УДК 621.224 **doi: 10.20998/2411-3441.2021.2.09**

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INFLUENCE OF HYDRODYNAMIC CHARACTERISTICS OF WATER PASSAGE ELEMENTS ON ENERGY PARAMETERS OF PUMP-TURBINE

Ukraine has sufficient potential for the development of renewable energy sources. Renewable energy of our country is actively developing. The demand for accumulating hydropower services will grow. This is due to the requirements of modern energy systems to align the schedule for operation in peak load zones. The solution to the problem of creating highly efficient equipment for pumped storage power plants largely depends on the correct selection of the geometry of the water passage elements of the reversible machine, which provide the required level of its energy parameters. The paper deals with the issues of modeling the hydrodynamic characteristics of the blade systems of a reversible hydraulic machine. Changes in energy parameters in the range of basic operating modes of the hill-chart are largely due to changes in the hydrodynamic characteristics of a reversible hydraulic machine. The general approach to describing the hydrodynamic characteristics of blade systems is based on the use of dimensionless parameters characterizing the flow in the characteristic section of the water passage. Expressions, which establish the relationship between the hydrodynamic characteristics and dimensionless complexes and express the general laws of the interaction of the flow with the runner of a reversible machine, are given. The influence of the hydrodynamic parameters of blade systems on the formation of the energy characteristics of a reversible hydraulic machine is considered. Analysis of the hydrodynamic characteristics of individual elements of the water passage allows to analyze their influence on the energy characteristics of a reversible hydraulic machine. The results of such an analysis are the basis for solving a wide range of issues that arise when designing a reversible hydraulic machine. This paper presents the calculations of the energy characteristics for the water passages of reversible hydraulic machines ORO200, ORO500. The calculated data indicate the decisive influence of the hydrodynamic parameters of the spatial lattice on the parameters of the optimal regime.

Keywords: reversible hydraulic machine, energy parameters, kinematic characteristics, energy losses, mathematical model, mode parameters, optimal mode.

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ВПЛИВ ГІДРОДИНАМІЧНИХ ХАРАКТЕРИСТИК ЕЛЕМЕНТІВ ПРОТОЧНОЇ ЧАСТИНИ НА ЕНЕРГЕТИЧНІ ПОКАЗНИКИ ОБОРОТНИХ ГІДРОМАШИН

Україна має достатній потенціал для розвитку відновлюваних джерел енергії. Відновлювана енергетика активно розвивається, попит на гідроенергетику, що акумулюється буде зростати, це обумовлено вимогами сучасних енергосистем до вирівнювання графіка для роботи в пікових зонах навантаження. Вирішення завдання створення високоефективного обладнання для ГАЕС багато в чому залежить від правильного вибору геометрії елементів проточної частини оборотної машини, які забезпечують необхідний рівень її енергетичних показників. В роботі розглянуті питання моделювання гідродинамічних характеристик лопатевих систем оборотної гідромашини. Зміна енергетичних параметрів у діапазоні основних робочих режимів універсальної характеристики значною мірою обумовлена зміною гідродинамічних характеристик оборотної гідромашини. Загальний підхід до опису гідродинамічних характеристик лопатевих систем базується на використанні безрозмірних параметрів, що характеризують потік у характерних перетинах проточної частини. Наведено вирази, які встановлюють зв'язок гідродинамічних характеристик з безрозмірними комплексами, та виражають загальні закономірності взаємодії потоку з робочим колесом оборотної машини. Розглядається вплив гідродинамічних параметрів лопатевих систем на формування енергетичних характеристик оборотної гідромашини. Аналіз гідродинамічних характеристик окремих елементів проточної частини дозволяє проаналізувати їхній вплив на енергетичні характеристики оборотної гідромашини. Результати такого аналізу є основою для вирішення великого кола питань, що виникають під час проектування оборотної гідромашини. У цій роботі наведено розрахунки енергетичних характеристик для проточних частин оборотних гідромашин ОРО200, ОРО500. Розрахункові дані свідчать про визначний вплив гідродинамічних параметрів просторових решіток на параметри оптимального режиму.

Ключові слова: оборотна гідромашина, енергетичні характеристики, кінематичні характеристики, втрати енергії, математична модель, режимні параметри, оптимальний режим.

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ВЛИЯНИЕ ГИДРОДИНАМИЧЕСКИХ ХАРАКТЕРИСТИК ЭЛЕМЕНТОВ ПРОТОЧНОЙ ЧАСТИ НА ЭНЕРГЕТИЧЕСКИЕ ПОКАЗАТЕЛИ ОБРАТИМЫХ ГИДРОМАШИН

Украина обладает достаточным потенциалом для развития возобновляемых источников энергии. Возобновляемая энергетика активно развивается, спрос на аккумулирующие услуги гидроэнергетики будет расти, это обусловлено требованиями современных энергосистем к выравниванию графика для работы в пиковых зонах нагрузки. Решение задачи создания высокоэффективного оборудования для ГАЭС во многом зависит от правильного выбора геометрии элементов проточной части обратимой машины, которые обеспечивают необходимый уровень ее энергетических показателей. В работе рассмотрены вопросы моделирования гидродинамических характеристик лопастных систем обратимой гидромашины. Изменение энергетических параметров в диапазоне основных рабочих режимов универсальной характеристики в значительной мере обусловлены изменением гидродинамических характеристик обратимой гидромашины. Общий подход к описанию гидродинамических характеристик лопастных систем базируется на использовании безразмерных параметров, характеризующих поток в характерных сечениях проточной части. Приведены выражения, которые устанавливают связь гидродинамических характеристик с безразмерными комплексами, и выражают общие закономерности взаимодействия потока с рабочим колесом обратимой машины. Рассматривается влияние гидродинамических параметров лопастных систем на формирование энергетических характеристик обратимой гидромашины. Анализ гидродинамических характеристик отдельных элементов проточной части позволяет проанализировать их влияние на энергетические характеристики обратимой гидромашины. Результаты такого анализа являются основой для решения большого круга вопросов, которые возникают при проектировании обратимой гидромашины. В данной работе приведены расчеты энергетических характеристик для проточных частей обратимых гидромашин ОРО200, ОРО500. Расчетные данные свидетельствуют об определяющем влиянии гидродинамических параметров пространственных решеток на параметры оптимального режима.

Ключевые слова: обратимая гидромашина, энергетические характеристики, кинематические характеристики, потери энергии, математическая модель, режимные параметры, оптимальный режим.

Introduction. The countries of the European Union continue to increase the capacity of alternative energy. According to the conservative scenario, despite the need to overcome the consequences of the economic crisis caused by the SARS-CoV-2 coronavirus, the renewable energy sources (RES) sector will continue to develop. It is indicative that the only source of energy, which during quarantine measures showed an increase in vacation by 2 %, was renewable energy [1].

Ukraine has sufficient potential for the development of renewable energy sources and the replacement of traditional fuel and energy resources in the annual section of 68 million tons, which corresponds to 73 billion cubic meters of natural gas. Consequently, our country has set clear goals for the development of the renewable energy sector [2, 3].

Hydropower is an energy industry that can collect excess energy and store it until the grid is in short supply. In addition, hydroelectric power plants, unlike solar and wind ones, are independent of weather conditions and can generate electricity at any time. It is expected that the demand for storage and balancing services of hydropower will only grow, as renewable energy is actively developing.

From the analysis of the works on the study of the working process of reversible hydraulic machines, it follows that at present the issue of creating the water passages of reversible hydraulic machines is quite relevant [4–7]. For a pumped storage power plant, the decisive factor in the selection of parameters is the pumping mode, since the reversible hydraulic machine must provide the necessary head and the necessary characteristics of cavitation in the pumping mode of operation when the required power with the maximum efficiency is reached in the turbine mode at the calculated head. The difference between the optimal mode and the calculated one requires a thorough study of the water passage of the reversible hydraulic machine in turbine operation mode in order to reasonably determination of the design power, reserves for increasing the hydraulic efficiency and reducing the intensity of hydrodynamic unsteadiness [8–12].

The modern approach to the development of the water passage implies a large number of studies aimed at identifying the influence of geometric and operating parameters on energy parameters. Mathematical models of the working process are the basis for such a numerical analysis. Along with the development of methods for modeling the working process, using the results of solving the problem of three-dimensional viscous flow [13–18], methods for calculating energy characteristics based on simplified flow models are widely used.

One of the mathematical models used at the initial stages is a model based on dimensionless averaged parameters (the macro level) [19–22]. In this paper, a method based on the use of dimensionless averaged parameters for a calculated study of the characteristics of a reversible hydraulic machine at a head of 200 m and 500 m with obtaining the parameters of the spatial flow in the water passage is considered (the micro level).

Main part. Changes in energy parameters (efficiency, power) in the range of basic operating modes of the hill-chart are largely due to changes in the hydrodynamic characteristics of a reversible hydraulic machine.

The general approach to describing the hydrodynamic characteristics of blade systems is based on the use of dimensionless parameters characterizing the flow in the characteristic section of the water passage [19].

The kinematic characteristic of the three-dimensional lattice of the runner establishes the connection between dimensionless complexes $\frac{\Gamma_2 D}{Q}$ and $\frac{\Gamma_1 D}{Q}$ at the inlet and outlet from the runner lattice $\frac{\Gamma_2 D}{Q} = f\left(\frac{\omega D^3}{Q}, \frac{\Gamma_1 D}{Q}\right)$.

The kinematic characteristic can be written [19–23]:

$$\frac{\overline{\Gamma}_2 D}{Q} = k\frac{\overline{\Gamma}_1 D}{Q} - (1-k)\mu + (1-k)\frac{\pi}{2}\Lambda^2 k_Q\,. \qquad (1)$$

Dimensionless complexes in absolute and relative motion are connected by the relation $\frac{\overline{\Gamma}_{1,2} D}{Q} = \frac{\pi}{2} K_{r1,2}^{\,2}\, k_Q - \frac{\overline{\Gamma}_{1,2w} D}{Q}$. Kinematic complexes $\frac{\overline{\Gamma}_{1,2} D}{Q}$ and $\frac{\overline{\Gamma}_{1,2w} D}{Q}$ are expressed in terms of the averaged angles of the absolute $\tilde{\alpha}_{1,2}$ and relative $\tilde{\beta}_{1,2}$ flows in a given section [19] $\frac{\Gamma_{1,2} D}{Q} = \frac{\operatorname{ctg}\alpha_{1,2}}{S_{1,2}}$, $\frac{\Gamma_{1,2\,W} D}{Q} = \frac{\operatorname{ctg}\beta_{1,2}}{S_{1,2}}$.

$$\operatorname{ctg}\tilde{\beta}_2 = k\frac{S_2 \operatorname{ctg}\tilde{\beta}_1}{S_1} - (1-k)S_2\mu + \\ +(1-k)\frac{\pi}{2}S_2\left(\Lambda^2 - \frac{\left(\frac{r_{2r}}{R}\right)^2 - \left(\frac{r_{1r}}{R}\right)^2}{1-k}\right)K_Q\,. \qquad (2)$$

In more detail, the meaning of the above designations concerning the kinematic description of the flow in the water passage is given in [19].

Depending on the kinematic complexes that characterize the flow in the characteristic sections of the water passage, the hydrodynamic characteristics of the blade systems are expressed.

The hydrodynamic characteristics of the wicket gate (WG) are the dependences of the loss coefficient on the dimensionless complex, which determines the direction of the flow behind the WG: $k_{h\ inlet} = f\left(\frac{\overline{\Gamma}_0 D}{Q}\right)$ is loss characteristic in the WG; expression $\frac{\overline{\Gamma}_0 D}{Q} = f\left(\overline{a}_0\right)$ is kinematic characteristic of WG (calibration of WG).

The hydrodynamic characteristics of the three-dimensional lattice of the runner include kinematic, theoretical characteristics (characteristics of the force interaction of the flow with the runner), characteristics of losses, presented in dimensionless form.

The given kinematic description is a basis of the functional model of the working process, which establishes the relationship between the energy and operating parameters with the hydrodynamic characteristics of the water passage:

$$\eta_H=\frac{K_{HT}\left(k_Q,\ \frac{\overline{\Gamma}_0 D}{Q},\ L^{`}\right)}{g}Q_I^{`2}; \qquad (3)$$

$$Q=\sqrt{\frac{g}{K_{HT}\left(k_Q,\ \frac{\overline{\Gamma}_0 D}{Q},\ L^{`}\right)+k_h\left(k_Q,\ \frac{\overline{\Gamma}_0 D}{Q},\ L^{`}\right)}}; \qquad (4)$$

$$N_H^{`}=\gamma\frac{K_{HT}\left(k_Q,\ \frac{\overline{\Gamma}_0 D}{Q},\ L^{`}\right)}{K_{HT}\left(k_Q,\ \frac{\overline{\Gamma}_0 D}{Q},\ L^{`}\right)+k_h\left(k_Q,\ \frac{\overline{\Gamma}_0 D}{Q},\ L^{`}\right)}\times$$
$$\times\sqrt{\frac{g}{K_{HT}\left(k_Q,\ \frac{\overline{\Gamma}_0 D}{Q},\ L^{`}\right)+k_h\left(k_Q,\ \frac{\overline{\Gamma}_0 D}{Q},\ L^{`}\right)}}. \qquad (5)$$

From (3) and (4) follows the efficiency expression:

$$\eta_H=\frac{K_{HT}\left(k_Q,\ \frac{\overline{\Gamma}_0 D}{Q},\ L^{`}\right)}{K_{HT}\left(k_Q,\ \frac{\overline{\Gamma}_0 D}{Q},\ L^{`}\right)+k_h\left(k_Q,\ \frac{\overline{\Gamma}_0 D}{Q},\ L^{`}\right)}, \qquad (6)$$

where $k_h=\frac{(1-\eta_H)g}{Q_I'^2}$ is the coefficient of hydraulic losses.

In the functional model of the working process presented by (3)–(6): $K_{HT}\left(k_Q,\ \frac{\overline{\Gamma}_0 D}{Q},\ L^{`}\right)$ is theoretical pressure characteristic, $k_h\left(k_Q,\ \frac{\overline{\Gamma}_0 D}{Q},\ L^{`}\right)$ is water passage loss characteristic.

The theoretical characteristic establishes the dependence of the theoretical coefficient K_{HT} on the generalized kinematic parameters $k_Q,\ \frac{\overline{\Gamma}_0 D}{Q}$ and geometric parameters of the runner – $L^{`}$. The characteristic of losses $k_h$ reflects the relationship of the coefficient of the lost head with the parameters $k_Q,\ \frac{\overline{\Gamma}_0 D}{Q}$ and geometry of the runner – $L^{`}$.

The structure of the dependence of the theoretical pressure coefficient on the hydrodynamic parameters is established in [20] for different types of the runner:

$$k_{HT}=\frac{g\,H_T\,D^4}{Q_\kappa^2}=$$
$$=\frac{(1-k)}{2\pi}\left(\frac{\overline{\Gamma}_1 D}{Q}+\mu-\frac{\pi}{2}\Lambda^2\frac{\omega D^3}{Q_\kappa}\right)\frac{\omega D^3}{Q_\kappa}. \qquad (7)$$

Taking into account that $N_H=\gamma Q_k H_T$ find $k_{HT}=k_{\Delta NH}$:

$$k_{N\Gamma}=\frac{N_\Gamma\,D^4}{\rho Q_\kappa^3}=k_{HT}=$$
$$=\frac{(1-k)}{2\pi}\left(\frac{\overline{\Gamma}_1 D}{Q}+\mu-\frac{\pi}{2}\Lambda^2\frac{\omega D^3}{Q_\kappa}\right)\frac{\omega D^3}{Q_\kappa}, \qquad (8)$$

where $k_{N\Gamma}$ – hydraulic power coefficient.

The structure of dependence (7) is in good agreement with the experimental data for various types of hydraulic turbines [2]. The task of the structure of the dependence of the loss coefficient of the water passage has not been sufficiently studied. The solution to this task is one of the main in the theory of the working process.

The data of experimental studies of elements show the minima in the characteristics of losses in the wicket gate $k_{h\ wg}=f\left(\frac{\overline{\Gamma}_{sc} D}{Q},\frac{\overline{\Gamma}_0 D}{Q}\right)$ and in the runner $k_r=f\left(\frac{\overline{\Gamma}_{1W} D}{Q},\ \frac{\overline{\Gamma}_2 D}{Q}\right)$ [7, 8].

The complexes included in these dependencies characterize: $\frac{\overline{\Gamma}_{sc} D}{Q}$ – direction of flow generated by spiral casing and stator, $\left(\frac{\overline{\Gamma}_{1W} D}{Q}\right)=\left(\frac{\mathrm{ctg}\tilde{\beta}_1}{S_1}\right)$ and $\left(\frac{\overline{\Gamma}_2 D}{Q}\right)=\left(\frac{\mathrm{ctg}\tilde{\alpha}_2}{S_2}\right)$ – respectively, the direction of the relative flow in front of the runner and the direction of the absolute flow behind the runner ($\tilde{\beta}_1$ – averaged flow angle in relative motion in front of the runner, $\tilde{\alpha}_2$ – averaged angle of absolute flow behind the runner).

The presence of a minimum in the characteristics of losses makes it possible to represent their structural dependences in the following form:

$$k_{wg}=k_{wg\ m}+a\left(\frac{\overline{\Gamma}_{sc} D}{Q}-\frac{\overline{\Gamma}_0 D}{Q}\right)^2;$$

$$k_r=k_{r\ m}+\mathrm{b}\left(\frac{\overline{\Gamma}_{1W} D}{Q}-\mu_m\right)^2+c\left(\frac{\overline{\Gamma}_2 D}{Q}\right)^2,$$

where k_{wgm}, k_{rm} – minimum loss, due to frictional losses in the wicket gate and the runner, respectively; $\mu_m=\frac{\mathrm{ctg}\tilde{\beta}_{1m}}{S_1}$ – the direction of the relative flow, at which there are no losses due to separation of the flow when flowing around the leading edge of the blade; *a* and *b* – parameters determined by the geometry of the inlet elements, respectively, WG and runner; *c* – parameter determined by the geometry of the output elements of the runner blade.

Taking into account the kinematic dependences, the characteristic of hydraulic losses of the entire water passage can be represented as:

$$k_h = k_{sc} + k_{st} + k_{wg\ \min} + k_{r\ \min} + k_{dt\ \min} + \\ + a\left(\frac{\overline{\Gamma}_{sc} D}{Q} - \frac{\overline{\Gamma}_0 D}{Q}\right)^2 + b\left(\frac{\pi}{2} K_{r1}^2 k_Q - \mu_m - \frac{\overline{\Gamma}_0 D}{Q}\right)^2 + \\ + c\left(\frac{\pi}{2} \Lambda^2 k_Q - \mu\right)^2, \qquad (9)$$

where k_{sc}, k_{st} – the minimum value of the loss coefficient due to friction losses in the section of the fwater passage, including the spiral casing and the stator.

Parameters *a*, *b* and *c* in (9) do not depend on the operating mode and are determined using experimental data. In accordance with [20], it can be approximately assumed:

$$a = \frac{k_{wg}}{2\pi^2 K_{r1wg}^2};\ b = \frac{k_1}{2\pi^2 K_{r1}^2};\ c = \frac{k_2}{2\pi^2 K_{r2}^2},$$

where $K_{r1wg} = \frac{1}{Q}\int\left(\frac{r_{1wg}}{R_{wg}}\right)^2 dQ$; $K_{r1,2} = \frac{1}{Q}\int\left(\frac{r_{1,2}}{R}\right)^2 dQ$.

Substitution of the obtained expressions for K_{HT} (7) and k_h (9) allows you to replace functional descriptions of the workflow (3)–(4) with detailed equations of its mathematical model. For cascade of small pitch-chord ratio of the runner (Francis turbine), the transparency coefficient of the lattice *k* is small; therefore, in formulas (7, 8) $k = 0$.

Due to the cumbersomeness of the expressions obtained, they are not presented. Integral hydrodynamic parameters of the runner included in the obtained expressions: Λ, μ, μ_m and K_{r1} can be found both by calculation and experimentally [20].

To determine the hydrodynamic parameters of the three-dimensional lattice, the problem of parametric identification was solved. The parameters of model (9), the structure of which was defined above, were found from the data of energy experiments. When solving the problem, the least squares method was used and such values of the parameter-coefficients were determined in order for the model (9) provides the best approximation to the given experimental points.

Table 1 shows the values of hydrodynamic parameters for reversible hydraulic machines ORO200, ORO500.

Hydrodynamic parameters of the three-dimensional lattice of the runner K_{r1} and μ_m are integral characteristics of the inlet blade geometry. In this case K_{r1} is determined mainly by the location of the entrance edge in the meridional projection of the runner, and the parameter μ_m is a generalized (integral) characteristic of the shockless flow angle.

Table 1 – Hydrodynamic parameters of the three-dimensional lattice of the runner

Water passage type	ORO200	ORO500 1st variant	ORO500 2nd variant
n'_I	91,8	79	78
Q'_I	0,313	0,151	0,150
η	94,1	88,3	90,3
μ	0,53	0,46	0,45
Λ	10,79	15,6	15,6
μ_m	3,3	3,9	4,6
K_{r1}	1	1	1

Hydrodynamic parameters μ, λ characterize the geometry of the exit edge of the blade. The parameter μ is the integral characteristic of the distribution of the outlet geometric angles along the exit edge, and the parameter λ is determined by the location of the exit edge in the meridional projection of the runner.

The given mathematical description of the working process can be used both to assess the influence of the elements as a whole, and individual elements of the water passage on the formation of the energy characteristics of a reversible hydraulic machine.

For a more detailed analysis of the character of the flow and determination of the necessary characteristics of the elements of the water passage of a reversible hydraulic machine, CFD software packages are used. The results of such numerical studies are presented in the form of distributions of velocities and pressures in the required sections of the water passage of the pump-turbine.

In this paper, the inlets of the water passages of ORO200 and ORO500 (two variants) were investigated. Fig. 1 shows the velocity distributions in the form of streamlines.

The analysis of these results made it possible to determine the measure of the uniform distribution of the flow in the elements of the inlet of hydraulic machines.

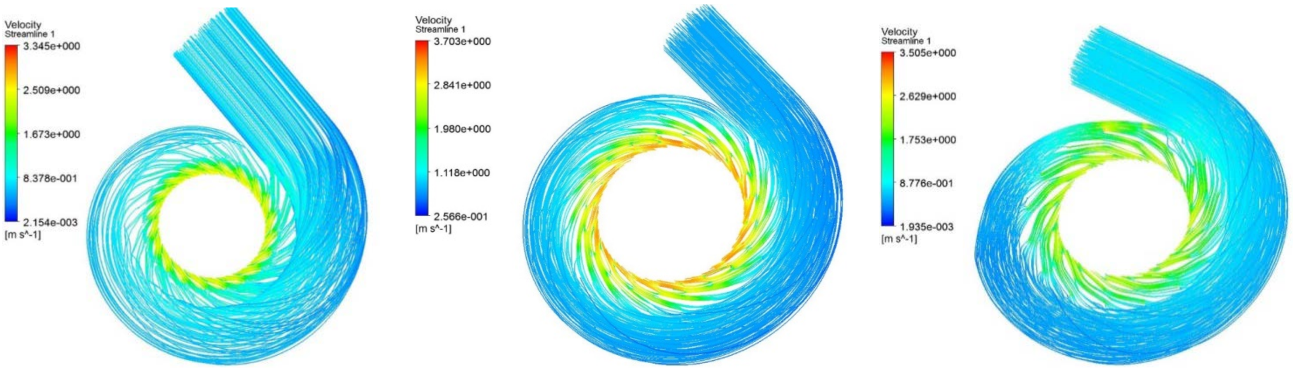
One of the necessary stages in the design of reversible hydraulic machines is the analysis of the blade system (Fig. 2).

It is also important to understand the character of the fluid flow in the outlet of a reversible hydraulic machine in order to prevent the formation of a secondary flow behind the blade system and the occurrence of so-called bundles. Visualization of the flow in the draft tube is shown in Fig. 3.

Conclusions. 1. The given mathematical description of the working process can be used both to assess the influence of the elements as a whole, and individual elements of the water passage on the formation of the energy characteristics of a reversible hydraulic machine.

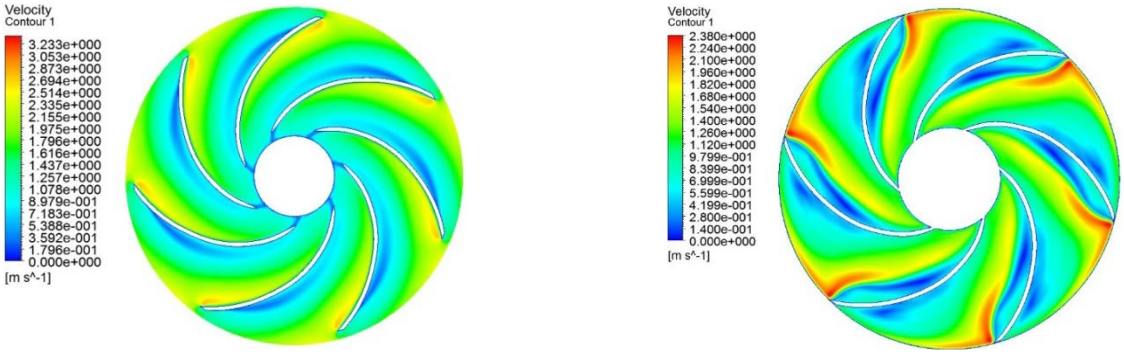
2. Calculations can be refined using programs for the numerical study of the spatial flow. The use of software packages makes it possible to more effectively analyze the character of the flow in the elements of the water passage of a reversible hydraulic machine, thereby ensuring correct research results.

3. The choice of a more efficient method depends on the design stage of the water passage and on the set task.



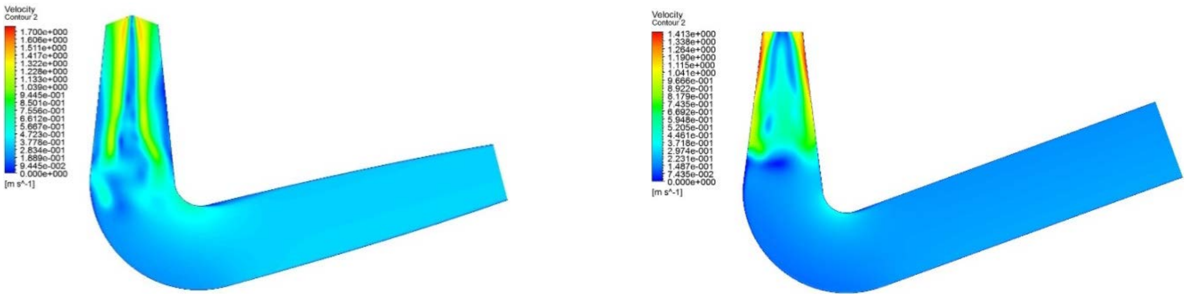
a *b* *c*

Fig. 1. Velocity distributions in the inlets:
a – ORO200; *b* – ORO500 (1 variant); *c* – ORO500 (2 variant)



a *b*

Fig. 2. Velocity distributions in the blade system:
a – ORO200; *b* – ORO500 (1 variant)



a *b*

Fig. 3. Velocity distributions in the draft tube:
a – ORO200; *b* – ORO500 (1 variant)

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Received 10.11.2021

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