The object of the study in this paper is collecting perforated drainage pipelines, in particular, the determination of the hydraulic friction factor λ_{dr}, which significantly affects the parameters of the investigated pipes. Clarifying this issue will solve an important engineering problem – to develop a reliable method for hydraulic calculation of collecting perforated drainage pipes. As the main drawback of most of the available theoretical and experimental works on this topic is the insufficient consideration of the filtration characteristics of the surrounding soil and the material of the pipeline walls. Experimental studies of pressure drainage pipes with different design characteristics made it possible to find out the real picture of fluid flow in the pipe. Based on the research results, experimental dependences of λ_{dr} on the ratio of the fluid inflow velocity to the average flow velocity in the corresponding section (U_h/V), as well as on the design characteristics of the channel were obtained. The maximum possible flow that can be collected and passed by a collecting drainage pipeline with the specified design and filtration characteristics is determined. It is shown that a larger value of the specified ratio corresponds to larger values of λ_{dr}. This result can be explained by the effect of the attached flow on the main flow. Obviously, some energy is spent on the interaction of the attached and the main flow in the pipe, which leads to additional head losses. In the paper, dependencies were obtained for calculating the studied factor for collecting drainage pipelines. Using them in the calculation of drainage pipes will increase the reliability and efficiency of land reclamation systems, in which these pipelines are important structural elements

Keywords: collecting drainage pipeline, variable flow, filtration resistance, hydraulic friction factor

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DETERMINATION OF THE PARTICULARITIES OF THE HYDRAULIC FRICTION FACTOR VARIATION OF COLLECTING DRAINAGE PIPELINES

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1. Introduction

Drainage pipelines of various designs are widely used in the construction of land reclamation systems and underground water intakes [1, 2]. The main feature of such pipes is that they operate with a variable flow along their length. The flow enters the drainage pipe through its side surface in filtration mode. Other flow characteristics, such as velocity, head, size and shape of the pipeline cross-section, etc. also change. Depending on local conditions and tasks to be solved, these flows can be steady or unsteady, and pipelines can operate in pressure or non-pressure mode.

Collecting drainage pipelines usually have a fairly long length. Therefore, the results of the calculation of such pipes are significantly affected by the reliable determination of the hydraulic friction factor λ_{dr}. This issue was studied by a large number of experimental and theoretical works [3, 4]. The main drawback of most of them is the insufficient consideration of the filtration characteristics of the surrounding soil and the material of the pipeline walls, which does not correspond to the actual flow pattern.

Scientific research on this topic is important, since the development and improvement of the methodology for calculating the parameters of drainage pipelines, including the factor λ_{dr}, will ensure reliable operation of the corresponding structures, more efficient use of rather limited water resources, provide the necessary water flow rates and quality.

The results of such studies are needed in practice, as they will contribute significantly to the protection and rational use of surface and underground water sources and the preservation of public health [5].

2. Literature review and problem statement

Many works, for example [6], show that variable flow in collecting perforated drainage pipelines is described by a system of differential equations. It consists of a variable flow hydraulics equation and a continuity equation, presented as a modified equation for fluid filtration through the soil and the lateral surface of the drainage pipeline walls. In [7], the analysis of the first of the equations shows that one of the main parameters affecting the calculations of the considered drainage systems is the hydraulic friction factor λ_{dr}. Much attention is devoted to the study of the dependence of this factor on the hydraulic flow mode and the design characteristics of pressure drainage pipelines. As a rule, researchers took it constant along the length and equal to its value in the channel with uniform flow [8]. However, it is not specified under what conditions this assumption can be applied. The impact of variable flow in the pipelines under consideration was studied by the authors in [9, 10]. In this case, this factor was also taken constant along the path, but different from its standard value. At the same time, no reliable method for calculating the studied factor is given. Analysis of the original differential equation shows that the hydraulic friction factor of λ_{dr} is part of the term that takes into account head losses along the length of the drainage pipeline. Since these pipes usually have a fairly long length, the head losses along the path in them have a major impact. Accordingly, the effect of the value of the desired factor on their operating characteristics is very important, and the attention paid to its determination is clear.

As is known, pipelines and channels operating with a constant flow along the path are commonly used in various fields of technology. Therefore, the vast majority of studies in this direction, including the hydraulic friction factor, are devoted to determining their characteristics with uniform flow λ_0, which does not always correspond to the real flow pattern.

In the case of turbulent flow, the value of the hydraulic friction factor functionally depends on the Reynolds number (Re) and the material of the pipeline walls, which is characterized by a relative equivalent roughness Δ_{eq}/D [11].

Obviously, the presence of mass transfer (fluid attachment along the path) on the pipe walls significantly changes the kinematics of the main flow and should definitely affect the value of the hydraulic friction factor. When the fluid is attached along the length of a drainage pipe in filtration mode, the functional dependence of the hydraulic friction factor, without taking into account secondary factors, can be represented as $\lambda_{dr}=\psi(\mathrm{Re}, \Delta_{eq}/D, U_h/V, \overline{F})$ [12, 13]. In the presented dependence, U_h/V is the ratio of the fluid inflow velocity through the side wall of the pipe to the average flow velocity in the channel in this section; $\overline{F}$ is the filtration resistance, a parameter that comprehensively takes into account the design and filtration characteristics of the "drain-soil" system. Determining it is a separate task and is not considered in detail in this work. For calculating it, a number of empirical and semi-empirical dependencies are proposed [14].

As a rule, the fluid movement inside a perforated pipeline is turbulent. At the same time, drainage pipelines operate with a full section with continuous, usually uneven, liquid attachment along their length. Accordingly, reliable determination of the design and filtration characteristics of such pipes will ensure reliable and efficient operation of the entire system.

To determine the specific form of the dependence λ_{dr} for collecting drainage pipelines, a large number of works were considered, for example [15, 16]. It is noted that as the ratio (U_h/V) increases from 0 to ∞, the factor λ_{dr} changes from the maximum value to its value in a solid-wall constant flow pipeline.

Available experimental data relate to the specific characteristics and operating conditions of collecting drainage pipelines and are difficult to apply in other conditions. At the same time, generalizing calculation dependencies for determining this factor are quite approximate and require additional adjustment and investigation. The main drawback of the presented dependencies is that they practically do not take into account the filtration characteristics of the system. Using them does not allow reliable calculation of the parameters of the pipes under consideration.

3. The aim and objectives of the study

The aim of the study is to find the dependence of the hydraulic friction factor of a collecting drainage pipeline on its design and filtration characteristics.

The obtained data will make it possible to develop a reliable method for the hydraulic calculation of such pipes.

To achieve the aim, the following objectives were set:

– to carry out the necessary experimental studies to determine fluid flow rates and head losses in perforated pipelines with a filtration mode of flow attachment along the path;

– based on the results of processing the obtained experimental data, to determine the influence of the Reynolds number of the flow and the ratio of the fluid inflow velocity through the wall surface to the average velocity in the considered channel section $\lambda_{dr}=f(U_h/V)$ on the value of the hydraulic friction factor λ_{dr};

– to determine the type of dependencies for calculating the experimental factor β_{dr}, which takes into account the effect of increasing head losses in these pipelines compared to uniform movement.

4. Materials and methods

The object of the presented study was a perforated pipeline. According to its design features, in particular the diameter, length, and nature of perforation, it corresponded to the characteristics of pipelines used in existing drainage systems.

The hypothesis of the study was that if the experimental conditions are met, experimental data should correspond to the parameters of real drainage pipelines.

During the research, methods of experimental measurements and analytical processing of the obtained experimental data were comprehensively applied. They were supplemented with the results of solving the original theoretical dependencies, which describe variable flow in pressure collecting drainage pipelines.

The experimental part of the work was carried out on a specially prepared hydraulic stand, the scheme of which is shown in Fig. 1. The working fluid in the experiments was water.

The latter included a hydraulic tray with parameters $L\times B\times H$=10×0.6×0.5 m. A special shield was installed at the end of the tray to keep the required water level constant. At a height of 0.1 m from the bottom of the tray, the test steel pipe with a diameter of D=22×3.0 mm and a total length of L=9.0 m was laid. The length of the perforated part of the pipe was 8.0 m. The relative length of the test pipeline varied from $(l/D)_{min}$=62.5 to $(l/D)_{max}$=500. The pipe walls were perforated with holes with a diameter of d_h=0.003 m. Four holes were taken in each section, the distance between these sections was 0.1 m.

The filtration mode of water supply to the drainage pipeline was provided using special rolled filter materials. An increase in the number of winding layers increased the filtration resistance of the pipeline, which varied in the experiments within $\overline{F}=0.01-0.5$ (day/m).

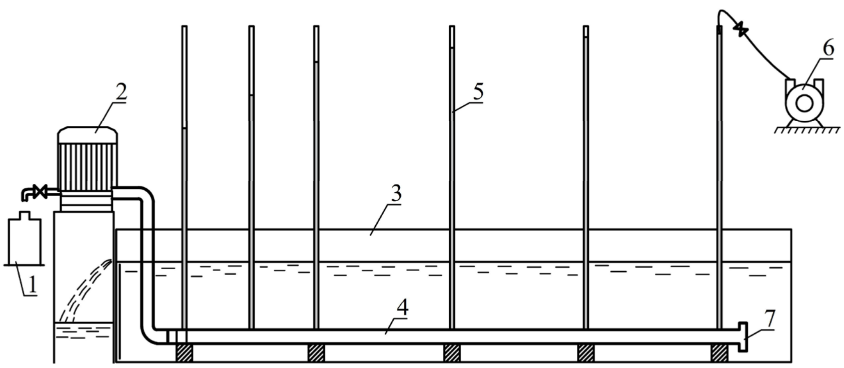

Fig. 1. Scheme of a hydraulic experimental unit: 1 — measuring tank; 2 — pump; 3 — hydraulic tray; 4 — test pipeline; 5 — piezometers; 6 — vacuum pump; 7 — plug

The pressure flow of water through the pipeline was provided by the SCV-1.5M pump. To control the same water level in piezometers and adjust the required head, a valve was installed at the beginning of the pipe. The variation in the pressure gradient along the test pipeline was determined using piezometers attached to the pipe in 1.0 and 2.0 m and connected for taking readings to a special board. The readings were taken on a millimeter scale. The flow in the final section of the collecting pipeline was measured with a measuring capacity of 10 liters, and the filling time was determined by a stopwatch with a division value of 0.2 s. The correctness of measurements (no air bubbles) was monitored along the horizon of the water level in the tray in the absence of movement. The water temperature was controlled by a mercury thermometer with a division value of 0.2 °C.

To obtain reliable data on the experimental stand, an appropriate measurement method was developed and used.

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

– taking the specified relative pipeline length using pipes of the required length;

– creating different operating heads. To do this, the discharge branch pipe of the pump or fan was closed on the stands, or the water level in the tray was changed;

– varying the perforation of the pipeline side walls by sealing or opening perforation holes in a certain sequence and volumes corresponding to the accepted research plan.

The value of the hydraulic friction factor of the drainage pipeline was calculated based on the experimental values obtained as a result of their substitution in the original system of differential equations [17]:

$$\frac{dh}{dx}+\frac{2}{g}Q\frac{dQ}{dx}+\frac{\lambda_{dr}}{2gD}Q^2=0, \quad (1)$$

$$\frac{dQ}{dx}=\frac{k_f(H-h)}{\overline{F}}=k_f\frac{z}{\overline{F}}, \quad (2)$$

where H is the immersion depth of the pipeline axis from the groundwater level; h is the piezometric head in the pipe; $z=H-h$ is the length-varying pressure drop, under which fluid flows from the environment to the pipeline; Q is the flow rate at a distance x from the beginning of the pipe; g is the acceleration of gravity.

The second term of equation (1) describes the head losses associated with the effect of fluid attachment, and the third – the hydraulic friction losses along the length.

When conducting and processing the results of experimental studies, errors of the obtained measurement results were determined and estimated, the values of which depended on the measuring devices used and the experimental conditions.

5. Results of studies on determining the characteristics of collecting drainage pipelines

5. 1. Determination of fluid flow rates and head losses in perforated pipelines with filtration mode of flow attachment along the path

Based on the experimental results, graphic dependencies were obtained that reflect the variation in relative flow rate ($\overline{Q}/\overline{Q}_f$, Fig. 2) and relative pressure drop ($\overline{z}=z/z_f$, Fig. 3) along the length of the drainage pipeline (l/D=250), depending on the filtration and design characteristics of the pipe walls $\overline{x}/\overline{f}$.

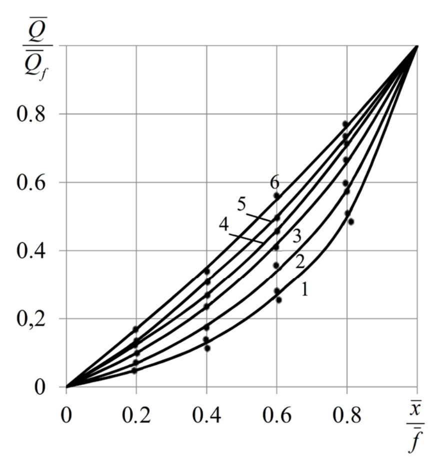

Fig. 2. Variation in the relative flow rate along the length of the pressure drainage pipeline (l/D=250) at filtration resistance values: 1 — $\overline{F}=730$ s/m; 2 — $\overline{F}=1{,}630$ s/m; 3 — $\overline{F}=2{,}710$ s/m; 4 — $\overline{F}=3{,}850$ s/m; 5 — $\overline{F}=8{,}640$ s/m; 6 — $\overline{F}=17{,}280$ s/m

In this case, $\overline{Q}=\frac{Q}{\Omega\sqrt{gz_f}}$ is a dimensionless length-varying fluid flow rate; $\overline{x}=\frac{x}{\Omega\Phi}\sqrt{\frac{z_f}{g}}$ is a dimensionless length-varying parameter that takes into account the design and filtration characteristics of the drainage pipeline. In the final section, these dimensionless variables take the form:

$$\overline{Q}_f=\frac{Q_f}{\Omega\sqrt{gz_f}};\ \ \overline{z}_f=1;\ \ \overline{f}=\frac{l}{\Omega F}\sqrt{\frac{z_f}{g}}.$$

The given graphs confirm the fact that the intensity of liquid attachment to the drainage pipeline is uneven along its length. In the initial sections, it is minimal, increases along the length of the drain and reaches its maximum value in the final section.

At the same time, pipes with higher filtration resistance have less uneven flow of liquid along the path. At $\overline{F}>18{,}000$ s/m, there is almost uniform fluid attachment along the drainage pipeline (curves 5, 6).

The information is the graph in Fig. 4, which shows the variation in the relative flow rate at the end of the drain $\overline{Q}_f$ depending on the design parameter (pipeline resistance factor $\zeta_l=\lambda_{dr}\dfrac{l}{d}$).

The presented graphical dependencies indicate the following. Each pressure drainage pipeline with specific design and filtration characteristics has a certain effective length (the value of the resistance factor ζ_l) on which the main liquid attachment to the pipeline is carried out. If the given drain length is exceeded, there is almost no fluid flow in this section. So, for example, with a drain resistance factor $\overline{F}=1{,}630$ s/m, the effective pipe length will have a resistance factor ζ_l=20.

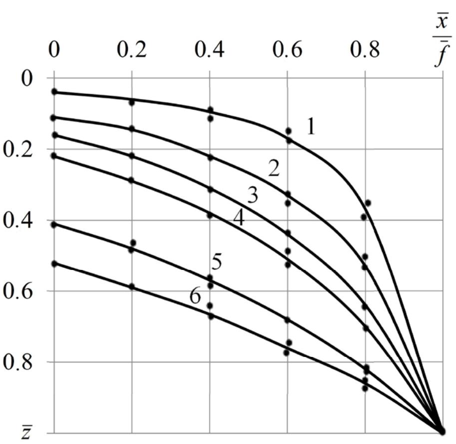

Fig. 3. Variation in the relative pressure drop along the length of the pressure drainage pipeline (l/D=250) at filtration resistance values: 1 – $\overline{F}=730$ s/m; 2 – $\overline{F}=1{,}630$ s/m; 3 – $\overline{F}=2{,}710$ s/m; 4 – $\overline{F}=3{,}850$ s/m; 5 – $\overline{F}=8{,}640$ s/m; 6 – $\overline{F}=17{,}280$ s/m

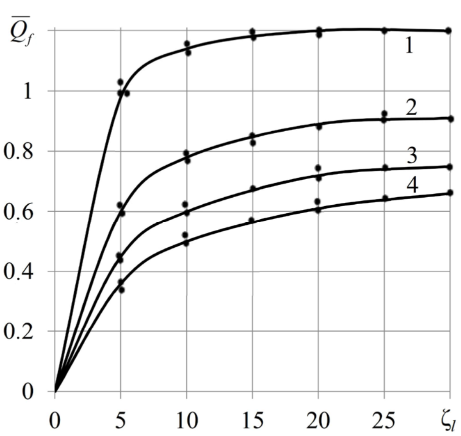

Fig. 4. Variation in the relative flow rate at the end of the drainage pipeline $\overline{Q}_f$ depending on the value of the filtration resistance $\overline{F}$ at different values of the resistance factor ζ_l: 1 – $\overline{F}=730$ s/m; 2 – $\overline{F}=1{,}630$ s/m; 3 – $\overline{F}=2{,}710$ s/m; 4 – $\overline{F}=3{,}850$ s/m

As the studies have shown, the value of the operating parameters of drainage pipelines is significantly affected by the variation in the hydraulic friction of these pipes λ_{dr}. In accordance with dependence (2), one of the main factors affecting the value of this factor is the ratio of the fluid inflow velocity in the section U_h to the average flow velocity in this pipe section V. Individual characteristic data for determining the U_h/V ratio that varies along the pipe length are shown in Fig. 5.

It follows from the given data that for the values of the parameter $\overline{f}$, or the ratio $\overline{x}/\overline{f}>0.4$, the velocity ratio U_h/V constantly takes the minimum value for the given pipe filtration resistances $\overline{F}$.

The obtained graphical dependencies show that the highest U_h/V value occurs in the initial sections of collecting pipes and gradually decreases towards the end of the pipeline. The same trend occurs in pipelines with a lower value of the design parameter $\overline{f}$. Accordingly, the depth of penetration of liquid flows into the main flow will decrease, that is, their impact on it will be smaller.

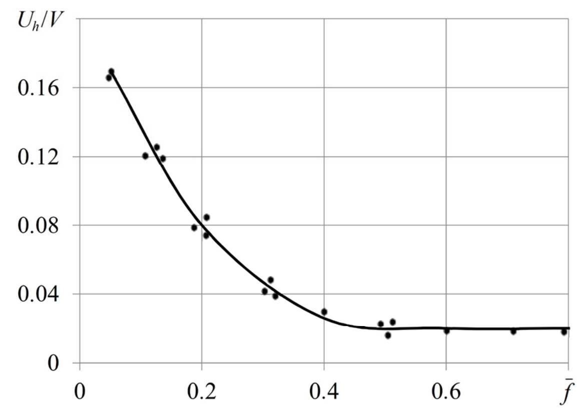

Fig. 5. Graph of the ratio of the fluid inflow velocity to the average velocity in the section (U_h/V) against the parameter $\overline{f}$

5. 2. Influence of the Reynolds number of the flow and the ratio of the fluid inflow velocity through the wall surface to the average velocity in the considered channel section $\lambda_{dr}=f(U_h/V)$ on the value of the factor λ_{dr}

During the experiments, the value of the hydraulic friction factor of the studied pipes λ_{dr} was also determined depending on the Reynolds number of the flow. The results of processing the relevant experimental data are shown in Fig. 6.

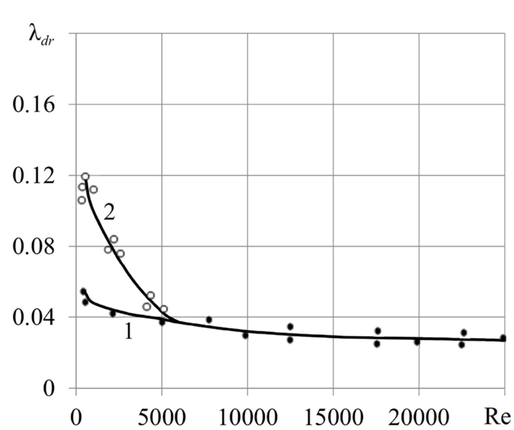

Fig. 6. Graph of the hydraulic friction factor λ_{dr} against the Reynolds number Re

On it, curve 1 corresponds to the operation of the pipeline under study without perforation with a constant flow rate. Curve 2 is the case of operation of a perforated drainage pipeline coated with filter materials. It follows from the given graph that for the values of the Reynolds number of the flow Re>6,000, the effect of the attached flow on the value of the hydraulic friction factor λ_{dr} can be neglected and taken similar as for the same pipe with a constant flow rate λ_0.

5. 3. Dependencies for calculating the experimental factor β_{dr} taking into account the design and filtration characteristics of the drainage system

More convenient for use and determining the value of the factor λ_{dr} is the graph of its dependence on the parameter $\bar{f}$, which comprehensively takes into account the design and filtration characteristics of the drainage pipe.

Based on the presented studies, for practical calculations, it is recommended to consider the effect of variable flow along the path on the value of the hydraulic friction factor as a function of:

$$\lambda_{dr}=\beta_{dr}\cdot\lambda_0, \quad (3)$$

where $\beta_{dr}=\lambda_{dr}/\lambda_0$ is an empirical factor that takes into account the design and filtration characteristics of the drainage system and is determined from the graph in Fig. 7.

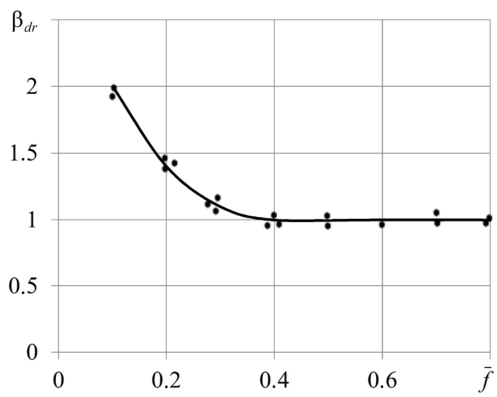

Fig. 7. Graph of the factor β_{dr} against the parameter $\bar{f}$

As follows from it, $\beta_{dr}>1$ only at $\bar{f}<0.4$. For higher values of $\bar{f}$, the factor $\beta_{dr}=1$ and the effect of the attached fluid on the value of λ_{dr} in engineering calculations can be neglected.

Processing of the experimental results allowed us to recommend the following empirical formula for determining the desired factor:

$$\beta_{dr}=0.71\bar{f}^{-0.28}, \quad (4)$$

which is fair within $0.05\leq\bar{f}\leq0.4$.

6. Discussion of the results of studying the influence of the design and filtration characteristics of collecting drainage pipelines on the value of λ_{dr}

Experimental studies of pressure drainage pipes allowed us to determine the main parameters that significantly affect the value of the hydraulic friction factor in the considered case λ_{dr}. During the experiments, the required accuracy of the measured parameters was ensured, which was within the limits, as confirmed by the data in Fig. 2–5:

– when determining the flow rate on the hydraulic stand using the capacity tank – up to 3 %;

– when measuring pressures in control sections of pipelines using piezometers – up to 3 %;

– when calculating the hydraulic friction factor in the pressure drainage pipeline based on experimental data – up to 7 %.

Unlike [8, 14], which consider the operation of collecting drainage pipelines with a constant flow rate, the results obtained confirm a significant increase in the value of the hydraulic friction factor λ_{dr}. The result obtained is explained by the effect of the attached flows, their additional mixing and corresponding energy losses on the characteristics of the main flow in the channel.

It is determined that for engineering calculations of the considered pipelines, the dependencies (3) and (4) are the simplest and most convenient to use. Their main advantage is the adoption of the hydraulic friction factor λ_{dr} constant along the length of the collector and dependent only on its design and filtration characteristics.

An empirical dependence (4) is proposed for determining the constant factor β_{dr} along the drainage pipeline, which takes into account the design and filtration characteristics of the drainage system. It was found out that its value depends on the ratio between the velocity of the attached and the main flow in the drainage pipe section (U_h/V), as well as on the value of the design parameter $\bar{f}$. It was revealed that lower values of $\bar{f}$ and larger U_h/V ratio correspond to more active adjustment of the velocity field in the corresponding sections.

The obtained calculation dependence (4) quite fully describes the obtained experimental results within the design parameter value $0.05\leq\bar{f}\leq0.4$ (or Reynolds numbers Re>6,000), which corresponds to the parameters of real drainage pipelines of land reclamation systems.

The increase in the hydraulic friction factor λ_{dr} compared to λ_0 of channels operating with constant uniform flow can be explained by spending additional energy on the interaction and transformation of the main and attached flows.

The limitations that occurred in the presented work include the fact that experiments were conducted on pipes of small diameter (D=22×3.0 mm) and relative length (l/D=62.5–500). This is explained by the fact that when studying relatively long drainage pipes of large diameter, objective difficulties arise in the practical study of the kinematics of the studied flows.

Further research should include the study of kinematic pulsation characteristics of flows in these pipes and, taking this into account, the improvement of the method for calculating them.

7. Conclusions

1. As a result of experimental studies, it was found that unlike uniform fluid flow, depending on the value of the filtration resistance of the studied drainage pipelines, the

water flow rate and head loss in them occurred unevenly: from the maximum values at $\overline{F}=730\,\text{s/m}$ to the minimum – $\overline{F}=17{,}280\,\text{s/m}$. These differences are explained by the influence of the flow attached along the length of the channel on the characteristics of the main flow.

2. It was found that the value of the resistance factor (section length) of the drainage pipeline, on which intensive attachment of the flow along the length occurs, depending on the design and filtration characteristics of the pipe, can increase by two or more times.

3. Based on the mathematical processing of the obtained experimental data, an empirical dependence is obtained and recommended for use to take into account the influence of the attached flow on the main flow, where the increase in the value of the hydraulic friction factor is proposed to be taken into account by introducing the factor β_{dr}, which is represented as a power function. It was found that the given formula is recommended to be used for the value of the parameter $\overline{f}\leq 0.4$. At the same time, it is proved that depending on the design and filtration characteristics of collectors, this factor can vary from 1.0 at $\overline{f}>0.4$ to 2.0 at $\overline{f}\leq 0.05$.

Conflict of interest

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

Financing

The study was conducted without financial support.

Data availability

The manuscript has no related data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the presented work.

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