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Analysis of dependences for hydraulic calculation of pipes made of polymer materials

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Abstract. Assess the influence of the equivalent roughness coefficient and roughness parameters on the value of the calculated pressure losses in pipelines made of polymer materials. Consider normalized calculation dependencies for the hydraulic calculation of pressure pipes made of polymer materials. Assess the difference in the pipeline hydraulic characteristics constructed using various formulas. Give recommendations on the choice of calculation dependence for determining the coefficient of hydraulic resistance, determining the specific pressure loss along the length for pipelines made of polymer materials. The dependence of the calculated specific pressure loss along the length on the equivalent roughness coefficient has been constructed. Hydraulic calculations were carried out using various calculation dependencies to determine the coefficient of hydraulic resistance of a pipeline with a diameter of 400 mm, made of PVC-O 500, on a 1 km long section. The hydraulic characteristics of the pipeline are obtained and comparative results of calculating the values of specific pressure losses along the length when calculated using different calculation dependencies are presented. The magnitude of the change in pressure loss along the length is determined depending on the change in the value of the equivalent roughness coefficient. A calculation formula is recommended for determining the coefficient of hydraulic resistance for pipes made of polymer materials, taking into account the values of the height and step roughness parameters. Key words: polymer pipeline, pressure pipeline, roughness parameters, hydraulic calculation, pressure losses.

1 Introduction

One of the most important tasks in the development of water supply systems is to increase the accuracy of hydraulic calculations. In this direction, at the department of Water Supply, Sewerage and Hydraulics of Emperor Alexander I St. Petersburg State Transport University, many studies have been carried out to improve the accuracy of determining pressure losses along the length of the pipeline [1, 2, 3].

When determining pressure losses in pipes made of polymer materials, the world practice uses various calculation dependencies to determine the hydraulic resistance coefficient λ. The

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amount of pressure loss along the length, in turn, depends on the roughness properties of the inner surface of pipes made of polymer materials.

The most common calculation dependence for determining λ is the Colebrook-White formula, which gives the most accurate results to experimental values [4, 5]. In foreign countries it is legally used on the basis of DIN EN-805 [6]. Its significant disadvantage is the presence of unknowns on the left and right sides of the equation, which make it possible to solve the equation only implicitly using the iteration method.

Research carried out at different times by I. I. Nikuradze [7], Altshul Yu.E. [8], Blasius P.R.G. [9], Dobromyslov A.Ya., as well as Fang X [10], Brkic D. [11, 12], Achour B. [13, 14] made it possible to reduce the Colebrook-White dependence to an explicit form using approximation.

For polymer pipelines, according to [15], it is customary to use the approximation of A.Ya. Dobromyslov, presented in SP 399.1325800, in which the influence of the values of roughness characteristics is described by the coefficient of equivalent roughness Ke, determined for different types of polymer materials based on experimental studies.

The disadvantage of this approach is the need to conduct expensive and labor-intensive bench experimental studies to determine the values of the equivalent roughness coefficient K_e for each type of polymer material, the number of which has increased significantly over the past decades. SP 40-102-2000 proposes to consider K_e for all types of polymer materials equal to 0.01 mm, however, it is known that for different materials the values of K_e differ (Appendix A, Table A.1).

Research by O.A. Prodous, A.Ya. Dobromyslov, according to [16], established the dependence of the equivalent roughness coefficient on the actual (measured) parameters of the pipe wall roughness, which, according to MI 41-75 «Methodology for measuring surface roughness parameters in accordance with GOST 2789-73 using profile method instruments», are characterized by the roughness values R_a and S_m. The advantage of these parameters is the possibility of measuring them using a profilometer-profilograph device and subsequent processing of profilograms without conducting expensive experiments. The result of the research carried out by hydraulic scientists was the calculation dependence K_e = f(R_a), used in compiling tables for the hydraulic calculation of pipelines made of pressure polyethylene, which were made by Russian scientist Prodous O.A., and which are widely used in domestic engineering practice.

The formula looks like:

$$K_\mathrm{e} = 2 \cdot {R_a}^{1,33}, \mu\mathrm{m} \tag{1}$$

Later, as a result of research by O.A. Prodous and P.P. Iakubchik became a calculation dependence that takes into account the measured values of the parameters R_a and S_m, excluding the use of the equivalent roughness coefficient K_e, which in hydraulic calculations has a constant standard value for a large list of polymer materials.

Not long ago, “methodological recommendations for the use of SP 399.1325800 were published [17], which contain supplemented tables for the hydraulic calculation of polymer pipelines (Appendix E of SP 399.1325800). These tables were developed using the calculation dependence for determining the hydraulic resistance coefficient K_e according to the Dobromylsov's dependence, with the substitution of the values of K_e from SP 399.1325800. In the described document, these tables are recommended for use when carrying out hydraulic calculations, although they do not take into account the actual values of the roughness of the internal surface of the pipeline, but are guided by K_e values generalized for several types of materials. Modern followers of the theory of use of the equivalent roughness coefficient as a value describing the nature of the roughness of the inner surface of the walls of polymer pipelines are employees of the scientific and technical center

POLYPLASTIC Group, LLC. They are also the developers of methodological recommendations for SP 399.1325800 and authors of other scientific works, which are showing advantages of this method [18, 19].

The purpose of this study is to assess the influence of changes in the geometric value of roughness on the value of specific pressure losses, to compare the results of hydraulic calculations of a polymer pipeline when determining the coefficient of hydraulic resistance using various calculation dependencies, as well as with the results of determining pressure losses using tabular data widely used today, based on the results obtained, recommend the preferred calculation dependencies for determining the coefficient of hydraulic resistance for calculating the values of actual specific pressure losses along the length in polymer pressure pipelines.

2 Materials and Methods

To assess the influence of roughness parameters of the inner surface of the polymer pipelines walls on the value of specific pressure losses, hydraulic calculations have been made using the formula of A. Y. Dobromyslov from SP 399.1325800 for a polymer pipeline at a flow rate of 100 l/s with a water temperature of 10°C.

In order to separate out the influence of roughness parameters, it was assumed that the type of polymer material of the pipeline is anonymized and has the same nominal diameter of 400 mm with a wall thickness of 23,7 mm with varying values of the equivalent roughness coefficient of the K_e. The range of known K_e values is taken as considered, where the minimum K_e = 0,000005 mm, calculated by the formula (1), and R_a =0,350 µm [16], the maximum K_e = 0,014 mm according to Appendix A, Table A.1 of SP 399.1325800.

The results of hydraulic calculations are summarized in Table 1. Based on the data obtained, a graph of the dependence of specific pressure losses along the length on the coefficient of equivalent roughness of the K_e (Figure 1) is formed.

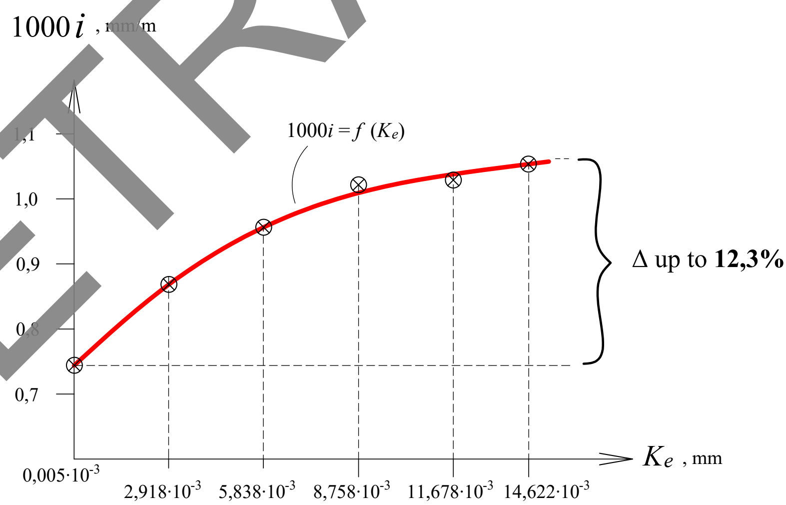

Fig. 1. The dependence of the values of 1000i on the values of the equivalent roughness coefficient K_e

As follows from the graph, depending on the change in the values of the equivalent roughness, the specific pressure losses can vary up to 12%.

For a comparative analysis of various calculation dependencies for determining the coefficient of hydraulic resistance λ, hydraulic calculations of a pipeline made of PVC-O 500 with an outer diameter of 315 mm, a wall thickness of 18.7 mm, with a water temperature of 10C, at various flow rates: 20, 45, 75, 106 and 136 l/s were carried out.

At the same time, the hydraulic calculation was first carried out using the calculation dependence of A.Ya. Dobromyslov SP 399.1325800 with the substitution of the K_e value given in Appendix A of SP 399.1325800. The following hydraulic resistance coefficients were determined according to the same calculation dependence, but with K_e calculated using the parameter R_a according to formula 1. After the values of λ were found using the Prodous-Iakubchik formula, which does not take into account the values of K_e, but contains the values of the roughness parameters R_a and S_m measured by the device.

Hydraulic calculation according to the SP 399.1325800 method using the dependence λ of A.Ya. Dobromyslov, K_e = 0.008 mm at a flow rate of 75 l/s.

Estimated internal diameter of the pipeline, m:

$$d = d_{in} - 2e = 0{,}315 - 2 \cdot 0{,}0187 = 0{,}2776\, m\,, \quad (2)$$

where : d_{in} – is the estimated outer diameter of the pipe, mm;
e is the wall thickness of the pipe according to GOST 18599-2001 "Pressure pipes made of polyethylene. Technical specifications (with a Change of N 1", mm.

The water movement speed:

$$V = \frac{4 \cdot q}{\pi \cdot d^2} = \frac{4 \cdot 0{,}075}{3{,}14 \cdot 0{,}2776^2} = 1{,}24\ m/\mathrm{sec} \quad (3)$$

The coefficient of hydraulic resistance, λ, determined by the calculation dependence of Dobromyslov A.Ya. from SP 399.1325800:

$$\sqrt{\lambda} = \frac{0{,}5\left[\frac{b}{2} + \frac{1{,}312(2-b)\cdot \lg\left(\frac{3{,}7d}{K_e}\right)}{lgRe_f - 1}\right]}{\lg\left(\frac{3{,}7d}{K_e}\right)}; \quad (4)$$

$$\sqrt{\lambda} = \frac{0{,}5\left[\frac{1{,}75}{2} + \frac{1{,}312(2-1{,}75)\cdot \lg\left(\frac{3{,}7 \cdot 0{,}2776}{0{,}008 \cdot 10^{-3}}\right)}{\lg(262724) - 1}\right]}{\lg\left(\frac{3{,}7 \cdot 0{,}2776}{0{,}008 \cdot 10^{-3}}\right)} = \sqrt{0{,}01507}$$

$$\lambda = 0{,}01507\,,$$

where : b is a certain similarity number of fluid motion modes, calculated by the formula:

$$b = 1 + \frac{lgRe_f}{lgRe_{quad}}; \quad (5)$$

$$b = 1 + \frac{\lg(262724)}{\lg(17350000)} = 1{,}75\,,$$

for b > 2, b = 2 is assumed, in this case b < 2.
where : Re_f is the actual Reynolds number determined by the formula:

$$Re_f = \frac{V \cdot d}{\nu} = \frac{1{,}24 \cdot 0{,}2776}{1{,}31 \cdot 10^{-6}} = 262724\,, \quad (6)$$

where : ν is the coefficient of liquid kinematic viscosity which depends on the water temperature, m²/sec. At a water temperature equal to 10°C, the coefficient $\nu = 1{,}31 \cdot 10^{-6}\ \mathrm{m^2/sec}$;

Re_{quad} is the Reynolds number corresponding to the beginning of the quadratic region of hydraulic resistances, determined by the formula (1):

$$Re_{\mathrm{quad}} = \frac{500 \cdot d}{K_\mathrm{e}} - \frac{500 \cdot 0{,}2776}{0{,}008 \cdot 10^{-3}} = 17350000,$$

where K_e is the coefficient of even-grained roughness equivalent of the inner surface of the pipe walls, m, equal to 0.008 mm [Appendix A, Table A.1, 4].

The specific friction pressure loss along the length of the pipeline, m/m, is determined by the Darcy-Weisbach formula:

$$i = \lambda \frac{V^2}{2g \cdot d} = 0{,}01507 \cdot \frac{1{,}24^2}{2 \cdot 9{,}81 \cdot 0{,}2776} = 0{,}004253026\,\frac{\mathrm{m}}{\mathrm{m}}; \quad (7)$$
$$i = 4{,}253\ \mathrm{mm/m},$$

where : g is the free fall acceleration, m2/sec;

1. Hydraulic calculation according to the method of SP 399.1325800, the value of K_e is determined through the parameter R_a at a flow rate of 75 l/s.

1. $d = d_\mathrm{ex} - 2e = 0{,}315 - 2 \cdot 0{,}0187 = 0{,}2776\ \mathrm{m}$,
2. $V = \frac{4 \cdot q}{\pi \cdot d^2} = \frac{4 \cdot 0{,}075}{3{,}14 \cdot 0{,}2776^2} = 1{,}2398\ \mathrm{m/sec}$
3. $Re_\mathrm{f} = \frac{V \cdot d}{\vartheta} = \frac{1{,}2398 \cdot 0{,}2776}{1{,}31 \cdot 10^{-6}} = 262724$,
4. $K_\mathrm{e} = 2 \cdot {R_\mathrm{a}}^{1{,}33} = 2 \cdot 0{,}00000035^{1{,}33} = 0{,}5 \cdot 10^{-8}, =$
$$K_\mathrm{e} = 0{,}000005\ \mathrm{mm},$$

where : R_a is the height characteristic of the roughness – the arithmetic mean absolute value of the profile deviations within the base length. The value of this indicator is determined according to the standard MI 41-75 methodology "Methodology for measuring surface roughness parameters according to GOST 2789-73" using profiling devices" using a profilograph–profilometer and processing profilograms of the roughness of the inner surface of pipe walls. For pipes made of polyvinyl chloride, the value of ${R_\mathrm{a}}^{\mathrm{PVC-O}} = 0{,}350\ \mu\mathrm{m}$.

5. $Re_\mathrm{quad} = \frac{500 \cdot d}{K_\mathrm{e}} - \frac{500 \cdot 0{,}2776}{0{,}5 \cdot 10^{-8}} = 27760000000,$
6. $b = 1 + \frac{lgRe_\mathrm{f}}{lgRe_\mathrm{quad}} = 1 + \frac{\lg(262724)}{\lg(27760000000)} = 1{,}52$,
7. $\sqrt{\lambda} = \frac{0{,}5\left[\frac{b}{2} + \frac{1{,}312(2-b)\cdot \lg\left(\frac{3{,}7d}{K_\mathrm{e}}\right)}{lgRe_\mathrm{f} - 1}\right]}{\lg\left(\frac{3{,}7d}{K_\mathrm{e}}\right)}$;

$$\sqrt{\lambda} = \frac{0{,}5\left[\frac{1{,}52}{2} + \frac{1{,}312(2-1{,}52)\cdot \lg\left(\frac{3{,}7 \cdot 0{,}2776}{0{,}5 \cdot 10^{-8}}\right)}{\lg(262724) - 1}\right]}{\lg\left(\frac{3{,}7 \cdot 0{,}2776}{0{,}5 \cdot 10^{-8}}\right)} = \sqrt{0{,}01368}\,,$$

8. $i = \lambda \frac{V^2}{2g \cdot d} = 0{,}01368 \cdot \frac{1{,}2398^2}{2 \cdot 9{,}81 \cdot 0{,}2776} = 0{,}003860743\,\frac{\mathrm{m}}{\mathrm{m}}$;

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$i = 3{,}8607$ mm/m

2. Hydraulic calculation according to the formula of O.A. Prodous and P.P. Iakubchik [14] with the definition of λ using the roughness parameters $\boldsymbol{R}_{\mathbf{a}}$ and $\boldsymbol{S}_{\mathbf{m}}$.

1. $\boldsymbol{d = d_{ex} - 2e = 0,315 - 2 \cdot 0,0187 = 0,2776}$ **m**,
2. $\boldsymbol{V = \frac{4 \cdot q}{\pi \cdot d^2} = \frac{4 \cdot 0,075}{3,14 \cdot 0,2776^2} = 1,2398 \frac{m}{sec}}$
3. $\boldsymbol{Re_f = \frac{V \cdot d}{\vartheta} = \frac{1,2398 \cdot 0,2776}{1,31 \cdot 10^{-6}} = 262724}$,
4. $$\boldsymbol{\lambda = \frac{0,3162}{Re_f^{0,25}} \cdot \left(\frac{10R_a \cdot 10^2}{Sm} + 1\right)^{0,172} \cdot \left(\frac{2R_a \cdot 10^3}{d} + 1\right)^{0,475}}, \quad (8)$$

where : $R_a = 0{,}350$ μm $= 0{,}00000035\ m$;

$\boldsymbol{S}_{\mathbf{m}}$ is the average step between the irregularities, $\boldsymbol{S}_{\mathbf{m}}{}^{PVC-O} = 7800$ μm $= 0{,}0078\ m$;

$$\lambda = \frac{0,3162}{262724^{0,25}} \cdot \left(\frac{10 \cdot 0,00000035 \cdot 10^2}{0,0078} + 1\right)^{0,172} \cdot \left(\frac{2 \cdot 0,00000035 \cdot 10^3}{0,2776} + 1\right)^{0,475};$$

$$\lambda = 0{,}01409$$

5. $i = \lambda \frac{V^2}{2g \cdot d} = 0{,}01409 \cdot \frac{1{,}2398^2}{2 \cdot 9{,}81 \cdot 0{,}2776} = 0{,}003976452 \frac{m}{m}$;

$$i = 3{,}9765 \frac{mm}{m},$$

The results obtained are summarized in Table 2 and shown in Figure 2.

3 Results

The analysis of the dependence of $1000i = f(K_e)$, shown in Figure 1, and the results of calculating specific pressure losses (Table 1) for a pipeline with a nominal diameter of 400 mm with a wall thickness of 23,7 mm at a flow rate of 100 l/s with a water temperature of 10 °C shows that the difference in pressure losses, depending on the values of K_e, reaches 12.3%.

Table 1. the results of calculating specific pressure losses

Hydraulic characteristics of pipes									
d, mm	V, m/sec	q, l/s	Re_f	K_e, mm	Re_{quad}	b	λ	i, m/m	$1000i$, mm/m
400x23,7	1,0246	100	275782	0,000005	35260000000	1,52	0,01347	0,00204407	2,0441
400x23,7	1,0246	100	275782	0,002918	60418095	1,7	0,01429	0,0021685	2,1685
400x23,7	1,0246	100	275782	0,005838	30198698	1,73	0,01458	0,00221251	2,2125
400x23,7	1,0246	100	275782	0,008758	20130167	1,74	0,01501	0,00227776	2,2778
400x23,7	1,0246	100	275782	0,011678	15096763	1,76	0,01503	0,0022808	2,2808
400x23,7	1,0246	100	275782	0,014622	12057174	1,77	0,01522	0,00230963	2,3096

According to the results of hydraulic calculations using various calculation dependencies, as well as data from tables for hydraulic calculation, for each linear meter of the length of the PVC-O 500 pipeline with a nominal diameter of 315 mm, meeting the task conditions, when calculated using the SP 399.1325800 method using the dependence λ A.Ya. Dobromyslov, $K_e = 0{,}008$ mm is lost 4,253 mm/m of head, according to the method of SP 399.1325800, where the value of K_e is determined through the parameter R_a, 3.8607 mm/m of pressure is lost, using the formula of Prodous O.A. and akubchik P.P. [14] with with the λ being determined using the roughness parameters R_a and S_m, the pressure loss is 3,9765 mm/m. According to the tables for hydraulic calculation presented in the methodological guidelines for the use of SP 399.1325800, the pressure loss is 4,2660 mm/m.

Based on the results of calculations based on the data (Table 1), in Figure 2 graphs of the dependence $1000i = f(q)$ are plotted.

The results of hydraulic calculations performed using different formulas λ at flow rates of 20, 45, 75, 106 and 136 *l/s.*

Table 2. The results of hydraulic calculations

q = 20 l/s										
Methodology	D, mm	Speed, *m/sec*	d_{ex}, mm	d_{in}, mm	q, m^3/sec	K_e	λ	i,m/m	1000i, mm/m	Δ in % from (3)
1. By Dobromyslov's calculation dependencies, K_e from SP 399.1325800.2018	300	0,3306	315	277,6	0,020	$0{,}008\cdot10^{-3}$	0,01905	0,000382281	0,3823	**2,9**
2. By Dobromyslov's calculation dependencies, K_e through the parameter R_a						$0{,}5\cdot10^{-8}$	0,01850	0,000371244	0,3712	**5,7**
3. Based on the research of Prodous O.A. and Iakubchik P.P. (Ra and Sm)						-	0,01961	0,000393518	0,3935	**-**
4. Tables from the methodological guidelines for the use of SP 399.1325800.2018						$0{,}008\cdot10^{-3}$	-	-	0,383	**2,7**
q = 45 l/s										
Methodology	D, mm	Speed, *m/sec*	d_{ex}, mm	d_{in}, mm	q, m^3/sec	K_e	λ	i,m/m	1000i, mm/m	Δ in % from (3)
1. By Dobromyslov's calculation dependencies, K_e from SP 399.1325800.2018	300	0,7439	315	277,6	0,045	$0{,}008\cdot10^{-3}$	0,01637	0,001663257	1,6633	**2,2**

2. By Dobromyslov's calculation dependencies, K_e through the parameter R_a						$0{,}5 \cdot 10^{-8}$	0,01519	0,001543364	1,5434	**5,2**
3. Based on the research of Prodous O.A. and Iakubchik P.P. (Ra and Sm)						-	0,01630	0,001626679	1,6267	**-**
4. Tables from the methodological guidelines for the use of SP 399.1325800.2018						$0{,}008 \cdot 10^{-3}$	-	-	1,67	**2,6**
q = 75 l/s										
Methodology	D, mm	Speed, *m/sec*	d_{ex}, mm	d_{in}, mm	q, m^3/sec	K_e	λ	i,m/m	1000i, mm/m	Δ in % from (3)
1. By Dobromyslov's calculation dependencies, K_e from SP 399.1325800.2018	300	1,2398	315	277,6	0,075	$0{,}008 \cdot 10^{-3}$	0,01507	0,004253026	4,2530	**6,9**
2. By Dobromyslov's calculation dependencies, K_e through the parameter R_a						$0{,}5 \cdot 10^{-8}$	0,01368	0,003860743	3,8607	**3,0**
3. Based on the research of Prodous O.A. and Iakubchik P.P. (Ra and Sm)						-	0,01409	0,003976452	3,9765	**-**
4. Tables from the methodological guidelines for the use of SP 399.1325800.2018						$0{,}008 \cdot 10^{-3}$	-	-	4,266	**7,2**

q = 106 l/s										
Methodology	*D*, mm	Speed, *m/sec s*	d_{ex}, mm	d_{in}, mm	*q*, m³/sec	K_e	*λ*	*i*,m/m	1000*i*, mm/m	Δ in % from (3)
1. By Dobromyslov's calculation dependencies, K_e from SP 399.1325800.2018	300	1,7523	315	277,6	0,106	$0{,}008\cdot10^{-3}$	0,01431	0,008067484	8,0675	10,7
2. By Dobromyslov's calculation dependencies, K_e through the parameter R_a						$0{,}5\cdot10^{-8}$	0,01288	0,007261299	7,2613	0,4
3. Based on the research of Prodous O.A. and Iakubchik P.P. (Ra and Sm)						-	0,01292	0,007283850	7,2838	-
4. Tables from the methodological guidelines for the use of SP 399.1325800.2018						$0{,}008\cdot10^{-3}$	-	-	8,085	10,9
q = 136 l/s										
Methodology	*D*, mm	Speed, *m/sec*	d_{ex}, mm	d_{in}, mm	*q*, m³/sec	K_e	*λ*	*i*,m/m	1000*i*, mm/m	Δ in % from (3)
1. By Dobromyslov's calculation dependencies, K_e from SP 399.1325800.2018	300	2,2482	315	277,6	0,136	$0{,}008\cdot10^{-3}$	0,01391	0,012908582	12,909	**14,5**
2. By Dobromyslov's calculation dependencies, K_e through the parameter R_a						$0{,}5\cdot10^{-8}$	0,01228	0,011395930	11,396	**1,1**
3. Based on the research of Prodous O.A. and Iakubchik P.P. (Ra and Sm)						-	0,01214	0,011266009	11,266	**-**
4. Tables from the methodological guidelines for the use of SP 399.1325800.2018						$0{,}008\cdot10^{-3}$	-	-	12,839	**13,9**

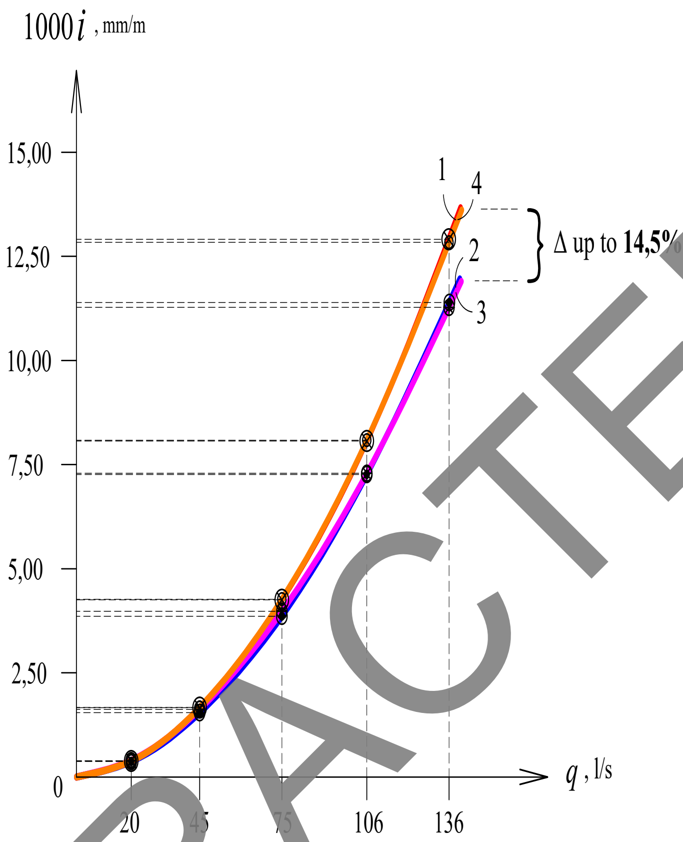

Fig. 2 - Dependence $1000i = f(q)$, where: 1 – According to the formula of Dobromyslov A.Ya., K_e from SP 399.1325800; 2 – According to the calculation dependence of Dobromyslov A.Ya., K_e through the parameter R_a; 3 – Based on the research of Prodous O.A. and Iakubchik P.P. (R_a and S_m); 4 – Data from tables [17].

According to Table 1, the difference in $1000i$ values for the same pipeline diameter, with the same flow rates, but calculated using different hydraulic calculation methods, reaches 14.5% at a speed of 2.25 m/s with a flow rate of 136 l/s.

4 Discussion and Conclusions

The analysis of the data from Table 1 and the dependence 1000i = f(K_e) shown in Figure 1 confirms the significant influence of the roughness parameters on the pressure loss value and the high importance of accurately determining their values.

It follows from Figure 2 that the difference in the values of specific pressure losses according to calculation dependencies (2) and (3), which take into account the roughness parameters, is significantly less than according to the results determined by dependence (1) and values (4).

5 Conclusion

Based on the above, the following conclusions can be drawn:

the largest specific pressure losses in polymer pipelines are given by the calculation dependences according to the formula of Dobromyslov A.Ya. from SP 399.1325800, the smallest according to the Prodous-Iakubchik formula. The discrepancy is more than 14%.

experimental studies with measurement of R_a and S_m are needed to confirm or inconsistency of the Prodous-Iakubchik formula.

the actual values of the R_a and S_m parameters are determined based on the developed methodology for production monitoring of the roughness parameters of the inner surface of pipes.

it is required to develop limit values for the parameters R_a and S_m and justify them hydraulically, taking into account the energy consumption of pumping equipment selected for specific pipelines [20].

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