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I. TYNIANOVA, K. REZVAYA, V. DRANKOVSKIY, D. SAVENKOV, O. TYNIANOV

DESIGN OF HIGHLY EFFICIENT WATER PASSAGE OF PUMP-TURBINE

The problem of the need to develop renewable energy sources as a way to save the energy supply and energy independence of Ukraine by changing the consumption of carbohydrates is considered. It is shown that the development of Ukrainian renewable energy must occur in parallel with the development of energy storage systems and balancing of the energy system. The most effective system for storing energy and balancing the energy system is pumped storage power stations (PSPS). The work shows that the design of a highly effective equipment of a hydroelectric power plant depends on the correct selection of the element geometry of the pump-turbine water passage. Therefore, it is possible to ensure the necessary level of energy characteristics of hydraulic equipment. A method of dimensionless average parameters was established, which allows even at the initial stages of designing new reversible hydraulic machines to determine the optimal geometry of the watter passage elements. This method showed good results during the numerical research of Francis hydraulic turbines at a wide range of heads, as well as reversible hydromachines at heads of 300–500 m. Using expressions that establish the connection of hydrodynamic characteristics with dimensionless complexes, three variants of the flow part of the high-pressure pump-turbines (ORO500) were investigated. Based on the obtained results, a significant influence of the geometry on the hydraulic indicators of the machine was noted. The distribution of energy losses in the inlet, blade system and outlet was analyzed. The greatest energy losses occur in the inlet of the pump-turbines. To increase the energy and kinematic indicators of the ORO500 pump-turbines, the geometry of the feed elements, as well as the spiral casing and stator, was changed. Variants for improving the parameters in the elements of the supply of the water passage of the pump-turbine are proposed.

Keywords: reversible hydraulic machine, water passage, averaged parameters, energy parameters, mathematical model, energy losses, optimal mode.

I. I. ТИНЬЯНОВА, К. С. РЄЗВА, В. Е. ДРАНКОВСЬКИЙ, Д. А. САВЕНКОВ, О. Д. ТИНЬЯНОВ

ПРОЄКТУВАННЯ ВИСОКОЕФЕКТИВНИХ ПРОТОЧНИХ ЧАСТИН ОБОРОТНОЇ ГІДРОМАШИНИ

Розглянуто проблему необхідності розвитку відновлюваних джерел енергії як засобу збереження довкілля та енергонезалежності України з метою зменшення використання органичного палива. Показано, що розвиток української відновлюваної енергетики повинен відбуватися паралельно з будівництвом систем накопичення енергії та балансування енергосистеми. Найефективніший у системі накопичення енергії та балансування енергосистеми є гідроакумулюючі електричні станції (ГАЕС). В роботі показано, що створення високоефективного устаткування ГАЕС багато в чому залежить від правильного вибору геометрії елементів проточної частини оборотних гідромашин, завдяки чому виникає можливість забезпечити необхідний рівень енергетичних показників гідрообладнання. Застосування методу осереднених безрозмірних характеристик в характерних перерізах проточної частини дозволяє вже на початкових етапах проектування нових оборотних гідравлічних машин обрати оптимальну геометрію елементів проточної частини. Даний метод позитивно зарекомендував себе при чисельному дослідженні радіально-осьових гідротурбін у широкому діапазоні напорів, а також оборотних машин на напори 300–500 м. Використовуючи вирази, які встановлюють зв'язок гідродинамічних характеристик з безрозмірними комплексами були досліджені три варіанти проточної частини високонапірної оборотної гідромашини ОРО500. На основі отриманих результатів відмічено значний вплив геометрії на показники гідромашини. Проаналізовано розподіл втрат енергії у підводі, лопатевій системі та відводі. Найбільші втрати енергії відбуваються у підводі оборотної гідромашини. Для підвищення енергетичних та кінематичних показників оборотної гідромашини ОРО500 було змінено геометрію елементів підводу, а саме спіральної камери і статору. Запропоновано варіанти покращення показників в елементах підводу проточної частини оборотної гідромашини.

Ключові слова: оборотна гідравлічна машина, проточна частина, осереднені параметри, енергетичні параметри, математична модель, втрати енергії, оптимальний режим.

Introduction. Energy security is a priority for Ukraine during and after the end of the war unleashed by russia. One of the key ways to guarantee Ukraine's security is to develop renewable energy sources. Renewable energy is not just a means of preserving the environment. It is now a matter of survival, energy independence, and abandonment of hydrocarbons, which have become a blackmail tool for dictatorships in the modern world. The further development of Ukrainian renewable energy should become one of the priorities when the war is over. The development of renewable energy should go hand in hand with the construction of energy storage and power system balancing systems. Of the modern technologies for balancing electricity in the integrated power system, (pumped storage power plant) PSPPs are the most efficient. PSPPs account for almost 94 % of all regulating capacities. They have significant advantages over industrial batteries in terms of cost, capacity and lifetime. That is why pumped storage power plants are built wherever there are favourable natural conditions. They can not only generate electricity like hydroelectric power plants, but also consume excess electricity (for example, generated by NPPs at night or by solar and wind power plants during the day) by pumping water from a lower reservoir to an upper reservoir, thus regulating the load schedule in a wide range [1–3].

Multivariate analysis is necessary for the modern approach to the design of water passages of PSPP. In this approach, not only the influence of regime parameters on energy performance is investigated, but also the geometrical parameters of individual elements of the water passage.

At present, there are various methods and approaches to study the working process in reversible hydraulic machines. At the same time, the selection of the most efficient of them depends on the stage of design and on the task facing the designers.

Interaction of different mathematical models for describing working process (i.e. application of block-hierarchical approach) is effective at different stages of hydraulic machine design [1–7].

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 operation mode 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 [8–11]. 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 3D viscous fluid flow [12–17], 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) [18–20].

In this paper, the method of dimensionless averaged parameters was applied to the design study of the characteristics of a high-head reversible hydraulic machine at a head of 500 m [8].

Modeling method. The use of dimensionless averaging method to investigate flow in the water passage allows to determine the averaged kinematic and energy characteristics in the characteristic cross-sections. In general case the following cross-sections are selected for verification of flow parameters calculations (Fig. 1):

0-0 – at the outlet of the wicket gate (WG);

1-1 – at the inlet to the runner;

2-2 – at the outlet of the runner;

3-3 – at the suction inlet draft tube.

To perform calculations in determining the kinematic parameters of the flow in the spiral casing with the stator it is necessary to have data on the angle of twist of the flow, which depends on the geometric parameters of the flow part: the angle of spiral coverage in plan φ, radius of inlet section of the spiral ρ_1, outer radius of the spiral R, height of the wicket gate b_{wg}. The kinematic and energy parameters in the characteristic sections can be determined at known regime parameters (ω, Q, a_0, n); kinematic characteristics of the wicket gate (average flow angle a_0, distribution of flow angles over the height of the wicket gate vanes); geometrical parameters of a water passage (b_{wg}/D_r, z_{wg}, D_{wg}), outlines of inlet and outlet edges in meridional projection, geometrical angles of the blade at inlet and outlet edges; geometrical characteristics of meridional flow in the points of flow lines section with characteristic sections (angle between the meridian component of speed and normal to the section γ, angle between tangent to the flow line and turbine axis δ). Thus, at change of geometrical parameters at early stages it is possible to calculate several variants of a water passage to select more optimal with the maximum power and optimal kinematic parameters.

For a computational study of the influence of geometric parameters on the characteristics of the pump-turbine water passage, it is necessary to select the appropriate mathematical model and accepted loss coefficients, which make it possible to describe the working process of the energy interaction of the flow with the water passage elements. The selected model has proven itself well in the calculations of reversible hydraulic machines for heads of 200 and 500 m [8].

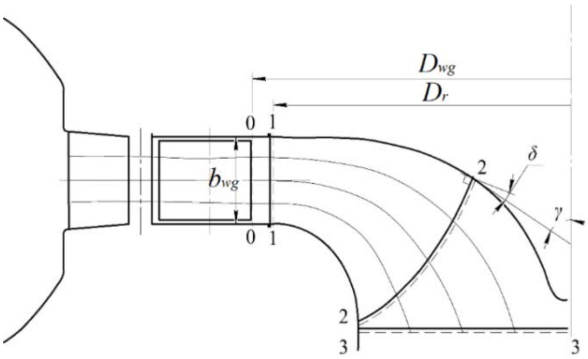

Fig. 1. The main cross-sections of the water passage of the reversible hydraulic machine in the turbine operation mode

The kinematic characteristic of the 3D 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 as:

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

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 [18–20] $\frac{\Gamma_{1,2} D}{Q} = \frac{\operatorname{ctg}\alpha_{1,2}}{S_{1,2}}$, $\frac{\Gamma_{1,2\ W} D}{Q} = \frac{\operatorname{ctg}\beta_{1,2}}{S_{1,2}}$.

$$\operatorname{ctg}\tilde{\beta}_2 = k\frac{S_2 \operatorname{ctg}\tilde{\beta}_1}{S_1} - (1-k)S_2\mu +$$

$$+(1-k)\frac{\pi}{2}S_2\left(\Lambda^2 - \frac{\left(\frac{r_{2r}}{R}\right)^2 - \left(\frac{r_{1r}}{R}\right)^2}{1-k}\right)K_Q.$$

In more detail, the meaning of the above designations concerning the kinematic description of the flow in the water passage is given in [18–20].

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; $\frac{\overline{\Gamma}_0 D}{Q} = f\left(\overline{a}_0\right)$ is kinematic characteristic of WG (calibration of WG).

The hydrodynamic characteristics of the 3D 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:

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

$$\grave{N}_H = \gamma \frac{K_{HT}\left(k_Q,\ \frac{\overline{\Gamma}_0 D}{Q},\ L^{`}\right)}{K_{HT}\left(k_Q,\ \frac{\overline{\Gamma}_0 D}{Q},\ L^{`}\right) + k_h\left(k_Q,\ \frac{\overline{\Gamma}_0 D}{Q},\ L^{`}\right)} \times$$

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

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

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: theoretical pressure characteristic $K_{HT}\left(k_Q,\ \frac{\overline{\Gamma}_0 D}{Q},\ L^{`}\right)$, water passage loss characteristic $k_h\left(k_Q,\ \frac{\overline{\Gamma}_0 D}{Q},\ L^{`}\right)$.

The theoretical characteristic establishes the dependence of the theoretical coefficient K_{HT} on the generalized kinematic parameters k_Q, $\overline{\Gamma}_0 D / Q$ 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 – $L^{`}$.

Initial data. *Parameters' calculation of the of the first variant of the water passage.* Spiral casing with circular meridional cross-sections, which is calculated according to the law $V_u \cdot r = \text{const}$ with the angle of coverage $\varphi_{\text{сп}} = 360°$. The calculated angle of the spiral $\alpha_{\text{сп}} = 27°$. The velocity in the inlet section was determined from the flow rate in the design turbine mode of operation. Diameter of the inlet section of the spiral casing $D_{\text{sc}} = 0.484D_r$, stator lattice densification $l/t = 1.48$. The number of stator columns is 20. Diameter of the stator at the inlet $D_{\text{in.st}} = 1.56D_r$, at the outlet – $D_{\text{out.st}} = 1.31D_r$. Height of the stator – $b_{\text{st}} = 0.943D_r$. Geometrical parameters of the wicket gate: number of vanes $z_{\text{wg}} = 20$, lattice densification $l/t = 1.07$, diameter $D_{\text{wg}} = 1.198D_r$, height – $b_{\text{wg}} = 0.674D_r$. Parameters of the runner: diameter $D_r = 1$ m, the ratio of diameter at the inlet of the runner and its outlet is 0.5, the number of blades $z_r = 6$. The draft tube consists of a conical part, a bend and a cylindrical part. Parameters of the draft tube: diameter at the inlet $D_{\text{dt.in}} = 0.5D_r$, diameter at the outlet $D_{\text{dt.out}} = D_r$, length $l_{\text{dt}} = 5D_r$.

Parameters' calculation of the of the second variant of the water passage. Spiral casing was replaced by the second variant with the following parameters: the design angle of the spiral is increased to 370°. The diameter of the inlet section of the spiral casing $D_{\text{sc}} = 0.59D_r$, stator lattice densification is reduced – $l/t = 0.897$. The number of stator columns is reduced to 16. The diameter of the stator at the inlet is increased up to $1.6D_r$, at the outlet without changes. The stator height is unchanged. All other elements (wicket gate, runner and draft tube) remained with the same geometrical parameters as in the first version of the water passage.

Parameters' calculation of the of the third variant of the water passage. The modified second variant was taken as a basis and the following changes were made to the geometry of the wicket gate only. The number of vanes – 16, the diameter was increased $D_{\text{wg}} = 1.25D_r$, $l/t = 0.897$.

Calculation results. As a result of calculations of three variants of the water passage, the following results were obtained: parameters of the optimal operating mode of the hydraulic machine, energy losses in the water passage elements, hydraulic efficiency, flow angles at the inlet and at the outlet of the runner.

These parameters are necessary to determine the most suitable geometrical parameters of water passage elements. Table 1 summarizes the parameters of the optimal mode.

Table 1 – The parameters of the optimal mode

Variant	n'_I, rpm	Q'_I, m^3/sec	η, %
1st	80	0.147	84.3
2nd	77	0.156	84.6
3rd	79	0.150	86.5

One of the main parameters that characterise the operation of a reversible hydraulic machine is the hydraulic efficiency. The efficiency surfaces are presented in Fig. 2–4. This makes it possible to visualise more clearly the nature of loss changes in the water passage.

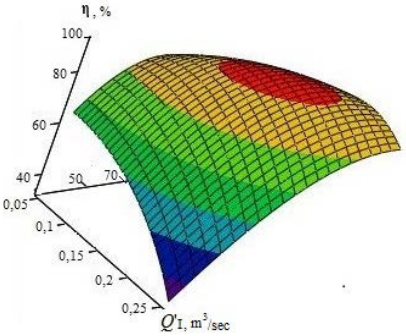

Fig. 2. The efficiency surface of the ORO500-B-100 (1 version)

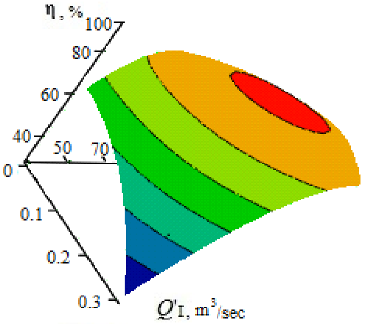

Fig. 3. The efficiency surface of the ORO500-B-100 (2 version)

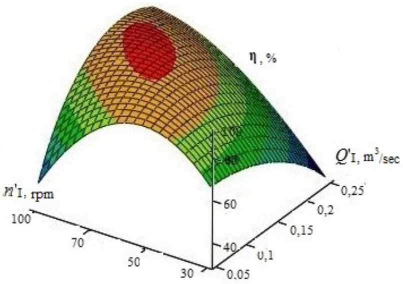

Fig. 4. The efficiency surface of the ORO500-B-100 (3 version)

Graph of energy losses in water passage elements gives an opportunity to analyse element by element where losses have larger value. This helps to understand where it is necessary to reduse losses for improvement of parameters of the reversible hydraulic machine. For this purpose the graph at optimal values n'_I and Q'_I of three variants of the pump-turbine water passage was drew, the data for which were obtained by calculation with the use of the method of averaged dimensionless parameters (Fig. 5).

The graph shows that the inlet elements have the highest losses. Due to changes in the geometry of these elements, the losses are significantly reduced relative to the first variant.

To verify the correctness of the obtained results on the basis of the selected method, we also conducted experimental studies of three variants of flow parts of reversible hydraulic machine at the department "Hydraulic Machines" NTU "KHPI" on the hydraulic set.

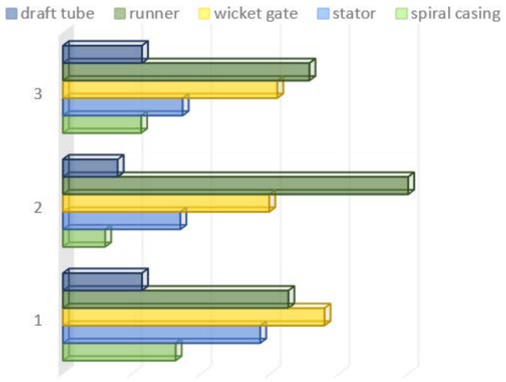

Fig. 5. Losses in the elements of the flow part of three variants of the flow part

The universal characteristic of three variants of the flowing part, which is presented in Fig. 6, shows the character of parameters change and optimum on it.

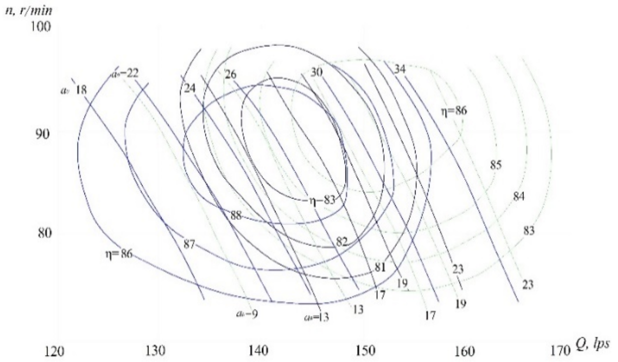

Fig. 6. Comparison of universal characteristics

After investigation of the first variant of the water passage of the reversible hydraulic machine, a universal characteristic was obtained (Fig. 6, black lines).

Further modifications of the first variant were carried out.

The results of experimental studies showed that the universal characteristic was shifted and the mode parameters of the hydraulic machine operation were changed in comparison with the first variant. The optimum of the characteristic was formed at slightly higher reduced flow rates and rotations (Fig. 6, lines of green colour). The mode of the reversible hydraulic machine have changed for the better: the number of rotations decreased and the reduced flow rate also decreased by 3.4 % (from 147 to 142 l/s), which is better for the hydrounit with the given head (Fig. 6, blue lines).

Parameters of optimal operating modes of the hydrounit are summarised in Table 2.

Table 2 – Optimal mode parameters

Variant	n'_I, rpm	Q'_I, m^3/sec	η, %
1st	89	0,145	83.6
2nd	92	0.147	86.7
3rd	88	0.142	88.8

During calculation, it was determined that in the water passage of a slow-speed reversible hydraulic machine the largest energy losses are observed in the inlet

(60–65 %) [8]. Therefore, after the calculation of the first variant, the geometry of the spiral casing with stator was changed. This resulted in 1.16 % reduction of losses in the spiral casing (1.02 %), stator (1.16 %) and wicket gate. But due to incomplete coordination of inlet and blade system, losses in the runner redused by 2.17 %. As a consequence, the hydraulic efficiency and consequently the total efficiency increased by 1.16 %.

Further, the geometry of the wicket gate was also changed. This resulted in the following: losses in the inlet elements increased slightly (total increase – 0.67 %), but at the same time losses in the runner decreased by 2.17 %. As a result of matching the inlet and blade system, the efficiency was increased by 0.84 %.

If we compare the last variant of the flow part with the original (first variant), the efficiency was increased by 2 %.

Conclusions. 1. Application of the dimensionless averaged parameter method to the study of water passages of reversible hydraulic machines in turbine operation mode shows that geometrical parameters influence hydrodynamic, energy and kinematic parameters.

2. Using the method of averaged dimensionless parameters the flow angles β_1 and α_2 are determined, which give information about the flow of the runner blade system and about the coordination of the elements of the water passage of the reversible hydraulic machine.

3. In a slow-speed reversible hydraulic machine, the greatest losses are in the inlet (60–62 %). Thus, to increase the energy and kinematic parameters it is necessary to modify (change the geometry) exactly the elements of the inlet (spiral casing, stator and wicket gate).

4. As a result of calculations it was determined that the change of geometrical parameters of the spiral chamber, stator led to a decrease in losses by 1.16 %, and when changing the geometry of the wicket gate – 0.84 %.

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Відомості про авторів / About the Authors

Тиньянова Ірина Іванівна (***Tynyanova Irina***) – кандидат технічних наук, доцент, Національний технічний університет «Харківський політехнічний інститут», доцент кафедри «Гідравлічні машини ім. Г. Ф. Проскури»; м. Харків, Україна; ORCID: https://orcid.org/0000-0003-1185-3458; e-mail: t.irinai@ukr.net

Рєзва Ксенія Сергіївна (***Rezvaya Kseniya***) – кандидат технічних наук, доцент, Національний технічний університет «Харківський політехнічний інститут», доцент кафедри «Гідравлічні машини ім. Г. Ф. Проскури»; м. Харків, Україна; ORCID: https://orcid.org/0000-0002-2457-0097; e-mail: rezvayaks@gmail.com

Дранковський Віктор Едуардович (***Drankovskiy Viktor***) – кандидат технічних наук, доцент, Національний технічний університет «Харківський політехнічний інститут», професор кафедри «Гідравлічні машини ім. Г. Ф. Проскури»; м. Харків, Україна; ORCID: https://orcid.org/0000-0002-9011-2094; e-mail: drankovskiy50@ukr.net

Савенков Дмитро Анатолійович (***Savenkov Dmytro***) – Національний технічний університет «Харківський політехнічний інститут», аспірант кафедри «Гідравлічні машини ім. Г. Ф. Проскури»; м. Харків, Україна; ORCID: https://orcid.org/ 0009-0008-8654-627X; e-mail: dmytro.savenkov@gmail.com

Тиньянов Олександр Дмитрович (***Tynianov Oleksandr***) – Національний технічний університет «Харківський політехнічний інститут», аспірант кафедри «Гідравлічні машини ім. Г. Ф. Проскури»; м. Харків, Україна; ORCID: https://orcid.org/0009-0002-7224-7152; e-mail: oleksandr.tynianov@mit.khpi.edu.ua