coefficient C was determined for a given set of values of arithmetic mean deviation of the roughness profile R_a. According to [9], if the value of the arithmetic mean deviation of the roughness profile R_a for orifice plates with any type of pressure tappings does not exceed the value in Table 1 and is not less than the value in Table 2, the correction factor for the pipe internal surface roughness is taken K_r = 1 for this range of R_a values. If the value of R_a for orifice plates with any type of pressure tappings is greater than the value specified in Table 1, the correction factor will be K_r > 1. If the value of R_a for orifice plates with any type of pressure tappings is less than the value specified in Table 2 the correction factor K_r will be K_r < 1.

Table 1. The maximum allowable value of relative roughness of pipe internal surface $10^4R_{a\,max}/D$ [9]

β	$10^4R_{a\,max}/D$ for Re								
	$\le 10^4$	3×10^4	10^5	3×10^5	10^6	3×10^6	10^7	3×10^7	10^8
≤ 0.20	15	15	15	15	15	15	15	15	15
0.30	15	15	15	15	15	15	15	14	13
0.40	15	15	10	7.2	5.2	4.1	3.5	3.1	2.7
0.50	11	7.7	4.9	3.3	2.2	1.6	1.3	1.1	0.9
0.60	5.6	4.0	2.5	1.6	1.0	0.7	0.6	0.5	0.4
≥ 0.65	4.2	3.0	1.9	1.2	0.8	0.6	0.4	0.3	0.3

Table 2. The minimum allowable value of relative roughness of pipe internal surface $10^4R_{a\,min}/D$ [9]

β	$10^4R_{a\,min}/D$ for Re			
	$\le 3\times10^6$	10^7	3×10^7	10^8
≤ 0.50	0	0	0	0
0.60	0	0	0.003	0.004
≥ 0.65	0	0.013	0.016	0.012

If the value of arithmetic mean deviation of roughness profile R_a exceeds the value specified in Table 1 or is less than that given in Table 2 while measuring the flow rate using an orifice plate, the discharge coefficient will change as

$$\Delta C = C \cdot K_r - C . \tag{2}$$

From (2), we obtain the correction factor

$$K_r = 1 + \frac{\Delta C}{C}. \tag{3}$$

The value of the correction ΔC depends on the diameter ratio β and the change in the hydraulic resistance of the pipe $\Delta\lambda$ caused by deviation of the value R_r from its allowable values. According to [8], [16], the change of discharge coefficient is determined by the equation

$$\Delta C = 3.134\,\beta^{3.5}\,\Delta\lambda. \tag{4}$$

Substituting (4) into (3) and taking into account $C = 0.6$ [8], we obtain the equation for calculating the correction factor K_r for pipe internal surface roughness

$$K_r = 1 + \frac{\Delta C}{C}, \tag{5}$$

where λ and λ^* are the friction factors calculated for the real Reynolds number *Re* and the values of pipe equivalent roughness, which is equal to its real value R_r, and at the allowable value R^*_r respectively.

The values λ and λ^* are calculated according to the Colebrook-White formula [4], [8], [14]. Thus, the national standard [4] contains dependencies to compensate the effect of uniform roughness on the measured value of flow rate. However, there is often a situation where the pipe upstream of the orifice plate has a non-uniform roughness, particularly in the treated pipe in the 2*D* area and untreated pipe areas. The influence of such inhomogeneous roughness of individual sections of the MP on the measured flow rate requires additional research.

In [18], the results of an experimental study of the influence of the roughness of the MP sections on orifice discharge coefficient are presented. The analysis was performed for MP with a diameter of 3, 4, 6 inches.

Considering obtained data, conclusions were made about the roughness effect in flowmeters with a diameter of up to 6 inches and based on data [16] – for 10-inch flowmeters. Particularly, the following conclusions were made taking into account the results of [17]:

1) For orifice plates with β less than 0.5, there is no statistically significant roughness effect on flow rate within the specification in ANSI / API 2530 [3].
2) For values of roughness R_a less than 3.8 μm (150 microinches), the roughness effect on flow rate is less than 0.5% for any β less than 0.75.
3) For orifice plates with $\beta > 0.55$ and $R_a > 3.8$ μm (150 microinches), there is a statistically significant roughness effect on flow rate.
4) For orifice plates with $\beta = 0.73$ and $R_a \approx 7.6$ μm (300 microinches), the roughness effect on the flow rate may exceed 1%.
5) The scope of processing tolerance in both standards [3], [4] is insufficient to prevent flow measurement errors that may exceed 1%.
6) Mechanic treatment of the MP flowmeter for two or four pipe diameters upstream of the measuring orifice plate to a roughness of 1.3 μm (50 microinches) does not remove all the pipe roughness effects upstream of the orifice plate with $\beta = 0.67$ and above.

In [19], the limits of roughness change were determined for the application of the equation for the orifice plate discharge coefficient proposed by Reader-Harris and Sattary. To take into account the roughness effect on the orifice discharge coefficient, they offered to use the equation

$$\Delta C = \beta^4\,\Delta\lambda. \tag{6}$$

However, this equation has been improved in subsequent works, and equation (4) has been recommended for use in current standards.

We should note that CFD modeling was used to study the roughness effect on orifice plate discharge coefficient in many works. Particularly, based on the results of CFD modeling, the discharge coefficient *C* for different friction factors λ (respectively, different roughness) was calculated to determine the type of dependence (6) in the NEL laboratory [18].

In [19], a study of roughness influence of the pipe measuring section, which corresponds to the state of industrial operation of flow meters, on orifice discharge coefficient was carried out. The study was performed using high-pressure natural gas as a fluid at the NOVA plant in Didsbury, Alberta. The paper shows that different surface treatment quality of pipe sections can lead to step changes in surface roughness and, consequently, to changes in the flow rate profile. A significant increase in surface roughness upstream of the measuring orifice plate is very important. The authors found that even a 1.5*D* length of a pipe section with high roughness may be enough to change the flowmeter readings by more than 1% at a large diameter ratio.

The test results presented in [19] allow us to make the following conclusions:

- flowmeters based on an orifice plate with a diameter ratio β greater than 0.60 are sensitive to changes in measuring section roughness;
- increase in the measuring section roughness leads to a higher discharge coefficient and, accordingly, to decreasing in the measured flow rate;
- measurement errors increase for higher Reynolds numbers *Re*;
- in some cases, the measurements results of flowmeters with standard orifice plates may differ by 1.3% because of surface roughness effects;
- a relatively short section (2.5*D*) with a higher surface roughness installed directly upstream of the orifice plate can have a significant effect on the measured flow rate;
- a short section of the processed (smooth) pipe does not improve the accuracy of pressure differential flowmeter.

The paper [20] presents the experimental investigation of the influence of pipes roughness of different degrees on discharge coefficient for different lengths of the pipe section. The experiments were carried out for air flow through 12-inch, 6-inch, and 3-inch pipes and water flow through 3-inch pipes.

It was found that heavy deposits on the sections' surface downstream do not significantly affect the measurement results. Upstream, the effects vary depending on the roughness degree, pipe diameter, relative area *m* of the orifice plate throat, and the Reynolds number. For $m = 0.5$ and significant roughness, the combined effects of roughness and pipe diameter reduction (due to deposits) cause a roughness factor $K = C_{rough}/C_{smooth}$ about 1.40, 1.17 and 1.08, respectively for 3, 6 and 12-inch pipes. Installing a section of pipe with a high roughness with 2*D* length directly upstream of the measuring orifice plate gives an effect similar to such one for a very long rough pipe. It was found possible to extrapolate the results for very large pipe diameters.

One of the most important results of [13] is that cleaning and reducing the roughness of the pipe section with a relatively short length upstream of the orifice plate reduces errors that may otherwise be quite significant. The paper provides a table for choosing the length of sections for cleaning depending on pipes diameter, the value of *m*, and roughness (see Table 3). The results of these studies and Table 3 were included in [14].

Table 3. Recommendations for cleaning MP [13], [14]

Internal diameter of MP D, mm	β	Roughness type	MP section for cleaning to obtain errors not exceeding:				
			± 3 %	± 2 %	± 1 %	± 0.5 %	0
76	0.5 - 0.59	balls 7.0 mm	3 – 4	4 – 5	5 – 15	15 – 20	> 20
	0.71	balls 7.0 mm	4 – 10	10 – 20	20 – 25	25 – 30	> 30
	0.71	sand		3 – 5	5 – 25	25 – 30	> 30
152	0.5 – 0.59	balls 7.0 mm	2.5 – 4	3 – 5	5 – 12	12 – 20	> 20
	0.71	balls 7.0 mm		4 – 15	15 – 25	25 – 30	> 30
	0.71	sand		1 – 3	3 – 4	4 – 20	> 20
305	0.71	balls 7.0 mm		2.5 – 4	4 – 6	6 – 15	> 15
	0.71	sand			1 – 3	3 – 5	> 5

To achieve the required flow rate measuring accuracy of dirty liquids, flowmeters should be designed so that there is a possibility for easy periodic inspection and cleaning of MP sections upstream of the orifice plate.

The results of research presented in [20] showed that thin liquid oil films on the MP internal surface lead to an increase in roughness and, consequently, to the rise in orifice discharge coefficient. However, very thin oil films on the MP internal surface, the thickness of which is within the greatest height of irregularities profile of MP surface, can reduce their roughness. Therefore, it is necessary to clean the pipe internal surfaces periodically. The regulations for surface cleaning should be developed, taking into account the operation experience of the measuring unit.

4. Conclusion

The analysis of scientific and technical sources on the influence of constructive features of variable pressure flowmeters on the measurement error of the flow rate was carried out in the paper. We found that such an effect can be significant and lead to significant additional errors in flow rate measurement. Therefore, investigating such errors is an important task, which makes it possible to estimate the uncertainty of the measured gas flow rate and to conclude the possibility of applying a specific metering system for commercial accounting of natural gas.

Studies from many sources have shown that the significant surface roughness of the sections downstream of the orifice plate does not affect the flow measurement results. Upstream of the orifice plate, the effects vary depending on the degree of roughness, pipe diameter, the relative area of the orifice plate throat, and Reynolds number.

The results of analysis of the influence of roughness of pipe measuring section for industrial flowmeters on the orifice plate discharge coefficient indicate that different treatment quality of pipe sections surface can lead to gradual changes in surface roughness and, consequently, changes in flow rate profile. The rapid increase in surface roughness upstream of the measuring orifice plate is very important. It was found that even a pipe section length of 1.5*D* with high roughness might be enough to change the flow meter readings by more than 1% at a large diameter ratio of the orifice plate.

Therefore, it is necessary to carry out some additional research to form clear recommendations for changing the uncertainty of the orifice plate discharge coefficient in conditions of inhomogeneous roughness for pipe section length of 10*D* upstream of the orifice plate. Such recommendations will make it possible to expand the application area of pressure differential flowmeters.

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Аналіз впливу шорсткості внутрішньої поверхні трубопроводу на результат вимірювання витрати за допомогою стандартних звужувальних пристроїв

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Анотація

У статті виконано аналіз науково-технічної літератури, присвяченої питанням впливу конструктивних особливостей витратомірів змінного перепаду тиску на похибку вимірювання витрати. За результатами досліджень, отриманих з багатьох джерел, встановлено, що значна шорсткість поверхні секцій після діафрагми (вниз за потоком), не впливає істотно на результат вимірювання витрати. Вплив шорсткості трубопроводу перед діафрагмою залежить від геометричних характеристик шорсткості, діаметра трубопроводу, значення відносного діаметра отвору діафрагми і числа Рейнольдса. Проаналізовано зміну невизначеності коефіцієнта витікання діафрагми в умовах неоднорідної шорсткості вимірювального трубопроводу на ділянці труби довжиною $10D$ перед діафрагмою. Відзначено, що навіть $1.5D$ довжини секції вимірювального трубопроводу з грубою шорсткістю може вистачити, щоб змінити покази витратоміра більше 1% при великому значенні відносного діаметра діафрагми.

Ключові слова: витратомір змінного перепаду тиску; стандартний звужувальний пристрій; шорсткість; коефіцієнт витікання діафрагми; похибка вимірювання.