Filtration characteristics of pressure pipelines previous being in operation

E Loktionova 1[0000-0002-0499-0203], D Miftakhova 1[0000-0003-2586-5142] and
E Yaroslavtseva 1[0000-0001-7091-6362]

1Peter the Great St. Petersburg Polytechnic University, Saint Petersburg, Russia
miftahova.dr@edu.spbstu.ru

Abstract. The issue of changing the hydraulic characteristics of the pipelines previous being in operation is of great practical importance. To determine convenient objective parameters for assessing the reduction in pipeline throughput during their operation the experimental studies results of three sections of the pressure pipeline with artificial clogging were presented. It is shown that for pipelines with the same initial resistance at the same degree of clogging, the numerical values of the resistance coefficients are practically independent of the ratio of length to diameter. The rationale for the transition from traditional hydraulic resistance coefficients to filtration coefficients was given. The dependence of the relative filtration coefficient on the clogging degree is recommended as a universal characteristic of the throughput of pressure pipelines previous being in operation. It is proved that with small degrees of clogging, a relative decrease in the pipeline throughput occurs more intensively than with large degrees of clogging.

1. Introduction
The decrease in pipeline throughput during their operation leads to the necessity for criteria for a possible forecast of these changes.

At the design stage of pipelines (water conduits) and their systems, a turbulent flow regime of fluid and, most often, the area of quadratic resistance is assumed. During the operation of pipelines due to corrosion, clogging, and other causes, the inner surface state of the pipelines changes, up to a change in the resistance area and even the flow regime of fluid. A lot of research has been devoted to monitoring changes on the inner surface of pipes to detect and prevent network accidents early [1, 2, 3, 4]. There are also known attempts to study and predict the hydraulic resistances of pipelines based on the creation of computed mathematical models [5, 6, 7]. However, the reliability of such studies is also confirmed by in-place tests.

For example, the article [8] is devoted to an experimental study of the characteristics of migration and the physical clogging mechanism of suspended solids particles in gravel and zeolite columns. The results show that the permeability of the filter medium is significantly reduced at the initial stage of infiltration, which is also consistent with the conclusions in the study [9]. The authors also have proposed a simple double-layered analytical model that takes into account the accumulation of solid particles in the form of a protective layer and allows estimating the change in the permeability of gravel and zeolite columns. However, this analytical model applies to a particular case and is not universal.

The study [10] investigates the problem of the formation of clogs in microchannels during the deposition of particles in the course of transport of colloidal suspensions. It is shown that advected
particles are forming an aggregate upstream from the site of the blockage as soon as clogging appears in a microchannel. This aggregate leads to a significant reduction in the flow rate. The authors have developed an analytical description that captures the time evolution of the aggregate volume, which have confirmed by experiments. The model for the growth of aggregates in multiple parallel microchannels where the clogging events are described using a stochastic approach has been derived.

Some works consider the effect of clogging not for linear objects (pipelines), but for example, to assess the drainage properties of certain structures. Thus, in [11], the drainage of a porous asphalt pavement evaluation method suited for use in analyzing the clogging effect is considered. To predict a decrease in the permeability of asphalt pavement, the authors have proposed a device for assessing the anisotropy of permeability, which is affected by clogging. Laboratory tests have carried out, and a finite element model for a porous coating with a hydrodynamic response has been applied. Conclusions have been drawn that, in the case of clogging and the impossibility of vertical diffusion, an improvement in horizontal diffusion can help maintain drainage characteristics. However, as is well known, anisotropy assessment in pipelines is an extremely difficult task, and permeability reduction analysis must be carried out differently.

To ensure the calculated throughput value of a simple pipeline or pipeline network, it is necessary to increase the entrance heads, clean the pipes, or replace them [12–20]. The first measure is quite expensive and, also, can cause accidents and even lead to the destruction of pipes. The pipe cleaning event also requires material costs and is not always efficient enough, as each of the traditional cleaning methods has several disadvantages that limit their application field.

To improve the hydraulic characteristics of a pipeline network, it is sometimes advisable to replace one or more particular pipe sections. In this case, as a rule, pipes made of new modern materials are used, which have undoubted advantages: the absence of corrosion and residue, contributing to the fouling of the section, reducing its area, and reducing throughput. However, as discussed in many studies, the combination in one pipelines layout (network) made of different materials leads to some hydraulic imbalance: an unaccounted headfall at the pipe joints and a change in the fluid flow rate. The consequence of such a replacement may be a slight (compared to expected) increase in network throughput with its subsequent rapid decrease. In the hydraulic sense, such a process is also similar to the clogging of pipelines.

Following the requirements of standard documentation, pipes are replaced due to clogging after a specific period of operation, established depending on the pipeline material. However, in the operation of pipelines under the influence of unpredictable factors unscheduled repair of the network section with its possible replacement may become necessary.

Thus, it is obvious that the issue of the influence of wear and clogging during the operation of engineering networks on the true throughput of pipelines is an important practical problem.

The purpose of this work is to establish convenient objective parameters for assessing the reduction in pipelines throughput during their operation.

Achieving this goal is possible by solving the following tasks:

1. Develop a methodology and conduct experimental research.
2. Propose criteria to predict changes in throughput of the pipeline with a known type of clogging.
3. Assess the impact of the pipelines’ durability on the change in their hydraulic characteristics.
4. Assess the dependence of the hydraulic properties of pipelines with clogging on their geometrical parameters.

2. Methods

To solve these tasks, experimental studies of pipelines clogged artificially with expanded clay extender of fraction 5-10 were carried out.

The main parameter determining the change in the throughput of the studied sections was their clogging degree $n$.

$$
n = \frac{V_{ef}}{V_0} \times 100\%.
$$

(1)
where \( V_{fil} \) is the volume of the filler (clogging) and \( V_0 \) is the internal volume of the pipeline section. During the experiments, the following series were investigated:

1. two sections of the pipeline with different initial total hydraulic resistance with the same ratio of length to diameter \( l/D=20 \). The following symbols are used in the diagrams and the text below: \( l/D=20-I \) and \( l/D=20-II \). Herewith, case \( I \) refers to a pipe with a larger initial resistance compared to \( II \) (conditionally with longer durability). Subsequent clogging of the pipes was carried out at the same clogging degrees;
2. two sections of the pipeline with the same initial hydraulic resistance with the ratio of length to diameter \( l/D=20-II \) and \( l/D=40 \). Their subsequent clogging was also carried out at the same clogging degrees.

3. Results and discussion
Figures 1a and 1b show the experimental values of the resistance coefficients as a function of the Reynolds number for all cases.

**Figure 1a.** Dependency diagram \( \zeta = f(Re) \) for pipelines with the same initial resistance at \( l/D=20-II \) and \( l/D=40 \).
As can be seen from the diagram in Figure 1a, for pipes with the same initial resistance at the same clogging degrees, the numerical values of the resistance coefficients are practically independent of the ratio \( l/D \). The experimental points for the pipe, which initially had lower throughput, were located on the continuation of the representative curve \( \zeta = f(Re) \) (Figure 1b).

Figure 2 shows the experimental results in coordinates \( Re = f(n) \) for a hydraulic drops series \( J = \frac{h_f}{l} \), where \( h_f \) is the pressure losses over the length of the pipeline section \( l \).

From Figure 2 it follows that the behavior of number \( Re \) (rate) at pipeline clogging depends little on the ratio \( l/D \), it is more sensitive to the drop \( J \) (head at the pipe inlet) and the initial hydraulic resistance.

The values of real pipeline resistance coefficient depending on the material, roughness, a set of local resistance, durability and other factors may differ by several times and in some cases – by orders (as conducted studies showed Figure 1b). In this regard, in [9], for the convenience of common use, it was suggested, along with traditionally accepted resistance coefficients, to estimate the decrease in pipeline throughput during operation by changing the infiltration coefficient (permeability) of the pipeline.

It should be noted that the filtration coefficient in these studies refers to the permeability of a pipe with clogging, but not the filtration ability of a clogging substance.

For the turbulent regime and the area of quadratic resistance, in [9], a relation between the filtration coefficients \( k \) and the resistance coefficients \( \zeta \) was obtained:

\[
k = \frac{1}{\sqrt{\zeta + 1}} \cdot \sqrt{\frac{2g}{l}} = \phi \sqrt{\frac{2g}{l}},
\]

where \( \phi = \frac{1}{\sqrt{\zeta + 1}} \) is the pipeline velocity coefficient.

From the definition of \( k \) it follows that the filtration coefficient has the dimension and order of the velocity \( v \) of fluid flow in the pipeline, which also illustrated in Figure 3.
Figure 3. The change in the filtration coefficients of pipelines during clogging – $k = f(Re)$

Comparison of Figures 3 and 1b gives a visual representation of the usability of $k$, as a characteristic parameter in estimate the reduction in pipe throughput during clogging.

In Figure 4 measured data in coordinates $k = f(n)$ are plotted. Being a hydraulic analog of Figure 2, Figure 4 has the same advantages as Figure 3 in comparison with Figure 1b. The approximation of the experimental data on Figure 4 indicates that the nature of the reduction in the permeability of pipelines during clogging does not depend on the ratio $l/D$ and the initial state of the pipe inner surface.

Figure 4. Dependency diagram $k = f(n)$
The diagram in Figure 5 is plotted in dimensionless coordinates \( k/k_0 = f(n) \), where \( k_0 \) – filtration coefficient of the pipeline without clogging. As can be seen, the values of the relative filtration coefficients \( k/k_0 \) for all studied sections of pipelines can be approximately described by a general approximation

\[
k/k_0 = \frac{k}{v_0} \cdot \sqrt{J} \approx \frac{0.5}{\sqrt{n}},
\]

where \( v_0 \) is the average fluid velocity in the pipe without clogging.

From Eq. (3) (and from Figure 5) it follows that for small clogging degrees the relative decrease in the permeability (and therefore the throughput) of the pipeline comes more intensively (for \( n < 20 \% \)), a further decrease is insignificant. This fact may be interpreted as a confirmation of studies based on full-scale hydraulic tests of real pipelines. The experiment result was, among others, the conclusion that the hydraulic resistance coefficients increase rapidly in the first 5-6 years of pipe operation. Thus, dependences of the Eq. (3) can be used for an approximate forecast of changes in the throughput of the pipeline with a known clogging type.

![Figure 5. Change in the relative permeability of pipelines during clogging – \( k/k_0 = f(n) \)](image)

In conclusion, it should be noted that Equation (2) is obtained under the assumption of a quadratic law of turbulent filtration:

\[
v = k \cdot \sqrt{J}.
\]

Obviously, if the pipeline becomes clogged, the quadratic filtration law may be violated, and in the general case

\[
v = k \cdot J^m,
\]

where the index \( m \) can vary from 0.5 in the region of quadratic resistance to 1 in the laminar flow. Because of Equation (5), Equation (2) will have the form
\[ k = \varphi \cdot \frac{2g \cdot I}{J^{2m-1}} , \] (6)

Thus, for \( m = 0.5 \) Equation (2) is valid, for \( m = 1 \) this equation \( k = \varphi \cdot \frac{2g \cdot I}{J} \) is valid.

However, the definition of \( J \) influence in case of changing the resistance region requires additional studies involving information from the filtration theory [21, 22].

4. Conclusions
1. The transition from resistance coefficients to filtration coefficients allows making a practical forecast of a decrease in the throughput of pipelines with a known type of clogging.
2. With small clogging degrees, the permeability of the pipeline decreases much faster than with subsequent clogging. Therefore, the main changes in the hydraulic parameters of real pipes occur in the first years of operation. With large clogging degrees (“locked” pipeline), the friction losses become negligible, and the pipes work as hydraulically very short.
3. For pipelines made of the same material with the same type and clogging degree, the influence of the ratio \( l/D \) on the change in the hydraulic properties of the pipeline is insignificant.

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