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Fluid filtration in the clogged pressure pipelines

Фильтрация жидкости в засоренных напорных трубопроводах

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Key words: throughput of pipeline; discharge coefficient; resistance coefficient; clogged pipelines; degree of clogging; relative flow rate; filtration coefficient of pipeline

Ключевые слова: пропускная способность трубопровода; коэффициент расхода; коэффициент сопротивления; засоренные трубопроводы; степень засорения; относительный расход; коэффициент фильтрации трубопровода

Abstract. Reducing of the hydraulic characteristics of pressure pipelines in the course of their operation due to corrosion, clogging and other causes leads to an increasing of operating costs. The existing information on the change in the capacity of pipelines under the influence of certain factors is currently insufficient. The aim of the work is to determine the influence of the clogging degree of the pipeline on its throughput. This paper describes the results of hydraulic tests of a pressure pipeline with clogging of two types: expanded clay gravel and medium-grained sand. The discharge coefficient and resistance coefficient of the "clean" pipeline and the pipeline with clogging were determined during the experiments. The dependence of the relative flow rate of the pipeline on the clogging degree of the pipe was obtained. Influence of the type of filler on the throughput of the pipe was shown. An insignificant difference in the values of the relative flow rate for both fillers at low degrees of clogging of the pipeline was established. The transition from the discharge and resistance coefficients to filtration coefficients of pipeline was proposed. The values of the filtration coefficients of pipe from the experiments on the flow measurement were found. The ratio between the discharge coefficient and the filtration coefficient of pipeline was set. The values of filtration coefficients of pipe for emptying the pressure tank were found. The coincidence of the values of the filtration coefficients by the two methods was obtained.

Аннотация. Снижение гидравлических характеристик напорных трубопроводов в процессе их эксплуатации вследствие коррозии, засорения и других причин приводит к увеличению эксплуатационных затрат. Имеющиеся в литературе сведения об изменении пропускной способности трубопроводов под воздействием тех или иных факторов на настоящий момент недостаточны. Цель работы – установить влияние степени засорения трубопровода на его пропускную способность. Для достижения цели проведены гидравлические испытания напорного трубопровода с засорением двух типов: керамзит и среднезернистый песок. В ходе опытов определены коэффициенты расхода и сопротивления "чистого" трубопровода и трубопровода с засорением. Получена зависимость относительного расхода трубопровода от степени засорения трубы. Показано влияние вида наполнителя на пропускную способность трубы. Установлено несущественное различие в значениях относительных расходов для обоих наполнителей при малых степенях засорения трубопровода. Предложен переход от коэффициентов расхода и сопротивления к коэффициентам фильтрации трубопровода. Найдены численные значения коэффициентов фильтрации трубы из опытов по измерению расхода. Установлена связь между коэффициентом расхода и коэффициентом фильтрации трубы. Найдены значения коэффициентов фильтрации трубы по опорожнению напорного бака. Получено совпадение значений коэффициентов фильтрации по двум способам.

Introduction

Changes in the internal surface of the pipes occur during their operation. During design, the recording of these changes occurs, as a rule, within the reference range of the height variation of the roughness protrusions [1, 2], or there is no accounting at all. The forecast of the change in roughness is extremely difficult in view of the large number of factors determining the nature and intensity of this process. The change in the state of the internal surface of the pipes occurs both because of corrosion [3], and as a result of clogging, settling of suspended particles and other processes that increase the overall hydraulic resistance. In practice, this means an increase in pressure losses during fluid motion, which leads to a gradual decrease in the capacity of the pipelines and the average velocity of the fluid in comparison with the design values assumed. Reducing the throughput of pipes, for example, for water supply systems, can reach 50% or more, depending on the material, type of coating, pipe diameter, operating conditions, fluid properties, sediment profile, etc. [4].

The problem of clogging of pipes over time, and as a result, deterioration of their hydraulic characteristics (below the normative values) is an important practical task, because to provide consumers with the required amount of liquid, regular pipe cleaning or increasing pressure must be carried out, which leads to an increase in operational costs. However, these measures are not always sufficient, and there is a need to replace pipes or lay new pipelines, which, in turn, leads to an increase in capital costs.

A number of authors evaluated the pressure losses depending on the service life of the pipelines [4], and recommendations were given to increase design head losses at the design stage. However, as more recent research showed, the formation of deposits in pipelines is a complex multifactor process, the development of which is difficult to foresee. The currently available data about the influence of clogging on the pipeline throughput is mainly obtained experimentally [5–11]. There are also attempts to investigate clogged pipes on mathematical models [12–19].

For example, work [5] is devoted to a model, developed for the city's water supply system in St. Petersburg and includes more than 6.200 km of water networks with diameters up to 1.400 mm. The paper defines the actual hydraulic resistance of pipelines under different operating conditions. It was found that the resistance is 2-5 times higher than design engineers accepted for non-new pipes (lower values refer to pipes that are in operation for 5-10 years, larger ones to pipes with longer service lives).

The paper [12] presents the results of computer calculations of areas with an abruptly changing fluid motion, due to the presence of a sudden increase or decrease in the diameter of the pipeline and other devices.

The results of a study of the effect of operating parameters, diameter and weight of suspended particles on the rate of gas-abrasion wear of pipeline bends are presented in [13]. The main tasks solved by the authors were to analyze the statistics of the reasons for the failure of the gas pipeline offsets, and to verify the real objects and calculation models using the FLOWVISION PC. As a result, the zone location of the maximum concentration of particles on the wall of the tap was determined as a function of pressure, the mass of the abrasive at the inlet, and the diameter of the abrasive particles.

The results of numerical calculations are largely determined by the choice of the computational grid and the correct assignment of boundary conditions, so the reliability and veracity of these results should also be checked in the full-scale experiment.

Thus, the question of wearing and clogging of building services to the true hydraulic resistance of pipelines located in various operating conditions is an important practical problem.

The purpose is to study the influence of the degree of clogging of the pressure pipeline on its throughput.

To achieve the purpose, the following objectives were set and solved:

1. Develop a methodology for conducting the experiment;
2. Conduct a comparison of the results with the data of stationary resistances in pipelines;
3. Propose the approximate criteria for estimating the throughput capacity of a clogged pipeline.

Methods and Materials

To solve the problems, experimental studies were carried out on a model with a ratio of length to diameter equal to $l/D = 20$.

Hydraulic measurements of the pipeline contained several series of experiments. Initially, the intensity of flow was determined by the volumetric method at the outlet from the pipeline with a free flow. Further, the numerical values of the discharge coefficients μ and the total resistance coefficient ζ_f of the "clean" pipe were determined from formulas

$$\mu = \frac{Q}{\omega_0 \cdot \sqrt{2gH}}, \tag{1}$$

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$$\zeta_f = (1/\mu^2) - 1, \tag{2}$$

where Q – intensity of flow, ω_0 – sectional area of the "clean" pipe, H – pressure head above the gravity center of the outlet section of the pipe.

Then, the same characteristics were determined in a similar way for pipe with filler at different degrees of filling (degrees of clogging) of the pipe $\mathrm{V_{fil}}/\mathrm{V_0}$ ($\mathrm{V_{fil}}$ – volume of filler, $\mathrm{V_0}$ – volume of "clean" pipe). In the experiments, there were used two types of filler: claydite gravel and medium-grained sand (Fig. 1).

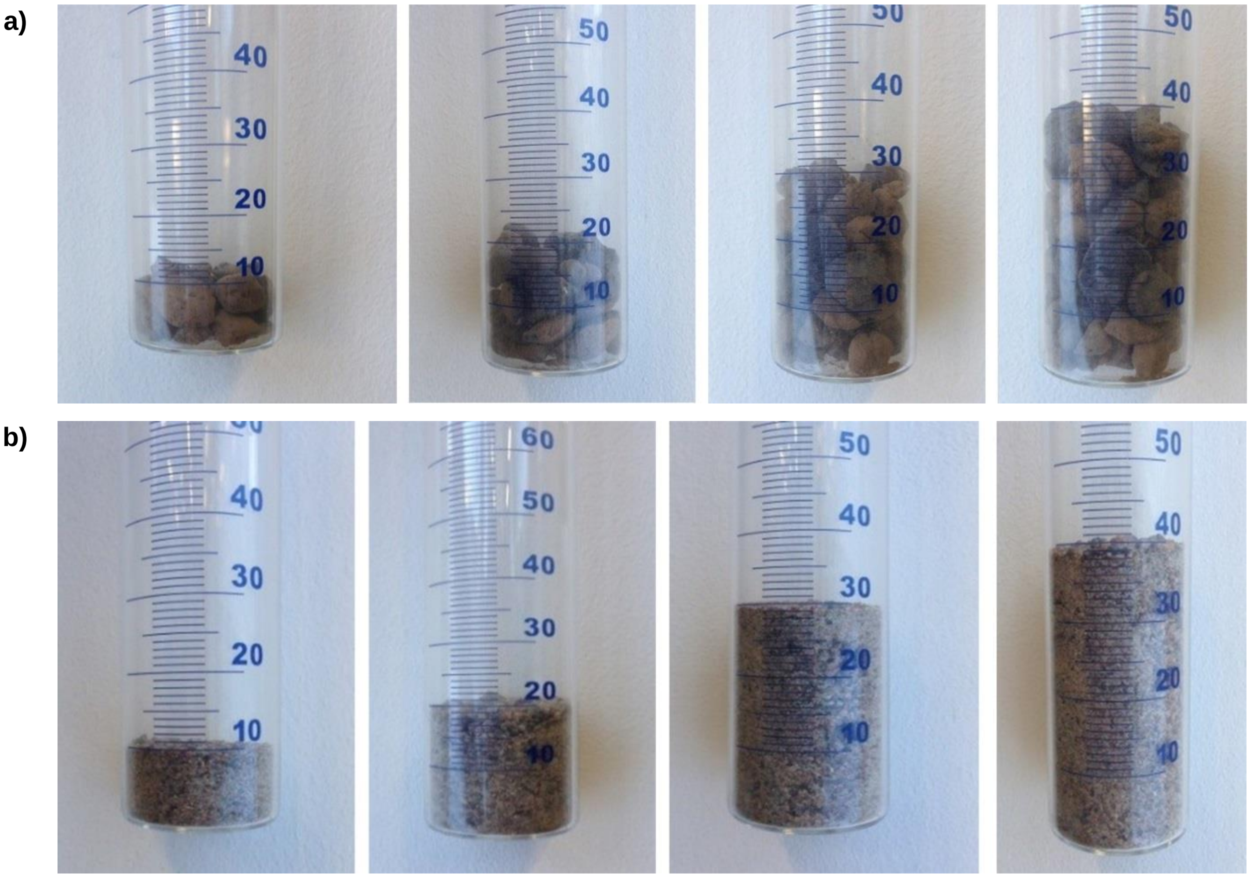


Figure 1. Samples of the test fillers: a) claydite gravel; b) medium-grained sand

To prevent the removal of the filler from the pipe, a sieve-containing grating was installed at the outlet, chosen in such a way so that the dimensions of its cells do not exceed the particle sizes of the test filler in both cases.

Results

The results of some series of experiments are shown on Figure 2 as a graph of the dependence $\mu = f(H/H_{max})$, where H_{max} – is the maximum possible pressure head in the current model. As can be seen from the graph, the values of discharge coefficients do not depend on the value of the pressure head (with an acceptable error), but are determined only by the type of filler and the degree of pipe clogging.

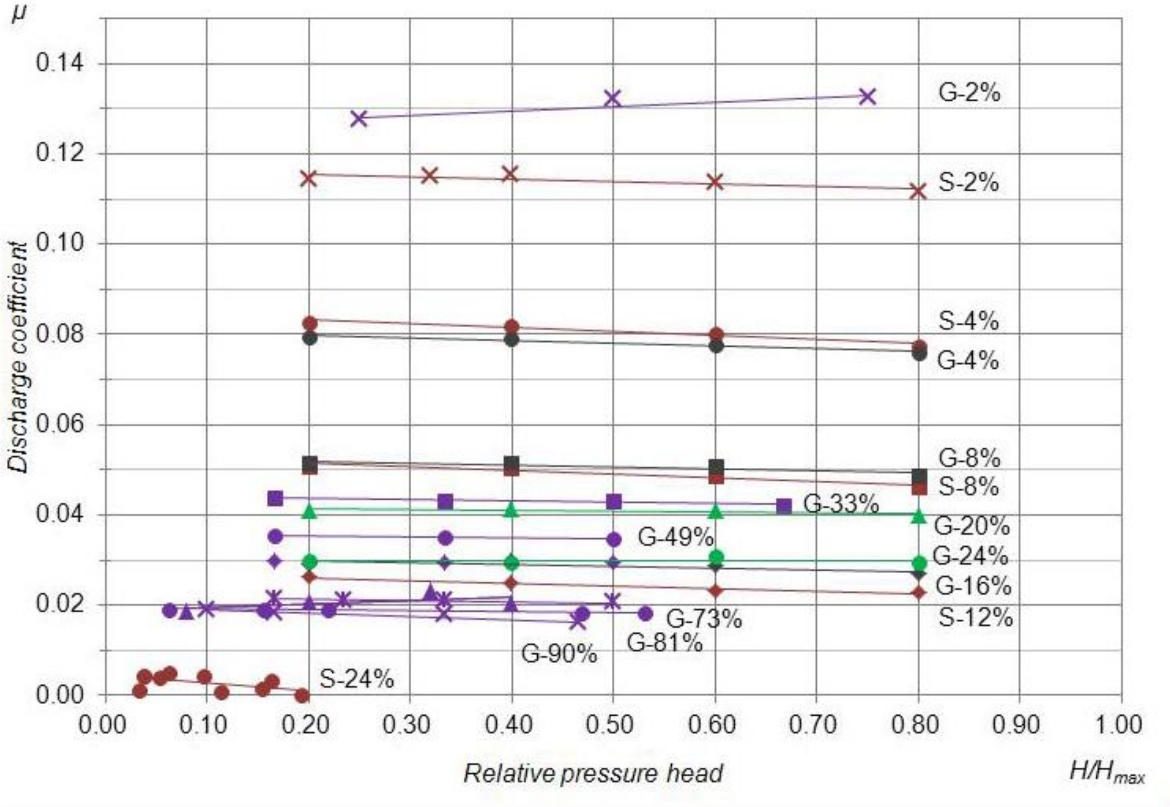
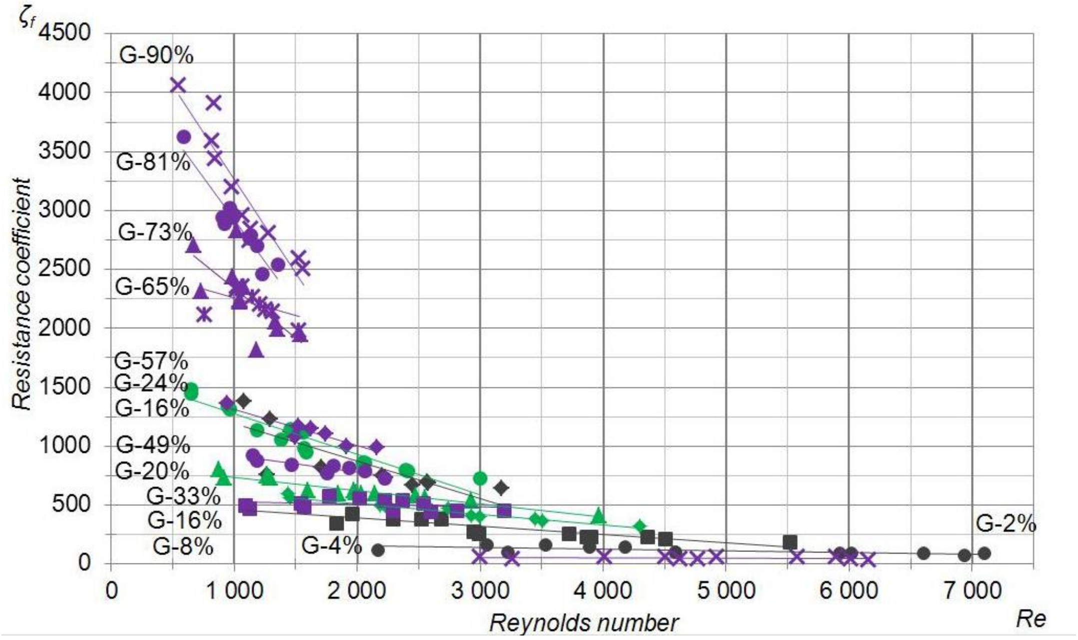


Figure 2. Dependence diagram μ=f(H/H_max)
(G – experimental data with claydite gravel, S –experimental data with sand)

Figure 3 shows the dependence of the total resistance coefficients of the pipeline ζ_f from the Reynolds number Re, calculated from the average velocity in the pipe. From Figure 3 it follows that for small degrees of clogging corresponding to Re > 2000, the values of ζ_f do not depend on the Reynolds number, but are determined only by the clogging degree of the pipe.

a)



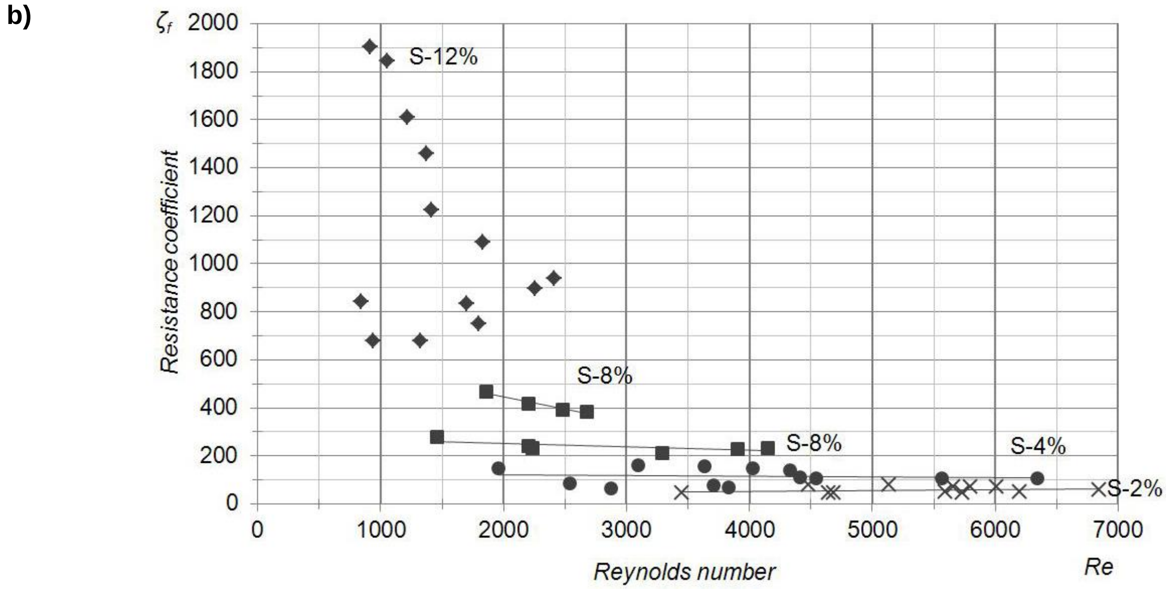


Figure 3. Dependence diagram $\zeta_f = f(\mathrm{Re})$
a) experiments with claydite gravel; b) experiments with sand

Figure 4 gives the dependence ζ_f as a function of the values V_0/V_{fil}. Experimental points on the diagram of figure 4 are approximated by power functions. It is evident from figures 3 and 4 that for large clogging, the spread of experimental data (corresponding to different pressure heads H) increases, because the size of the filler particles, their shape, the packing peculiarities within the flow section, and other factors exert an increasing influence as the Reynolds numbers decrease. In addition, it was found that for small clogging degrees ($V_{fil}/V_0 \leq 0{,}1 (\leq 10\%)$) the influence of the filler type (the nature of the clogging) is insignificant, and with the increase of clogging degrees $V_{fil}/V_0 > 10\%$ the influence of the filler type is more noticeable.

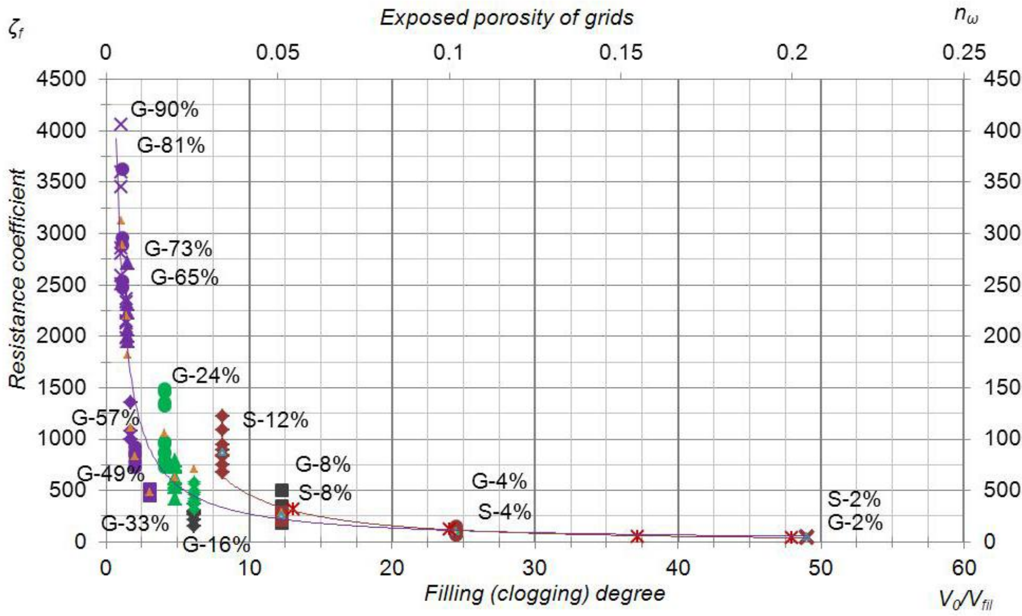


Figure 4. Dependence diagram $\zeta_f = f(V_0/V_{fil})$

For an approximate estimate of the change in throughput of pipeline with its clogging the dependence diagram $Q/Q_0 = f(V_0/V_{fil})$ was constructed, where Q – intensity of flow in the pipe with filler, Q_0 – intensity of flow in the clean pipe at the same pressure head H. The presented diagram makes it possible to determine the clogging degree of the pipeline with a known drop of intensity of flow in it during operation, and also to find the limiting clogging of the pipe with the containment grid, at which the flow of liquid in the pipe is practically absent. As can be seen from the Fig. 5, the ultimate clogging for sand occurs approximately when the content of the pipe is 20 % filler, and for claydite gravel – more than 90 %.

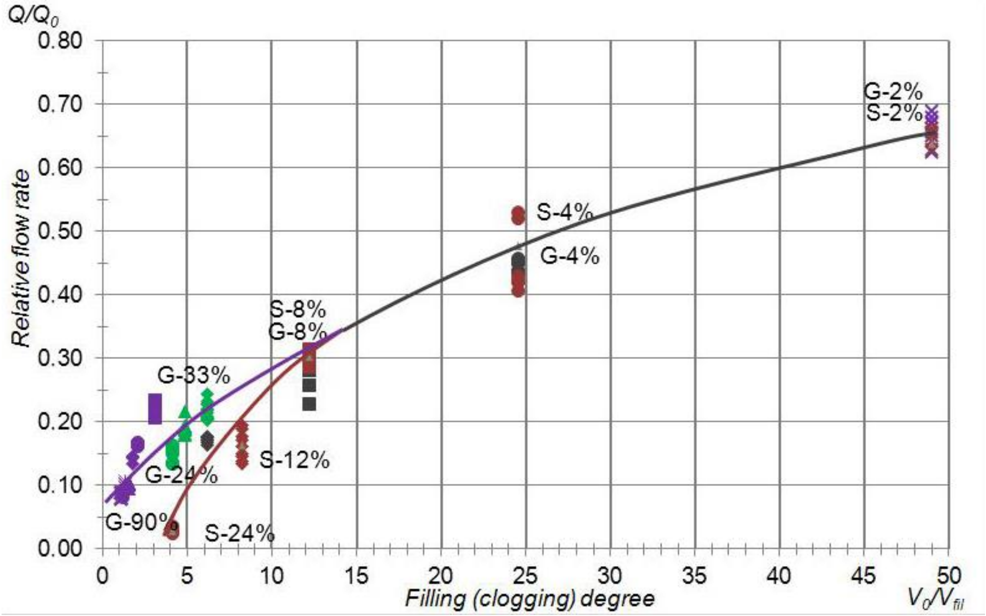


Figure 5. Dependence diagram $\boldsymbol{Q/Q_0 = f(V_0/V_{fil})}$

Discussion

The research above is carried out under conditions where the filler in the pipe was in nonsteady state and had the ability to move, change its packaging, form compacted structures, settle, etc. The results of this research were compared with similar experiments in a pipeline without a filler with the same ratio $l/D = 20$, at the outlet of which perforated grids (Fig. 6) with different exposed porosity $n_\omega = \omega_h/\omega_0$ (ω_h– the total area of the grid holes (clearance area)) were set [20, 21].

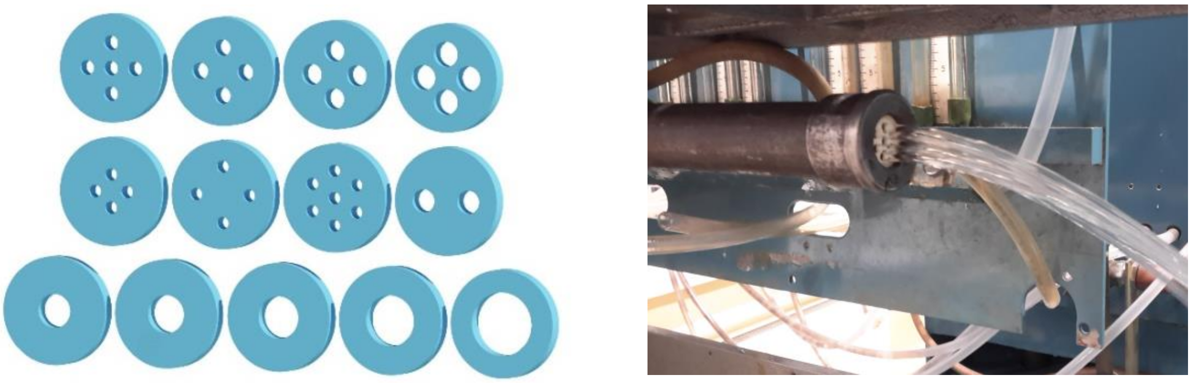


Figure 6. Types of perforated grids and imagine of the flow on the outlet of the pipe

Comparison of experimental data in pipelines with filler and with grids (Fig. 7) showed that in the general range of resistance coefficients ($\zeta \leq 500$) dependences $\zeta_f = f(V_0/V_{fil})$ and $\zeta_f = f(n_\omega)$ do not qualitatively differ. This means that there is a unique connection between the exposed porosity of the grids and the reciprocal of the clogging degree of the pipe. For clarity, the two horizontal axes on Fig. 7 are used: lower axis is for V_0/V_{fil}; the upper one is for n_ω.

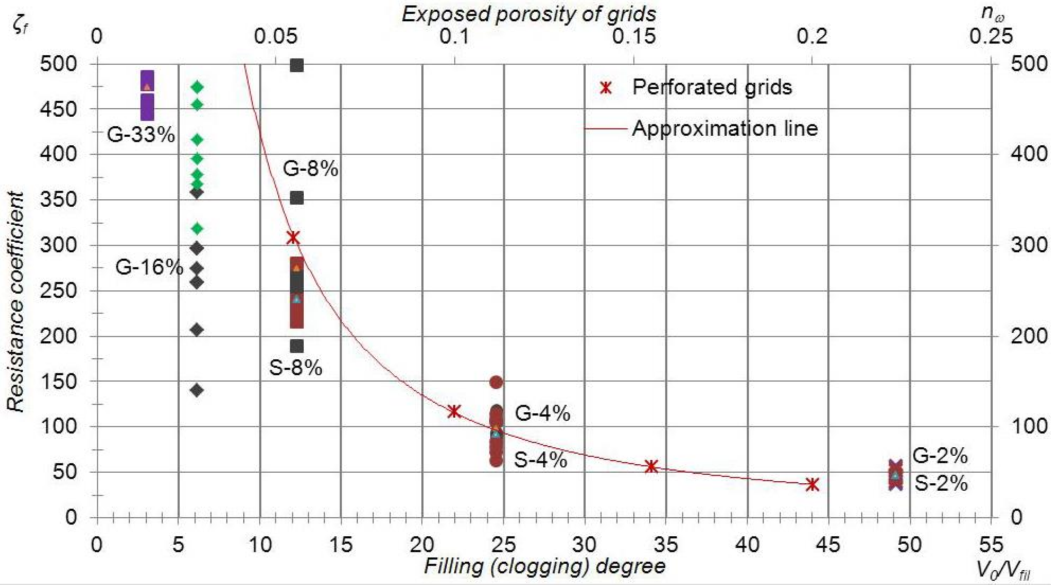


Figure 7. Combined dependency diagram $\zeta_f = f(V_0/V_{fil})$ and $\zeta_f = f(n_\omega)$ (markers – experimental points for the pipe with filler; solid line – approximation of data on grids without filler, proposed in [20])

The correspondence between the scales n_ω and V_0/V_{fil}, found by the averaged values of the experiments, is shown on Figure 8.

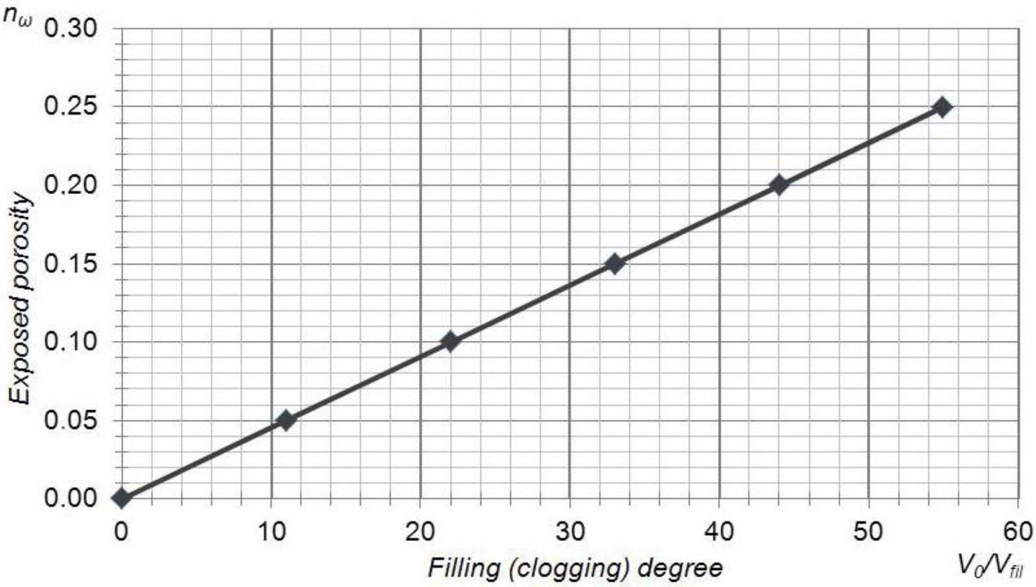


Figure 8. Relation between the clogging degree of the pipeline $\frac{V_0}{V_{fil}}$ with exposed porosity of grids n_ω

Thus, the dependence of Fig. 8 allows simulation of pipe clogging using any stationary devices, for example, grids.

As can be seen from Fig. 4, at large degrees of clogging of the pipe (>10% of the pipeline volume, $V_0/V_{fil} < 10$) the numerical values of the resistance coefficients ζ_f increase sharply, and their range of variation is several orders of magnitude. The obtained range significantly complicates the perception of the values, and also makes the amount of the resistance coefficient of the clogged pipeline absurd.

If instead of resistance we introduce the so-called permeability of the pipe (actually the value reciprocal of the resistance (some analog of the discharge coefficient)), then it is possible to imagine the flow of liquid in the pipeline with clogging as a filtration flow. Then the average velocity in the pipe v_0 will be interpreted as the filtration velocity, determined by the relation.

$$v_0 = k \cdot \sqrt{J}, \tag{3}$$

where k – filtration coefficient, J – hydraulic drop.

Equation (3) is the law of turbulent filtration in the theory of filtration [22-24].

Since for v_0 it is also true

$$v_0 = \mu \cdot \sqrt{2gH}, \tag{4}$$

where H – pressure head above the center of the outlet section of the pipeline. Equating (3) and (4), we obtain

$$\mu \cdot \sqrt{2gH} = k \cdot \sqrt{J} \text{ or}$$

$$k = \mu \cdot \frac{\sqrt{2gH}}{\sqrt{J}} \tag{5}$$

Substitution of the hydraulic drop in (5) $J = H/l$ (l – pipe length) leads to the expression for k

$$k = \mu \cdot \sqrt{2gl}. \tag{6}$$

According to the formula (6), k is a constant value for a pipe with a given geometry and fixed degree of clogging with a filler of a certain type. Filtration coefficient has unit of measurement of velocity and is a measure of the filtration conductivity of a clogged pipe in terms of its physical meaning. In this case, k should not be considered as a parameter expressing the filtration properties of the filler material, but as a characteristic of a particular pipe with specific filler.

The dependence of the pipeline filtration coefficients k on the value V_0/V_{fil} is shown in accordance with (6) on Figure 9.

The range of the values of the filtration coefficients on Fig. 9 for all degrees of clogging (from 2 % to 90 % of the volume of the pipe) is of the order of the average speed in the "clean" pipe.

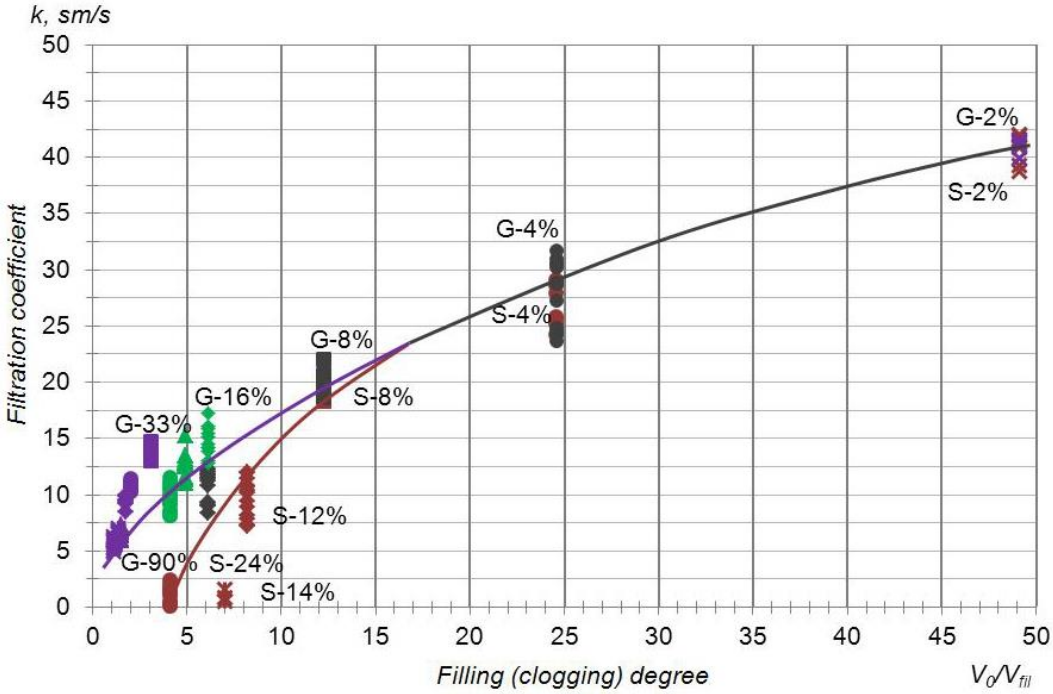


Figure 9. Dependence diagram $k = f(V_0/V_{fil})$

Equation (6) gives a directly proportional relation between the filtration coefficient and discharge coefficient of pipeline μ.

To determine the filtration coefficient in another way, experiments based on measuring the time of emptying the pressure tank between fixed heads at different degrees of clogging with claydite gravel and sand were used. From the continuity condition of fluid motion in the pipe and in the pressure tank, it follows that

$$\frac{dH}{dt}\cdot\Omega = k\cdot\sqrt{J}\cdot\omega_0$$

or

$$\frac{dH}{dt}\cdot\Omega = k\cdot\sqrt{\frac{H}{l}}\cdot\omega_0, \tag{7}$$

where Ω – area of the horizontal section of the pressure tank.

Integration of (7) from the initial pressure head H_0 to the final H_t in time t leads to expression

$$k = \frac{2\cdot\Omega\cdot\sqrt{l}}{\omega_0\cdot t}\cdot\left(\sqrt{H_0}-\sqrt{H_t}\right). \tag{8}$$

Experimental points, which were found from the time of emptying the pressure tank, are also plotted on Fig. 9. These data do not fall out of the range, which were found by the flow measurement.

Conclusions

1. The dependence of the relative flow rate of the pipeline from the degree of its clogging gives an approximate estimate of the reduction in the throughput of the clogged pipe.

2. At small degrees of clogging of the pipeline (<10% by volume of the pipe), the influence of the type of clogging on the flow rate is insignificant. With a further increase in the clogging degree, the curved lines of relative flow rate are qualitatively different.

3. An alternative to the discharge coefficient is filtration coefficient of pipeline. The filtration coefficient has the dimension and order of velocity in a clean pipe, so that it is more preferable in practical calculations of clogged pipes as a measure of the filtration conductivity of a pipe.

References

1. Idel’chik I. E. *Handbook of hydraulic resistance* 4th ed. rev. and augmented. United States: Begell House in Redding, CT, 2008. 881 p.
2. Buhalov A.A., Orehova E.E., Andreev V.V. Razrabotka metodiki prognozirovanija gidravlicheskogo soprotivlenija v gladkih trubah na osnove obobshhenija jeksperimental'nyh dannyh [Development of models and procedures for hydraulic resistance in smooth tubes prediction of the basis ot the experimental data generalization]. *Sovremennye problemy nauki i obrazovanija.* 2014. No. 6. Pp. 242–248. (rus)
3. Shabangu T.H., Ponnle A.A., Adedeji K.B., Abe B.T., Olubambi P.A., Jimoh A.A. Effects of soil properties on corrosion of buried steel pipeline: A case study of rand water pipeline, South Africa. *AFRICON 2015. IEEE Conference Publications*. 2015. Pp. 1–5.
4. Al'tshul' A.D. *Gidravlicheskie soprotivlenija* [Hydraulic resistances]. Moskow: Nedra, 1982. 224 p. (rus)
5. Hjamjaljajnen M.M., Judin M.Ju. Kompleksnye gidravlicheskie raschety sistemy podachi vody Sankt-Peterburga. [Complex hydraulic calculations of the water supply system of St. Petersburg]. *Vodosnabzhenie i sanitarnaja tehnika*. 2006. No. 9-1. Pp. 22–24. (rus)
6. Andreev V.V., Turchenko M.V., Abramov A.A. Preobrazovanie harakteristik gidravlicheskogo soprotivlenija s cel'ju obobshhenija jeksperimental'noj informacii o techenii zhidkosti v trubah. [Transformation of hydraulic resistance characteristics in order to generalize experimental information on fluid flow in pipes]. *Nauchno-tehnicheskij vestnik Povolzh'ja.* 2012. No. 4. Pp. 35-37. (rus)
7. Novoselov A.G., Chebotar' A.V., Guljaeva Ju.N., Meradzhi V.V. Jeksperimental'noe issledovanie gidravlicheskih soprotivlenij pri techenii vodno-zernovyh suspenzij v trubah. [Experimental study of hydraulic resistance during flow of water-grain suspensions in pipes]. *Nauchnyj zhurnal NIU ITMO, Serija “Processy i apparaty pishhevyh*

Литература

1. Idel’chik I. E. Handbook of hydraulic resistance 4th ed. rev. and augmented. United States: Begell House in Redding, CT, 2008. 881 p.
2. Бухалов А.А., Орехова Е.Е., Андреев В.В. Разработка методики прогнозирования гидравлического сопротивления в гладких трубах на основе обобщения экспериментальных данных // Современные проблемы науки и образования. 2014. № 6. С. 242–248.
3. Shabangu T.H., Ponnle A.A., Adedeji K.B., Abe B.T., Olubambi P.A., Jimoh A.A. Effects of soil properties on corrosion of buried steel pipeline: A case study of rand water pipeline, South Africa // AFRICON 2015. IEEE Conference Publications. 2015. Pp. 1–5.
4. Альтшуль А.Д. Гидравлические сопротивления. М.: Недра, 1982. 224 с.
5. Хямяляйнен М.М., Юдин М.Ю. Комплексные гидравлические расчеты системы подачи воды Санкт-Петербурга // Водоснабжение и санитарная техника. 2006. № 9-1. С. 22–24.
6. Андреев В.В., Турченко М.В., Абрамов А.А. Преобразование характеристик гидравлического сопротивления с целью обобщения экспериментальной информации о течении жидкости в трубах // Научно-технический вестник Поволжья. 2012. № 4. С. 35–37.
7. Новоселов А.Г., Чеботарь А.В., Гуляева Ю.Н., Мераджи В.В. Экспериментальное исследование гидравлических сопротивлений при течении водно-зерновых суспензий в трубах // Научный журнал НИУ ИТМО. Серия «Процессы и аппараты пищевых производств». 2014. № 3. С. 273–284.
8. Анциферов С.А., Филенков В.М. Апробация экспериментального стенда для определения гидравлического сопротивления шероховатой трубы // Вестник НГИЭИ. 2015. № 6(49). С. 10–15.
9. Duan H.F., Lee P.J., Tuck J. Experimental Investigation of Wave Scattering Effect of Pipe Blockages on Transient

proizvodstv”. 2014. No. 3. Pp. 273–284. (rus)

8. Anciferov S.A., Filenkov V.M. Aprobacija jeksperimental'nogo stenda dlja opredelenija gidravlicheskogo soprotivlenija sherohovatoj truby. [Approbation of the experimental stand for the determination of the hydraulic resistance of a rough pipe]. *Vestnik NGIJeI*. 2015. No. 6(49). Pp. 10–15. (rus)
9. Duan H.F., Lee P.J., Tuck J. Experimental Investigation of Wave Scattering Effect of Pipe Blockages on Transient Analysis. *Procedia Engineering*. 2014. Vol. 89. Pp. 1314-1320.
10. Huang J., Chen G., Shu L., Chen Y., Yu Zhang. Impact of fouling on flow-induced vibration characteristics in fluid-conveying pipelines. *IEEE Journals & Magazines*. 2016. Vol. 4. Pp. 6631–6644.
11. Khan T.S., Al-Shehhi M.S. Review of black powder in gas pipelines – An industrial perspective. *Journal of Natural Gas Science and Engineering*. 2015. Vol. 25. Pp. 66–76.
12. Chemezov D. The character of the fluid flow in the pipelines with the local hydraulic resistances. *ISJ Theoretical & Applied Science.* No. 12(44). Pp. 62–68.
13. Zakirnichnaja M.M., Adeev I.Ju., Perederej T.I., Isanchurina G.F. Specifika modelirovanija gazodinamiki s abrazivnymi chasticami v truboprovode s ispol'zovaniem PK FlowVision. [Specificity of simulation of gas dynamics with abrasive particles in the pipeline using the software package FlowVision]. *Trudy mezhdunarodnogo foruma ”Inzhenernye sistemy”.* Moskow. 2016. Pp. 78-92. (rus)
14. Kaljakin A.M., Chesnokova E.V. Novaja zavisimost' dlja opredelenija kojefficienta gidravlicheskogo soprotivlenija v perehodnoj zon soprotivlenija (ot laminarnogo k turbulentnomu). [A new functional connectionfor determining the coefficient of hydraulic resistance in the transition resistance zone (from laminar to turbulent)]. *Magazine of Civil Engineering*. 2012. No. 2. Pp. 51-55. (rus)
15. Gomez-Martinez P., Cubillo F., Martin-Carrasco F.J., Garotte L. Statistical dependence of pipe breaks on explanatory variables. *Water (Switzerland).* 2017. No. 9.
16. Lecreps I., Orozovic O., Erden T., Jones M.G., Sommer K. Physical mechanisms involved in slug transport and pipe blockage during horizontal pneumatic conveying. *Powder Technology.* 2014. Vol. 262. Pp. 82–95.
17. Izmailova E.V., Politova T.O., Serov V.V. Development of methods of detection of pipelines corrosion defeat by computer modeling. 2016*. 2nd International Conference on Industrial Engineering, Applications and Manufacturing (ICIEAM).* 2016. Pp. 1–4.
18. Aiyejina A., Chakrabarti D.P., Pilgrim A., Sastry M.K.S. Wax formation in oil pipelines: A critical review. *International Journal of Multiphase Flow.* 2011. Vol. 37. No. 7. Pp. 671–694.
19. Achebo Joseph I. Computational analysis of flow properties that could cause pipeline failure. *International Conference on Engineering Computation.* 2009. Pp. 257–260.
20. Latuhina A.I., Loktionova E.A., Polupanova Ju.R. Gidrodinamicheskoe soprotivlenie setok v napornyh vodovodah. [Hydraulic resistance of the grid in the pressure water conduit]. *St. Petersburg State Polytechnical University Journal*. 2016. No. 2(243). Pp. 174−180. (rus)
21. Latuhina A.I., Loktionova E.A., Miftakhova D.R., Polupanova Ju.R. Soprotivlenie i pronicaemost' napornyh gidrolinij s setkami [The resistance and permeability of the pressure hydroline with grids]. *St. Petersburg polytechnic university journal of engineering sciences and technology*. 2017. Vol. 23. No. 2. Pp. 205–214. (rus)
22. Polubarinova-Kochina P.Ja. *Teorija dvizhenija gruntovyh vod.* [Theory of ground water motion]. Moskow; Nauka.

Analysis // Procedia Engineering. 2014. Vol. 89. Pp. 1314-1320.

10. Huang J., Chen G., Shu L., Chen Y., Yu Zhang. Impact of fouling on flow-induced vibration characteristics in fluid-conveying pipelines // IEEE Journals & Magazines. 2016. Vol. 4. Pp. 6631–6644.
11. Khan T.S., Al-Shehhi M.S. Review of black powder in gas pipelines – An industrial perspective // Journal of Natural Gas Science and Engineering. 2015. Vol. 25. Pp. 66–76.
12. Chemezov D. The character of the fluid flow in the pipelines with the local hydraulic resistances // ISJ Theoretical & Applied Science. № 12(44). Pp. 62–68.
13. Закирничная М.М., Адеев И.Ю., Передерей Т.И., Исанчурина Г.Ф. Специфика моделирования газодинамики с абразивными частицами в трубопроводе с использованием ПК FlowVision // Труды международного форума «Инженерные системы». Москва. 2016. С. 78–92.
14. Калякин А.М., Чеснокова Е.В. Новая зависимость для определения коэффициента гидравлического сопротивления в переходной зон сопротивления (от ламинарного к турбулентному) // Инженерно-строительный журнал. 2012. № 2. С. 51–55.
15. Gomez-Martinez P., Cubillo F., Martin-Carrasco F.J., Garotte L. Statistical dependence of pipe breaks on explanatory variables // Water (Switzerland). 2017. № 9.
16. Lecreps I., Orozovic O., Erden T., Jones M.G., Sommer K. Physical mechanisms involved in slug transport and pipe blockage during horizontal pneumatic conveying // Powder Technology. 2014. Vol. 262. Pp. 82–95.
17. Izmailova E. V., Politova T. O., Serov V. V. Development of methods of detection of pipelines corrosion defeat by computer modeling // 2nd International Conference on Industrial Engineering, Applications and Manufacturing (ICIEAM). 2016. Pp.1–4
18. Aiyejina A., Chakrabarti D.P., Pilgrim A., Sastry M.K.S. Wax formation in oil pipelines: A critical review // International Journal of Multiphase Flow. 2011. Vol. 37. № 7. Pp. 671–694.
19. Achebo J.I. Computational analysis of flow properties that could cause pipeline failure // International Conference on Engineering Computation. 2009. Pp. 257-260.
20. Латухина А.И., Локтионова Е.А., Полупанова Ю.Р. Гидродинамическое сопротивление сеток в напорных гидролиниях // Научно-технические ведомости СПбГПУ. 2016. № 2(243). С. 174−180.
21. Латухина А.И, Локтионова Е.А., Мифтахова Д.Р., Полупанова Ю.Р. Сопротивление и проницаемость напорных гидролиний с сетками // Научно-технические ведомости СПбПУ. Естественные и инженерные науки. 2017. Т. 23. № 2. С. 205–214.
22. Полубаринова-Кочина П.Я. Теория движения грунтовых вод. М.: Наука. Главная редакция физико-математической литературы, 1977. 664 с.
23. Петриченко М.Р. Термодинамические тождества и уравнения неизотрмической фильтрации в изотропной пористой среде // Научно-технические ведомости СПбГПУ. 2013. № 2(171). С. 188–192.
24. Даценко Е.Н., Васильев Н.И., Авакимян Н.Н., Савенок О.В., Кошелев А.Т. Гидравлическое сопротивление течению жидкости через пористую среду // Строительство нефтяных и газовых скважин на суше и на море. 2014. № 12. С. 18–20.

Glavnaja redakcija fiziko-matematicheskoj literatury, 1977, 664 p. (rus)

23. Petrichenko M.R. Termodinamicheskie tozhdestva i uravnenija neizotermicheskoj fil'tracii v izotropnoj poristoj srede. [Thermodynamic identities and equations of non-isothermal filtration in an isotropic porous medium]. *St. Petersburg State Polytechnical University Journal.* 2013. No. 2 (171). Pp. 188–192. (rus)
24. Dacenko E.N., Vasil'ev N.I., Avakimjan N.N., Savenok O.V., Koshelev A.T. Gidravlicheskoe soprotivlenie techeniju zhidkosti cherez poristuju sredu. [Hydraulic resistance to flow of liquid through a porous medium]. *Stroitel'stvo neftjanyh i gazovyh skvazhin na sushe i na more*. 2014. No. 12. Pp. 18–20. (rus)

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