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ASSESSING THE VALUE OF THE HYDRAULIC FRICTION FACTOR IN PIPELINES WORKING WITH A FLOW CONNECTION ALONG THE PATH

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The results of an experimental study of the hydraulic friction factor of perforated pipelines that work with the collection of fluid along the path are reported. Clarification of this issue will make it possible to solve an important engineering task – to devise a reliable procedure for the hydraulic calculation of perforated pipes. The experiments were carried out on an assembled experimental bench. A steel pipeline with a perforated part of 1–3 m was investigated. Perforation holes were taken with a diameter of 3.6 and 9 mm. In the experiments, fluid flow, pressure loss, and average velocity were measured. Based on the data obtained, the values of the coefficient under study were calculated. It has been established that it is significantly larger than its values with uniform movement and is variable in length of the pipeline. Experimental dependences λ_{col} on the value of the ratio of the velocities of the flowing jets of liquid to the average flow velocity in the corresponding section (U_h/V), as well as on the design characteristics of the channel, were obtained. It is shown that the lower value of the degree of pipe perforation corresponds to the higher values of λ_{col}. This result can be explained by the influence of the attached flow rate on the main flow. The confirmation of this conclusion is the resulting shapes of diagrams of the average flow velocity obtained in the experiments, which differ significantly from standard diagrams with uniform motion. Obviously, additional energy is spent on the reformation of the velocities, and this causes additional head losses. Dependences were obtained for calculating the considered coefficient for prefabricated pipelines, including in the presence of transit flow rate. Their use in the calculation of the pipes under consideration will increase the reliability and efficiency of the sewage treatment plant, in which they are important structural elements

Keywords: prefabricated perforated pipeline, variable flow rate, hydraulic friction factor

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1. Introduction

Perforated pipelines are widely used in various industries, in particular water supply and drainage, land reclamation, ventilation, mechanical engineering, energy, chemical production, etc. [1–3]. Such pipes usually work with the addition of liquid along the path (prefabricated pipelines); they serve as important structural elements of treatment facilities of water supply and drainage systems. With their help, the design conditions for the flow of fluid into the pipe and its discharge from the capacitive treatment plant are maintained. This ensures the technologically specified mode of operation for both a separate structure and the entire treatment complex as a whole. However, it is impossible to ensure satisfactory results of the calculation of these pipes without a reasoned determination of the value of the hydraulic friction factor λ_{col}. The dependences proposed up to this time for calculating λ_{col} do not fully correspond to the specificity of fluid movement with variable flow along the path since they do not take into consideration the influence of the variable length of the channel of the value of the velocity of the connected flow on the velocity of the main flow. Also, the nature and magnitude of the perforation of the side walls of the channel are not sufficiently estimated. Given the difficult current situation with water supply, deterioration of water quality in natural water sources, and in order to protect water resources in the world. Designing new effective structures of water treatment facilities represents an important technical problem [4]. The same applies to the calculation of prefabricated perforated pipes, which are important structural elements of these structures. Therefore, scientific research into the development of a perfect and reliable methodology for determining the coefficient λ_{col} and for the hydraulic calculation of perforated pipelines in general can be considered timely and important for practical application.

2. Literature review and problem statement

As is known [5, 6], the movement of a fluid with variable flow along the path of prefabricated perforated pipelines is described by a system of differential equations, which consists of the hydraulic equation of motion of a liquid with variable mass and the equation of continuity, represented in the form of an equation of flow through a hole.

One of the main parameters that affect the calculations of such pipelines is the hydraulic friction factor λ_{col}. In [7], this coefficient was taken to be constant along the length of the pipe; the degree and nature of its influence on the characteristics of the flow in pressure perforated channels of different lengths are not estimated. In addition, there is no reliable method for its determination. However, depending on the length of the considered pipes, the influence of this coefficient on their calculation parameters is different. It practically does not affect the operation of relatively short pipelines, in the calculation of which the losses of head on hydraulic friction compared to losses associated with changes in flow along the path can be neglected. In this case, the coefficient λ_{col} is excluded from consideration [8].

In the case of the use of pipelines of greater length, when the losses of head on hydraulic friction become significant, determining the actual value of the coefficient λ_{col} is an important task. This issue is especially relevant when calculating relatively long pipelines. In this case, the coefficient λ_{col} is directly related to the total energy losses in the pipeline. Therefore, the attention paid by researchers to the study of the issue of its reliable calculation is quite understandable.

The technical literature includes works [9, 10], which consider the calculation of pressure pipelines operating at a constant flow rate of liquid and gas. Depending on the hydraulic mode of operation and the material of the pipelines, many empirical dependences have been proposed to determine the hydraulic friction coefficient λ_0 in the case under consideration.

According to [9], in the case of fluid movement in the pipeline, the value of the hydraulic friction factor functionally depends on the mode of movement (Reynolds number Re) and the roughness of the material of the pipeline walls, characterized by a relative equivalent roughness Δ_{eq}/D, where the parameter Δ_{eq} determines the equivalent (the same and uniformly distributed in area) height of the protrusions of roughness, and D is the diameter of the pipeline.

The most well-known and often used in the calculations of the coefficient λ_0, with different Reynolds numbers and the roughness of the material of the channel walls, is the proposed empirical dependence, which is given in work [9].

A much more complex character is demonstrated by the pattern of the flow during the operation of perforated pipelines under the mode of water collection when its flow occurs through the holes in the side wall of the pipe [11, 12]. In this case, the flow of streams is carried out into a stream moving inside the channel and demolishing them in the direction of the main stream. In this case, the component of the velocity of movement in the plane of the hole becomes different from zero. This circumstance indicates that the presence of mass transfer (fluid attachment) on the walls of the pipe significantly changes the kinematics of the main flow and should certainly affect the value of the hydraulic friction factor [10, 13]. However, the kinematics of flow in the perforated channel have not been investigated in the works under consideration; velocity diagrams in cross-sections were not considered.

The analysis [14, 15] showed that in the prefabricated perforated pipeline there is an uneven mode of fluid movement along the path. The nature of this unevenness is determined by the magnitude of the ratio of the flow rate of the liquid jet through the hole to the average in this section α flow rate in the channel (U_h/V). The latter, in turn, depends on the structural ratio of the pipe $f=\alpha_p l/\Omega$ (where α_p is the area of the perforation holes per unit length of the pipe). At the same time, the nature of the impact of the flow attached in length to the main flow is estimated only qualitatively. Quantitative relationships between the considered parameters are not given.

In this case, the value of the hydraulic friction factor λ_{col}, without taking into consideration secondary factors, will depend on four main factors: the Reynolds number of the main stream, the equivalent roughness of the material of the channel walls, the design parameter f, and the ratio of the velocities of movement of the main and connected flows.

To determine the specific form of functional dependence of the considered coefficient on the specified parameters for prefabricated pipelines, a large number of works were analyzed, for example [16, 17]. However, the given dependences are partial in nature and refer to the pipelines of reclamation systems in which the inflow and outflow of liquid into the soil occurs using various nozzle designs.

It is noted that with a change in the ratio (U_h/V) from the maximum value in the initial sections of the collector to the minimum values at its end, the coefficient λ_{col} also varies from maximum to minimum values. However, no satisfactory mathematical relationships have been proposed that would link the specified parameters and, on this basis, allow calculating the value of the coefficient λ_{col}. The only thing that unites studies under consideration is the statement of the fact of an increase in the specified coefficient compared to its value with a uniform movement λ_0.

Experimental studies, for example [18], which report determining this coefficient for prefabricated perforated pipelines involved specific characteristics and operating conditions of prefabricated pipelines. Therefore, its use in other design characteristics of perforated pipes requires additional justification.

Summarizing the research into this area to determine the hydraulic friction factor λ_{col}, it is necessary to note its partial nature. Its main disadvantage is the fact that the studies do not sufficiently take into consideration the features of the hydrodynamics of the flow, which take place in the channels working with the addition of fluid along the path, compared with uniform movement.

3. The aim and objectives of the study

The aim of this study is to establish the functional dependence of the value of the variable and average length of the prefabricated pipeline of the hydraulic friction coefficient λ_{col} and $\lambda_{col.av}$ on the structural characteristics of pipes. An important factor is also to determine the influence exerted on the values of the indicated coefficients by the ratio of the velocities of fluid inflow through the hole to the average flow rate in the channel cross-section under consideration. The obtained data will make it possible to devise a reliable procedure for the hydraulic calculation of these pipes.

To accomplish the aim, the following tasks have been set:

– to carry out the necessary experimental studies to determine the kinematic characteristics of perforated pipelines that operate with variable flow along the path;

– based on the results of processing the obtained experimental data, to derive empirical formulas for calculating the value of the hydraulic friction factor λ_{col} in prefabricated perforated pipelines;

– to establish the type of dependences for calculating the experimental coefficient β_{col}, which takes into consideration the effect of increasing head losses in prefabricated pipelines compared to uniform movement, for the cases of the absence and presence of transit flow.

4. The study materials and methods

The object of our research was a short perforated pipeline. In terms of its design, in particular, diameter, length, nature of perforation, it fully corresponded to the characteristics of pipelines that are used in existing treatment facilities. In this regard, it can reasonably be considered that the experimental data obtained from the experiments should correspond to the parameters of real pipelines.

During the research, methods of experimental measurements and analytical processing of the obtained research data were comprehensively applied, which were supplemented by the results of solving the initial theoretical dependences, with the help of which they describe the movement of a liquid with variable flow rate in pressure prefabricated pipelines.

The experimental part of this work was carried out at a specially prepared aerodynamic bench. Air was used as a working fluid.

As a prototype, a steel pipeline D=159×4.5 mm was used, with a total length of L=4.0 m. The length of the working perforated part was l=3.0 m. Perforation in the pipe was arranged in the form of holes with a diameter d_h=0.003 m, with a pitch of Δl=0.03 m; 8 holes in each cross-section (800 holes in total). During the work, the diameter of the holes increased (at first, d_h=0.006 m, then, d_h=0.009 m). The holes were arranged along the product pipeline perpendicular to its longitudinal axis. The relative length varied from $(l/D)_{\min}$= =6.6 to $(l/D)_{\max}$=20. The change in the design parameter $f=\alpha_p l/\Omega$ ranged from 0.3 to 2.8. We measured the average velocity profile and the nature of the piezometric line in specially equipped structures located after 0.5 and 0.25 m.

The pressure and vacuum in the working pipeline were provided by a centrifugal fan. Depending on the characteristics of the experiment, the end of the pipeline could be either closed or open. The measurements used the appropriate working and measuring equipment and instruments. Procedures for treating the obtained results of the experiments corresponded to the tasks set.

Changes in the hydrodynamic characteristics of flows in perforated pipelines were achieved in several ways:

– by taking a given relative length of the pipeline by using use pipes of the required length and diameter;

– by creating various operating pressures. To do this, the head pipe of the fan to the bench was locked;

– by changing the perforation of the side walls of the pipeline, by sealing or opening the perforation holes in a certain sequence and volumes that corresponded to the adopted research plan.

In the study of the average characteristics of the considered motion at the aerodynamic bench at certain points of all control sections of pipelines, the average values of static and dynamic pressures were measured using the Pitot-Prandtl tube and the TsAGI micromanometer.

The values of the hydraulic friction coefficient λ_{col} were calculated using the initial differential equation [5, 6], after substituting the obtained experimental values into it

$$\frac{dh}{dx}+\frac{A}{g\Omega^2}Q\frac{dQ}{dx}+\frac{\lambda_{col}}{2g\Omega^2 D}Q^2=0, \qquad (1)$$

where λ_{col} is the hydraulic friction factor of the prefabricated pipeline; A is the parameter that for these pipes is assumed to be equal to 2 [5]; D, Ω are the diameter and cross-sectional area of the pipeline; Q, h are the flow rate and piezometric height in cross-section at a distance x from the beginning of the pipeline.

In equation (1), the second term takes into consideration the head losses that are associated with the effect of attaching the liquid, the third – the loss of head on hydraulic friction.

When conducting experimental studies, the errors of the obtained measurement results were determined and evaluated, the value of which depended on the measuring devices used and the conditions for conducting experiments.

The scheme of the experimental installation and a detailed description of the experimental and measuring equipment, as well as the procedures of measurement and processing of the results obtained, are given in [19].

5. Results of investigating the dependence of the hydraulic friction factor on the design characteristics of the prefabricated pipeline

5. 1. Results of the experimental study of the kinematic characteristics of prefabricated perforated pipelines

In the study of prefabricated perforated pipelines, the value of the design parameter f varied from $f_{\min}$=0.3 to $f_{\max}$=2.8, covering almost the entire range of its change under real conditions. Fig. 1, *a*, *b* shows a number of characteristic profiles of the average velocity of fluid movement, which were obtained in the cross-sections along the length of the collector under study (cross-section 6 corresponds to the final cross-section; cross-sections 5, 4, 3, 2 are located at a distance of every 0.25 m from the end of the pipe).

The shape of the resulting diagrams differs significantly from typical diagrams of average velocities observed with the uniform movement of the liquid. This difference must necessarily affect the magnitude of the hydraulic friction factor λ_{col}.

Understanding the nature of the processes that occur during the movement of a liquid with a variable mass in perforated pipelines is possible only on the basis of studying the features of the kinematics of the flow in the channel. However, it should be noted that experimental data on this issue are not yet enough.

Analysis of the diagrams in Fig. 1 revealed that their difference from the standard type is caused by an additional macroscopic exchange of the amount of motion between the flowing jets of liquid and the main flow. In this case, there is an intensive conversion of mechanical energy into heat, which explains a significant increase in energy losses (head) during the considered movement compared to uniform.

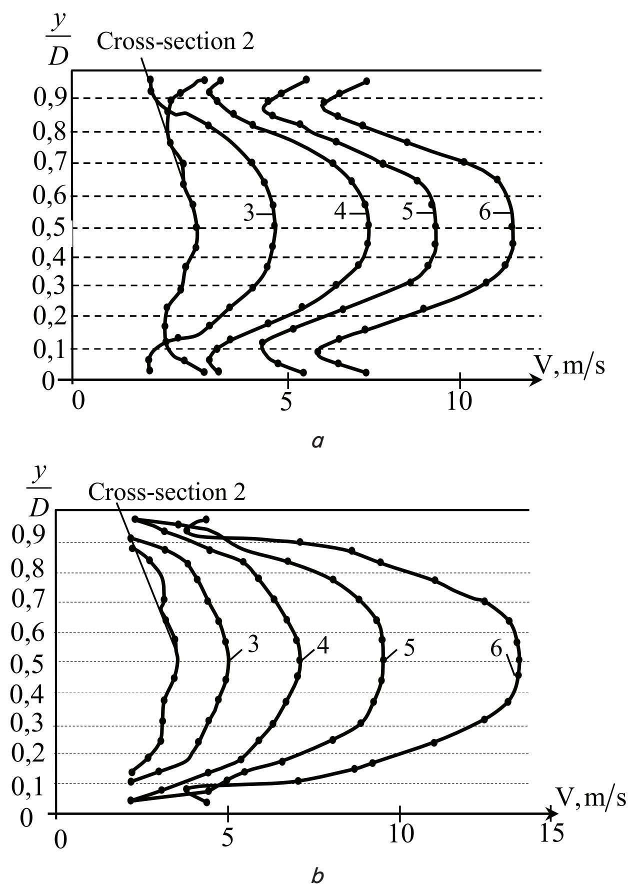

Fig. 1. Profiles of average velocities when moving with connection: *a* – f_1 = 1.41; *b* – f_2=2.82; 2–6 – numbers of cross-sections along the path

It is shown in [20] that numerically the intensity of deformation of the diagram of averaged velocities in a cross-section is conveniently characterized by the ratio between the rate of its inflow and the average flow rate (U_h/V). It is found that in general, this ratio is variable along the pipe. Moreover, the larger this ratio is, the more significant the impact of the variable flow rate on the main flow. In this case, the jet of liquid penetrates to a greater depth in the main stream and more intensively deforms the field of averaged velocities in the cross-section of the prefabricated channel.

The effect of the connected jets on the main flow of fluid in the pipeline, in the first approximation, can be represented as a conditional increase in the height of the protrusions of the roughness of the channel walls. Moreover, the height of these protrusions (y_δ) will be variable in length and depend on the design parameters of the prefabricated pipeline ζ_1 and f. At the same time, the upper boundary of the protrusion zone is assumed not to be rigid but flexible and mobile. Inflowing streams push the main flow away from the walls of the pipeline, which causes a certain increase in averaged velocities in the core of the main transit flow compared to uniform movement.

The limit value of the relative distance y_δ/D from the pipeline wall to the decay zone, depending on the variable in the length of the relative perforation $x'=\alpha_p x/\Omega$ is recommended to be found according to the plot in Fig. 2.

It follows from the plot in Fig. 2 that the value y_δ varies in length (x'). With this, the maximum value of y_δ is achieved in the initial cross-sections of the pipe (with a symmetrical arrangement of perforation holes even up to the value y_δ=0.5D). With an increase in the parameter x' the dimensions of the near-wall zone gradually decrease and, at values x'=1.7, become almost constant and equal to 0.07D. This circumstance indicates that in this case the influence of the attached flow on the main one becomes constant in length. This conclusion is well confirmed by the same plot where, at $x'\geq1.7$, the ratio U_h/V remains constant. Thus, it can be expected that the hydraulic friction factor in these areas should also be constant.

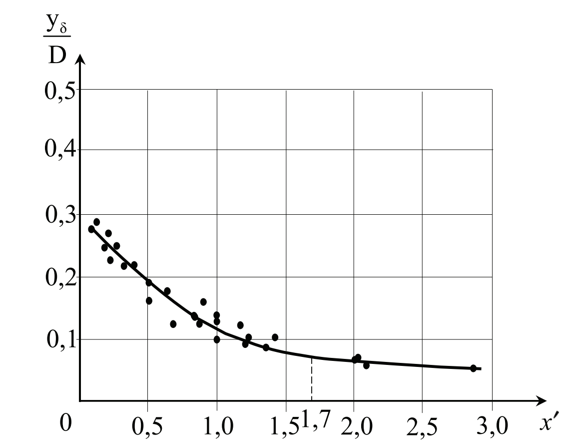

Fig. 2. Change in the size of the wall zone (y_δ) depending on the parameter x' by the length of the prefabricated pipeline

Empirical dependence, which corresponds to the plot in Fig. 2, takes the following form:

$$\frac{y_\delta}{r}=1-0.86th(kx'), \quad (2)$$

where r is the radius of the pipeline.

The degree of deformability of the diagram of the average velocities in the cross-sections of the prefabricated pipes was estimated by the value of the Coriolis coefficient α and the Boussinesq ratio α_0. The results of the experiments showed that these coefficients are variable in length of the head channel and depend on the design parameter f. The smaller values of f correspond to the larger values of α and α_0. Conversely, with an increase in f, they decrease. In addition, it can be argued that in the initial sections of the collector, the values of these coefficients are greater, and closer to the final section, they are significantly reduced. Thus, the elevated values of α and α_0 will be observed in the sections of pipes where a small part of the flow is connected (compared to the flow rate in the final cross-section Q_f) and its impact on the main flow is relatively small.

Describing the operation of prefabricated pipes as a whole, as well as taking into consideration the range of changes in the design characteristics of real systems, it is recommended to take $\alpha\approx1.3$; $\alpha_0\approx1.1$ for engineering calculations.

5. 2. Results of processing experimental data on determining the hydraulic friction factor of the prefabricated pipeline λ_{col}

Obviously, the presence of an inflow along the length of the channel and additional mixing of the flow indicate that the head losses in the prefabricated pipeline should significantly exceed the losses during uniform movement. The same applies to the value of the hydraulic friction factor λ_{col}.

Comparative data on determining this coefficient and its dependence on the Reynolds number of the main flow in the head pipeline for the cases of uniform movement (λ_0) and movement with the addition of fluid along the path (λ_{col}) are shown in Fig. 3.

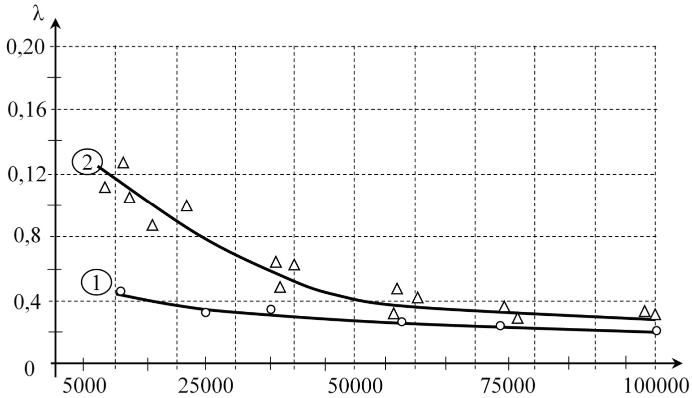

Fig. 3. Experimental determination of the hydraulic coefficient λ in the investigated pipelines: 1 — the case of uniform movement; 2 — the case of movement of fluid attachment along the path

The plot in Fig. 3 shows that curve 1 corresponds to the value $\lambda=\lambda_0$ for the pipelines under study with solid walls. Curve 2 reflects the change in the hydraulic friction coefficient λ_{col} under study for the case of fluid movement in the pipe with an increase in the flow along the length.

Analysis of plots in Fig. 3 indicates that the presence of a fluid inflow along the pipeline under study significantly increases the value of the hydraulic friction factor and, respectively, the loss of energy (head) in it.

This can be confirmed by the plot in Fig. 4 where the change in the value of the coefficient λ_{col} is represented depending on the value of the ratio (U_h/V), variable along the length. The larger value of the parameter (U_h/V) corresponds to larger values of λ_{col}.

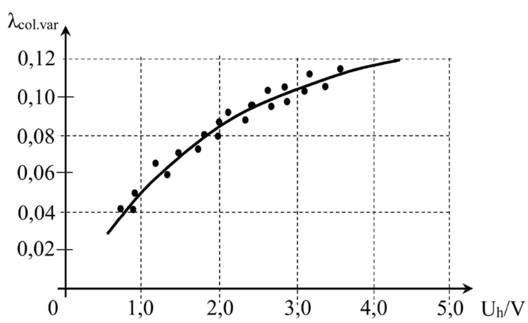

Fig. 4. Plot of the dependence of coefficient $\lambda_{col.var}$ in prefabricated pipelines on the ratio U_h/V

More convenient for practical calculations are dependences in which the change in the desired characteristics is observed depending on the design parameters of the installation or system. In the case under consideration, the value of the hydraulic friction factor $\lambda_{col.var}$ is more convenient to determine depending on the design parameter x', variable along the length of the pipeline. Then the plot in Fig. 4 can be represented in the form shown in Fig. 5.

The empirical dependence for determining the value of $\lambda_{col.var}$, variable by the length of the prefabricated pipeline, which describes the given plot, is:

$$\lambda_{col.var} = 0.048x'^{-0.67}. \tag{3}$$

Evaluating the obtained graphic dependences in Fig. 4, 5, and their corresponding empirical dependence (3), it should be noted that smaller numbers x' correspond to the larger values of $\lambda_{col.var}$. That is, with less perforation, there is a more intense mixing and interaction between the main and changing flows, which leads to a significant increase in energy losses.

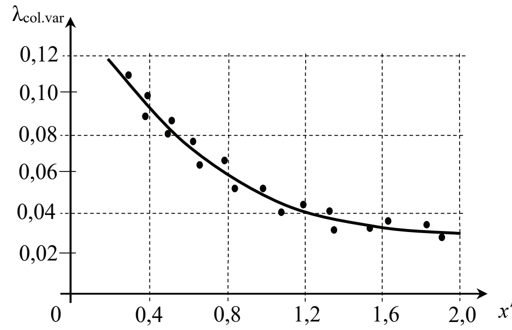

Fig. 5. Plot of dependence $\lambda_{col.var}$ on the design parameter x'

5. 3. Experimental dependences for calculating the coefficient β_{col}

Most often, the general dependence for determining the hydraulic friction factor with uneven movement of fluid in the prefabricated perforated pipeline is represented in the form [21]

$$\lambda_{col} = \beta\lambda_0, \tag{4}$$

where the coefficient λ_0, as indicated above, can be calculated from known dependences; $\beta=\lambda_{col}/\lambda_0$ is the experimental coefficient that takes into consideration the effect of the perforation value of the channel walls on the value of the hydraulic friction coefficient λ_0.

The nature of change in the average, constant over the length of the prefabricated pipeline, coefficient $\beta_{col.av}$, obtained on the basis of processing existing data and those reported in this work (Fig. 3–5), is depicted in Fig. 6.

The corresponding empirical formula for determining the average value of this coefficient for the entire prefabricated pipeline operating without transit is obtained in the form

$$\beta_{col.av} = 1.62 f^{-0.37}. \tag{5}$$

The latter dependence is recommended for use at $0.2 \leq f < 1.7$. In the case of $f \geq 1.7$, we have $\beta_{col.av}=1.33$.

In the presence of transit flow in pipelines, according to the research given, the corresponding dependence is proposed in the form

$$\beta_{col.av} = \left(1.62 - 1.44\frac{Q_{tr}}{Q_f}\right) f^{-0.37}, \tag{6}$$

where Q_{tr}/Q_f is the ratio of transit flow to the flow rate in the final cross-section of the prefabricated perforated pipeline. In all cases, the value of $\beta_{col.av}$ must be at least one. Dependence (6) indicates that the presence of transit flow in the prefabricated channel leads to a decrease in the coefficient of $\beta_{col.av}$ and, accordingly, to a decrease in the value of the hydraulic friction factor $\beta_{col.av}$.

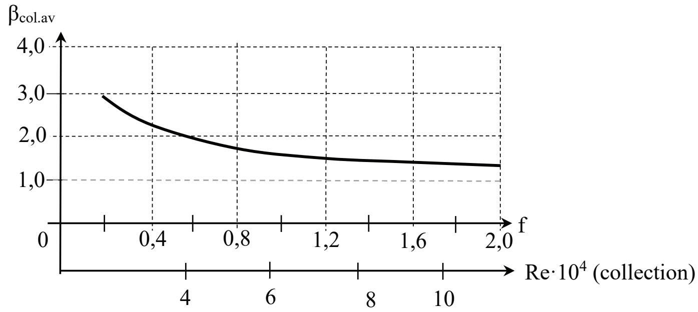

Fig. 6. Plot of dependence $\beta_{col.av}$ on the design characteristics of prefabricated pipelines

6. Discussion of results of investigating the influence of the design characteristics of prefabricated pipelines on the value of λ_{col}

Our experimental studies of perforated pipes made it possible to determine the basic parameters that significantly affect the value of the hydraulic friction factor λ_{col} in the considered case. When performing experiments, the required accuracy of the measured parameters was ensured, which was within:

– when determining the flow rate at the aerodynamic bench using diaphragms – to 5 %;

– when measuring excessive static pressures in the control cross-sections of pipelines with a liquid pressure gauge of the MMN type – to 3 %;

– when calculating, according to experimental data, the hydraulic friction factor in the perforated pipeline – to 7 %.

The obtained estimation dependences (3) to (6) quite fully describe the experimental results obtained within $0.3 \leq f < 1.7$, which corresponds to the parameters of real catchment systems of treatment facilities of water supply and sewerage systems.

By analogy with the results of other works under consideration, a significant increase in the value of the hydraulic friction factor during the operation of prefabricated pipelines compared to its value for a pipe with a constant flow rate was confirmed. Also, according to the experimental studies of fluid movement in prefabricated pipelines, the fact of variability of this coefficient along the length of these channels has been established. We have proposed an empirical dependence for its calculation. This conclusion is based on the analysis of the variable nature of the diagrams of average velocities in the cross-sections of the collector (Fig. 1). The result is explained by the influence of the flows of the connected jets, their additional mixing, and the corresponding energy losses, on the characteristics of the main flow in the channel.

It is determined that for engineering calculations of the pipelines under consideration, dependences (5), (6) can be considered the simplest and most convenient to use. Their main advantage is to take a hydraulic friction coefficient $\lambda_{col.av}$ constant along the length of the collector and dependent only on its structural characteristics.

In prefabricated pipelines, the diagrams of average velocities under the influence of inflowing streams are significantly deformed along the perforated part. It is obtained that the intensity of this transformation depends on the ratio between transit and path flow rates (Q_{tr}/Q_{path}) or (U_h/V), as well as on the value of the design parameter f. It is established that the lower value of f and the ratio Q_{tr}/Q_{path} correspond to a more active restructuring of the velocity field in the corresponding cross-sections.

The increase in the hydraulic friction factor λ_{col} compared to λ_0 of the channels, which operate at a constant flow rate with uniform movement, can be explained by the expenditure of additional energy on the interaction and transformation of the main and connected flows.

The disadvantages of this work include the fact that the experiments were carried out on pipes of relatively short length. This circumstance is explained by the fact that in the study of relatively long tubes there are objective difficulties in the practical study of the kinematics of the studied flows.

The areas of further research include the study of the pulsation characteristics of the streams under consideration and taking into consideration this improvement in the methodology for calculating these pipelines.

7. Conclusions

1. As a result of our experimental studies, the nature of the diagrams of average velocities that occur in the cross-sections of prefabricated perforated pipelines operating with variable flow along the path has been established. Their difference is shown in relation to standard diagrams of fluid movement with uniform movement, which involves a sharp decrease in the value of the average velocities in the near-wall zones and their increase in the core of the stream. The above differences are explained by the influence of the flow connected by the length of the channel on the characteristics of the main flow.

2. On the basis of mathematical processing of the experimental data obtained, relatively simple empirical dependences have been established, recommended for use when calculating the variable and averaged by the magnitude of the hydraulic friction coefficient of prefabricated pipelines λ_{col}, depending on the degree of perforation of the pipeline walls.

3. We have refined the form of formulas for determining the experimental coefficient $\beta_{col.av}$, which takes into consideration the effect of the connected flow and the increase in pressure losses in the pipeline under study in comparison with the uniform movement of the liquid. It was established that the given formulas are recommended to be used at the value of the design parameter f in the range of 0.3–1.7. It is proved that, depending on the design characteristics of the collectors, this coefficient can vary from 1.33 at $x' \geq 1.7$ to 3.0 at $x' \leq 0.3$.

Conflict of interests

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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