Substantiation of the influence of the channel shape and the roughness of machine canals on the pressure loss of irrigation pumping stations

Bakhtiyor Uralov¹, Ruzimurod Choriev¹, Lyudmila Maksudova¹, Mukaddas Sapaeva¹, Anvar Shernaev² and Panji Nurmatov³

¹Tashkent Institute of Irrigation and Agricultural Mechanization Engineers, Tashkent, Uzbekistan
²Tashkent Institute of Chemical Technology, Tashkent, Uzbekistan
³Samarkand State Institute of Architecture and Construction, Samarkand, Uzbekistan

E-mail: vohidov.oymb@bk.ru

Abstract. To take into account the influence (on the value of head losses) of the channel cross-sectional shape and the presence of a flow with a free surface in it, additional correction factors are introduced (when using the concept of hydraulic radius), as well as new dependencies and formulas for determining the coefficient of hydraulic friction are presented, taking into account the influence of the morphometric elements of the channel on the hydraulic resistance of the machine channels of pumping stations. The article presents the results of hydraulic studies in free-flow and pressure water pipelines, the results of which showed that the dependencies obtained for calculating hydraulic resistance in round pressure pipes cannot be extended without appropriate adjustments to the pressure-free channels (provided that the pipe diameter is replaced in the corresponding calculations \( D \) - value \( 4R \), where \( R \) - hydraulic radius). This position is justified by the presence of a number of factors that distinguish the pressure movement of liquid in pipes from its free-flow movement in the channels, where there is a free flow surface, a wider range of roughness of the channel bottom and walls, a different (than in pipes) distribution of tangential stresses along the wetted perimeter, the possibility of two different flow states (depending on the slope of the channel bottom). The work also considers the general equation of fluid motion in free-flow channels and the functional dependences of the hydraulic friction coefficient on the Reynolds number, relative roughness and on the shape of the free section of the channel; resistance formulas, first for the simplest channels with respect to the cross-sectional shape (round and infinitely wide rectangular), and then for channels with a more complex cross-sectional shape.

1. Introduction
In the literature, the turbulent pressure movement of fluid in pipes with various types of uneven-grain roughness has been studied to a lesser extent [1]. This situation is due to fundamental difficulties associated with the fact that the variety of types of uneven roughness creates a variety of types of turbulent motion in pipes, each of which corresponds, strictly speaking, its own "law of resistance" (the law of pressure losses). Less fully (in comparison with axisymmetric) has been investigated at
present the plane-parallel turbulent pressure flow of fluid in wide rectangular smooth hydraulic channels [23]. Extensive experimental data obtained in the study of the two indicated types of turbulent fluid motion are in good agreement with the semiempirical theory of Prandtl–Karman near-wall turbulence constructed in due time [24, 25]. The unpressurized uniform movement of fluid in channels of various cross-sectional shapes has been completely insufficiently studied. Generally spatial turbulent flow in these channels can no longer be fully considered from the standpoint of the aforementioned theory [2, 26], the results obtained in the study of plane parallel turbulent flow in pressure channels allows here only to outline the structure of the corresponding dependences and to clarify that the simplest case of non-pressure fluid movement, when this movement can also be reduced to plane-parallel, or, in other words, to movement in a channel of infinitely large width with a flat bottom. In all other cases, the only way to solve the problem is experiment. But the possibilities of the experiment are limited, as limited, and in a number of cases debatable, and accumulated to date information on the uniform free-flow movement of fluid in channels of various cross-sectional shapes. From the data collected in [22] by Shiller and Nikuradze on the pressure flow of fluid in smooth channels of non-circular cross-section, it can be seen that these data are in close agreement with the mentioned Prandtl–Karman curve. Hence it follows that the effect of the influence of the shape of the living section of the channel on the value \( \lambda \) in the area of smooth resistance is small.

The object of research in this work is the Karshi machine channel (KMC), in the area of a damless water intake from the Amu Darya river bed of the Kashkadarya region of Uzbekistan. Sections of machine channels of pumping stations № 1 and № 2 of the "KMC Operations Department" were taken as the object of hydraulic research.

Subject of research: water supplying machine channels of pumping stations № 1 and № 2, “KMC Operations Department”; hydraulic and channel processes occurring in the supplying machine channels of pumping stations; turbidity of the stream; basic equations of hydrodynamics.

In connection with this formulation of the question and the purpose of the study of this work, it was to conduct laboratory experiments in free-flow machine channels with obtaining dependencies: 1) the influence of the shape of the free cross-section of the channel on the amount of pressure loss; a) in the case of a "smooth" wetted surface; b) in the case of a channel with a rough wetted surface; 2) the effect of the degree of roughness of the wetted surface on the amount of head loss.

In connection with the above, the following main research tasks can be formulated: 1) to collect experimental data on the pressure losses along the length at steady-state free-flow motion; 2) highlight the materials related to the channels of the "correct" form and analyze them; 3) to carry out additional experimental studies necessary to generalize the materials on head losses along the length in the case of channels of the "correct" shape; 4) generalize the issue of head losses along the length, taking into account the shape of the cross-section of the free-flow flow on the graphs \( \lambda = f(Re) \).

2. Results and Discussion
An extensive study of the turbulent movement of water in free-flow channels of rectangular cross-section with uneven-grained (sandy) artificial roughness of the surface of the bottom and walls of the channel was carried out by the author of [1]. The results of this study led the author of work [1] to the dependence graph:

\[
\lg \lambda_R = f \left( \lg \text{Re}, \frac{R}{\Delta} \right)
\]  
(1)

For a quadratic area of resistance, the author of [1] obtained the following dependence:

\[
\frac{1}{\sqrt{\lambda_R}} = 4 \lg \frac{R}{\Delta} + 4.25 = 4 \lg 11.5
\]  
(2)

where: \( \Delta \) - absolute granular roughness (the diameter of the grains of sand, which were glued to the surface of the bottom and walls of the channel to create uneven grain roughness).
Almost coinciding with each other, as well as close to formula (2) dependences for the region of quadratic resistance, were obtained by the authors of [2, 3].

Analyzing then Bazin’s experimental data and the values \( \beta \) for Bazin’s experimental trays, Kelegan comes to the conclusion that for the forms of cross-sections of trays and channels used in practice, it is possible, with sufficient accuracy for engineering calculations, to be taken for smooth surfaces:

\[
\frac{V}{V_*} = 5.751 \log \frac{RV}{V} + 3.25
\]

and for rough surfaces

\[
\frac{V}{V_*} = 5.751 \log \frac{R}{K_2} + 6.25
\]

The general theoretical equation obtained by Kelegan for the average speed of uniform motion in a free-flow channel can be written like this [4].

\[
V = V_* \left( \omega_0 + 5.751 \frac{mR}{y_0} \right)
\]

where: \( V \) - average flow rate; \( V_* \) - dynamic flow rate; \( R \) - hydraulic radius; \( \omega_0 \) - generalized constant depending on the shape of the channel cross-section.

Using Bazin's experiments for a wavy surface close to smooth, Kelegan obtained the value \( \omega_0 = 1.3 \) for small wooden canals and value \( \omega_0 = 3.0 \) for large wooden canals. In rough channels, he found that the value varied widely from 3.23 to 16.92. Analyzing then Bazin's experimental data, Kelegan took the average value for smooth surfaces \( \omega_0 = 25.30 \) and for rough surfaces \( \omega_0 = 25.60 \). A more detailed analysis of Bazin's experiments and some later studies showed that the approximate approach adopted, ultimately by Kelegan, to assessing the magnitude of the influence of the shape of the channel cross-section on the pressure loss by the mean value, especially in rough channels, is rather incorrect.

According to the author of the work [2]

\[
\frac{1}{\sqrt{\lambda}} = 4.061 \log \frac{R}{\Delta} + 4.42 = 4.061 \log 12.3 \frac{R}{\Delta}
\]

The author of the work [5] came to a dependence of the form:

\[
\frac{1}{\sqrt{\lambda}} = 4 \log \frac{R}{\Delta} + 4.38 = 4 \log 12.4 \frac{R}{\Delta}
\]

Dependence (7) was obtained by the author of [3] on the basis of his experimental study (similar to the study of AP Zegzhd [1]) the movement of water in a channel, the bottom of which had an artificial uneven-grain roughness. A dependence practically identical to dependences (6) and (7) is also proposed in [1].

Nikuradze [6] for the area of quadratic resistance in pipes at one time received the dependence:

\[
\frac{1}{\sqrt{\lambda}} = 4 \log \frac{R}{\Delta} + 4.68 = 4 \log 14.8 \frac{R}{\Delta}
\]

The author of [7], relying on the experimental data of Nikuradze, proposes a dependence of the form for free-flow flows:

\[
\frac{1}{\sqrt{\lambda}} = 4 \log \frac{R}{\Delta} + 3.46 = 4 \log 7.42 \frac{R}{\Delta}
\]

The author of the work [8], on the basis of the same experimental data, comes to a dependence of the form:
\[
\frac{1}{\sqrt{\lambda_R}} = 4.061 \log \frac{R}{\Delta} + 4.25 = 4.061 \log \frac{11.03 R}{\Delta}
\]

(10)

As you can see, the dependences obtained by various authors for the coefficient in free-flow channels with uniform artificial roughness have the form:

\[
\frac{C}{\sqrt{2g}} = \frac{1}{\sqrt{\lambda_R}} = a \log \frac{R}{\Delta} + b_3 = a \log \frac{c_3 R}{\Delta}
\]

(11)

And they differ in the values of the constants \(a\), \(b_3\), and \(c_3\). Proposed works [1 – 2] the values of these constants are collected in Table 1.

| Formula № | a  | \(b_3\) | \(c_3\) | Authors and published work. |
|-----------|----|--------|--------|----------------------------|
| 2         | 4.0| 4.25   | 11.25  | Zegjda                     |
| 6         | 4.06| 4.42  | 12.3   | Kelegan                    |
| 7         | 4.0| 4.38   | 12.4   | Erling                     |
| 5         | 4.06| 4.39  | 12.0   | Tiise                      |
| 8         | 4.0| 4.68   | 14.8   | Nikuradze                  |
| 9         | 4.0| 3.48   | 7.42   | Sabaneev                   |
| 10        | 4.06| 4.25  | 11.03  | Lyakhon                    |

The results of experimental studies of the authors of works [1, 3], considered above, on the movement of fluid in free-flow channels with unequal-grained artificial roughness, as it was said, qualitatively agrees with the data of Nikuradze on the pressure movement of fluid in pipes with uneven-grain roughness. Experimental points on the graph \(\Delta = f \left(\log \text{Re}, \frac{R}{\Delta}\right)\) at \(\Delta = \text{const}\) form curves, the origin of which lies on the curve of smooth resistance; then as the number increases \(\text{Re}\) these curves rise (region of transient resistance), and finally, upon reaching the region of complete turbulence (region of quadratic resistance), they occupy a position parallel to the abscissa axis. Curves corresponding to the experimental data of the authors of [2], obtained, as reported, also in channels with different-grain artificial roughness, on the graph \(\Delta = f \left(\log \text{Re}, \frac{R}{\Delta}\right)\) are arranged in a slightly different way than the curves of Zegzda, Erling, etc. These curves begin not from a smooth resistance curve, but from a certain curve parallel to it and located slightly above it. Further, the Warwick curves rise and turn into a horizontal position.

Another feature of the Warwick data is that the curves corresponding to the channel of the triangular cross-section, according to the Warwick data, do not coincide with the curves corresponding to the channel of the trapezoidal cross-section, for the same value \(\frac{R}{\Delta}\) (fig 1). The two named features of the Warwick curves in Fig. 1, the authors of some works [4] argue that these curves reflect the influence on the coefficient \(\lambda_R\) canal shapes. It is suggested that with the same roughness, the decrease in the value and dependence on the shape of the channel cross-section occurs in the following sequence: rectangular, triangular and round. The influence of the cross-sectional shape of the channel on the value according to the author of [4] is explained by the existence in the channels of a secondary flow, the most intense with a rectangular cross-section of the channel and the least intense in the channels with a circular cross-section. This secondary flow is a source of additional energy loss.

Schiller's experience, Nikuradze's experiments noted in [12] with smooth pressure channels of various cross-sectional shapes do not indicate such a significant, as in Warwick's, influence of the
channel shape on the coefficient $\lambda_R$. The data of the authors of works [1, 3, 13, 14] do not agree with the data of Warwick and the mentioned experiments.

For pipes with non-grained (technical) roughness, the author of [15] proposed a formula in the form:

$$\frac{1}{\sqrt{\lambda_D}} = -2\lg \left[ \frac{2.51}{\text{Re}_s} \frac{\Delta_3}{3.7D} \right]$$

(12)

where, $D$ - pipe diameter; $\Delta_3$ - equivalent granular absolute roughness.

At $\text{Re}_D \to \infty$ formula (12) turns into Nikuradze dependence for rough pipes in the area of quadratic resistance; at $\Delta_3 \to 0$ formula (12) takes the form of the Prandtl-Karman formula for the region of the same resistance.

Formula (12) can be rewritten as:

$$\frac{1}{\sqrt{\lambda_R}} = 4.1\lg \left( \frac{14.8}{\frac{3.3}{\text{Re}_{sr}} + \frac{\Delta_3}{R}} \right) = 4.69 - 4.1\lg \left( \frac{3.3}{\text{Re}_{sr}} + \frac{\Delta_3}{R} \right)$$

(13)

where $\text{Re}_{sr} = \frac{V^2R}{g} -$ Reynolds number recorded for dynamic speed; $V = \sqrt{gR}$ - dynamic speed.

As seen, at $\frac{3.3}{\text{Re}_{sr}} << \frac{\Delta_3}{R}$ formula (13) turns into formula (8), and at $\frac{\Delta_3}{R} << \frac{3.3}{\text{Re}_{sr}}$ - into formula (2). Formula (13) when calculating free-flow channels with non-grained roughness of the bottom and wall surfaces is suggested by the author of [14].

By substituting somewhat different values of the constants into formula (13), one can obtain a formula that, in the two indicated limiting cases, will lead to dependence (2) or (10). Such a formula is a formula of the form:

$$\frac{1}{\sqrt{\lambda_R}} = 4.06\lg \left( \frac{11.03}{\frac{3.3}{\text{Re}_{sr}} + \frac{\Delta_3}{R}} \right) = 4.24 - 4.06\lg \left( \frac{3.3}{\text{Re}_{sr}} + \frac{\Delta_3}{R} \right)$$

(14)

The author of [9] proposes a formula of the form for calculating free-flow channels with non-grained roughness:

$$\frac{1}{\sqrt{\lambda_R}} = 4.06\lg \left( \frac{12.0}{\frac{3.3}{\text{Re}_{sr}} + \frac{\Delta_3}{R}} \right) = 4.39 - 4.06\lg \left( \frac{3.3}{\text{Re}_{sr}} + \frac{\Delta_3}{R} \right)$$

(15)

Formula (15) in the two indicated limiting cases leads to dependencies (1) and (13). If in formulas (14) and (13) the influence of the flow state on the regularities of hydraulic resistance is taken into account by the term $\text{Re}_{sr}$, the term $\frac{\Delta_3}{R}$ should take into account the effect of roughness and shape of the free cross-section of the channel. Subsequent studies have shown that the hydraulic radius included in most formulas, which should fully take into account the influence of the shape of the free cross-section of the channel (on the pressure loss), does not fully meet this goal.

Quite detailed studies of the influence of the channel cross-sectional shape and the degree of roughness of the wetted surface on hydraulic resistance were carried out during the Second World War at the Higher University of Dresden. The main results of these studies were published shortly after the war by O. Kirschmer, in the form of graphs of dependence $\lambda = f \left( \text{Re}_{sr}; \frac{R}{\Delta} \right)$ (see Figure 1) for ducts of various cross-sectional shapes. The main result that this study led to, as can be seen, was that the experimental curves for different values of the relative roughness are connected not with the resistance curve for smooth surfaces, but with a curve almost parallel to it and spaced from it at a distance
depending on the roughness and on channel cross-sectional shapes. Studies have also shown that for the same hydraulic radius, the smallest coefficient of hydraulic friction is obtained in relatively narrower channels. In this work, on the basis of a planned flow velocity diagram, a method is proposed for the hydraulic calculation of prismatic channels.

The author of [21], who considered separately the laws of resistance of the side walls and the bottom of a rectangular channel, obtained a formula of the form:

\[
V = \sqrt{\frac{2g \cdot h}{\lambda_g \cdot \sqrt{1 + \frac{\lambda_c \cdot h}{\lambda_g \cdot B}}}}
\]

in which the average speed \( V \) in a rectangular channel is put in dependence on the coefficients of hydraulic friction of the bottom \( \lambda_g \) and side walls \( \lambda_c \).

Further, expressing the hydraulic radius of the flow in terms of its obtained width \( b \) and depth \( h \) the author obtained a relationship between the total resistance of the channel of the side walls and the bottom:

\[
\lambda = 4 \cdot \frac{h}{b} \left( \frac{1 + \frac{\lambda_c \cdot h}{\lambda_g \cdot b}}{1 + \frac{b}{h}} \right) \lambda_g.
\]

It is shown in the work that the coefficient of hydraulic friction of the flow against the side walls and the bottom of the channel can be expressed through the Reynolds number and the relative roughness of the side walls and the bottom of the channel in the following form:

\[
\lambda_c = f \left( \frac{\text{Re}_c \cdot A_c}{b} \right)
\]

\[
\lambda_g = f \left( \frac{\text{Re}_g \cdot A_g}{b} \right)
\]

where \( \text{Re}_c = \frac{V b}{\nu} \); \( \text{Re}_g = \frac{V h}{\nu} \).

Expression \( \text{Re}_c \) and \( \text{Re}_g \) through the Reynolds number of the entire flow can be represented as:

\[
\text{Re}_c = \frac{\text{Re}}{4} \left( 1 + \frac{b}{h} \right)
\]

\[
\text{Re}_g = \frac{\text{Re}}{4} \cdot \frac{1 + \frac{b}{h}}{\frac{b}{h}}
\]

The work used the experiments of L.A. Tepaks made in smooth rectangular pipes with the aspect ratio \( \frac{b}{h} = 1 \div 20 \); experiments of A.P. Zegzhda [1], made in smooth glass rectangular trays of different widths; experiments I. Nikuradze [6] in a smooth pipe with \( \frac{b}{h} = 1 \div 3.50 \); and the data of other authors, as well as the author's experiments carried out in air in a smooth rectangular channel 6 m long and 25 cm high with an aspect ratio varying from 1 to 25, led him to the need to rewrite the law of resistance for a flat flow in this form:
For rough channels:

\[
\frac{1}{\sqrt{\beta_{n,1}}} = 4 \lg \Re_{n,1} \sqrt{\lambda_{n,1}} + 0.70
\]  

(22)

For the case when the roughness is estimated using a coefficient, formula (16), according to the author, takes the form:

\[
V = \frac{C_{\text{dwa}} \sqrt{hi}}{\sqrt{1 + h \left( \frac{C_{\text{dwa}}}{b \left( \frac{C_{\text{cm}}}{C_{\text{dwa}}} \right)} \right)^2}},
\]  

(24)

Where: \(C_{\text{dwa}}\) – bottom Shezy coefficient calculated from the bottom roughness and flow depth \(h\); \(C_{\text{cm}}\) - Chezy coefficient of the side wall, calculated from the wall roughness and channel half-width \(b\).

The author's experimental data, obtained in studies carried out in a rectangular tray, showed that as the tray filling increases, the Shezy formula gives a systematic deviation from the experimental points up to 8%, and the calculation method proposed by him, taking into account the uneven distribution of friction stresses along the wetted perimeter of the channel, in to some extent compensates for the shortcomings caused by the application of the Shezy formula. It is shown that the carrying capacity of channels of different shapes can be determined using the same law of resistance of a flat channel, if the channel discharge is calculated from a planned plot of flow velocities, which makes it possible to take into account the uneven distribution of shear friction stresses. It is noted that the tabular values of the coefficient \(n\) for various materials are compiled according to the test results of channels of unequal shape, leads to an expansion of the range of recommended values of the coefficient \(n\) for the same material. In this regard, it is proposed to develop a scale of values for the coefficient \(n_{\text{m}}\).

According to the proposed method of hydraulic calculation of prismatic channels on the basis of the planned velocity diagram, it is possible to approximately estimate the magnitude of the error that occurs when calculating the cultivation capacity of open channels with different cross-sectional shapes using the Shezi-Manning formula. The work opens only the possibility of determining the culvert capacity of channels of various shapes on the basis of the planned diagram of the flow velocities. Recommendations for the practical application of this method in design practice have not yet been implemented.

H. Wagner in work [19], also carried out at the Dresden Technical University, constructed dependences for calculating uniform and smoothly varying fluid flows in smooth and rough channels of rectangular cross section and again, following Kelegan and Kirschmer, drew attention to the rich experimental material , received, in due time, Bazin [20].

The dependences obtained by Wagner have the following form for \(\frac{B}{h} > 20\):

\[
\frac{1}{\sqrt{\beta_{R}}} = 3.7 \left(1 + 2 \frac{h}{B}\right)^{K_{d}} \cdot \lg \left(1 + 2 \frac{h}{B}\right)^{3/2} \sqrt{K_{d}} \Re_{cB} + \frac{A_{d}}{h}
\]  

(25)
at \( \frac{B}{h} \to \infty \) dependence (26) will look like this:

\[
\frac{1}{\sqrt{\lambda_{R-h}}} = 3.7 \log \left( \frac{10.6}{3.3 \frac{A_3}{Re_h} + \frac{h}{h}} \right) \tag{26}
\]

When \( \frac{B}{h} < 20 \),

\[
\frac{1}{\sqrt{\lambda_R}} = 3.7 \sqrt{1 + 2 \frac{h}{B}} K_n \cdot \log \left( \frac{10.6}{3.3 \left( \frac{1}{\sqrt{K_n Re_R}} \frac{h}{h} \right)^{3/2} + \frac{A_3}{h}} \right) \tag{27}
\]

According to Wagner, channels with a non-rectangular cross-section can be reduced to an equivalent (in resistance) rectangular, in the following relations:

\[
\bar{\omega} = b \cdot h
\]

\[
\bar{\chi} = 2h + b
\]

Moreover, from the system of equations (28) we obtain the following equations:

\[
2h^2 + \bar{\chi}h + \bar{\omega} = 0 \tag{28}
\]

\[
h_{1,2} = \frac{1}{4} \left( \bar{\chi} \pm \sqrt{\bar{\chi}^2 - 8\bar{\omega}} \right) \tag{29}
\]

In equation (29), the problem has a solution for \( \bar{\chi}^2 - 8\bar{\omega} > 0 \). Это означает, что \( \frac{\bar{\chi}^2}{\bar{\omega}} \geq 8 \). Only if this condition is fulfilled, this free cross-section can be reduced to an equivalent (in terms of resistance) rectangular. It is easy to show that the equivalent rectangular section should characterize the conditions \( \frac{\bar{\chi}^2}{\bar{\omega}} \geq 8 \). But, with the help of the indicated transformations, the certain equations obtained by Wagner can only be approximately transferred to other cross-sectional shapes that differ from the rectangular profile.

According to our method, the formulas of hydraulic resistance for trapezoidal channels and other forms of the correct cross-section can be represented as.

\[
\frac{1}{\sqrt{\lambda}} = \frac{1}{\pi \sqrt{2}} \left( \ln \frac{b \cdot R}{\delta} - 1 + \ln \left( \frac{h}{\xi_R} - \frac{\xi h^2}{4\omega} \right) \right) \tag{30}
\]

The same ratio is obtained according to V.T. Chow for channels with a curved cross-section.

In relation (30) it is accepted: \( \bar{\chi} - Karman's \ constant; \bar{\omega} = 0.4; \bar{\eta}_\Delta - Reynolds \ number \ for \ a \ viscous \ sublayer; \bar{\eta}_\Delta = \delta_\Delta V/\bar{\omega}; \bar{\delta}_\Delta - viscous \ sublayer \ thickness; h - channel \ filling \ depth; \xi - channel \ shape \ function \ in \ relation \ b(y) = x - \xi y; \chi - wetted \ perimeter; \omega - channel \ free \ area.

Formula (30) is valid for both fluid motion in smooth (\( \bar{\eta}_\Delta = 1/9 \)), and in rough canals (\( \bar{\eta}_\Delta = 1/30 \), at that \( \bar{\eta}_\Delta = \delta_\Delta /\Delta \)). The third and last terms in this formula take into account the influence of the shape of the free cross-section of the channel on its hydraulic resistance. However, formula (30) does not fully take into account the influence of the free surface on the distribution of velocities and head losses. Bearing this in mind, there are some other assumptions made in the derivation of formula (30). It should be assumed that formula (30) only allows us to outline the general form of the terms that
determine the dependence of the hydraulic resistance of the channel on the shape of its open section. The specific form of the corresponding dependence can be established only from consideration of the corresponding experimental data.

According to the results of the experiments carried out, and according to Bazin's data, it became possible to plot the dependence of the hydraulic friction coefficient $\lambda$ on the Reynolds number $Re$, the graphs in Figs. 9 and 10. show that in the case of relatively hydraulically smooth channels, when the relative roughness $\Delta/R$ almost does not play a role, with the same Reynolds number in Bazin's experiments, (series № 9, 27), where the surface of the bottom and walls of the channels of rectangular and semicircular cross-section is smooth cement, the coefficients of hydraulic friction $\lambda$ are not the same.

With an increase in the relative roughness $\Delta/R$ in Bazin's experiments of series № 4, 27, where the surface of the bottom and walls of the channels of rectangular and semicircular cross-section is gravel $d=0.01–0.02$ and, with the same Reynolds number $Re$ and with the same relative roughness $\Delta/R$, the difference between the coefficients of hydraulic friction $\lambda$ increases.

At small values of relative roughness, in the area of resistance close to smooth, the difference between $\lambda$ for channels of rectangular and semicircular cross-section is 13–15%, with an increase in $\Delta/R$, the ratio between increases to 30–43%.

Theoretically, according to dependence (30) for up to a quadratic region of resistance, the coefficient of hydraulic friction $\lambda$ (depending on the Reynolds number $Re$ and the relative roughness $\Delta/R$) at the same value of the Reynolds number $Re$ and the relative roughness $\Delta/R$ for two channels with different shapes of the transverse the section should have been the same, but this does not follow from figure 1. The fact is that the hydraulic radius included in dependence (30) as a parameter intended to take into account the influence of the geometry of the living section of the channel on the value of the pressure losses is insufficient for this purpose. On the other hand, the question may arise that the slopes of these channels can also affect the mentioned difference in the values of the coefficients of hydraulic friction.

As the graph in Fig. 9 and Fig. 10 shows, at $R = \text{const}$, the coefficients of hydraulic friction $\lambda$ for channels with two different cross-sectional shapes (rectangular and semicircular) differ from each other, while the difference between the values of the coefficients of hydraulic friction increases with increase in roughness along the wetted surface of the channels.

The graphs in Fig. 7 and Fig. 8 show the dependences of the average flow velocity $\vartheta$ on $R$, for a series of our experiments (№ 7 and № 1a).

To determine the equivalent height of the roughness protrusions and the location of the protrusions in the above channels, we plotted the dependence graphs $\Delta_R = f(R)$, for each series of our experiments and Bazin's series of experiments. Dependency graphs $\Delta_R = f(R)$, are shown in Figures 1 – 10.
Figure 1. Dependence $\Delta = f(R)$
The author’s experiments, series № 1; rectangular duct; the surface of the channel bottom and walls - smooth concrete; $B = 1.51 \text{ m}$; $i = 10^{-3}$; $T = 20$ degrees $C$; $v = 10^{6} \text{ m}^2/\text{s}$

Figure 2. Dependence $\Delta = f(R)$
The author’s experiments, series № 3; trapezoidal canal; the surface of the channel bottom and walls - smooth concrete; $b_g=0.16 \text{ m}$; $m=1.723; i=10^{-3}$; $T=16.2$ degrees $C$; $v = 1.1 \times 10^{-6} \text{ m}^2/\text{s}$
Figure 3. Dependence $\Delta = f(R)$

The author's experiments, series no. 7; trapezoidal canal; the surface of the bottom and walls of the channel – gravel; $d = 5 – 7 \text{ mm}; b_g = 0.16 \text{ m}; m = 1.732; i=10^{-5}; T = 16.2 \text{ degrees } ^\circ \text{C}; v=1.1\times10^{-6} \text{ m}^2/\text{s}$

Figure 4. Dependence $\Delta = f(R)$

The author's experiments, series no. 1a; rectangular duct; the surface of the bottom and walls of the channel - gravel; $d=5 – 7 \text{ mm}; b=1.51 \text{ m}; i=10^{-5}; T=19.8 \text{ degrees } ^\circ \text{C}; v=1.02\times10^{-6} \text{ m}^2/\text{s}$
Figure 5. Dependence $\Delta = f(R)$
Processing of Bazin's experiments, series № 27; semicircular canal; bottom and wall surfaces - gravel
$d = 0.01\text{--}0.02\text{ m}; \Delta_s = 12\cdot10^{-3}\text{ m}$

Figure 6. Dependence $\Delta = f(R)$
Processing of Bazin's experiments, series № 9, semicircular canal, bottom surface and walls - boards,
$B = 1.983\text{ m}, i = 1.5\cdot10^{-3}$. 
Fig. 7. Dependence of $v$ on $R$.
The author's experiments, series no. 7; trapezoidal canal; the surface of the bottom and walls of the channel – gravel; $d = 5 – 7 \, mm$; $b_x = 0.16 \, m$; $m = 1.732$; $i=10^{-4}$; $T = 16.2 \, degrees \, ^{C}$; $v=1.1x10^6 \, m^2/s$

Fig. 8. Dependence of $v$ on $R$
The author's experiments, series № 1a; rectangular duct; the surface of the bottom and walls of the channel - gravel; $d=5 – 7 \, mm$; $b=1.51 \, m$; $i=10^{-3}$; $T=19.4 \, degrees \, ^{C}$; $v=1.02x10^6 \, m^2/c$
3. Conclusions

The general conclusions that it seems to us possible to draw as a result of considering (according to literary sources) the studies previously carried out by various authors in the field of interest to us can be formulated as follows.

1. Studies state that the shape of the cross-section of gravity channels significantly affects the amount of head loss in them, but to assess this effect it is not enough (as previously thought) to know only the hydraulic radius; it is required to involve some additional coefficients of the parameters of the free cross-section, which must be introduced in dependences, which make it possible to determine the numerical value of the coefficient of hydraulic friction, and therefore to find the pressure loss. The above is confirmed, for example, by experimental studies (Neronova L.P and Titov Y.P) channels of...
rectangular cross-section, as well as research by Kasyanova N.D. channels of triangular cross-section. Kasyanova research, in particular, established the influence of the slope coefficient in triangular channels on the value of head losses.

2. H. Wagner [3] and G. Kelegan [17] attempted a theoretical solution to the question of the influence of the cross-sectional shape of the channels on the amount of pressure losses in them. At the same time, Wagner, considering channels of rectangular cross-section, found out the influence of the shape of this section on the magnitude of pressure losses. Kelegan, dealing first with channels with the simplest cross-sectional shape (round, rectangular with infinite width), and then with channels with a more complex cross-section, came to the conclusion that the influence of the cross-sectional shape on the value of pressure losses in free-flow channels should be taken into account by introducing into the corresponding dependences of the additional "shape parameter", the numerical value of which can only be found empirically.

3. Thus, it should be recognized that the above-named researchers have certainly made a certain contribution to the development of the issue we are considering. It should be noted, however, that a significant gap in their works is that they investigated (in order to clarify the effect of the cross-sectional shape of unpressurized channels on the pressure loss in them) only hydraulically smooth channels, while channels with a wetted surface close to smooth, or rough – not investigated. At the same time, it is known that such channels are very widespread in engineering practice.

4. At small values of the relative roughness, in the area of resistance close to smooth, the difference between $\lambda$ for channels of rectangular and semicircular cross-section is 13 – 15%. with an increase in $\Delta/R$, the ratio between $\lambda$ increases to 30 – 43%.

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