https://doi.org/10.33271/nvngu/2024-3/056

O. M. Khoryev[1],
orcid.org/0000-0001-6940-4183,
O. V. Lynnyk[2],
orcid.org/0000-0003-1946-3032,
P. O. Korotaiev[1],
orcid.org/0000-0002-7473-9508,
Yu. A. Bykov[*1],
orcid.org/0000-0001-7089-8993,
Ye. S. Ahibalov[1],
orcid.org/0000-0003-3866-9992

1 – Anatolii Pidhornyi Institute of Mechanical Engineering Problems of National Academy of Sciences of Ukraine, Kharkiv, Ukraine
2 – JSC "Ukrainian Energy Machines", Kharkiv, Ukraine
[*] Corresponding author e-mail: yubykoff@gmail.com

EFFECT OF CIRCUMFERENTIAL LEAN OF PUMP-TURBINE RUNNER BLADES ON ENERGY CHARACTERISTICS

Purpose. Improving the efficiency of the model of the radial-axial pump-turbine of the Dniester PSP based on spatial profiling of runner blades using circumferential lean.

Methodology. The design of the new runners was carried out by means of spatial profiling of the blades, which differed only in the layout of the profiles (relative position) in the circumferential direction. The blades of the runner models with a diameter of 350 mm were manufactured by 3D printing from PLA plastic. Experimental studies were carried out on the IMEP ECS-30 hydrodynamic test stand, the characteristics of which meet the requirements of the international standard for model acceptance tests of hydraulic machines of various types.

Findings. Based on the proposed method of spatial profiling of runner blades, the effect of circumferential lean on the energy performance of pump-turbines is investigated. Characteristics in a wide range of turbine and pump modes of operation of three variants of flow parts are obtained. Parameters of optimal modes and values of maximum efficiency are calculated. A comparison of the energy characteristics in the turbine mode at the constant rotation speed corresponding to the maximum, design and minimum heads of the Dniester PSP is presented. In the pump mode, the dependences of the efficiency curves and heads on flow rate at different values of guide vane openings are shown.

Originality. The influence of circumferential lean (spatial profiling) of the runner blades of a radial-axial pump-turbine on the energy characteristics in the turbine and pump modes was established for the first time, which made it possible to significantly increase the level of efficiency in almost the entire range of turbine operating mode.

Practical value. The newly designed high-performance runner is planned to be implemented at hydraulic units 5–7 of the Dniester PSP. To confirm the results, it is intended to manufacture and study large-scale models of pump turbines with metal runners together with JSC "Ukrainian Power Machines".

Keywords: *pump-turbine, Francis turbine, runner, hydrodynamic test stand, experimental studies*

Introduction. Based on forecasts from leading scientific organizations, the Earth's civilization is threatened by a climate catastrophe associated with uncontrolled global warming. The Paris agreement on the reduction of greenhouse gas emissions sets the goal of maintaining the rate of global warming at the level of 1.5 °C and envisages reducing emissions to zero by 2050 [1]. This goal can be achieved with fairly intensive development of "clean" energy, which includes solar, wind, nuclear, and hydraulic power plants. According to statistics [2], in 2021 share of "clean" energy reached 37.88 %, which is slightly less than 38.24 % a year earlier. Against the background of significant growth of solar and wind energy, the share of hydropower decreased slightly – from 16.52 % a year earlier to 15.28 % in 2021. The capacity of pumped storage plants in the world has increased significantly – by 6.3 GW [3], which is about a quarter of the increase in hydropower capacity. The pumped storage plants produced only 0.4 % of total electricity in 2021, but they play an important role in balancing production and consumption of electricity [4], especially with rapid development of renewable energy, which is significantly dependent on weather conditions, season, and time of day.

The hydropower potential of Ukraine's major rivers is almost exhausted. Therefore, the most realistic way to increase the shunting and balancing capacity is to build new PSPs, first of all, to complete the construction of the Dniester PSP (5–7 hydraulic units). The contractor has set conditions not only to increase the efficiency of the hydropower units but also to expand the range of operation in generating mode while at least maintaining the pumping performance. To accomplish such tasks, it is necessary to study the workflow in detail based on numerical and physical modeling of flow in the flow parts, as well as to apply new methods for designing runners, primarily through spatial profiling of the blades.

Literature review. A significant number of hydropower plants and almost all PSPs are equipped with the Francis radial-axial turbines. They have high efficiency values and can work in both turbine and pump modes. Unlike other types of reactive hydraulic machines (axial, diagonal), the runner blades of Francis turbines have a significantly spatial shape, which, in addition (as well as the shape of the contours in the meridional section), significantly depends on the specific speed. This circumstance significantly complicates the process of designing and optimizing the flow parts.

In Ukraine and around the world, a significant number of design methods have been developed and implemented for the design of flow elements of both large Francis [5], Kaplan [6], and other hydroturbines, as well as mini- and micro-hydroelectric power plants [7].

Optimizing energy characteristics requires the presence of a limited number of parameters describing the geometric and operation characteristics of the turbine. The blade shape of Francis runners is more often described using simplified methods, for example, the construction of a blade by separate design sections using polynomials [8, 9]. In recent years, complex full-spatial design and optimization methods have also been used; with this approach, the geometric parameters of the flow part do not depend on the operating parameters.

It is possible to obtain geometric data of the Francis runner blades for further optimization by the initial parameters (shape of the meridional section, inlet and outlet angles, cross-sectional wrapping angles, etc.) using open source or commercial software [10, 11].

The latest studies show that among numerous geometric parameters of the blade, circumferential and axial leans of edges and cross-sections of the blade play an important role [12]. The use of lean affects both the structure of flow [13], the pulsation characteristics in the blade channel and behind the runner [14], and the energy characteristics of the flow part. Also important is the change in profile thickness [15], which in some cases can lead to a decrease in efficiency and an increase in losses. Since the possibility of using variable-speed generators (±15–20 % of the synchronous speed) has been increasingly considered recently, the turbine shaft speed is also used as an optimization parameter [16]. In such cases, the optimization parameters can be either only the operating parameters or the geometric characteristics of the flow parts [17, 18].

Most often, the optimization of the energy performance of radial-axis hydraulic machines is performed for a single design mode point of operating characteristic [18]. If the project objective is to increase the weighted average efficiency or expand the operating range, then optimization can be performed for several operating points [19]. In the case of designing and studying a pump-turbine, optimization can be performed for the operating points of both turbine and pump modes [20].

Also, the goal of optimization may include cavitation characteristics of the turbine [21] and parameters of erosive wear [22].

An important stage of design is to determine the calculation area in which optimization studies will be conducted. The most common is the numerical modeling of flow in the calculation domain of turbine, which includes runner and guide vane [22]. Some researchers consider it necessary to include stator columns and draft tube in the numerical simulation [21].

Experimental studies on the designed turbines are the most reliable, albeit costly, way to obtain energy, overspeed, cavitation, and pulsation characteristics. The main task of experimental studies, primarily acceptance tests, is to confirm the guaranteed energy performance of the hydraulic machine model, which was determined by calculation [23, 24]. At the same time, nonstationary phenomena that were not detected in the mathematical modeling of fluid flow can be detected [25].

Purpose. The aim of the work was to establish the dependence of the circumferential lean value of the runner blades on the energy characteristics on in a wide range of turbine and pump modes based on experimental studies of models of Francis pump-turbines with a head up to 200 m. To achieve the goal, the following tasks were set and solved:

- to develop a methodology for spatial profiling of blades of radial-axial runners with the help of circumferential lean;
- with the help of the developed methodology, to design 2 modifications of pump-turbine runners with a head of up to 200 m;
- to manufacture parts of the model unit, including 3 variants of runners: base and 2 modifications;
- to conduct selective experimental studies on models on the hydrodynamic stand;
- to establish the influence of the circumferential lean of the runner blades on the energy characteristics in turbine and pump modes.

Methods. The model of highly efficient Francis pump-turbine ORO5217 for heads up to 200 m, which was developed at the Institute of Mechanical Engineering Problems of the National Academy of Sciences of Ukraine (IMEP) and implemented on units No. 1–4 of the Dniester PSP, was adopted as the research object. The PSP units are characterized by the following in-situ parameters: maximum head in turbine mode (gross) – 161.9 m, minimum head (gross) – 138.4 m, rated power in turbine mode – 324 MW, in pump mode – 410 MW, design flow rate in turbine mode – 270 m^3/s, in pump mode – 252 m^3/s, synchronous rotation speed – 150 min^{-1}, runner diameter – 7.3 m. The flow part consists of a spiral case with circumferential cross-sections and a wrapping angle of 360°, 20 stator columns, 20 guide vanes, runner with 7 blades, and draft tube with a KU-3RO elbow and a constant-diameter outlet tube. In the RK5217 runner, the trailing edge is located in the radial plane, the angle of inclination of the leading edge in circumferential direction is 10° in direction of rotation of the rotor.

Until recently, the methods for designing and calculating runner blades were based on the hypothesis that the stream surfaces correspond to the type of flow selected in the flow part (equal-speed, potential, etc.) and do not depend on the operating mode. With this approach, the hydrodynamic calculation of blade profiles was performed almost without taking into account their mutual influence. The energy performance of runners with the same but differently arranged blade profiles was considered to be the same, although in reality the spatial shape of the blades of such runners is different, and therefore they are affected by different flows. This leads to a significant difference in the energy characteristics of hydraulic machines.

When using the blade leans proposed in [26], a new blade layout was obtained by changing the relative position of the design profiles in the circumferential direction. The shape of the leading and trailing edges is also changed. The shape of the profiles remains unchanged. We conditionally call the lean positive ($\varphi > 0$) if the hub profile is shifted in the direction of runner rotation in the turbine mode, and negative in the opposite direction ($\varphi < 0$) (Fig. 1).

This approach allows optimizing the blade shape due to better edge flow, forming a more favorable flow in the runner channels and at the inlet to the draft tube.

To study the dependences of the energy characteristics of the pump-turbine model on the proposed method of blade spatial profiling, the critical (in terms of production) values of the blade circumferential lean $\varphi = +45°$ and $\varphi = -45°$ were determined using numerical modeling. On the basis of the original runner RK5217 of the Dniester PSPP, new runners RK5217M and RK52M2 were designed with the specified values of the leans, respectively. In RK5217M, the hub profile is shifted by 12.8° in the circumferential direction clockwise relative to the original version, in RK5217M2 in the opposite direction by 18.2°.

Fig. 2 shows models of the original and new runners with circumferential leans.

For experimental research on the pump-turbine on the hydrodynamic test stand, three runner models with a diameter of 350 mm were manufactured. The blades are made from PLA plastic by 3D printing (each blade is printed separately). The advantages of this material are its natural origin, non-toxicity and safety for human health, dimensional stability, no need to heat the platform when printing, ideal for moving models, smooth surfaces, and more. The blades were printed in layers

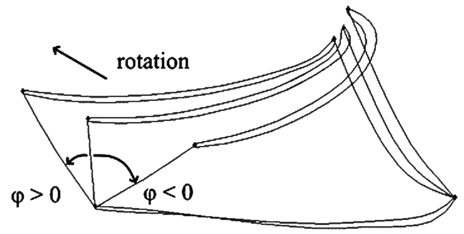


Fig. 1. Definition of the circumferential lean angle φ

Fig. 2. Computer models of the blades of the investigated runners

with a layer thickness of 0.1 mm, which ensured high quality of the blade surface. Finally, a minor cleaning with fine sandpaper and polishing with flannel were performed, after which the surface was glossy. The runner hub and shroud were made of stainless steel to ensure structural strength, and the lower covering disk was made of transparent block plexiglass, attached to the blades with 16 screws and dichloroethane-based glue. The runner design is lightweight and quite durable. The inspection of the geometric dimensions of the blades showed that the deviation of the dimensions of individual blades does not exceed 0.1–0.2 mm, which does not exceed the requirements of the international model standard IEC 60193. This approach made it possible to significantly reduce the time and cost of conducting research. Preliminary calculation of the strength of the blades proved the possibility of conducting research on the test stand at heads of up to 12 m. Fig. 3 shows a photo of the three investigated runners.

Energy studies on the pump-turbine models were conducted on the ECS-30 hydrodynamic test stand of the IMEP laboratory, which has the status of national heritage. The test stand is equipped with modern equipment and a set of measuring instruments, has passed metrological verification, and has a certificate. The measurement error of head and torque is ±0.10 %, rotational speed – ±0.03 %, flow rate – ±0.20 %, which guarantees an error of ±0.25 % in measuring efficiency and meets the requirements of IEC 60193 [25].

The main parameters of the experimental stand ECS-30 are as follows: diameter of the runner model 300–400 mm; head up to 25 m in the turbine mode, up to 30 m in the pump mode; flow rate in the turbine mode up to 0.300 m^3/s, flow rate in the pump mode up to 0.500 m^3/s; power of the circulation pumps' DC drive motors up to 160 kW; power of the balancing motor-generator 200 kW.

The equipment of the ECS-30 is located on three floors of the stand building, Fig. 4 shows its layout.

In Fig. 4, there is marked: *1* – head water tank; *2* – tailwater tank; *3* – model unit; *4* – balancing machine; *5* – electromagnetic flow rate meter (main) and Venturi-type flow rate meter (backup); *6* – head pipeline; *7* – circulation pump; *8* – absorber; *9* – drain pipeline.

Results of numerical study. Hydraulic machine models are studied both numerically and experimentally. Physical modeling of the turbine operation on hydrodynamic stands provides more reliable energy characteristics. At the same time, numerical modeling requires significantly less labor and financial costs, significantly reduces research time, and is more informative in terms of the flow structure in any cross-section of the flow part elements. Therefore, both numerical and experimental studies were carried out to determine the effect of blade leans (layout) of pump-turbine runners on energy characteristics.

Fig. 3. Photo of three 5217 series runners (*from left to right: RK5217M, RK5217, RK5217M2*)

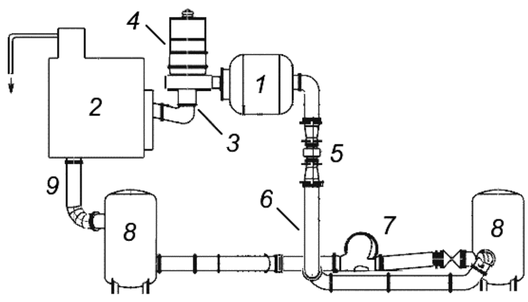


Fig. 4. Simplified scheme of the energy cavitation test stand ECS-30

Preliminary, selective numerical studies on the incompressible viscous flow in models of all three variants of runners was carried out with the help of *IPMFlow* software, developed at the IMEP [27]. The goal was to establish the presence of a qualitative effect of circumferential lean of runner blades on the flow structure and energy characteristics in the turbine mode. Modeling of the flow was carried out by the method of artificial compressibility, integration of the equations of motion, and two-parameter turbulence model of Menter (SST) was performed by the finite volume method with the second order of accuracy in space and time [28]. The *IPMFlow* software package is designed to simulate fluid flows of various types [29] in the flow parts of a wide range of power machines [30]. The use of modern models in the software package allows the creation and implementation of innovative turbomachinery designs [31].

Numerical studies were carried out for the computational domain containing one channel each of the guide vanes and the runner. The computational mesh was normalized, hexagonal, and had thickening near the walls. The value of the y+ parameter did not exceed 10. The number of cells: the channel of the guide vanes 72 × 72 × 80 = 414,720; the channel of the runner 72 × 72 × 120 = 622,080. The diameter of the runner model was 350 mm, which is equal to the dimensions used on the ECS-30 test stand.

Numerical studies were carried out for the Reynolds number in the range $Re = 1.2 \cdot 10^6 – 2.85 \cdot 10^6$.

As boundary conditions at the inlet, a head of 6 m was set and rotor speeds of 85, 91 and 95 min^{-1} were given, which, according to the formula $n'_I = nD_1 / \sqrt{H}$, (here n is the rotation speed, D_1 is the wheel diameter, H is the head) corresponds to heads of 166, 144.8 and 133 m at the Dniester PSP. The openings of the guide vane a_0 were 12, 16, 20, 24, 28 and 34 mm.

Fig. 5 shows a comparison of the dependence of the efficiency of the computational domains of the studied runner models on the flow rate at three values of the head in the turbine mode [27].

The results of the numerical experiment showed that over the entire operating range of the Dniester PSP, the RK5217M2 pump-turbine model with a negative blade lean (φ = –45°) has the highest energy performance. It also has the best flow structure in the flow part elements. In this case, we understand better flow structure as more uniform pressure profiles, more uniform distribution of velocities and pressures in the runner channel, more uniform distribution of components (circular, radial, axial) of the absolute velocity behind the runner, and no separations on the blade surface. More details can be found in [27].

The purpose of the numerical studies was to establish the qualitative effect of circular leans on efficiency in the turbine mode, so numerical studies in the pumping mode were not carried out.

To confirm the established dependencies and determine their reliable quantitative values, selective experimental tests of the investigated runners were carried out on a hydrodynamic test bench.

Results of experimental research in turbine mode. Energy studies on the pump-turbine models in the turbine mode were carried out at a constant head H = 6 m, and openings of the guide vane varied from 8 to 44 mm with a step of 2 mm. At each opening of the guide vane, 18–20 mode points were measured. The methodology for conducting modeling studies met the requirements of IEC 60193. It should be noted that this head is not enough to conduct cavitation tests, as well as to

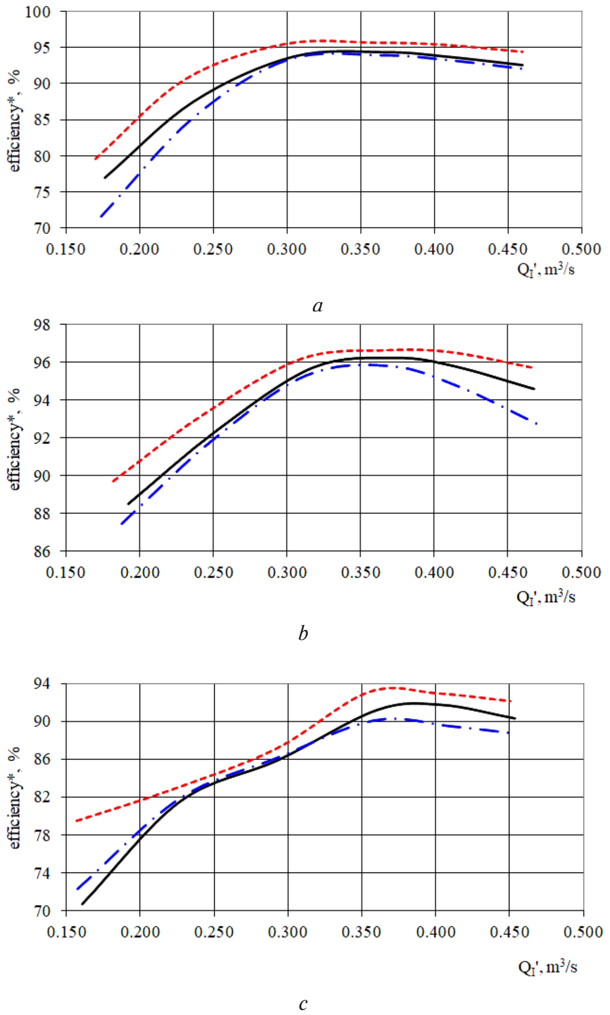


Fig. 5. Comparison of the dependences of the calculated efficiency on the flow rate in models of the flow part of a pump-turbine with runners of different spatial shapes:

a – minimum head; b – design head; c – maximum head

—— – RK5217; —•— – RK5217M; – – – – – RK5217M2

study unsteady and transient modes. The Reynolds numbers during the research were in the range $Re = 1.2 \cdot 10^6$–$2.85 \cdot 10^6$.

Measurement and processing of parameters for each studied mode point is carried out automatically using the measuring and computing equipment of the test stand. Measurement of all indicators (head, rotation speed, flow rate, torque) of each operating point is carried out within 10 seconds, 100 samples of signals/data of measured values are received by the equipment every second, after which the values are averaged. Using well-known formulas, the values reduced to 1 m of head and 1 m of runner diameter are calculated (unit flow rate, unit rotation speed, unit torque on the runner shaft, unit power) and efficiency.

The efficiency was determined by the well-known formula $\eta = M\omega/(gQH)$ in the turbine mode and, accordingly, $\eta = gqH/(M\omega)$ in the pumping mode. Here, M is torque; $\omega = \pi n/30$ is angular velocity; g is gravity acceleration; Q is flow rate; H is the head. The computational system provides complete mathematical processing and final presentation in the form of digital and graphical information, including the construction of all the necessary characteristics.

The operating characteristics (dependence of efficiency on the reduced rotational speed) for all studied guide vane openings were obtained, and on their basis, hill charts for models with three variants of runners were built.

In Table 2 the parameters of optimal modes of the flow parts for three variants of runners are shown. Relative efficiency here means the ratio of the current efficiency value to the maximum value of the original version of RK5217 runner in percent. In the table $Q'_I = Q/(D_1^2\sqrt{H})$ (here Q is the flow rate, D_1 is the runner diameter, H is the head).

Table 1

Parameters of optimal turbine modes of flow parts of three 5,217 series runners

Runner	Unit flow rate Q'_I, m^3/s	Unit speed of rotation n'_I, min^{-1}	Relative efficiency η^*, %
RK5217	0.312	78.0	100.00
RK5217M	0.317	76.0	98.56
RK5217M2	0.313	79.0	100.74

The maximum relative efficiency value of 100.74 % is received in the flow part with RK5217M2. It is shown that the values of the unit flow rate of the optimal modes depend insignificantly on the value of the lean. The use of the positive circumferential lean (RK5217M) led to a decrease in rotation speed in the optimal points for 2 min^{-1} relative to the original version (RK5217 runner), and the negative one (RK5217M2) – to an increase of 1 min^{-1}. It should be added that the optimum operating points of all three model variants are located at the openings of the guide vane a_0 of approximately 20 mm.

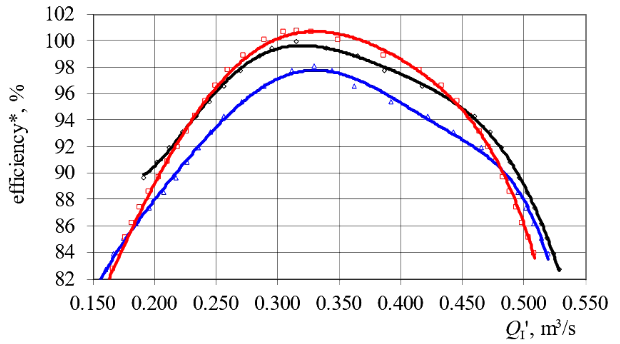
Fig. 6 shows the dependence of the relative efficiency of the pump-turbine models on the unit discharge for three variants of the runners in the turbine mode at section of hill chart of n'_I = const, which correspond to the design rotation speed $n'_I = 80$ min^{-1} and the maximum, design and minimum heads of the Dniester PSP, correspondingly 85, 91 and 95 min^{-1}.

The use of circumferential leans leads to a shift in the flow rate of the operating points with the maximum efficiency. Thus, at the unit rotational speeds of 80, 85 and 91 min^{-1}, the maximum efficiency of the RK5217M2 with a negative lean, shifts towards higher flow rates, and at a frequency of 95 min^{-1}, which corresponds to the minimum head at the Dniester PSP, to lower flow rates. A similar picture is observed when using a positive lean in the RK5217M.

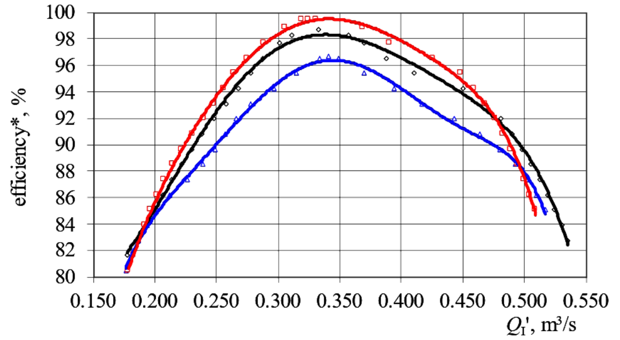
As can be seen, in the almost entire range of operation of the power station units – both in terms of head and flow rate – the efficiency value of the flow part model with the RK5217M2 runner with the negative circumferential lean $\varphi = -45°$ significantly exceeds the similar indicators of the original version. This can be explained by the fact that the surface area of this runner increased by 5.15 % compared to RK5217. In addition, as shown by numerical studies [27], optimization of the layout of the design profiles led to a more favorable distribution of pressure and velocity vectors in the flow part, a more uniform distribution of velocity components behind the runner at the inlet to the draft tube. At the design head and flow rate in the range of 0.300–0.470 m^3/s, the efficiency of the flow part with the new RK5217M2 is higher than that of the original one by 1.1–2.0 %.

The option with the RK5217M with the positive circumferential lean $\varphi = +45°$ (the blade surface area of which decreased by 1.8 % when using a circumferential lean) has the lowest indicators in the almost entire range of operation of the unit, with exception of low flow rate ($Q'_I < 0.290$ m^3/s) at the minimum head (Fig. 6, *d*), but under such operating parameters, the units of the Dniester PSP do not operate.

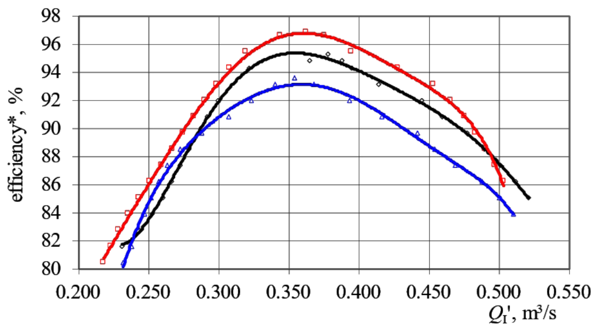
Results of experimental research in pump mode. Energy tests in pump mode were carried out at a constant rotation speed of 700 min^{-1} and openings of the guide vane from 14 to 34 mm with a step of 2 mm. As a check, tests were conducted at rotational speeds of 800 and 900 min^{-1}, which showed almost identical results. Based on the test results, the dependences of efficiency and head on the unit flow rate (η, $H = f(Q'_I)$) at a_0 = const for three variants of runners were constructed.



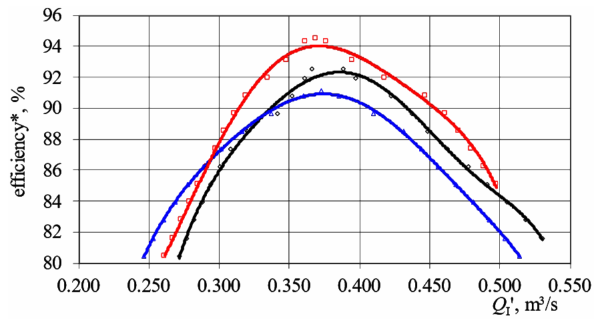
a



b



c



d

Fig. 6. Dependence of relative efficiency on unit flow rate for three variants of runners in turbine mode at different values $n_I' = \text{const}$:

a – design rotation speed $n_I' = 80$ *min*$^{-1}$; *b – maximum head* $n_I' = 85$ *min*$^{-1}$; *c – design head* $n_I' = 91$ *min*$^{-1}$; *d – minimum head* $n_I' = 95$ *min*$^{-1}$

—◊— – *RK5217*; —Δ— – *RK5217M*; —□— – *RK5217M2*

Table 2 shows the parameters of the optimal pump modes of the three models of the 5217 series pump-turbines.

The highest value of relative efficiency, which exceeds the performance of the original variant, was obtained in the model with a negative runner blade lean. The use of a positive lean of $\varphi = +45°$ led to an increase in the optimal unit speed by 1.2 min^{-1}, and a negative lean of $\varphi = -45°$ led to a decrease by 2.9 min^{-1}. In the model RK5217M2, compared to the original version, the flow rate in the optimum pump mode is 0.04 m^3/s less, which is also important because it requires less energy consumption when filling the head water reservoir.

Table 2

Parameters of optimal pump modes of three flow parts with runners of the 5217 series

Runner	Unit flow rate Q_I', m^3/s	Unit speed of rotation n_I', min^{-1}	Relative Efficiency η*, %
RK5217	0.438	94.98	100.00
RK5217M	0.348	96.18	98.73
RK5217M2	0.398	92.07	100.40

Fig. 7 shows the dependence of the relative efficiency and head on the unit flow rate of the pump-turbine models for three variants of runners in the pump mode at different values of guide vane opening of 18, 24, 30 and 34 mm.

The model with RK5217M at all guide vane openings in the almost entire flow rate range has the lowest values both in terms of efficiency and head compared to the other two runners. This can also be explained by a decrease in the blade surface area by 1.8 % compared to the original version with a positive lean of +45°. Thus, it was established that an increase in the positive lean of the blades leads to a worsening of the energy indicators of the flow part in the pump mode.

At flow rate $Q_I' > 0.350$ m^3/s, the RK5217 and RK5217M2 runners have an approximately equal head, but at lower rates, the head of the RK5217M2 drops significantly compared to the original version. A similar pattern is observed with the plots of the efficiency dependence at guide vane openings greater than 22 mm, but at smaller openings at flow rate $Q_I' > 0.350$ m^3/s, the efficiency of the RK5217M2 is higher. It should be noted that the maximum value of the efficiency in the pump mode was obtained precisely for the RK5217M2 with opening of 28 mm, which is 0.4 % higher than the indicator of the original runner. This is an important fact, since the pump-turbine in the pump mode is operated with one (optimal) opening of the guide vanes.

Selective experimental studies have shown that the use of a negative circumferential lean of runner blades has led to a significant increase in the level of efficiency in the turbine mode in almost the entire operating range, while at least maintaining the level of performance in the pump mode.

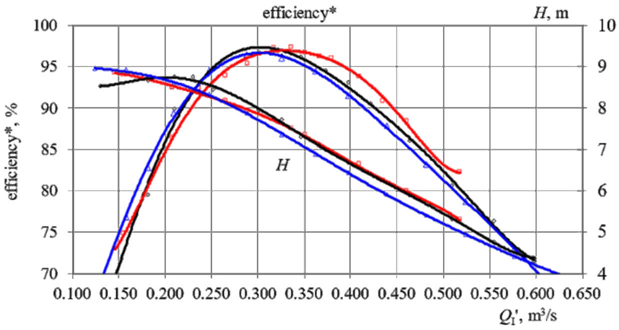
According to the results of selective experimental studies, it is planned to conduct a full set of acceptance tests of the large-scale model RK5217M2 with a metal runner with a diameter of 500 mm. These studies will include, in addition to energy, cavitation and pulsation studies, as well as tests on unsteady and transient modes and others. If the results of selective testing are confirmed, the RK5217M2 with negative blade lean will be installed at power units 5–7 of the Dniester PSP.

Conclusions. The following key results have been concluded:

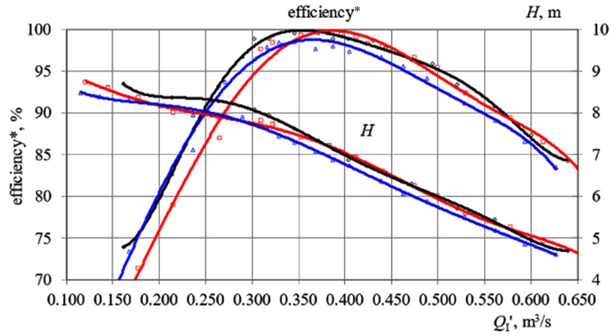
1. The proposed method of spatial profiling of radial-axis runner blades using circumferential lean made it possible to optimize the layout (shape) of the blades, which ensured an increase in the efficiency of the operation.

2. According to the results of experimental studies, it was found that the use of positive and negative circumferential blade leans does not affect the operating parameters of the best efficiency point on the hill chart in the turbine mode.

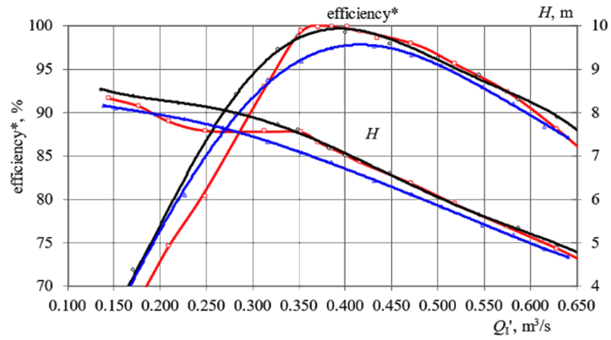
3. It was established that the RK5217M model with a positive circumferential lean $\varphi = +45°$ has the lowest energy indicators in almost the entire range of operation of both turbine and pump modes.



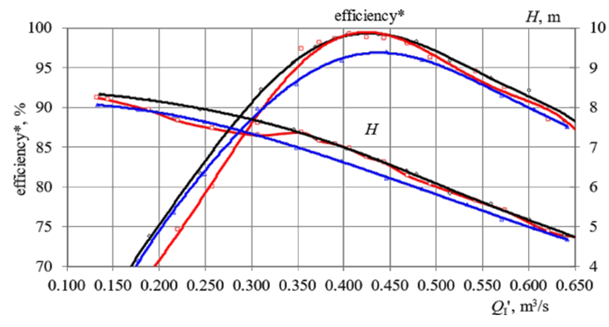
a



b



c



d

Fig. 7. Dependence of relative efficiency and head on unit flow rate for three variants of runners in pump mode at different values of the guide vane opening:

a – a_0 = 18 mm; b – a_0 = 24 mm; c – a_0 = 30 mm; d – a_0 = 34 mm

—◊— – RK5217; —Δ— – RK5217M; —□— – RK5217M2

4. It was established that the RK5217M2 model with a negative circumferential lean of blades φ = –45° has a maximum efficiency in turbine mode that is 0.74 % higher than the original version, which is installed on units No. 1–4 of the Dniester PSP. In all head range of the station, the efficiency of the flow part with the new RK5217M2 is significantly higher than that of the original one, and at the design head in the flow rate range of 0.300–0.470 m^3/s, the increase is 1.1–2.0 %.

5. In the pump mode, the maximum efficiency value, which is 0.40 % higher than the original version, was also obtained for the runner RK5217M2 with a negative lean of blades φ = –45°. At flow rate up to 0.350 m^3/s, the original runner has a higher level of efficiency and head. With larger flow rate, the head of these runners is approximately the same at all guide vane openings, the level of efficiency at guide vane openings of up to 22 mm is higher for the new runner, and at larger ones, it is practically the same as the original one.

References.

1. European Commission (2023). *2050 long-term strategy.* Retrieved from https://climate.ec.europa.eu/eu-action/climate-strategies-targets/ 2050-long-term-strategy_en.
2. IRENA (2023). *IRENA Renewable Energy Statistics 2022.* Retrieved from https://www.irena.org/publications/2022/Jul/Renewable-Energy-Statistics-2022.
3. IHA (2023). *IHA 2022 Hydropower Status Report.* Retrieved from https://www.hydropower.org/publications/2022-hydropower-status-report.
4. Hunt, J. D., Zakeri, B., Nascimento, A., & Brandão, R. (2022). Pumped hydro storage (PHS). In T. M. Letcher: *Storing Energy* (2nd ed., pp. 37-65). Elsevier. https://doi.org/10.1016/B978-0-12-824510-1.00008-8.
5. Flores, E., Bornard, L., Tomas, L., Liu, J., & Couston, M. (2012). Design of large Francis turbine using optimal methods. *IOP Conf. Series: Earth and Environmental Science*, *15*, 022023. https://doi.org/ 10.1088/1755-1315/15/2/022023.
6. Abeykoon, C. (2022). Modelling and Optimisation of a Kaplan Turbine – A Comprehensive Theoretical and CFD Study. *Cleaner Energy Systems*, *3*, 100017. https://doi.org/10.1016/j.cles.2022.100017.
7. Du, J., Ge, Z., Wu, H., Shi, X., Yuan, F., Yu, W., Wang, D., & Yang, X. (2022). Study on the effects of runner geometric parameters on the performance of micro Francis turbines used in water supply system of high-rise buildings. *Energy*, *256*, 124616. https://doi.org/10.1016/j.energy.2022.124616.
8. Cerriteño, A., Delgado, G., Galván, S., Dominguez, F., & Ramírez, R. (2021). Reconstruction of the Francis 99 main runner blade using a hybrid parametric approach. *IOP Conference Series: Earth and Environmental Science*, *774*, 012074. https://doi.org/10.1088/1755-1315/774/1/012074.
9. Rusanov, A., Rusanov, R., & Lampart, P. (2015). Designing and updating the flow part of axial and radial-axial turbines through mathematical modeling. *Open Engineering*, *5*, 399-410. https://doi.org/10.1515/eng-2015-0047.
10. Delgado, G., Galván, S., Dominguez-Mota, F., García, J. C., & Valencia, E. (2020). Reconstruction methodology of a Francis runner blade using numerical tools. *Journal of Mechanical Science and Technology*, *34*, 1237-1247. https://doi.org/10.1007/s12206-020-0222-4.
11. Leguizamón, S., & Avellan, F. (2020). Open-source implementation and validation of a 3D inverse design method for Francis turbine runners. *Energies*, *13*, 2020. https://doi.org/10.3390/en13082020.
12. Rusanov, A., Subotin, V., Shvetsov, V., Rusanov, R., Palkov, S., Palkov, I., & Chugay, M. (2022). Application of innovative solutions to improve the efficiency of the LPC flow part of the 220 MW NPP steam turbine. *Archives of Thermodynamics, 43*(1), 63-87. https://doi.org/10.24425/ather.2022.140925.
13. Ma, Z., Zhu, B., Rao, C., & Shangguan, Y. (2019). Comprehensive hydraulic improvement and parametric analysis of a Francis turbine runner. *Energies*, *12*, 307. https://doi.org/10.3390/en12020307.
14. Ye, W., Geng, C., & Luo, X. (2022). Unstable flow characteristics in vaneless region with emphasis on the rotor-stator interaction for a pump turbine at pump mode using large runner blade lean. *Renewable Energy, 185*, 1343-1361. https://doi.org/10.1016/j.renene.2021.12.129.
15. Kim, S.-J., Choi, Y.-S., Cho, Y., Choi, J.-W., & Kim, J.-H. (2019). Effect of blade thickness on the hydraulic performance of a Francis hydro turbine model. *Renewable Energy, 134,* 807-817. https://doi.org/10.1016/j.renene.2018.11.066.
16. Yu, Z.-F., Wang, W.-Q., Yan, Y., Wang, H.-Y., & Wu, W.-L. (2022). Evaluating energy-efficiency improvement of variable-speed operation with the help of entropy: A case study of low-head Francis turbine. *Sustainable Energy Technologies and Assessments, 53*, 102468. https://doi.org/10.1016/j.seta.2022.102468.
17. Iliev, I., Tengs, E.O., Trivedi, C., & Dahlhaug, O.G. (2020). Optimization of Francis turbines for variable speed operation using surrogate modeling approach. *Journal of Fluids Engineering, 142*, 101214. https://doi.org/10.1115/1.4047675.

18. Tengs, E., Charrassier, F., Jordal, M.R., & Iliev, I. (2021). Fully automated multidisciplinary design optimization of a variable speed turbine. *IOP Conference Series: Earth and Environmental Science, 774*, 012031. https://doi.org/10.1088/1755-1315/774/1/012031.
19. Lee, N.-J., Hwang, Y.-C., Inagaki, M., & Miyagawa, K. (2021). Design Optimization of High Specific Speed Prototype Francis Turbine by Design of Experiments. *Journal of Physics: Conference Series, 1909*(1), 012047. https://doi.org/10.1088/1742-6596/1909/1/012047.
20. Qin, Y., Li, D., Wang, H., Liu, Z., Wei, X., & Wang, X. (2022). Multi-objective optimization design on high pressure side of a pump-turbine runner with high efficiency. *Renewable Energy, 190,* 103-120. https://doi.org/10.1016/j.renene.2022.03.085.
21. Lestriez, R., Calvo, D., & Mendicino, D. (2021). Advanced Optimization Tools for Hydro Turbine Runner Design. *IOP Conference Series: Earth and Environmental Science, 774*, 012001. https://doi.org/10.1088/1755-1315/774/1/012001.
22. Aponte, R.D., Teran, L.A., Grande, J.F., Coronado, J.J., Ladino, J.A., Larrahondo, F.J., & Rodríguez, S.A. (2020). Minimizing erosive wear through a CFD multi-objective optimization methodology for different operating points of a Francis turbine. *Renewable Energy, 145,* 2217-2232. https://doi.org/10.1016/j.renene.2019.07.116.
23. Linnik, A.V., Ryabova, S.A., Varenko, V.D., Ryabov, A.V., & Khoryev, O.N. (2016). Calculated and experimental studies of the flow paths of PL20 turbines to modernize the Kremenchug hydroelectric power station hydro turbines. *Journal of Mechanical Engineering, 19,* 12-19. https://doi.org/10.15407/pmach2016.03.012.
24. Khoryev, O., Korotaiev, P., Agibalov, Y., Bykov, Y., & Maksymenko-Sheiko, K. (2023). Experimental Studies of Pump-Turbine Flow Part Models at Heads of 80–120 m. In H. Altenbach*: Advances in Mechanical and Power Engineering. CAMPE 2021. Lecture Notes in Mechanical Engineering,* (pp. 24-33). Springer, Cham. https://doi.org/10.1007/978-3-031-18487-1_3.
25. Bykov, Y., Khoryev, O., Korotaiev, P., Dedkov, V., & Agibalov, Y. (2022). Numerical Investigation of Unsteady Flow in Draft Tube with Ribs. In *Proc. of 2022 IEEE KhPI Week on Advanced Technology,* (pp. 589-594). IEEE. https://doi.org/10.1109/KhPIWeek57572.2022.9916461.
26. Rusanov, A., Chugay, M., & Rusanov, R. (2023). Advanced Computer Technologies in the New Flow Part Development for Reactive Type HPC Steam Turbine of T-100 Series. In H. Altenbach: *Advances in Mechanical and Power Engineering. CAMPE 2021. Lecture Notes in Mechanical Engineering,* (pp. 55-63). Springer, Cham. https://doi.org/10.1007/978-3-031-18487-1_6.
27. Rusanov, A.V., Subotin, V.H., Khoryev, O.M., Bykov, Y.A., Korotaiev, P.O., & Ahibalov, Y.S. (2022). Effect of 3D Shape of Pump-Turbine Runner Blade on Flow Characteristics in Turbine Mode. *Journal of Mechanical Engineering, 25,* 6-13. https://doi.org/10.15407/pmach2022.04.006.
28. Rusanov, A., & Rusanov, R. (2021). The influence of stator-rotor interspace overlap of meridional contours on the efficiency of high-pressure steam turbine stages. *Archives of Thermodynamics, 42*(1), 97-114. https://doi.org/10.24425/ather.2021.136949.
29. Rusanov, A., Rusanov, R., Klonowicz, P., Lampart, P., Żywica, G., & Borsukiewicz, A. (2021). Development and experimental validation of real fluid models for CFD calculation of ORC and steam turbine flows. *Materials, 14*(22), 6879. https://doi.org/10.3390/ma14226879.
30. Rusanov, A., Shubenko, A., Senetskyi, O., Babenko, O., & Rusanov, R. (2019). Heating modes and design optimization of cogeneration steam turbines of powerful units of combined heat and power plant. *Energetika, 65*(1), 39-50. https://doi.org/10.6001/energetika.v65i1.3974.
31. Rusanov, A.V., Kostikov, A.O., Shubenko, O.L., Kharlampidi, D.K., Tarasova, V.O., & Senetskyi, O.V. (2019). Highly efficient cogeneration power plant with deep regeneration based on air Brayton cycle. *Journal of Mechanical Engineering, 22*(4), 12-23. https://doi.org/10.15407/pmach2019.04.012.

Вплив колових навалів лопатей робочих коліс насос-турбін на енергетичні характеристики

О. М. Хорєв[1], *О. В. Линник*[2], *П. О. Коротаєв*[1], *Ю. А. Биков*[*1], *Є. С. Агібалов*[1]

1 – Інститут проблем машинобудування імені А. М. Підгорного НАН України, м. Харків, Україна
2 – АТ «Українські енергетичні машини», м. Харків, Україна
[*] Автор-кореспондент e-mail: yubykoff@gmail.com

Мета. Підвищення ефективності радіально-осьової насос-турбіни Дністровської ГАЕС на основі просторового профілювання лопатей робочого колеса за допомогою колових навалів.

Методика. Проєктування нових робочих коліс здійснювалось за допомогою просторового профілювання лопатей, що відрізнялися тільки компоновкою профілів (взаємним розташуванням) у коловому напрямку. Лопаті моделей робочих коліс діаметром 350 мм було виготовлено методом 3D-друку з пластику PLA. Експериментальні дослідження проведені на гідродинамічному стенді ІПМаш ЕКС-30, характеристики якого відповідають вимогам міжнародного стандарту щодо модельних приймально-здавальних випробувань гідромашин різного типу.

Результати. На основі запропонованого методу просторового профілювання лопатей робочих коліс досліджено вплив колових навалів на енергетичні показники насос-турбін. Отримані характеристики в широкому діапазоні роботи турбінного й насосного режимів трьох варіантів проточних частин. Наведені параметри оптимальних режимів і значення максимальних ККД. Дано порівняння енергетичних характеристик у турбінному режимі при постійних частотах обертання, що відповідають максимальному, номінальному й мінімальному напорам на Дністровській ГАЕС. У насосному режимі наведені залежності кривих ефективності та напорів від подачі при різних значеннях відкриттів напрямного апарату.

Наукова новизна. Уперше встановлено вплив колових навалів (просторового профілювання) лопатей робочих коліс радіально-осьової насос-турбіни на енергетичні характеристики в турбінному й насосному режимах, що дало змогу помітно підвищити рівень ефективності практично у всьому діапазоні роботи турбінного режиму.

Практична значимість. Спроєктоване нове високоефективне робоче колесо планується до впровадження на гідроагрегатах № 5-7 Дністровської ГАЕС. Для підтвердження результатів сумісно з АТ «Українські енергетичні машини» передбачається виготовлення та дослідження великомасштабних моделей насос-турбін із металевими робочими колесами.

Ключові слова: *насос-турбіна, радіально-осьова турбіна, робоче колесо, гідродинамічній стенд, експериментальні дослідження*

The manuscript was submitted 23.12.23.