This paper reports the results of the experimental and theoretical studies of the characteristics of perforated pipelines, which are used to collect and dispose water from capacitive treatment structures of water supply and sewerage systems. The value and nature of the change in the flow rate through the perforation holes μ_{col} lengthwise a pipeline have been examined depending on the design characteristics of the perforated pipes and parameters of a fluid flow in the pipeline. Measurements were carried out at a specially assembled experimental bench. The experiments determined the nature of changes in the flow rate value, as well as in the piezometric line along the collector. The obtained data showed that the flow rate factor μcol varies along the length of the collecting channel. Its value depends on the ratio of the velocity of the fluid jets that enter the pipe to the average velocity in the examined cross-section (U_h/V). In this case, this ratio also changes along the path; it has a maximum value at the beginning of the pipe and a minimum value at its end. The variable flow rate factor of perforation holes, on the contrary, had a minimum at the beginning and a maximum at the end of the collector. The result of the analysis of initial equations and the findings based on experimental data has shown that calculations may assume, without a significant error, the flow rate factor value of perforation holes μ_{col} to be constant lengthwise the collector. The impact of the transit flow rate on the value of this coefficient has also been estimated. It is shown that the increase in transit leads to a certain increase in the flow rate factor, which is averaged for the entire collector. The paper proposes empirical dependences that are convenient to use in order to calculate the flow rate factor, both variable and constant, for the case of the presence and absence of transit in the head drainage channel

Keywords: variable flow rate, collecting perforated pipeline, perforation hole flow rate factor, pipe duty factor

UDC 532.542

DOI: 10.15587/1729-4061.2020.216366

IMPROVING THE CALCULATION OF COLLECTING PERFORATED PIPELINES FOR WATER TREATMENT STRUCTURES

A. Kravchuk
Doctor of Technical Sciences, Professor*
E-mail: kravchuk.am@knuba.edu.ua

G. Kochetov
Doctor of Technical Sciences, Professor
Department of Chemistry**
E-mail: gkochetov@gmail.com

O. Kravchuk
PhD, Associate Professor*
E-mail: kravchuk.oa2@knuba.edu.ua

*Department of Water Supply and Water Disposal**
**Kyiv National University of Construction and Architecture
Povitroflotskyi ave., 31, Kyiv, Ukraine, 03037

Received date 03.10.2020
Accepted date 06.11.2020
Published date 25.12.2020

1. Introduction

The preparation of water for drinking and production needs, as well as the treatment of wastewater, typically involves capacitive treatment structures in the form of tanks of different design and shape. The purification effectiveness and quality, in this case, significantly depend on the character of the distribution and collection of water in a given structure. Most often, the collection of water and the operation of an entire treatment structure is carried out under a uniform mode. Pipelines and channels with perforated walls are usually used to ensure the uniform (or abiding by a certain law) water discharge from the volume of treatment structures [1–3]. In this case, perforation is most often executed in the form of holes or slits [4]. Hydraulic calculation of such pipelines is a rather complex engineering task. Acquiring reliable data on the structural and hydraulic characteristics of collecting channels, as well as research in this area, is important and relevant. The reliable operation of the considered systems largely affects the efficiency of treatment structures in general. Their high-quality work must ensure the necessary degree of treatment of natural and sewage water.

2. Literature review and problem statement

One of the important parameters whose proper establishment affects the accuracy of the resulting estimation is the value of a perforation hole flow rate factor. A large body of experimental research is aimed at determining dependences for its calculation [5–7]. The researchers focus on the variant implying the discharge of a liquid into the atmosphere or under the level of the fluid, which is at rest.

For this case, the patterns of changes in the factor of a flow rate from a small hole μ_h were studied in detail. Thus, according to [8], the flow rate factor μ_h for the case of the outflow of a heavy non-compressible liquid at constant viscosity (occurring during the operation of sanitary technical systems) through a small hole in the tank of large size is determined, in general, from the following functional dependence

$$\mu_h = \psi\left(\mathrm{Re}_h; \mathrm{Eu}_h; \mathrm{Fr}_h; \mathrm{We}_h\right). \quad (1)$$

In a given ratio, the relevant criteria are calculated according to the values of hydraulic parameters in the holes.

Based on examining a large volume of experimental data, it is shown that in most practical cases (when Fr_h>10 and

We_h>2,500), the discharge from a hole is characterized by a self-similar flow relative to the Fr_h and We_h numbers. The μ_h coefficient, in this case, can be considered a value proportional to Eu_h; then, from (1), we shall obtain

$$\mu_h = \psi(\mathrm{Re}_h). \quad (2)$$

For the laminar and turbulent mode of fluid movement through the hole, known formulae are proposed to determine the μ_h coefficient in this case.

As shown in work [4], the character of a liquid's outflow and, accordingly, the value of a flow rate factor, are also significantly influenced by the shape of the hole and the ratio of its hydraulic radius R (or the hole diameter d_h) to the wall thickness $r_*=\delta/R$ or ($\delta^*=\delta/d_h$).

A much more complex picture of liquid leakage through holes is observed when perforated pipelines are used under a collection mode [9, 10]. In this case, the component of the velocity of movement in the plane of the hole becomes different from zero. That is, in the case of water collection, its outflow through the holes in the side wall of the pipe occurs into the flow that moves inside and carries away the incoming stream.

The analysis showed that with uniform perforation of the side walls of the channel, there is, in the collecting perforated pipeline, an uneven mode of fluid movement along the path. The character of this unevenness is determined by the value of the ratio between the velocity of the connected (incoming) streams and the velocity of the main flow in the channel (U_h/V), averaged for a given cross-section [11, 12].

Thus, the value of the flow rate factor μ_{col}, in addition to the Re number of the connected and main flows, is significantly affected by their ratio (U_h/V). Moreover, in a general case, this ratio also varies lengthwise the collecting channels. Then functional dependence (1) takes the following form

$$\mu = \psi\left(\mathrm{Re};\mathrm{Re}_h;\frac{U_h}{V};\frac{\delta}{d_h}\right). \quad (3)$$

To determine a specific form of dependence (3) for collecting pipelines, many works were considered, for example [13–15]. They note that with a ratio of (U_h/V) growing from 0 to ∞, the coefficient μ_{col} changes from zero and asymptotically approaches the value of the flow rate factor of a single hole μ_o. It is shown that in some cases, when (U_h/V) grows from zero to unity, the flow rate factor in a collecting pipeline may even exceed its value for a single hole, that is, $\mu_{col}/\mu_h>1$. The authors indicate that at $U_h/V>3$ the flow is characterized by a self-similar flow with the value of the coefficient μ_{col} from this parameter.

Available data on experimental research refer to specific characteristics and operating conditions of collecting pipelines; they can hardly be used under other conditions. In this case, the generalizing estimation dependences to determine the flow rate factor of perforation holes μ_{col}, variable in terms of length, are approximate and thus require additional refinement and investigation. Applying them does not make it possible to calculate the value of the specified coefficient depending on the design characteristics of perforated pipelines, in particular a pipe duty factor. In addition, the disadvantage of the proposed estimation dependences is that they do not take into consideration the peculiarities of fluid movement through channels with a variable flow rate along the path.

3. The aim and objectives of the study

The aim of this study is to establish the dependence of the perforation hole flow rate factor's value μ_{col}, variable lengthwise a collecting pipeline, on the structural characteristics of pipes, and to assess the impact exerted on it by the ratio of the fluid velocity incoming through the hole to the average velocity in the considered cross-section of the channel $\mu_{col}=f(U_h/V)$. This would make it possible to devise a reliable methodology for calculating collecting perforated pipelines.

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

– to conduct the necessary theoretical and experimental studies on determining the characteristics of operation of collecting pipelines that accept the flow along the path;

– to derive, based on the results to be obtained, the appropriate estimation formulae to determine the flow rate factor μ_{col} in perforated collecting pipelines;

– to assess the impact of transit flow rate on the flow parameters.

4. Materials and methods to examine a collector's perforation hole flow rate factor

Our research involved the comprehensive methods of experimental measurements and analytical processing of the obtained experimental data, which were supplemented with the results from solving the initial theoretical dependences, which describe the movement of liquid with a variable flow rate in head collecting pipelines.

The experimental part of our work was carried out at a specially prepared aerodynamic bench, shown schematically in Fig. 1. In this case, air served as a working fluid.

The steel pipeline D=159×4.5 mm, with a total length of L=4.0 m, was used as the main experimental sample. In this case, the length of the working perforated part was l=3.0 m. Perforation in the pipe was executed in the form of holes with a diameter of d_h=0.003 m, with a pitch of Δl=0.03 m, 8 holes in each transverse section (800 holes in total). During operation, the diameter of the holes increased (first, d_h=0.006 m, then d_h=0.009 m). The holes were placed along the generatrix of the pipeline perpendicular to its longitudinal axis. Relative length varied from $(l/D)_{\min}$=6.6 to $(l/D)_{\max}$=20. A change in the structural parameter $f=\alpha_{in}l/\Omega$ varied from 0.3 to 2.8. We measured the profile of the averaged velocities and the character of the piezometric line in 10 specially equipped holes located in 0.5 and 0.25 m.

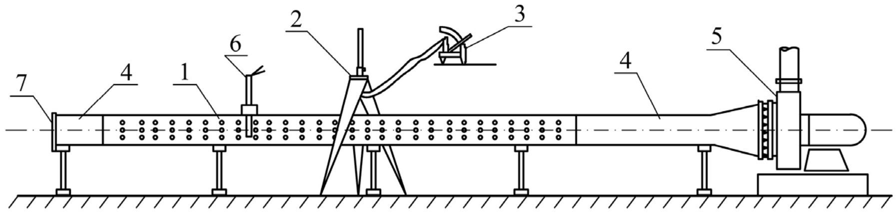

Fig. 1. Schematic of aerodynamic experimental installation: 1 – examined pipeline; 2 – coordinator with a measuring tube; 3 – micromanometer; 4 – solid section of the pipe; 5 – fan with an electric motor; 6 – strain gauge; 7 – stub

Our experimental study employed a perforated pipeline that, in terms of its design characteristics, in particular the diameter, length, character of perforation, corresponded to the characteristics of pipelines used at actual treatment structures. When operating these pipelines on the model and in the field, we maintained the turbulent mode of fluid movement, both when moving the main flow through the pipe and when it entered through the holes of the perforation. The Reynolds' number, depending on operating conditions, ranged between 10,000 and 120,000. That is, the hydraulic conditions of pipeline operation on the model and in the field were the same.

The pressure and liquefaction in the working pipeline were provided by a centrifugal fan, which was mounted on a fixed monolithic foundation. Depending on the features of the experiment, the end of the pipeline was either closed or open. The measurements used appropriate working and measuring equipment and instruments. The procedure for treating the results from our experiments corresponded to the tasks set.

5. Results of studying the dependence of a perforation hole flow rate factor on the structural characteristics of a collecting pipeline

5. 1. Results from the experimental and theoretical studies

Fig. 2 shows the results of measuring the change in the (U_h/V) characteristics (the ratio of the velocity of a stream entering a hole U_h to the average flow velocity in the corresponding cross-section of the pipe V) and $U_{h.av}/V_f$ (the ratio of the liquid entering velocity, averaged for the entire pipe, to the average flow velocity in the final cross-section of this pipe) depending on the ratio $x'=\alpha_{in}x/\Omega$ (or $f=\alpha_{in}l/\Omega$). Here, $\alpha_{in}=\sum\omega_h/l$ is the area of perforation holes per unit of pipe length.

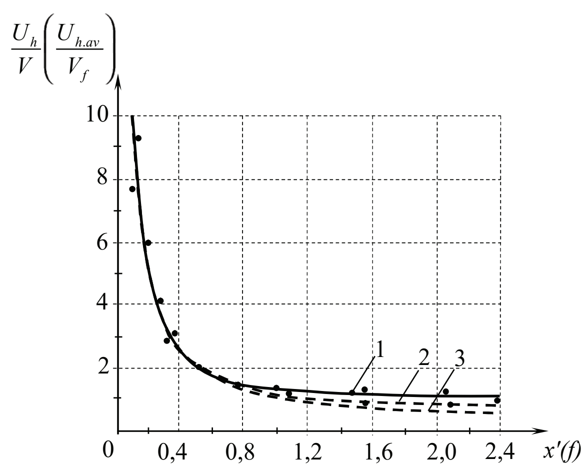

Fig. 2. Change in the ratio of the velocity of the connected liquid masses to the average velocity in the cross-section

In the chart, curve 1 (designation – •) characterizes the change in a given ratio along the pipeline length for different values of the structural parameter f for the case of using the values of the perforation hole flow rate factor μ_{col} that vary along the path. Curve 2 corresponds to the case when the calculations employ the values of the flow rate factor that are constant for a given particular value of the parameter $f(\mu_{col.av})$. Curve 3 shows a change in the ratio of the average incoming velocity for the entire collector to the average velocity at its final cross-section ($U_{col.av}/V_f$) at the same f values.

The above charts show that there is a fairly good match between the three curves. This is especially true within the limits of those structural characteristics of the collectors ($0.4<f<1.0$) that are commonly applied in practice. This circumstance indicates that it is also possible, when calculating the structural and hydraulic characteristics of collecting pipelines, to use the parameters that are averaged for a given channel and that this, within the permissible error, would correspond to the real pattern of the movement of the liquid at a flow rate that increases along the path.

To elucidate the character of change in the characteristics of collecting pipelines, it is useful to consider a chart in Fig. 3, which shows a change in the ratio of the Reynolds' number in the perforation hole to the Reynolds' number, which is calculated at an average velocity in the corresponding cross-section $\frac{\mathrm{Re}_h}{\mathrm{Re}}=\frac{U_h d_h/\nu}{VD/\nu}$ depending on the diameter of the perforation holes d_h.

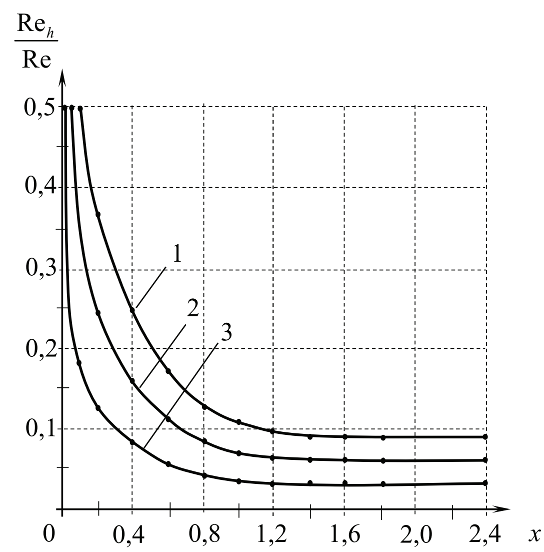

Fig. 3. Charts of changes in the $\mathrm{Re}_h/\mathrm{Re}$ ratio lengthwise the collector: 1 — d_h=0.003 m; 2 — d_h=0.006 m; 3 — d_h=0.009 m

The resulting graphical dependences demonstrate that under a turbulent mode of fluid movement in the holes of perforation and in the cross-sections of a collecting pipeline, the greatest value of the U_h/V and $\mathrm{Re}_h/\mathrm{Re}$ ratios is achieved at the initial sections of the collecting pipes and gradually decreases to the end of the pipeline. The same trend is in place relative to the distortion of the field of averaged velocity. It can also be concluded that the U_h/V, $U_{h.av}/V_f$, and $\mathrm{Re}_h/\mathrm{Re}$ ratios are greater in pipelines that have a lower value for the structural parameter f. When one increases f, these values will decrease.

The dependence of a flow rate factor, lengthwise variable, on the considered velocity ratios is shown in Fig. 4.

When calculating collecting perforated pipelines, it is important to be able to analytically estimate the considered ratios of velocities U_h/V, $U_{h.av}/V_f$ depending on the structural characteristics of the pipes. We shall use the approach proposed in [16], according to which the operational scheme of the examined collecting pipeline takes the following form (Fig. 5).

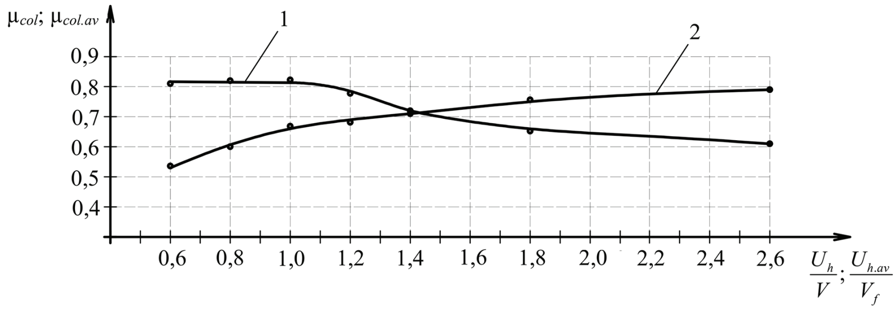

Fig. 4. A flow rate factor dependence on the considered velocity ratios: 1 – lengthwise variable flow rate factor value (U_h/V); 2 – lengthwise constant flow rate factor value ($U_{h.av}/V_f$)

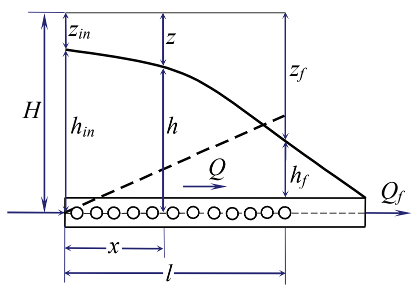

Fig. 5. Schematic operation of the collecting pipeline

As shown in many works, for example [14, 17], the movement of liquid with a variable flow rate in perforated pipelines is described by a system of differential equations, namely the equation of variable mass hydraulics and the equation of outflow through the hole

$$\frac{\mathrm{d}h}{\mathrm{d}x}+\frac{A}{g\Omega^2}Q\frac{\mathrm{d}Q}{\mathrm{d}x}+\frac{\lambda_{col}}{2g\Omega^2 D}Q^2=0, \tag{4}$$

$$\frac{\mathrm{d}Q}{\mathrm{d}x}=\mu_{col}\alpha_{in}\sqrt{2gz}, \tag{5}$$

where μ_{col}, λ_{col} are, respectively, the flow rate factor and the hydraulic friction coefficient of the collecting pipeline (accepted to be lengthwise constant); A is a parameter that is equal to 2 for these pipes; D, Ω is the diameter and area of the transverse section of the pipeline. Other designations are given in Fig. 5.

The solution to the initial system of differential equations (4), (5) takes the form:

– the relative flow rate at the end of the collector

$$\bar{Q}_f=\frac{1}{k}\mathrm{th}\left(k\bar{f}\right); \tag{6}$$

– the relative flow rate in an arbitrary cross-section

$$\bar{Q}=\frac{1}{k}\frac{\mathrm{sh}\left(k\bar{x}\right)}{\mathrm{ch}\left(k\bar{f}\right)}; \tag{7}$$

– the relative drop in heads in the same cross-section

$$\bar{z}=\frac{\mathrm{ch}\left(k\bar{x}\right)}{\mathrm{ch}\left(k\bar{f}\right)}. \tag{8}$$

Since $U_h=\mu_{col}\sqrt{2gz}$ and $V=Q/\Omega$, and by using new variables:

$$\bar{Q}=\frac{Q}{\Omega\sqrt{2gz_f}},\quad \bar{x}=\frac{\mu_{col}\alpha_{in}x}{\Omega},\quad \bar{z}=\sqrt{\frac{z}{z_f}}, \tag{9}$$

we shall obtain after simple transforms:

$$\frac{U_h}{V}=\frac{\mu_{col}\sqrt{2gz}}{\bar{Q}\sqrt{2gz_f}}=\frac{\mu_{\mathrm{col}}\bar{z}}{\bar{Q}}= =\mu_{col}\frac{\mathrm{ch}\left(k\bar{x}\right)/\mathrm{ch}\left(k\bar{f}\right)}{\mathrm{sh}\left(k\bar{x}\right)/k\cdot\mathrm{ch}\left(k\bar{f}\right)}=\frac{\mu_{col}k}{\mathrm{th}\left(k\bar{x}\right)}, \tag{10}$$

$$\frac{U_{h.av}}{V_f}=\frac{\mu_{\mathrm{col.av}}}{2}\frac{\bar{z}_{in}+1}{\bar{Q}_f}=\frac{k\mu_{\mathrm{col.av}}}{2}\frac{\mathrm{ch}\left(k\bar{f}\right)+1}{\mathrm{sh}\left(k\bar{f}\right)}. \tag{11}$$

where $\bar{f}=\mu_{col}\alpha_{in}l/\Omega$ is the pipeline duty factor.

The value of the k coefficient should be found on the basis of the chart given in work [18].

For relatively short collecting pipelines ($\zeta_l=\lambda l/D<2$), the coefficient $k=\sqrt{2}$.

Then ratios (10), (11) will take the form

$$\frac{U_h}{V}=\frac{\mu_{col}\sqrt{2}}{\mathrm{th}\left(\sqrt{2}\bar{x}\right)}, \tag{12}$$

$$\frac{U_{h.av}}{V_f}==\frac{\mu_{col.av}}{\sqrt{2}}\frac{\mathrm{ch}\left(\sqrt{2}\bar{f}\right)+1}{\mathrm{sh}\left(\sqrt{2}\bar{f}\right)}. \tag{13}$$

Fig. 6 shows data for a collector that operates without a transit.

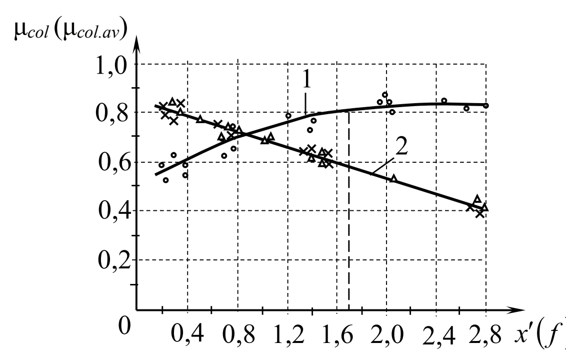

Fig. 6. Charts for determining the flow rate factor for collecting pipelines: 1 – variable values lengthwise the channel; 2 – the averaged values for the entire pipe

5. 2. Results of processing experimental data on determining a perforation hole flow rate factor μ_{col}

Based on processing the results of our experiments, as well as the data and analysis of existing experiments, we propose the empirical dependences to determine the flow rate factor of a collecting pipeline, which operates without a transit:

– a lengthwise variable value for the collector

$$\mu_{col.av} = 0.72x'^{0.17}; \tag{14}$$

– the averaged value lengthwise the same pipeline

$$\mu_{col.av} = 0.85 - 0.156f. \tag{15}$$

5. 3. Assessment of the impact of the transit flow on the operating conditions of collecting pipelines

During the experiments, we also investigated the impact of the transit flow on the main kinematic characteristics of flows in collecting pipelines. For collectors, an accepted transit flow rate was the flow rate at the beginning of the perforated part of the pipeline. Its value was adjusted by a valve installed at the initial cross-section.

Fig. 7 shows the character of the change in the ratio of relative path flow rate, which is connected along the entire length of the pipe, to the relative flow rate in its final cross-section $\left(\bar{Q}_p / \bar{Q}_f\right)$ depending on the duty factor $\bar{f}$ when passing the transit flow rate $\bar{Q}_{tr}$.

The upper straight line corresponds to the absence of the transit flow rate $\left(\bar{Q}_{tr} = 0\right)$. In this case, the flow rate in the final cross-section will be equal to that along the path. An increase in the transit flow rate leads to an increase in the total flow rate at the end of the pipe; however, the share of the connected flow rate is reduced.

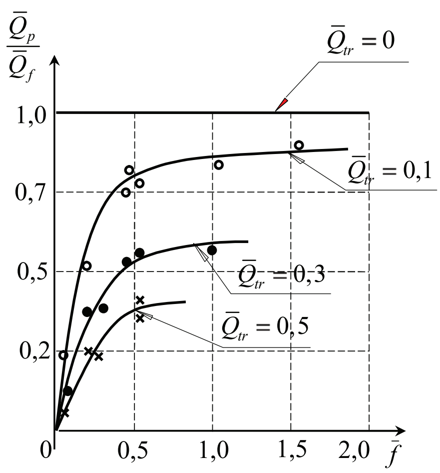

Fig. 7. Chart of change in the relative path flow rate at the end of the pipe depending on $\bar{f}$ and $\bar{Q}_{tr}$, ○, ●, × – experimental data

The empirical dependence to determine the value of the flow rate factor, averaged for the entire collector, in the presence of transit takes the form

$$\mu_{col.av} = 0.85 - 0.156f\left(1 - \frac{Q_{tr}}{Q_f}\right)^{0.5} + 0.12\frac{Q_{tr}}{Q_f}. \tag{16}$$

It shows that the presence of a transit flow rate in the cross-section of the collecting pipeline significantly affects the value of the perforation hole flow rate factor and it must be mandatorily taken into consideration in the calculations.

6. Discussion of results of studying the impact of the characteristics of collecting pipelines on a perforation hole flow rate factor

The estimation dependences (14) to (16) reported in this work describe fully enough the experimental results obtained within $0.1<f<2.8$ and $\delta_*=0.3–1.4$, corresponding to the parameters of actual catchment systems of treatment structures of water supply and sewerage systems.

We have confirmed a significant increase in the value of the flow rate factor when collecting liquid, compared to its value for a single hole, due to the presence of a certain effect of ejection, which is created by the interaction of the main flow in the channel and the jet running through the hole of the perforation.

As noted above, for engineering calculations of the considered pipelines, the simplest and most convenient to use are the dependences in which the value of the flow rate factor $\mu_{col.av}$ are accepted constant lengthwise the collector and is determined depending on its design characteristics (15), (16).

In collecting pipelines, when passing a transit flow rate, in the section in front of the perforated part, the diagrams of averaged velocities demonstrate a standard character, similar to the uniform movement. Under the influence of incoming streams, the field of the averaged velocities gradually deforms along the perforated part. The intensity of this transformation depends on the ratio between the transit and path flow rates (Q_{tr}/Q_p), as well as on the value of the structural parameter f. The lower values of these values correspond to the more active adjustment of the velocity field in the corresponding cross-sections. The increase in transit flow rate causes some increase in the flow rate factor values. This circumstance can be explained by the increased impact of the effect of ejection from the transit flow on the connected part of the flow rate.

Our study results, obtained through the study of a hydrodynamic flow structure inside collecting perforated pipelines, cover a wider range of changes in their structural characteristics. Thus, the value of the structural coefficient of the perforated pipeline varied within $0.1<f<2.8$; in this case, the ratio of the thickness of the pipe wall to the diameter of the perforation hole was $\delta_*=0.3–1.4$. These characteristics of the considered pipes comply with the acting norms and are used in the design and operation of catchment systems.

The area of further research includes the task of calculating the parameters of the specified pipelines in the presence of uneven perforation of the walls and a variable cross-section lengthwise the channel. Of special importance for understanding the peculiarities of fluid movement with a variable flow rate is the issue of studying the pulsation characteristics of these currents.

7. Conclusions

1. The result of our study has assessed the derived analytical solution to the initial differential equations, which describe the movement of liquid in collecting pipelines operated at a variable flow rate along the path. It is shown that the use of the proposed analytical dependences in the calculations and the application of appropriate empirical formulae in them makes it possible to obtain their fairly good agreement (up to 5 %).

2. Based on our experimental study, the relatively simple and user-friendly empirical formulae have been

proposed to determine the flow rate factor of perforation holes depending on the ratio of the velocities of the connected and main flows. It was established that the value of the lengthwise variable perforation hole flow rate factor μ_{col} increases lengthwise the pipeline, and the value that is average for the entire collector decreases with an increase in the length of the channel.

3. The impact of a transit flow rate on the value of the flow rate factor μ_{col} has been estimated. It was found that an increase in the transit flow rate from 0 to Q_{tr}/Q_f=1 at a change in the pipe duty factor from 0.1 to 2.8 leads to an increase in the perforation hole flow rate factor $\mu_{col.av}$, averaged for the entire collector, by 16–95 %, respectively.

Acknowledgments

We are grateful for the financial support to the research project at the Kyiv National University of Construction and Architecture 5 DB-2018 on the implementation of scientific studies, carried out with the support from the Ministry of Education and Science of Ukraine.

Reference

1. Egorov, A. I. (1984). Gidravlika napornyh trubchatyh sistem v vodoprovodnyh ochistnyh sooruzheniyah. Moscow: Stroyizdat, 95. Available at: http://books.totalarch.com/node/6916
2. Saitov, V., Kotyukov, A. (2019). Water filter with central perforated pipe for livestock complexes. IOP Conference Series: Earth and Environmental Science, 403, 012159. doi: https://doi.org/10.1088/1755-1315/403/1/012159
3. Polyakov, V., Kravchuk, A., Kochetov, G., Kravchuk, O. (2019). Clarification of aqueous suspensions with a high content of suspended solids in rapid sand filters. EUREKA: Physics and Engineering, 1, 28–45. doi: https://doi.org/10.21303/2461-4262.2019.00827
4. Gorkin, N. A. (1964). Koeffitsient rashoda pri sbore vody shchelevymi trubami. Vodosnabzhenie i sanitarnaya tehnika, 10, 34–37.
5. Clemo, T. (2006). Flow in Perforated Pipes: A Comparison of Models and Experiments. SPE Production & Operations, 21 (02), 302–311. doi: https://doi.org/10.2118/89036-pa
6. Murphy, P., Kaye, N. B., Khan, A. A. (2014). Hydraulic Performance of Aggregate Beds with Perforated Pipe Underdrains Flowing Full. Journal of Irrigation and Drainage Engineering, 140 (8), 04014023. doi: https://doi.org/10.1061/(asce)ir.1943-4774.0000740
7. Yuan, H., Sarica, C., Miska, S., Brill, J. P. (1997). An Experimental and Analytical Study of Single-Phase Liquid Flow in a Horizontal Well. Journal of Energy Resources Technology, 119 (1), 20–25. doi: https://doi.org/10.1115/1.2794217
8. Al'tshul', A. D. (1970). Gidravlicheskie soprotivleniya. Moscow: Nedra, 216. Available at: https://www.libex.ru/detail/book809719.html
9. Krogstad, P.-A., Kourakine, A. (1999). The response of a turbulent boundary layer to injection through a porous strip. Turbulence and Shear Flow. First Symposium on Turbulence and Shear Flow Phenomena. California, 1, 429–434. Available at: http://www.dl.begellhouse.com/references/3ce1b491115b5c16,17cc020a1e8f98da,50d9cfba30f65c40.html
10. Shima, N., Saito, N., Okamoto, M. (1999). Prediction of Wall-Bounded Turbulent Flows with Blowing and Suction. Testing of a Second-Moment Closure without Wall-Reflection Redistribution Terms. JSME International Journal Series B, 42 (4), 626–633. doi: https://doi.org/10.1299/jsmeb.42.626
11. Chehunov, V. I., Chehunov, P. V. (1990). Koeffitsient rashoda otverstiya perforatsii stenki truby pri pritoke vody. Sovershenstvovanie metodov gidravlicheskih raschetov vodopropusknyh i ochistnyh sooruzheniy. Saratov, 86–90.
12. Na, T. Y. (1972). Analysis of Turbulent Pipe Flow With Mass Transfer. Journal of Basic Engineering, 94 (3), 700–703. doi: https://doi.org/10.1115/1.3425529
13. Taliev, V. N. (1979). Aerodinamika ventilyatsii. Moscow: Stroyizdat, 295. Available at: http://books.totalarch.com/aerodynamics_of_ventilation
14. Naumenko, I. I., Voloshchuk, V. A. (2001). Matematychni modeli dlia hidravlichnykh rozrakhunkiv truboprovodiv z dyskretno zrostaiuchymy vytratamy. Visnyk Rivnenskoho derzhavnoho tekhnichnoho universytetu, 1 (8), 88–99.
15. Eliahou, S., Tumin, A., Wygnanski, I. (1998). Laminar–turbulent transition in Poiseuille pipe flow subjected to periodic perturbation emanating from the wall. Journal of Fluid Mechanics, 361, 333–349. doi: https://doi.org/10.1017/s002211209800888x
16. Kravchuk, A., Kravchuk, O. (2018). The examples of hydraulic calculations of pressure collecting and distributing perforated pipelines. Problems of water supply, sewerage and hydraulic, 30, 31–35. Available at: http://wateruse.org.ua/article/view/204850/204766
17. Claudio, D. (1961–1962). Icondotti emungenti da in serbatoio. Contronto fra risultati teorici esperimentali atti e men. Accad. patav. scilettere ed arti, 74 (2), 188–197.
18. Vasilenko, A. A., Kravchuk, A. M. (1991). Gidravlicheskiy raschet sbornyh truboprovodov v sooruzheniyah vodosnabzheniya i vodootvedeniya. Gidravlika i gidrotehnika, 52, 57–61.