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V. E. DRANKOVSKIY, K. S. REZVAYA

MATHEMATICAL MODELING OF HYDRODYNAMIC CHARACTERISTICS IN THE INLET OF A REVERSIBLE HYDRAULIC MACHINE BASED ON MATHEMATICAL MODELS

Розглянуто математичні моделі, які дозволяють визначати гідродинамічні характеристики потоку в підвідній частині оборотних гідравлічних машин. Описано особливості потоку рідини у підвідній частині оборотної гідравлічної машини. Виконано аналіз умов робочого процесу оборотної гідравлічної машини, здійснюваний в процесі проектування проточної частини. Визначено види втрат енергії з урахуванням просторових ефектів в'язкої рідини. Розроблено група математичних моделей, орієнтованих на різні стадії проектування. Визначені особливості математичних моделей.

Ключові слова: математичне моделювання, чисельне дослідження, гідродинамічні характеристики, підвідна частина, направляючий апарат, спіральна камера, коефіцієнт опору.

Рассмотрено математические модели, которые позволяют определять гидродинамические характеристики потока в подводящей части обратимых гидравлических машин. Описаны особенности потока жидкости в подводящей части обратимой гидравлической машины. Производен анализ условий рабочего процесса обратимой гидравлической машины, осуществляемый в процессе проектирования проточной части. Определены виды потерь энергии с учетом пространственных эффектов вязкой жидкости. Разработана группа математических моделей, ориентированных на различные стадии проектирования. Определены особенности математических моделей.

Ключевые слова: математическое моделирование, численное исследование, гидродинамические характеристики, подводящая часть, направляющий аппарат, спиральная камера, коэффициент сопротивления.

Mathematical models that allow determining the hydrodynamic flow characteristics in the inlet of reversible hydraulic machines are considered. The features of the fluid flow are described. An analysis of the operating conditions of a reversible hydraulic machine, carried out during the design of the water passage, is made. Types of energy losses, taking into account the spatial effects of a viscous fluid, are determined. A group of mathematical models, oriented at different stages of design, is developed. A new way to the design of the water passage based on the experimental results is proposed. Specific programs for the design of the water passage of reversible hydraulic machines are considered. Features of mathematical models are defined.

Keywords: mathematical modeling, numerical research, hydrodynamic characteristics, inlet, wicket gate, spiral casing, coefficient of resistance.

Introduction. The issue of predicting the hydrodynamic parameters of reversible hydraulic machines based on various models of calculating the flow of fluid in the elements of the inlet is relevant nowadays. There are models that describe the flow of fluid in reversible hydraulic machines, which have their own peculiarities in the design process. Specific programs for the design of the water passage of reversible hydraulic machines are considered.

Main part. The energy characteristics of a high-head hydraulic machine depend essentially on the shape of the fluid motion in front of the runner. In this case, the inlet must provide an axisymmetric velocity field in front of the runner. This is necessary for the realization of the model of the relative steady-state fluid motion in the runner, which is used in the design of the water passage.

The flow formed by the spiral casing and stay ring has a complex three-dimensional character. Experimental and calculated studies of the three-dimensional flow in the characteristic sections of the inlet of the hydraulic machine show that the flow in the section in front of the wicket gate can have a significant stepwise non-uniformity.

Irregularity of axial symmetry in the cross section before wicket gate occurs when spiral casing has incomplete (small) coverage angle. This disturbance is caused by the fact that some of the wicket gate blades are streamed by the flow from the spiral casing. While the other part of the blades is streamed by the flow, which comes directly from the open part of the casing [9]. There is the referenced non-uniformity in the circumferential direction in the cross section behind the wicket gate. If there is no axial symmetry of the flow in front of the wicket gate an asymmetry of the flow in the area of the runner can be. This is due to the appearance of transverse forces which acting on the rotor of the hydraulic machine [10].

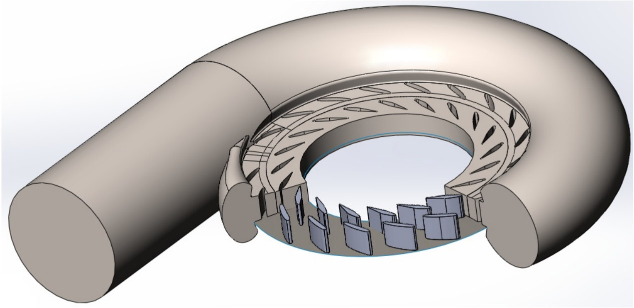


Fig. 1 – CAD model of the hydraulic machine

The non-uniformity of the distribution of the kinematic parameters in the entrance to the wicket gate along the vane height should be considered in more detail. Calculated and experimental studies show a significant uneven distribution of the radial and circumferential velocity components (1–3). In this case, the radial velocity graph has the character of a concave curve, and the graph of the distribution of the circumferential component has the form of a convex curve for high-head hydraulic machines.

The data about the flow structure in the section behind the wicket gate can be used in determination of the average kinematic characteristics of the flow.

The averaged kinematic characteristics of the wicket gate are:

$$\frac{\overline{\Gamma}_0 D}{Q} = f_1\left(\frac{\overline{\Gamma}_{sc} D}{Q}, a_0'\right); \qquad (1)$$

$$\mathrm{ctg}\tilde{\alpha}_0 = \frac{\overline{\Gamma}_0 b_0}{Q} = f_2\left(\frac{\overline{\Gamma}_{sc} D}{Q}, a_0'\right); \qquad (2)$$

where $\frac{\overline{\Gamma}_0 D}{Q}$ – nondimensional kinematic complex, which characterized the direction of flow at the exit from the wicket gate; $\mathrm{ctg}\tilde{\alpha}_0 = \frac{\overline{\Gamma}_0 b_0}{Q}$ – averaged angle of flow at the exit from the wicket gate; $a_0' = \frac{a_0 D_0}{z_0}$ – relative opening of the wicket gate.

Nondimensional parameters $\frac{\overline{\Gamma}_0 D}{Q}$ and $\frac{\overline{\Gamma}_0 b_0}{Q}$ connect ratio:

$$\frac{\overline{\Gamma}_0 D}{Q} = \frac{\mathrm{ctg}\tilde{\alpha}_0}{S_0},\ S_0 = \frac{b_0}{D}$$

When the condition of the geometric similarity is fulfilled, the kinematic similarity condition at the output from the wicket gate for the model machine and the full-scale machine can be written in the form:

$$\frac{\overline{\Gamma}_0 D}{Q} = \text{idem};\ \mathrm{ctg}\tilde{\alpha}_0 = \frac{\overline{\Gamma}_0 D}{Q}\frac{b_0}{D} = \text{idem} \qquad (3)$$

Experimental data [4] show that the reverse influence of the runner (in the area of normal operating conditions) practically does not effect on the averaged kinematic flow parameters behind the wicket gate. In other words, the averaged kinematic flow parameters behind the wicket gate do not depend on the operating mode of the turbine.

Therefore, the averaged nondimensional kinematic characteristics are determined by the geometry of the inlet. They are constant when the hydraulic machine operate with different runners of similar specific speed. That is why there is the possibility of using the kinematic characteristics (1, 2) for analyzing the working process of a hydraulic machine with different runners in a turbine-operating mode.

Referenced independence of the nondimensional kinematic characteristics shows that it is necessary to determine and investigate the kinematic characteristics of the wicket gate.

Nondimensional complexes $\frac{\overline{\Gamma}_0 D}{Q}$ and $\frac{\overline{\Gamma}_0 b_0}{Q}$ are very important parameters of the flow, which formed by the spiral casing and the stay ring. During variance of the regime parameters of the hydraulic machine in the turbine mode n_I' and Q_I' with that opening of the wicket gate the streamlines in the area of the spiral casing, stay ring and wicket gate practically do not change.

Consequently, the value of the averaged angle $\tilde{\alpha}_{sc}$ will be independent of the regime parameters in the turbine mode. The direction of flow created by the spiral casing and the stay ring can be characterized by a single averaged parameter is the angle $\tilde{\alpha}_{sc}$. The spiral casings of modern hydroturbines and reversible hydraulic machines form flows with averaged angles $\tilde{\alpha}_{sc}$ in the range 25^0 – 35^0.

The creation of a sufficiently reliable (from the engineering point of view) method of calculating energy characteristics presupposes the existence of reliable methods for calculating energy losses in the elements of the water passage.

Modern methods of calculating losses are based on the application of the equations of motion of a viscous incompressible fluid [11–13]. However, implementation of such approach, despite the existing software packages (*ANSYS CFX*, *FlowVision*, *FlowER*, *OpenFOAM*, etc.), requires the three-dimensional geometry of the water passage. Nevertheless, certain difficulties appear in the initial steps of design.

Therefore, the analysis of the conditions of the working process, which is done in the process of designing the water passage, set a problem of constructing loss models. This is the dependence of the energy loss on the geometric and regime parameters of the hydromachine in the turbine mode. The presence of such dependencies allows to determine the most effective variants of the water passage by carrying out multivariate calculations. These dependencies can be used for forecasting and optimization during the design of the water passage of hydraulic machines.

The known scheme of losses division in blade systems will be used in the compilation of the mathematical model of the resistance of the inlet. The losses depend their physical nature. There are friction losses, edge losses, detached losses, shock losses, boundary losses.

Determination of these types of losses, taking into account the three-dimensional effects of a viscous fluid, requires a solid model of the flow and requires the solution of an inverse problem in the theory of hydraulic machines. It is a difficult problem at the initial stages of design.

Approximate calculation schemes will be considered. They are used in modern practice of designing the water passages of hydraulic machines in turbine mode. The inlet of the hydraulic machine during operating in the turbine mode consists of a spiral chamber, circular stay ring vanes and wicket gate. Cylindrical wicket gate plays the most important role not only in the kinematics of the flow ahead of the impeller, but also in the energy balance of the hydraulic machine. Therefore, the first step of the determination of the resistance coefficients of the inlet starts from wicket gate.

The total value of losses in the wicket gate is determined by summing the individual loss types (friction losses, edge losses, detached losses, shock losses, boundary losses), which have averaged values over rate:

$$h_{wg} = \frac{1}{Q}\int_Q \xi_{fr}\frac{C_{2m}^2}{\sin^2\alpha_2}dQ + \frac{1}{Q}\int_Q \xi_e\frac{C_{2m}^2}{2g\sin^2\alpha_2}dQ +$$

$$\frac{1}{Q}\int_Q \xi_{sh}\frac{C_{2m}^2}{2g\sin^2\alpha_2}dQ + \xi_b\frac{\tilde{C}_{2m}^2}{2g\sin^2\alpha_2}. \quad (4)$$

These formulas for determination of various types of losses are used to construct the resistance model - dependence $K_{h_{wg}} = f\left(\frac{\overline{\Gamma}_0 D}{Q}, \frac{\Gamma_{sc}D}{Q}, L'_{wg}\right)$.

The structure of this dependence follows from the theory of dimension. The dependencies for individual types of losses are used to obtain detailed dependents of the mathematical model. Based on the principle of loss independence, the total loss in the water passage elements can be found by summing up individual types of losses. This approach gives certain advantages, which connect with the possibility of a detailed analysis of each type of loss, depending on the geometric and mode parameters.

The using of formulas for calculating individual types of losses is possible when the velocity distribution in the cross section behind the wicket gate is known. The description of the flow in the cross section behind the wicket gate by applying of averaged kinematic parameters (averaged velocities, angles) makes it possible to replace the integral dependences for individual types of losses by algebraic dependences that relate these losses to geometric and regime parameters.

Thus, the total losses in the wicket gate can be written using the average speed in the section behind the wicket gate:

$$\overline{h}_{wg} = \overline{\xi}_{fr}\frac{\tilde{C}_2^2}{2g} + \overline{\xi}_e\frac{\tilde{C}_2^2}{2g} + \overline{\xi}_{sh}\frac{\tilde{C}_2^2}{2g} + \xi_b\frac{\tilde{C}_2^2}{2g} \quad (5)$$

where $\overline{\xi}_{fr}, \overline{\xi}_e, \overline{\xi}_{sh}, \xi_t$ are determined by formulas [8].

Take into account, that:

$$\tilde{C}_2 = \frac{\tilde{C}_{2m}}{\sin\tilde{\alpha}_2} = \frac{Q}{\sigma_0\sin\tilde{\alpha}_2};\ \sigma_0 = 2\pi r_{2wg}b_0;\ k_h = \frac{g\overline{h}D^4}{Q^2}$$

rewrite (5) in nondimensional form:

$$k_{h\,wg} = \frac{1}{8\pi^2\left(\frac{b_0}{D}\right)^2\left(\frac{r_{2wg}}{D}\right)^2\sin^2\tilde{\alpha}_2}\times$$

$$\times\left[\overline{\xi}_{fr} + \overline{\xi}_e + \overline{\xi}_{sh} + \xi_b\right] \quad (6)$$

Coefficients ξ_{wg} и $k_{h\,wg}$ are related

$$\xi_{wg} = \frac{\overline{h}_{wg}}{\frac{\tilde{C}_2}{2g}} = \frac{\overline{h}_{wg}\sin^2\tilde{\alpha}_2}{\frac{\tilde{C}_{2m}^2}{2g}} = \frac{2gh_{wg}\sin^2\tilde{\alpha}_2 D_{2wg}^2 b_0^2\pi^2}{Q^2};\ (7)$$

$$\xi_{wg} = k_{h\,wg}2\pi^2 D'^2_{2wg}b'^2_0\sin^2\tilde{\alpha}_0, \quad (8)$$

where $D'_{2wg} = \frac{D_{2wg}}{D}$; $b'_0 = \frac{b_0}{D}$.

To transform the dependence (6) with allowance for the formulas for ($\overline{\xi}_{fr} + \overline{\xi}_e + \overline{\xi}_{sh} + \xi_t$) and to write the formula for the resistance coefficient, which depend on geometric and kinematic parameters in the form:

$$k_{h\,wg} = \frac{1}{8\pi^2\left(\frac{b_{wg}}{D}\right)^2\left(\frac{r_{2wg}}{D}\right)^2\sin^2\tilde{\alpha}_{2wg}}\times$$

$$\times\left\{\frac{2CI_{wg}l_{wg}}{\sin\tilde{\alpha}_{2wg}t_{2wg}} + \frac{0,2\Delta_{wg}}{t_{2wg}\sin\tilde{\alpha}_2} + \frac{0,13l_{wg}}{\mathrm{Re}_{wg}^{0,2}b_{wg}}\left(1 - \frac{l_{wg}}{r_{wg}}\right)^{0,8}\right.$$

$$\times\left[1 + 0,7\left(1 - \frac{ctg\tilde{\alpha}_{1wg}}{ctg\tilde{\alpha}_{2wg}}\right)^2\left(\frac{t_{2wg}}{l_{wg}}\right)^2\cos^2\alpha_{2wg}\right] +$$

$$\left. + \chi_{wg}\frac{\left(\mathrm{ctg}\tilde{\alpha}_{1wg} - \mathrm{ctg}\tilde{\alpha}_{bo\,wg}\right)^2 r_{2wg}^2\sin^2\tilde{\alpha}_2}{r_{1wg}^2}\right\} \quad (9)$$

The components in brackets are the coefficients of the friction $\xi_{fr\,wg}$, edge $\xi_{e\,wg}$, tip $\xi_{b\,wg}$ and shock $\xi_{sh\,wg}$.

A similar approach is used to write the formula of the loss factor in the stay ring vanes.

The current streamlets in the spiral casing and stay ring are constant in the range of the main turbine operation modes of the universal characteristic. This makes it possible not to take into account the shock losses that occur at the input edges of the stay ring with respect to the direction of the input flow velocity.

The total loss coefficient in the stay ring vanes:

$$k_{h\,st} = \frac{1}{8\pi^2\left(\frac{r_{2st}}{D}\right)^2\left(\frac{b_{st}}{D}\right)^2\sin^2\alpha_{st}}\times$$

$$\times\left[\frac{2CI_{st}l_{st}}{t_{2st}\sin\alpha_{2st}}+\frac{0,2\Delta_{kr.st}}{t_{2st}\sin\alpha_{2st}}+\right.$$

$$\left.+\frac{2CI_{st}l_{st}}{t_{2st}\sin\alpha_{2st}}\left(\frac{2t_{2st}\sin\alpha_{2st}}{b_{st}}\right)\right] \qquad (10)$$

The coefficient of resistance of the spiral chamber in a sufficiently wide range of operating conditions of the turbine varies insignificantly. In this case, coefficient can be considered constant, estimating from experimental data for hydroturbines of similar specific speed.

The losses in the spiral chamber are determined depending on the velocity head in the inlet section:

$$h_{sc}=\xi_{sc}\frac{C_{in}^2}{2g}.$$

Changing $C_{in}=\frac{Q}{F_{in}}$, we can find the formula for determine the relative loss (in relation to the head):

$$\frac{h_{sc}}{H}=\frac{\xi_{sc}}{F_{in}'^2 2g}Q_I'^2,$$

where $F_{in}'=\frac{F_{in}}{D^2}$, F_{in} – the inlet cross section of the spiral casing.

For metal spiral casings with an angle of coverage $\phi^0=345^0-360^0$ from the experience data [5] ξ_{sc} = 0.15–0.25.

Association of resistance coefficients ξ_{sc} and $k_{sc}=\frac{ghD^4}{Q^2}$ has form and in result coefficient for the spiral casing equals:

$$k_{hsc}=\frac{gh_{sc}}{HQ_I'^2}=\frac{\xi_{sc}}{2F_{sc}'^2} \qquad (11)$$

The expressions for the coefficients of the spiral casing, the stay ring, the wicket gate are summed. The final expression of the losses in the inlet for the turbine operation mode of the hydraulic machine is (12)

Expression (12) is a mathematical model of the resistance of the inlet of the hydraulic machine in the turbine mode. This model describes the dependence of the resistance coefficient on the geometric parameters and the average flow angles, which are created by the spiral casing $\tilde{\alpha}_{sc}$ and the wicket gate $\tilde{\alpha}_{2wg}$.

The mathematical model of resistance (12) is the basis for carrying out a numerical research of the influence of geometric parameters on the resistance characteristic of the inlet.

$$k_{h\,inlet}=\frac{\xi_{sc}}{2F_{in}'^2}+\frac{1}{8\pi^2\left(\frac{b_{st}}{D}\right)^2\left(\frac{r_{2st}}{D}\right)^2\sin^2\alpha_{2st}}\times$$

$$\left[\frac{2CI_{st}l_{st}}{t_{2st}\sin\alpha_{2st}}\left(1+\frac{2t_{2st}\sin\alpha_{2st}}{b_{st}}\right)+\frac{0,2\Delta_{kr.st}}{t_{2st}\sin\alpha_{2st}}\right]+$$

$$\frac{1}{8\pi^2\left(\frac{r_{2wg}}{D}\right)^2\left(\frac{b_{wg}}{D}\right)^2\sin^2\alpha_{2wg}}\left\{\frac{2CI_{wg}l_{wg}}{t_{2wg}\sin\alpha_{2wg}}+\right.$$

$$+\frac{0,2\Delta_{kr.wg}}{t_{2wg}\sin\alpha_{2wg}}+\frac{0,13l_{wg}}{\mathrm{Re}_{wg}^{0,2}b_{wg}}\left(1-\frac{l_{wg}}{r_{1wg}}\right)^{0,8}\times$$

$$\times\left[1+0,7\left(1-\frac{\mathrm{ctg}\alpha_{1wg}}{\mathrm{ctg}\alpha_{2wg}}\right)^2\left(\frac{t_{2wg}}{l_{wg}}\right)^2\cos^2\alpha_{2wg}\right]+$$

$$\left.+\chi\frac{\left(\mathrm{ctg}\alpha_{1wg}-\mathrm{ctg}\alpha_{b.o.wg}\right)^2 r_{2wg}^2\sin^2\tilde{\alpha}_{2wg}}{r_{1wg}^2}\right\} \qquad (12)$$

Obviously, for the reducing of the energy losses in the inlet of the turbine it is necessary to reduce the loss coefficients in the zone of the main turbine operation modes.

The goal of such study is to identify next factors: geometric and kinematic parameters. These parameters significantly affect the value and nature of the change in the loss factor in the inlet of the hydraulic machine. Such a study is necessary already at the initial stages of the design of the water passage when choosing the basic geometric parameters of the approach. The rate for high-pressure reversible hydraulic machines is chosen according for the turbine regime. Then it is examined for pumping regime.

It is known that an increase in the inlet section of the spiral casing contributes to a decrease in energy losses in the inlet and, consequently, to an improvement in the power parameters of the hydraulic machine, while the size of the spiral casing increases. This is due to increased construction costs, but there may be problems in the pump operation mode.

Therefore, the choice of the geometry of the inlet must be made in each particular case on the basis of a comparison numerical analysis of energy losses for various geometric parameters. Naturally, the results of such an analysis should be consistent with the data of technical and economic calculations to determine the cost of construction and hydraulic equipment.

The spiral casing and the stay ring form in front of the wicket gate a flow of a certain direction, which is characterized by the angle of flow. $\tilde{\alpha}_{sc}$.

When the geometry of the spiral chamber and the stay ring changes, the magnitude of the angle changes and, consequently, the flow conditions of the guide vane blades change. Due to this the resistance coefficient of the guide is changed.

In Fig. 2–4 there is the dependence of the coefficient of resistance k_{wg} on the average flow angles $\tilde{\alpha}_{sc}$ and $\tilde{\alpha}_0$ for the wicket gate with a height b_0=0,08 are represented as isolines.

These graphs $\tilde{\alpha}_{sc} = \text{const}$ show that change of the resistance coefficient of the wicket gate is a function of the averaged angle $\tilde{\alpha}_0$ while the geometry of the spiral casing and the stay ring is fixed. The graphs $\tilde{\alpha}_0 = \text{const}$ characterize the change of the resistance coefficient depending on the angle of the flow $\tilde{\alpha}_{sc}$ with given opening of the wicket gate $\left(\tilde{\alpha}_0 = \text{const}\right)$.

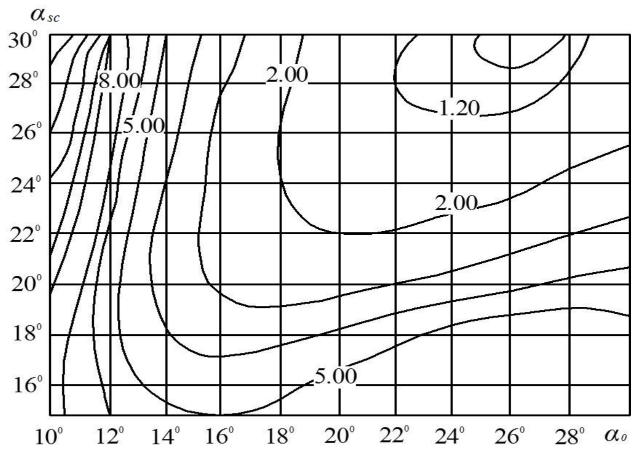


Fig. 2 – The resistant coefficient of the wicket gate with height b_o = 0,08

In spiral casings the angle change $\tilde{\alpha}_{sc}$ is achieved by changing the geometric sizes of the input section and the shape of the cross sections. Therefore, the graphs $k_{wg} = f\left(\tilde{\alpha}_{sc}\tilde{\alpha}_0\right)$ that are shown in fig. 1 indicate the influence of the geometric parameters of the spiral chamber and stay ring on the resistance characteristic of the wicket gate.

There are dependencies for the wicket gate $k_{wg} = f\left(\tilde{\alpha}_0\right)$ with a height $\frac{b_0}{D} = 0,08$ on fig. 2 (corresponding to different angles of the spiral casing $\tilde{\alpha}_{sc} = 20^0, 23^0, 30^0$). As follows from the graphs, an increase in the angle of the spiral casing $\tilde{\alpha}_{sc}$ displace the minimum angle $\alpha_{0\,\min}$ to the region of large values $\tilde{\alpha}_0$ (the angle at which the minimum of the resistance coefficient is reached). In this case, the minimum value of the coefficient of resistance $k_{wg\,\min}$ decreases.

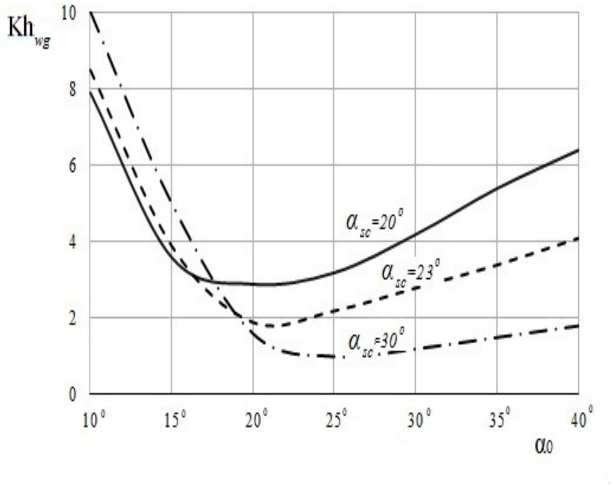


Fig. 3 – The influence of the spiral casing angle on the resistance coefficient of the wicket gate

The value $\tilde{\alpha}_{0\,\max}$, which corresponding to the minimum of the curve $k_{wg} = f\left(\tilde{\alpha}_0\right)$, is close with $\tilde{\alpha}_{sc}$.

The graphs are shown on fig. 1–2 can be used to select the basic geometric parameters of the inlet (the diameter of the input section of the spiral, the overall dimensions of the spiral in plan) when designing the water passage of the hydraulic machine in the turbine mode.

The influence of the relative height $\frac{b_0}{D}$ on the resistance characteristic of the wicket gate $k_{wg} = f\left(\tilde{\alpha}_0\right)$ with fixed angle α_{sc} is considered below.

The dependences of the wicket gate $k_{wg} = f\left(\tilde{\alpha}_0\right)$ with different heights: $\frac{b_0}{D} = 0,06$, $\frac{b_0}{D} = 0,08$, $\frac{b_0}{D} = 0,16$; $\frac{b_0}{D} = 0,25$ are shown in fig. 3.

As follows from the consideration of the graphs in fig. 4 the slope of the curves $k_{wg} = f\left(\tilde{\alpha}_0\right)$ increases with decreasing the height of the guide. Fig. 4 illustrates the increasing role of the wicket gate in the energy balance of the hydraulic machine with a decrease in its height.

The dependence of the loss coefficients $k_{wg} = f\left(\tilde{\alpha}_0\right)$ of the wicket gate with the vanes of the symmetrical and asymmetric profiles (convex and concave) are present on fig. 5. These graphs reflect the effect of the curvature of the vane profile on the resistance characteristic $k_{wg} = f\left(\tilde{\alpha}_0\right)$ of the wicket gate at a fixed angle of the spiral casing $\tilde{\alpha}_{sc} = 23^0$.

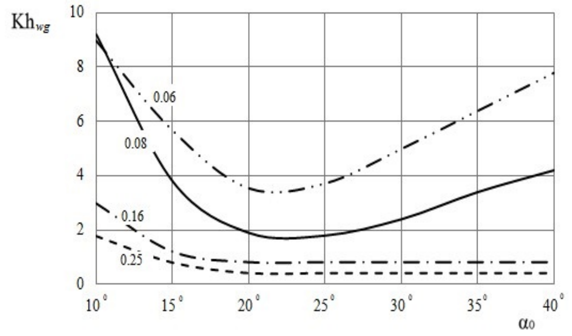


Fig. 4 – The influence of the height of the water passage on the resistance coefficient of the wicket gate

As follows from the graphs, the transition from an asymmetric profile of concave to a profile of convex leads to a shift of the curve minimum $k_{HA} = f\left(\tilde{\alpha}_0\right)$ to the region of large angles. The values $k_{HA\min}$, which corresponding to this minimum, decrease.

The results of a comparison of the numerical calculation with the experimental data [8] of the resistance coefficients in the inlet of the hydraulic machine ORO500 are presented on fig. 6, b. The investigated inlet consists of a spiral casing, stay ring grid and wicket gate grid (the number of columns equal to the number of vanes of the wicket gate) $z_{st} = z_{wg} = 20$. The vane of the wicket gate has the following characteristics: grid solidity $\frac{l}{t} = 1,09$, relative profile thickness 15.6 %, relative height $\overline{b_0} = 0{,}061$. The experimental hydrodynamic calibration of the research wicket gate is present on fig. 6, a. This calibration is consistent with the data obtained because of the calculation of the grating of the wicket gate with the help of the flow problem of the CKTI. The experimental values of the resistance coefficient of the inlet (fig. 6, b) agree well in the range of openings $a_0 = 20 - 40$ *mm* with the resistance coefficients, which are obtained because of computational studies using formula (9).

The results of numerical studies show the influence of the main geometric parameters of the water passage on the resistance characteristic of the wicket gate. It is necessary to know this factor for a purposeful change in the geometry of the water passage of the hydraulic machine for the improvement of its energy parameters in the turbine mode.

The using of a mathematical model for carrying out multivariate analysis in the process of numerical investigation of the influence of the geometric parameters of the inlet is complicated by the fact that certain geometric parameters (input and output edge radii, input and output angles, etc.) vary depending on the opening of the wicket gate. This fact substantially complicates the carrying out of optimization studies. The model (9) should be simplified due to a certain decrease in the number of variable parameters. Those parameters, whose influence is most significant, remain unchanged.

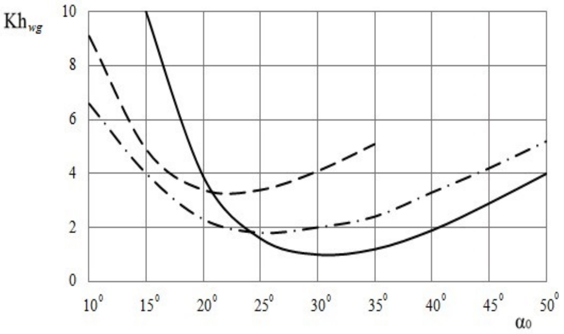
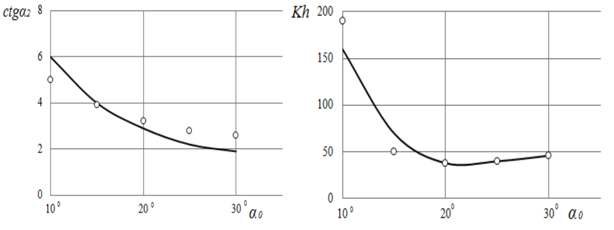


Fig. 5 – The influence of the profile of the wicket gate vane on the resistance coefficient of the wicket gate: 1 – convex (line); 2 – symmetrical (dot-dash); 3 – concave (dotted line)

Studies on simplified models are effective at the initial stages of the design of the flow section, where, as a rule, the influence of the main factors on the hydrodynamic characteristics of hydraulic machine components is revealed.

Identification methods are used to create simplified models. They provide for the construction of an identification model. The construction of the identification model is reduced to choosing the structure of the mathematical model and determining the coefficients of this model. In this case, the parameters of the model can be either by means of experimental data, that reflect the relationship between the input and output parameters of the technical researched object , or by means of a numerical experiment. The experiment is carried out on a more accurate model, which is taken as the initial one [6, 7].



a *b*

Fig. 6 – Hydrodynamic characteristics of the wicket gate with height $b_0 = 0.061$: *a* – ctgα$_2$=*f*(α$_0$); *b* – *K$_h$*=*f*(α$_0$) (dops – experimental data; lines – calculation data)

The calculation data on the initial model (9) are used in constructing a simplified model of the resistance of the wicket gate.

The main results of the calculation:

- curves $k_{wg} = f\left(\frac{\overline{\Gamma}_0 D}{Q}\right)$ have one minimum when $\frac{\overline{\Gamma}_{sc} D}{Q} = const$;
- values $\left(\frac{\overline{\Gamma}_0 D}{Q}\right)_{\min}$, which correspond curves

minimum $k_{wg} = f\left(\frac{\overline{\Gamma}_0 D}{Q}\right)$, close to the corresponding values $\left(\frac{\overline{\Gamma}_{sc} D}{Q}\right)$;

– values $k_{H\,ev\,\min}$ of curves $k_{wg} = f\left(\frac{\overline{\Gamma}_0 D}{Q}\right)$ depend on $\left(\frac{\overline{\Gamma}_{sc} D}{Q}\right)$;

– curves $k_{wg} = f\left(\frac{\overline{\Gamma}_0 D}{Q}\right)$ in the region of the minimum, can be described with sufficient accuracy by a quadratic parabola.

To assume $\frac{\overline{\Gamma}_{sc} D}{Q} = \left(\frac{\overline{\Gamma}_o D}{Q}\right)_{\min}$ and to take into account considerations on the character of the curves $k_{wg} = f\left(\frac{\overline{\Gamma}_0 D}{Q}\right)$ in the region of the minimum, we write the expressions for the resistance coefficient in the following structural form:

$$k_{wg} = k_{wg\,m}\left(\frac{\overline{\Gamma}_{sc} D}{Q}\right) + a\left(\frac{\overline{\Gamma}_{sc} D}{Q} - \frac{\overline{\Gamma}_o D}{Q}\right)^2. \quad (13)$$

The coefficient of the parabola a (13) depends only on the geometry of the wicket gate. The coefficient k_{wgm} depends on the angle of flow, which are created by spiral casing and stay ring. With a fixed geometry of the spiral casing and stay ring k_{wgm} has a constant value.

A simplified model (13) is used later for numerical research of the influence of the geometric parameters of the inlet on the power characteristics of the hydraulic machine.

A mathematical model of the resistance of the inlet has been constructed. Based on this model, an algorithm and a calculation program are compiled. The adequacy of the obtained model in the range of pressures H = 200-500 m is shown. An algorithm and a calculation program have been compiled, which makes it possible to carry out numerical studies of the effect of the geometric parameters of the approach on its resistance characteristic. Generalized graphs $k_{wg} = f\left(\tilde{\alpha}_{sc}\tilde{\alpha}_0\right)$,which reflect the effect of the spiral casing and stay ring on the resistance characteristic of wicket gate, are obtained. This can be used to select the basic geometric parameters of the water passage at the initial design stages in combination with the predictive calculations of the energy characteristics. Calculations show that with a decrease in speed (increase in pressure), the shape of the resistance curve changes. Calculations based on the model allow us to identify the character of the resistance curve with a change in the height of the wicket gate. There is a slight change in the coefficient of resistance in the range of working openings in hydraulic machines with high and medium specific speeds. The curves of the change of the resistance coefficient in slow-moving hydraulic machines are characterized by an increase in values when departing from the minimum value and have a clearly expressed minimum. This character of the change in the resistance curve with a change in the head is due to a change in the ratio of the end, shock, and friction losses. A group of mathematical models, which focuses on different stages of design, was developed. They are designed to assess losses in the case of variety of information. Based on the research performed, a new approach to the design of the water passage can be proposed. The choice of geometric parameters from normative data should be considered as the initial approximation. Geometric parameters should be refined based on a numerical analysis based on the above models, taking into account the conclusions obtained about the influence of geometric parameters.

Conclusions. When carrying out a numerical study of the water passage, one or another program can be used. This program allows at this stage to determine the necessary hydrodynamic parameters, depending on whether the geometric parameters of the characteristic sections or the water passage as a whole are known. After conducting the research, having two approaches to the problem and having obtained certain results, it is possible to choose one of several variants of the flow parts. It will be the most acceptable in the early stages of designing a reversible hydraulic machine.

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Відомості про авторів / Сведения об авторах / About the Authors

Drankovskiy Viktor Eduardovich – Candidate of Technical Sciences (Ph. D.), Docent, Professor of the department "Hydraulic machines" of National Technical University "Kharkiv Polytechnic Institute"; tel.: (057) 707-66-46; e-mail: drankovskiy@rambler.ru.

Дранковский Виктор Эдуардович – кандидат технічних наук, доцент, професор кафедри «Гідравлічні машини» Національного технічного університету «Харківського політехнічного інституту»; тел.: (057) 707-66-46; e-mail: drankovskiy@rambler.ru.

Rezvaya Kseniya Sergeevna - graduate student, National Technical University "Kharkiv Polytechnic Institute", assistant of the Department "Hydraulic machines"; tel.: (057) 707-66-46; e-mail: rezvayaks@gmail.com.

Рєзва Ксенія Сергіївна – аспірант, Національний технічний університет «Харківський політехнічний інститут», асистент кафедри «Гідравлічні машини»; тел.: (057) 707-66-46; e-mail: rezvayaks@gmail.com.