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The effects of morphometric elements of the channel on hydraulic resistance of machine channels of pumping stations

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Abstract. Presents the results of hydraulic studies in pressureless and pressure water conduits, the results of which showed that the dependences obtained for calculating the hydraulic resistance in round pressure pipes cannot be distributed without the corresponding adjustments of pressureless channels (provided that the diameter of the pipe is replaced in the corresponding calculations with a value where hydraulic radius). In particular, it follows (and this is confirmed by the data of the corresponding experimental studies published in the literature) that in the case of pressureless channels, the pressure loss coefficient, and therefore the pressure loss, depends not only on the relative roughness and Reynolds number, but also on the shape of the cross section the channel. Moreover, if for hydraulically smooth pressureless channels this dependence can be considered to a first approximation clarified, then for channels whose wetted surface is characterized by the presence of a certain roughness, the question of its influence, as well as the shape of the channel cross section on the pressure loss, is far from roughly approximate solution. The paper also considers the general equation of fluid motion in pressureless channels and the functional dependences of the coefficient of hydraulic friction on the Reynolds number, relative roughness, and on the shape of the living section of the channel; resistance formulas are first for the simplest with respect to the cross-sectional shape of the channels (round and infinitely wide rectangular), and then for channels with a more complex cross-sectional shape. To take into account the effect (on the pressure loss) of the channel cross-sectional shape and the presence of a flow with a free surface in it, additional correction factors are introduced (using the hydraulic radius concept) as well as new dependencies and formulas for determining the hydraulic friction coefficient are given, s taking into account the influence of morphometric elements of the channel on the hydraulic resistance of the machine channels of pumping stations.

1. Introduction

The issue of head losses with uniform steady motion in cylindrical channels — head length losses — has more than a century of history. The currently widely used calculated dependences for determining the Shezy coefficient are based on the assumption that the longitudinal shear stresses acting from the flow side on the channel walls are uniformly distributed along the wetted perimeter. Estimating the acceptability of this assumption for flows with different cross sections, three different groups of channels can be distinguished.

Group 1. In such channels, the assumption corresponds to reality exactly (in the case of round-cylindrical pressure channels) or almost exactly, so that in practical calculations the error is negligible (for example, in the case of very wide rectangular channels - pressure and pressureless - excluding sections of the cross-section directly adjacent to to the short sides of the rectangle, the flow can be considered flat and it can be assumed that the shear stresses along the long side of the rectangle are uniformly distributed).

Group 2. The assumption is not accurate enough with reality, and the error in performing practical calculations is not acceptable, however, for a wide range of Reynolds numbers, you can make an adjustment that takes into account the geometric features of the shape of the living section, and thereby ensure the required accuracy of calculations. We will say that the channels belonging to the second group have a "regular" shape. As the preliminary analysis showed, this group for the case of non-pressure movement can be attributed, in particular, rectangular, trapezoidal, parabolic, semicircular, which are often found in the practice of hydraulic engineering and hydropower construction, including the pump canals of pumping stations.

Group 3. In the beds of this group, the Weisbach-Darcy formula requires the introduction of corrections that depend not only on the geometric formula of the channel, but also on the Reynolds number, which makes the use of this formula practically impractical. This group includes channels, for example, with a star-shaped cross section.

In this work, we plan to study the pressure losses along the length during the non-pressure movement of water in the channels of the "regular" shape, i.e. in the channels of the 2nd group.

Until recently, it was believed that in pressure less channels with the "correct" cross-sectional shape, its effect on the pressure loss can be always estimated with an acceptable approximation using the hydraulic radius. However, this situation is far from always ensured in the case of channels having a "regular" shape, cross section [1,2]. The authors indicated in the literature showed that for pressure less channels with the "correct" cross-sectional shape, the hydraulic radius as a parameter that must take into account its influence on the pressure loss in these channels is insufficient. The work of a number of authors (as already mentioned and some others [3], it was also shown that the dependences obtained for calculating hydraulic resistance in round pressure pipes cannot be distributed without corresponding adjustments for pressureless channels (provided that the diameter of the pipe is replaced in the corresponding calculations D - size $4R$, where R - hydraulic radius). This situation is justified by the presence of a number of factors that distinguish the pressure movement of the liquid in the pipes from its pressure less movement in the channels, where there is a free flow surface, a wider range of roughness of the bottom and channel walls, a different (than in the pipes) distribution of shear stresses along the wetted perimeter, the possibility of the existence of two different flow states (depending on the slope of the channel bottom), etc. From this, in particular, it follows (and this is confirmed by the data of the corresponding experimental studies published in the literature) that in the case of pressureless channels, the head loss coefficient, and hence the pressure loss, depend not only on the relative roughness and Reynolds number, but also on the shape channel cross section. Moreover, if for hydraulically smooth pressureless channels this dependence can be considered to a first approximation clarified, then for channels whose wetted surface is characterized by the presence of a certain roughness, the question of its influence, as well as the shape of the channel cross section on the pressure loss, is far from roughly approximate solution.

Since, until now, there are no analytical dependences that completely describe the mechanism of turbulence and are suitable for practical calculations related to the non-pressure motion of a fluid, it is necessary to resort to experimental studies [4]. Due to the lack of sufficient knowledge of the factors determining the patterns of fluid movement in pressureless channels, as well as engine channels, it is accepted that the patterns of flow in round pressure pipes are also applicable to pressureless channels, if in their calculation we have in mind the hydraulic radius and not the diameter (as is done with respect to round pipes, with pressure movement).

2. Method

Analysis of the operation of the machine channels of pumping stations in various modes, operating in various hydraulic conditions and various values h - depth of flow, Ṛ- hydraulic radius and χ – wetted perimeter of the live flow section, taking into account the influence of the morphometric elements of the channel on the hydraulic resistance of the machine channels, is a method for studying this.

3. Results and discussion

The obtained experimental data showed that the intensity of the influence of morphometric elements of the channel on the hydraulic resistance of the machine channels is directly dependent on the operating mode of the pumping stations. The experimental studies published in the literature were carried out in order to clarify the above assumptions and clarify the mentioned patterns in pressureless channels, as well as engine channels, performed at different times and in different conditions, some of their results do not always agree with each other, and the calculated dependences recommended on their basis are very contradictory. In particular, the question of the influence of morphometric elements of the channel and its dimensions on the patterns of hydraulic resistance is not completely clear. To determine the equivalent height of the protrusions of the roughness and the location of the protrusions in the above channels, we constructed dependency graphs $\lambda_R = f\,(Re_R)$ and $\lambda_{R=}\ f\,(R)$, and $\Delta = f\,(R)$ for each series of our experiments and the series of experiments of Bazin.

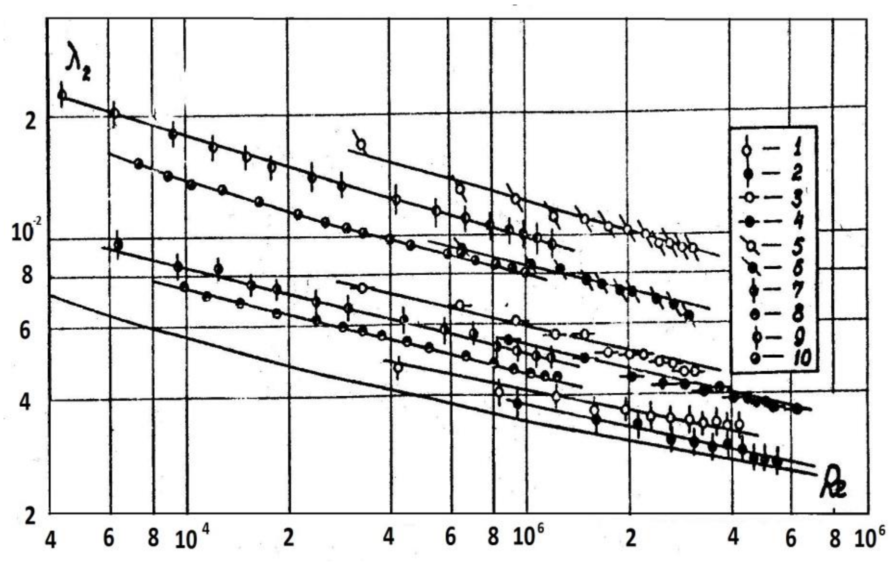

Figure 1. Dependence ʎ = *f (Re)*

1 – Bazin's experiments, series № 2, rectangular channel, surface of the bottom and walls - smooth concrete, 2 – same, series №. 24, semicircular canal, surface of the bottom and walls - smooth concrete, 3 – the same, series №. 6, a rectangular channel, the surface of the bottom and walls - desks, 4 – the same, series №. 26, a semicircular canal, the surface of the bottom and walls - boards, 5 - the same, series №. 4, a rectangular channel, the surface of the bottom and walls – gravel d = 0,01-0,02 м, 6 – same, series No. 27, semicircular canal, surface of the bottom and walls – gravel d = 0,01-0,02 м , 7 – experiments of the author, series №. 1, rectangular channel, surface of the bottom and walls – smooth concrete, 8 – author's experiments, series No. 3, trapezoidal canal, surface of the bottom and walls – smooth concrete, 9 – same, series No. 8, a rectangular channel, the surface of the bottom and walls – face d = 0,5 – 0,7 см, 10 – same series № 7, trapezoidal canal, surface of the bottom and walls – gravel d = 0,5-0,7 sm.

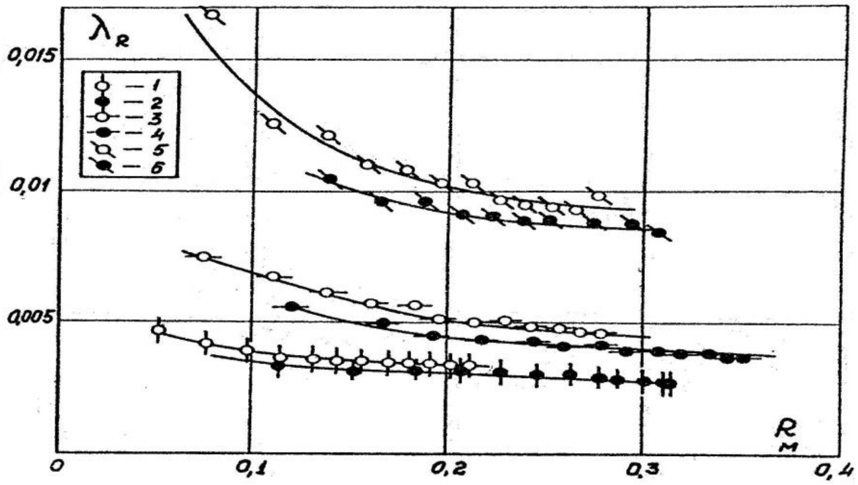

Figure 2. Dependence λ_R on R.

1.2 - experiments of Bazin, series № 2, 24, rectangular and semicircular channels, the surface of the bottom and walls of the channels - smooth concrete, 3, 4 - the same, series № 6, 26, rectangular and semicircular channels, the surface of the bottom and walls of the channels - boards , 5.6 - the same, series № 4.27, rectangular and semicircular channels, the bottom surface and the walls of the channels-gravel d = 0.1-0.02 m.

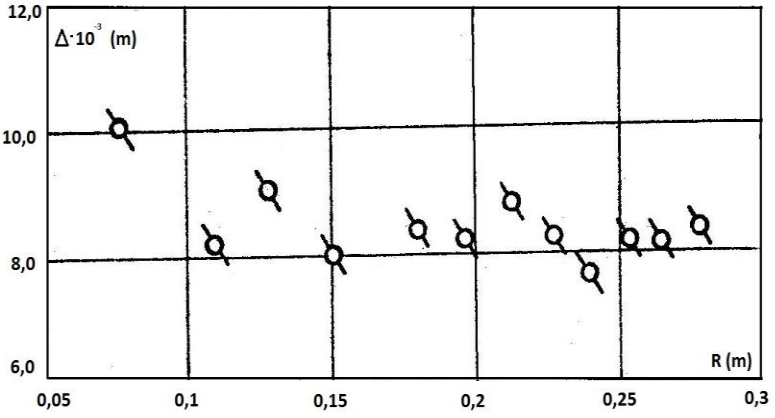

Figure 3. Dependence Δ = *f(R)*

Bazen's experiments, series № 4, a rectangular channel, the surface of the bottom and walls - gravel, d = 0,01 - 0,02 м , B = 1,832 м , i = $4.9\ 10^{-3}$

Moreover, a comparison of the values of the height of the protrusions of the absolute equivalent roughness for the pressureless machine and derivation channels under consideration, and in particular, channels of rectangular cross-section, calculated both under the assumption that the roughness of their walls is even-grained and under the assumption that their roughness is formed by protrusions of different sizes, rather indicates the validity of the second assumption. Based on this, the average values of the height of the protrusions of the equivalent roughness for channels of rectangular cross-section were determined by the interpolation formula:

$$1/\sqrt{\lambda_R} = 4.06\lg\left[11{,}03(3.3/\mathrm{Re}_{*R} + \Delta_{э}/R)\right] \quad (1)$$

Moreover, it was assumed that the Δ_e values obtained for the largest Δ / R ratios for these channels correspond to a plane. The Δ_e value corresponding to a rectangular channel of infinite width can also be determined from the N. Wagner dependence [1]. In addition, it was assumed that the cross-sectional shape effect manifests itself only in the second term of the denominator of this formula (1). From the experimental data of Bazin, in particular, it follows that for the same values of R, the value of λ for the channel of a semicircular cross section can be less than that for a channel of rectangular section by about 1.3 times. If in a certain range of Reynolds numbers on a graph expressing the relationship between λ_R, Re_R draw the corresponding curves for a channel of a very wide rectangular section; for a channel of a rectangular section of finite width, as well as for channels of a trapezoidal, triangular and semicircular section having the same slope and the same roughness of the wetted surface, it turns out that these curves are located from top to bottom in the following order: a very wide channel, and then channels of a rectangular, trapezoidal, triangular and semicircular cross section. The corresponding curves of the dependence of λR on the number Re_R in this case will run approximately parallel to the curve reflecting the law of “smooth resistance”. It is worth noting that the indicated order of the arrangement of the curves of the dependences of λ_R on the Reynolds number Re_R will change significantly, and at the same time, the shape of the curves themselves will also change if, for example, the quantity λ (hydraulic friction coefficient) is attributed not to the hydraulic radius R, but to the greatest depth h in the channel, i.e. calculate λ_h and Reynolds number $Re_h=Vh/\nu$.

The experimental data of Bazin in channels with regular cross sections of various geometric shapes (rectangular, trapezoidal, triangular, semicircular), as well as experimental data on the flow in rectangular and trapezoidal channels, obtained in this work; the results of some published data on water flows in channels of various geometric shapes were summarized on a graph in coordinates $[R/\chi\,(\lambda_{pl}/\lambda)^3;\ \lambda_{пл}/\lambda]$.

The results of processing experiments conducted with these channels are given in [2]. On the indicated graph, the points (Fig. 4) corresponding to the experimental data of Bazen [3], L.P. Neronova, Y.P. Titova [3], N.D. Kasyanova [4] and the authors of this work are quite well located near line having an equation of the form:

$$\lambda_{пл}/\lambda = R/\chi\,(\lambda_{пл}/\lambda)^3 + 1{,}0 \qquad (2)$$

Whence for the quantity λ we obtain the following cubic equation,

$$\lambda^3 - \lambda_{pl}/\lambda^2 + R/\chi\lambda^3_{pl} \qquad (3)$$

here λ – desired hydraulic friction coefficient; λ_{pl} – flat flow hydraulic friction coefficient; R– hydraulic radius; χ – wetted perimeter.

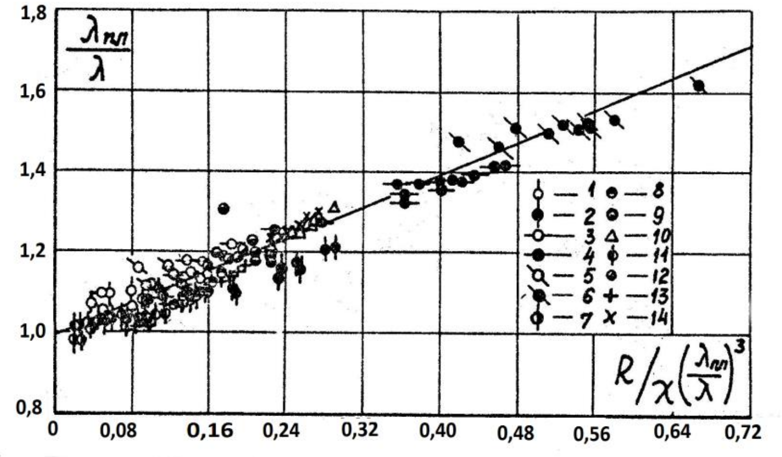

Figure 4. Dependence $\frac{\lambda пл}{\lambda} = f\left[R/\chi\left(\frac{\lambda пл}{\lambda}\right)^3\right]$

1,2 – experiments of Bazin, series № 2, 24; 3.4 – also series № 6, 26; 5.6 is the same series № - 4, 27; 7, 8 - experiments of the author, series № 1, 3; 9, 10 – experiments of Bazin, series № 23, 21; 11, 12 - experiments of the author, series № 6, 7, 13 - experiments of Neronova L.P., Titov Y.P. (rectangular channel); 14 - experiments of Kasyanova N.D. (triangular channel).

Equation (3) can be resolved with respect to the value for known values $\lambda пл.$, R и χ.

Consider the solutions of equation (3). The discriminant of equation (3) reduced to $y^3 + 3pg + 2q = 0$, where $y = \lambda - \lambda_{\text{pl}}/3$ vanishes at $R/\chi = 4/27$. At $R/\chi > 4/27$ discriminant is greater than zero and the cubic equation has one real solution:

$$\lambda = \lambda_{pl}\left[\sqrt[3]{\sqrt{\frac{1}{4}\left(\frac{R}{\chi}-\frac{2}{27}\right)^2-\frac{1}{9^3}-\frac{1}{2}\left(\frac{R}{\chi}-\frac{2}{27}\right)}}-\sqrt[3]{\sqrt{\frac{1}{4}\left(\frac{R}{\chi}-\frac{2}{27}\right)^2}}-\frac{1}{9^3}+\frac{1}{2}\left(\frac{R}{\chi}-\frac{2}{27}\right)\right] \quad (4)$$

At $R/\chi < 4/27$ discriminant is less than or equal to zero. In this case, equation (3) has three real solutions, of which (as the analysis showed) the conditions of the problem in question are satisfied only by a solution of the form.

$$\lambda = \frac{\lambda_{pl}}{3}\left\{1 + 2\cos\left[\frac{\arccos\left(1 - \frac{27}{2}R/\chi\right)}{3}\right]\right\} \quad (5)$$

4. Conclusions

- From a consideration of the collected experimental data with losses in the aforementioned pressureless channels, it follows that for several channels with different cross-sectional shapes, but with the same slopes and the same roughness of the wetted surface, the curves in the graph ($\mathrm{Re}_R = \vartheta R/\nu$, $\lambda_R = 2\vartheta_*^2/\vartheta^2$) will be arranged in the following order (top to bottom); a very wide channel of rectangular cross section, a relatively narrow channel of rectangular cross section, trapezoidal and triangular section channels, a semicircular cross section channel.

- The value of the coefficient of hydraulic friction for a very wide channel or a channel of rectangular cross-section, ceteris paribus, is greater than for a channel of a trapezoidal or semicircular section. In this case, the corresponding curves of the dependence on the number pass approximately parallel to the curve obtained for the law of "smooth resistance".
- From consideration of the results of experiments conducted;

a) Bazene in pressureless channels of a rectangular and semicircular cross section with a wetted surface of wood, smoothly grouted cement and concrete with gravel recessed in it ;

b) by us in channels of rectangular and trapezoidal cross-section with a wetted surface of smooth-concreted concrete and gravel;

v) some other authors (Neronova L.P., Titov Y.P., Kasyanova N.D. and others) – it follows that for the channels under consideration, the values of the coefficients of hydraulic friction can significantly (for example, 1.3 times) differ from each other under the same values of the hydraulic radius and other conditions being equal.

- The solutions of equation (3) given in the work can be resolved with respect to the value for known values λ_{pl}, R and χ.

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