

SIMULATION OF THE OPERATION OF A PRESSURE PIPELINE WITH AN INTERNAL LINING OF A PROTECTIVE COATING

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Abstract. The article presents the results of alternative methods for determining the hydraulic characteristics of a deteriorated pressure pipeline with a Subcote FLP spray-on protective coating applied to its inner surface. The results were processed using automated programs, with an ultimate goal of determining and comparing a number of hydraulic characteristics, resulting in energy indicators of pipeline's performance during water transportation. Approaches are presented for identifying the dynamics of possible transformations of certain pipeline hydraulic parameters, specifically, hydraulic friction coefficients and equivalent roughness, when using the studied protective coating after its service over a certain time interval and with changing ambient temperature conditions. Dependencies for changes in these coefficients, and their impact on the pipeline's performance energy indicators during long-distance water transportation were obtained by calculations.

Keywords: pipelines, coatings, hydraulic indicators, light imaging, mathematical modeling, temperature parameters, energy saving

МОДЕЛИРОВАНИЕ РАБОТЫ НАПОРНОГО ТРУБОПРОВОДА С ВНУТРЕННЕЙ ОБЛИЦОВКОЙ ЗАЩИТНЫМ ПОКРЫТИЕМ

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Аннотация. Приведены результаты альтернативных методов по определению гидравлических характеристик ветхого напорного трубопровода с нанесенным на его внутреннюю поверхность напыляемого защитного покрытия Subcote FLP. Обработка результатов производилась с использованием автоматизированных программ, где конечным итогом являлось определение и сопоставительный анализ ряда гидравлических характеристик с выходом на энергетические показатели работы трубопровода при транспортировке по нему воды. Приведены подходы к выявлению динамики возможной трансформации некоторых гидравлических показателей трубопровода, в частности, коэффициентов гидравлического трения и эквивалентной шероховатости при использовании исследуемого защитного покрытия после его эксплуатации в определенном временном интервале и при изменении температурных условий окружающей среды. Расчетным путем получены зависимости изменения этих коэффициентов и произведена оценка влияния их на энергетические показатели работы трубопровода в период его работы по транспортировке воды на большие расстояния.

Ключевые слова: трубопроводы, защитные покрытия, гидравлические показатели, светоскопия, математическое моделирование, температурные параметры, энергосбережение

INTRODUCTION

Given the significant wear and tear of pipeline networks, where, in particular, according to data from the Ministry of Regional Development, over 40% of water supply networks require prompt repair, the question of the effectiveness of new trenchless repair technologies is becoming

extremely relevant [1, 2]. An analysis of global experience in the operation and restoration of utility networks of water supply and sanitation systems shows that the most promising solution to the problem of extending their service life is rehabilitation through the application of internal protective coatings of various types, including polymer spray coatings (PSCs). Unlike metal and

ceramic linings, polymer coatings have a hydrophobic surface, which positively affects the hydrodynamics inside the pipe and prevents the formation of surface contaminants [3]. Based on an analysis of literature sources [4, 5], it can be concluded that such protective coatings are promising materials for pipeline protection.

To demonstrate the effectiveness of various types of polymer protective coatings, as well as to study the possible transformation of their hydraulic properties over time (in particular, the degree of surface roughness), and the impact of temperature conditions on this process, it is necessary to conduct full-scale studies under dynamic conditions using appropriate models and proven methodological approaches. Automated programs are used to speed up calculations and potentially predict the resulting basic hydraulic and energy parameters.

According to available certificates of conformity, protective polymer spray coatings do not alter the composition of the pumped fluid, maintaining a high level of reliability in water supply pipeline networks and reducing the negative impact on the urban environment during repairs. During pipeline rehabilitation using PSCs, despite a layer thickness of only 3–8 mm, it is possible to effectively seal various defects and increase pipeline wear resistance. Thus, the internal surfaces of restored pipelines generally become less rough, which improves the hydraulic characteristics of water supply and wastewater disposal pipeline networks.

METHODS

A steel pipeline coated with a protective Subcote FLP coating applied to its inner surface was used for comprehensive hydraulic studies, including modeling of the parameters under study using automated software and modern light-profiling and profilometry equipment.

Subcote FLP coating has sanitary and epidemiological expert approval No. 77.01.12.P.014303.09.11 dated September 22, 2011, issued by the Moscow Office of the Federal Service for Surveillance on Consumer

Rights Protection and Human Wellbeing, permitting its application to the inner surface of pipelines in drinking water systems.

The study involved physical testing (on a large-scale 10-meter-long and a small-scale 1-meter-long test bench) and then mathematical modeling of the pipeline's performance with the protective coating to determine its hydraulic characteristics at the same ambient temperature (20°C) using appropriate automated software [6, 7]. Hydraulic bench testing of the initial protective coating sample on a steel pipeline and processing of the results using automated calculation systems were conducted in the laboratory of the Department of Water Supply and Sanitation on a large-scale pressure rig (Fig. 1). The small-scale gravity rig was made in the form of an open steel inclined trough (gutter) with a nominal diameter of 100 mm with a thin layer of the coating being tested applied to it (Fig. 2), along which a mini-flow of water moved in the form of a lens at the end (Fig. 3) [8].



Figure 1. General view of a large-scale hydraulic test rig with 10 m long pipes with a nominal diameter of 100 mm made of various materials (the fourth pipe from the top is a steel pipe with a protective Subcote FLP coating)

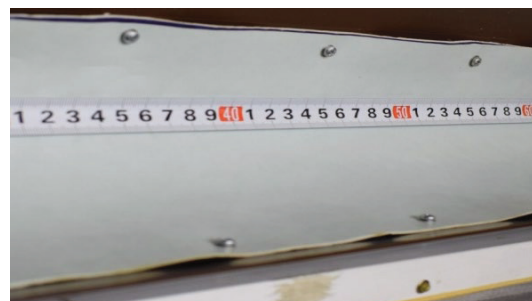


Figure 2. Detail of the top view of a 1 m long open inclined gutter with Subcote FLP coating applied to it

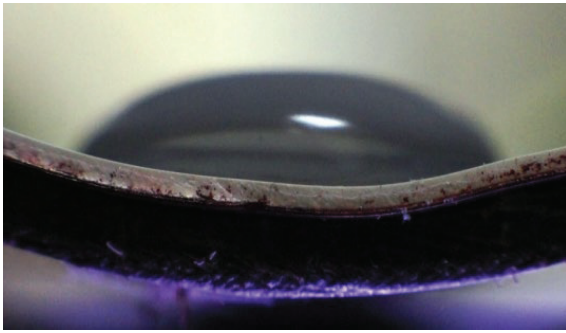


Figure 3. A fragment of the end section of a sloped gutter with a Subcote FLP protective coating and a mini-flow of moving water

To expand the experimental range, i.e., simulating extended water presence duration in pipelines and flumes, as well as elevated ambient temperatures, a special compact setup was developed. It consisted of a cylindrical vessel containing 1 liter of water, mounted on a magnetic stirrer. A rectangular coating sample of specified dimensions was immersed into the vessel and firmly secured. The coating samples were positioned at the periphery of the cylindrical vessel. The angular velocity of the stirrer armature was converted to linear velocity at the sample boundary at the vessel periphery. This design allowed for monitoring potential roughness changes in the protective coating samples during their prolonged immersion in water, and also at different temperatures. It should also be noted that chlorine was added to the water in the cylindrical vessel, providing a disinfectant effect. This allowed for the potential chemical interaction of the resulting chlorides with the test samples to be assessed. Thus, the process of water transportation through a long pipeline was simulated in a cylindrical vessel mounted on a magnetic stirrer, with chlorine consumption analyzed.

In parallel, light (optical) microscopy experiments were conducted on these samples using an Olympus GX53 inverted electron microscope (Japan), which provides high-quality images difficult to achieve using conventional optical microscopy methods.

The roughness of the samples was also studied using a SEITRONIK PSh 8-3 (SS) profilograph-profilometer, which allows roughness parameters to be determined digitally on a

microprocessor unit. In both cases, experiments were conducted over different time intervals.

The objectives of the study, when conducting research using the listed above alternative methods, included comparing the obtained hydraulic parameters for identity and the degree of their discrepancy. The final result of the study was the calculation of possible energy losses during water transportation as a result of potential changes in the hydraulic characteristics of the protective coating samples over time. In general, the combination of methods and measuring instruments used made it possible to obtain a preliminary picture of the possible transformation of the hydraulic parameters of protective coatings over time.

RESULTS AND DISCUSSION

Below are the hydraulic test data for each of alternative method and a comparative analysis.

The results of automated processing of hydraulic tests of protective coatings on large and small rigs at an ambient temperature of 20°C showed similar results. Specifically, the average value of the hydraulic friction coefficient λ for the Subcote FLP coating on the large rig was 0.01772, while on the small rig it was 0.0181, i.e., there is a difference of only 2.14%, indicating a high degree of reliability of the obtained results. Based on electron microscopy and profilometer studies, the following equivalent roughness coefficients k_e were obtained:

- 0.03716 mm (light microscopy)

- 0.0386 mm (profilometry).

Using Prandtl's formula (1), the hydraulic resistance coefficients λ were calculated for a pipeline with a Subcote FLP protective coating as follows [9]:

$$\frac{1}{\sqrt{\lambda}} = 2 \cdot \lg \frac{d}{k_e} + 1,14 \quad (1)$$

where λ is the hydraulic resistance coefficient of the pipeline; d is the internal diameter of the pipeline with protective coating (mm); k_e is the

equivalent roughness coefficient of the pipeline (mm) equal to

- 0.01563 (light microscopy)
- 0.01575 (profilometry).

The difference in the results was only 3.73%.

Thus, the results of experiments on hydraulic test benches and the data from light microscopy and profilometry can be considered reliable for determining the hydraulic friction coefficients and equivalent roughness, where, for example, the discrepancy between the largest absolute value ($k_e=0.0181$ mm) and the smallest ($k_e=0.0163$ mm) did not exceed 13.6%.

When modeling the evolution of hydraulic parameters under tangential water flow conditions in a cylindrical vessel with samples in a prolonged contact with water, the following dependencies for the equivalent roughness coefficient were obtained (Fig. 4).

The graph in Figure 4 clearly demonstrate the decrease in the equivalent roughness coefficient k_e : the higher the dose of chlorine introduced and the longer the sample is exposed to the cylindrical vessel, the lower the equivalent roughness value. This trend can be explained, for example, by incrustation, which in this situation should be considered a positive phenomenon, as it ultimately contributes to a reduction in the hydraulic friction coefficient λ by smoothing out microroughness depressions, i.e., roughness peaks.

A reduction in the hydraulic friction coefficient automatically leads to a reduction in energy costs during water transportation through pressure pipelines. This is confirmed by the graphs in Figure 5, where the calculation of electricity consumption E (kW h per year) was carried out using formula (2)

$$E=0,81 \cdot Q^3 \cdot l \cdot \lambda \cdot 24 \cdot 365 / (d^5 \cdot \eta_p), \quad (2)$$

where Q is the flow rate of water supplied by the pipeline (m³/s), at which the flow velocity is 1 (m/s); d is the internal diameter of the pipeline (m); l is the length of pipeline section (m); λ is the coefficient of hydraulic friction; η_p is the efficiency of the pumping unit (0.95); 24 is the number of hours the pump operates per day (h); 365 is the number of days in a year.

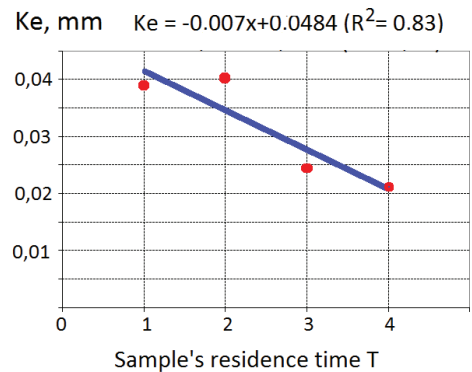


Figure 4. Graph of the change in the equivalent roughness coefficient k_e (mm) as a function of the sample's presence time T in a cylindrical vessel with a stirrer (Points along the abscissa axis: 1 - for the initial sample $T = 0$ min; 2 - after treatment in 167 min with a single dose of chlorine at 0.5 mg/l; 3 - after treatment in 334 min with a single dose of chlorine; 4 - after treatment in 167 min with a double dose of chlorine)

The graph in Figure 5 illustrates the reduction in energy consumption depending on the duration and dose of chlorine introduced into the water.

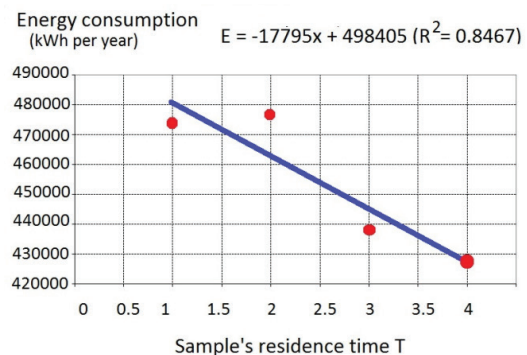


Figure 5. Graph of the change in energy consumption (E) (kWh per year) as a function of the sample's presence time T in a cylindrical vessel with a stirrer (Points on the abscissa axis: 1 - initial sample $T = 0$ min; 2 - treatment after 167 min with a single dose of chlorine; 3 - treatment after 334 min with a single dose of chlorine; 4 - treatment after 167 min with a double dose of chlorine)

Single-run pilot experiments conducted using a magnetic stirrer system to examine the effect of ambient temperature on changes in the roughness

of protective coating walls also revealed a tendency toward a decrease in the equivalent roughness coefficient as water temperature increased from 20 to 500°C. Therefore, the obtained results allow us to draw a reasonable preliminary conclusion regarding the need for continued experimental modeling studies across wide temperature ranges and durations of water presence in the water supply network to confirm the hypotheses regarding the transformation of the roughness of protective pipeline coatings during pipeline operation. For these purposes, a comprehensive and detailed analysis of the chemical composition of water and coating samples over time is envisaged.

CONCLUSIONS

1. The results of a study of the hydraulic characteristics of pipelines coated with Subcote FLP using alternative methods as well as promising methodological approaches for determining the possible transformation of equivalent roughness parameters and other parameters during long-term pipeline operation and changing temperature conditions are presented.
2. The experimental results demonstrate the validity of using various methods to determine the set of characteristics required by designers for pipes coated with protective coatings.
3. The focus of subsequent research will be on analyzing and establishing strict patterns of changes in the chemical composition of water and samples of Subcote FLP protective coatings and other types of polymer spray-on protective pipeline coatings, in particular, Scotchkote 169 HB, which has also found wide application in trenchless pipeline renovation.

REFERENCES

1. **Primin O.G.** Utechki vody. // Izdatel'stvo MISI-MGSU 2022. 167 p.
2. **Baymukanov M.A.** O vazhnosti analiza sostoyaniya vodoprovodnykh setey RF // Polimernyye truby. 2016. T. 5 (14). pp. 26–29.

3. **Zhuangzhu Luo, Zhaozhu Zhang, Wenjing Wang, Weimin Liu** Effect of polytetrafluoroethylene gradient-distribution on the hydrophobic and tribological properties of polyphenylene sulfide composite coating. *Surface and Coatings Technology*, Volume 203, Issues 10-11. 25 February 2009. Pages 1516-1522.
4. **Nabil Anagreh, Lutz Dorn, Christine Bilke-Krause** Low-pressure plasma pretreatment of polyphenylene sulfide (PPS) surfaces for adhesive bonding. *International Journal of Adhesion and Adhesives*, Volume 28, Issues 1-2. January-March 2008. Pages 16-22.
5. **Jinghui Yang, Tao Xu, Ai Lu, Qin Zhang, Hong Tan, Qiang Fu** Preparation and properties of poly (p-phenylene sulfide)/multiwall carbon nanotube composites obtained by melt compounding. *Composites Science and Technology*, Volume 69, Issue 2. February 2009. Pages 147-153.
6. **Orlov V.A., Zotkin S.P.** Programma analiza gidravlicheskih kharakteristik napornykh truboprovodov // Svidetel'stvo o gosudarstvennoy registratsii programmy dlya EVM № 2013610520 ot 09.01.2012.
7. **Orlov V.A., Zotkin S.P., Dezhina I.S., Pelipenko A.A.** Programma rascheta stepeni gidrofobnosti i gidravlicheskih parametrov trub i ikh zashchitnykh pokrytiy // Svidetel'stvo o gosudarstvennoy registratsii programmy dlya EVM № RU 2017612281 ot 20.02.2017.
8. **Dezhina I.S.** Povysheniye transportiruyushchey sposobnosti samotechnykh truboprovodov s uchetom gidrofobnosti i rel'yefa ikh poverkhnosti // Avtoreferat kand. diss. M. FGBOU VO «Natsional'nyy issledovatel'skiy Moskovskiy gosudarstvennyy stroitel'nyy universitet. 2021. 23. p.
9. **Prodous O.A.** Prognozirovaniye poter' napora v truboprovodakh iz raznykh polimernykh materialov // Vodostabzheniye i sanitarnaya tekhnika. 2018. № 11. pp. 60-64.

СПИСОК ЛИТЕРАТУРЫ

1. **Примин О.Г.** Утечки воды. // Издательство МИСИ-МГСУ. 2022. 167 с..
2. **Баймуханов М.А.** О важности анализа состояния водопроводных сетей РФ // Полимерные трубы. 2016. Т. 5 (14). С. 26–29.
3. **Zhuangzhu Luo, Zhaozhu Zhang, Wenjing Wang, Weimin Liu** Effect of polytetrafluoroethylene gradient-distribution on the hydrophobic and tribological properties of polyphenylene sulfide compositecoating. Surface and Coatings Technology, Volume 203, Issues 10-11. 25 February 2009. Pages 1516-1522.
4. **Nabil Anagreh, Lutz Dorn, Christine Bilke-Krause** Low-pressure plasma pretreatment of polyphenylene sulfide (PPS) surfaces for adhesive bonding. International Journal of Adhesion and Adhesives, Volume 28, Issues 1-2. January-March 2008. Pages 16-22.
5. **Jinghui Yang, Tao Xu, Ai Lu, Qin Zhang, Hong Tan, Qiang Fu** Preparation and properties of poly (p-phenylene sulfide)/multiwall carbon nanotube composites obtained by melt compounding. Composites Science and Technology, Volume 69, Issue 2. February 2009. Pages 147-153.
6. **Орлов В.А., Зоткин С.П.** Программа анализа гидравлических характеристик напорных трубопроводов // Свидетельство о государственной регистрации программы для ЭВМ № 2013610520 от 09.01.2012.
7. **Орлов В.А., Зоткин С.П., Дежина И.С., Пелипенко А.А.** Программа расчета степени гидрофобности и гидравлических параметров труб и их защитных покрытий // Свидетельство о государственной регистрации программы для ЭВМ № RU 2017612281 от 20.02.2017.
8. **Дежина И.С.** Повышение транспортирующей способности самотечных трубопроводов с учетом гидрофобности и рельефа их поверхности // Автореферат канд. дисс. М. ФГБОУ ВО «Национальный исследовательский Московский государственный строительный университет». 2021. 23 с.
9. **Продоус О.А.** Прогнозирование потерь напора в трубопроводах из разных полимерных материалов // Водоснабжение и санитарная техника. 2018. № 11. с. 60-64.

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