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ENERGY CHARACTERISTICS OF THE TORQUE-FLOW PUMP TFP 125-50: RESULTS OF AN EXPERIMENTAL STUDY

ЕНЕРГЕТИЧНІ ХАРАКТЕРИСТИКИ ВІЛЬНОВИХРОВОГО НАСОСА TFP 125-50: РЕЗУЛЬТАТИ ЕКСПЕРИМЕНТАЛЬНОГО ДОСЛІДЖЕННЯ

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Abstract. The paper presents the results of an experimental study of the TFP 125-50 torque-flow pump carried out using a specialized test bench with a closed hydraulic circuit. A methodology for experimental testing was developed and validated, enabling the determination of the main operating parameters of the pump, including flow rate, head, power consumption, and efficiency, with consideration of systematic and random measurement errors. Experimental investigations were performed for a base impeller and a modernized impeller over a wide operating range of flow rates. Statistical processing of the measurement results showed that the relative limiting errors of the main parameters do not exceed the permissible values specified by relevant standards. Head and energy characteristics of the pump were obtained and comparatively analyzed. It was demonstrated that the use of the modernized impeller provides an increase in pump efficiency by 4–5% within the operating flow rate range. Verification of the experimental results was carried out by comparison with numerical simulation data, which confirmed the adequacy of the applied CFD model. The obtained results can be used for further research and optimization of torque-flow pump designs.

Keywords: torque-flow pump, experimental test bench, impeller, energy characteristics, head characteristic, measurement errors, numerical simulation, CFD verification.

Problem Statement.

The modern development of pump engineering is taking place under increasing requirements for the energy efficiency, reliability, and service life of pumping equipment [1]. The rise in energy costs necessitates further improvement of hydraulic machines, in particular through optimization of the design of the main components and reduction of hydraulic losses in the flowing part.

Torque-flow pumps (Fig. 1) are widely used for transporting liquids containing solid abrasive impurities, fibrous inclusions, and an increased gas content [2]. At the same time, the specific features of the operating process of such pumps complicate both the analytical description of the flow and the experimental determination of their energy and hydraulic characteristics [3].

A significant portion of recent research on torque-flow pumps is based on numerical simulation methods. However, the results of numerical calculations require mandatory experimental validation, especially when non-standard impeller designs and complex flow regimes are investigated.

The lack of universal test benches adapted to studying a range of torque-flow pump sizes, with the capability to accurately measure the main operating parameters and to evaluate experimental errors, limits comprehensive analysis of their characteristics.

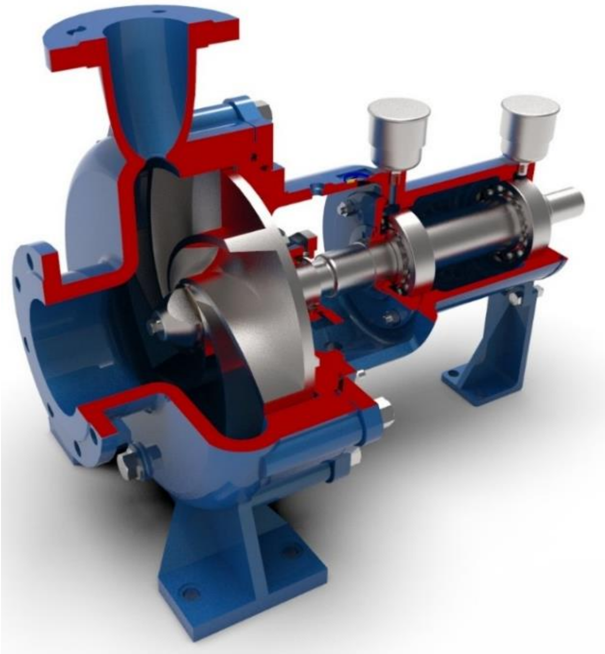

Fig. 1. General view of a TURO-type torque-flow pump

This determines the need to develop specialized experimental test benches suitable for verifying numerical results and assessing the effectiveness of design improvements.

Analysis of Recent Research.

In general, the methodology for experimental testing of dynamic pumps and for constructing their head and energy characteristics is regulated by current standards, which ensure the unification of approaches to determining the main operating parameters and evaluating measurement uncertainties [4]. At the same time, the specific features of the operating process of torque-flow pumps (such as pumping liquids containing solid abrasive particles, fibrous inclusions, and an increased gas content) impose higher requirements on the organization of experiments and the reproducibility of test conditions.

In recent years, a number of studies in related fields have been published that address the development and improvement of experimental test benches for investigating pumping and hydraulic machinery systems [5]. In particular, solutions have been proposed for test benches designed for turbomolecular pumps operating under conditions of high gas concentrations; test benches for studying centrifugal–vortex pump stages have been described; and experimental facilities for modeling hydrodynamic processes in the flowing parts of hydraulic turbines have been reported.

Experimental investigations of torque-flow pumps in specific design configurations have also been considered separately, along with test bench solutions for heat pumps as examples of organizing closed-loop circuits and measurement systems [6].

Alongside the development of experimental facilities, the role of numerical simulation in the design of torque-flow pump components has increased significantly. In particular, the applicability of numerical methods for designing impellers with curved blade profiles has been demonstrated [7].

At the same time, the results of CFD simulations require mandatory experimental validation, since the adequacy of numerical models strongly depends on the formulation of boundary conditions, the choice of turbulence model, and the accuracy of reproducing the complex vortex flow structure [8]. In this context, the combination of numerical simulation—particularly using Ansys CFX—with physical experiments conducted on a specialized test bench that ensures sufficient measurement accuracy and uncertainty control is considered a promising approach.

Research Methodology.

The aim of this study is to develop and experimentally validate a specialized test bench for investigating torque-flow pumps, as well as to experimentally assess the effect of design modifications of the impeller on the energy and head characteristics of the TFP 125-50 pump, taking into account measurement uncertainties and verification of numerical simulation results.

To achieve this aim, the following objectives were formulated and accomplished:

1) to develop an experimental test bench with a closed hydraulic circuit that ensures stable pump operating modes and reproducibility of experimental conditions;

2) to develop a methodology for experimental testing of a torque-flow pump with determination of the main operating parameters, including flow rate, head, power consumption, and efficiency;

3) to perform statistical processing of measurement results with consideration of systematic and random errors, as well as to evaluate the limiting errors in the determination of direct and indirect parameters;

4) to experimentally investigate the head and energy characteristics of the TFP 125-50 torque-flow pump equipped with base and modernized impellers over a wide range of flow rates;

5) to carry out a comparative analysis of experimental results for different impeller design variants and to assess the effectiveness of the proposed design modifications;

6) to verify the results of experimental studies by comparison with numerical simulation data obtained using Ansys CFX software.

General Scheme of the Experimental Study

The experimental study was carried out using a specially developed test bench (Fig. 2) operating according to a closed-loop circulation scheme of the working fluid. Such a configuration ensures stable hydraulic operating modes, the possibility of repeated experiments, and reproducibility of measurement conditions [9].

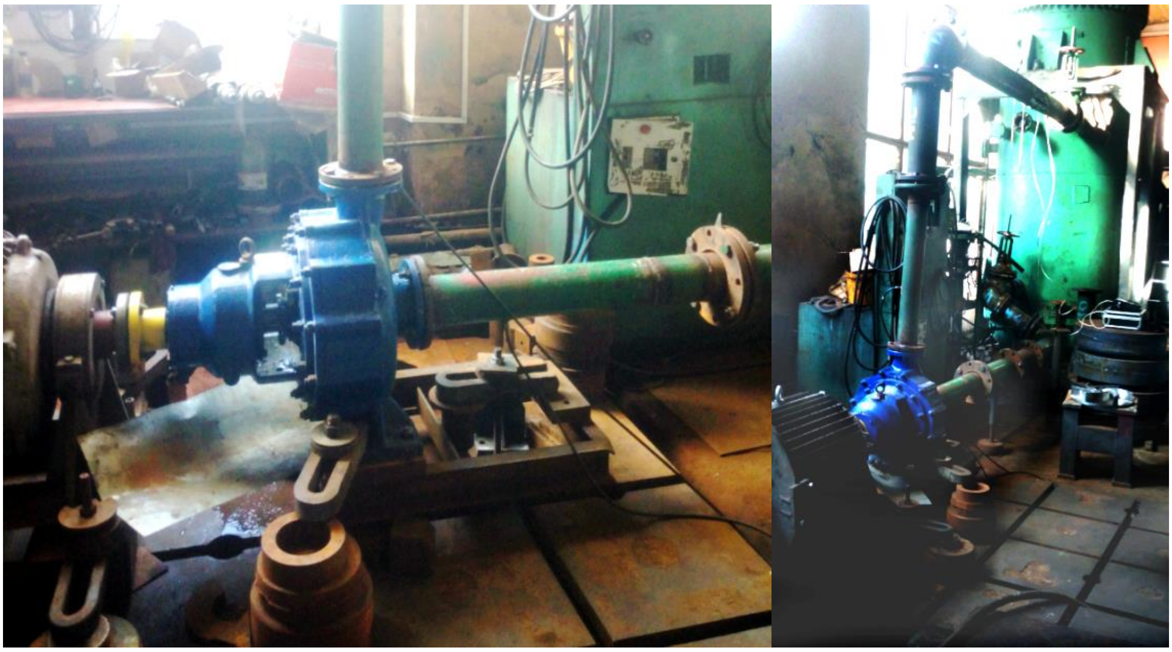

Fig. 2. Experimental test bench with the installed TFP 125-50 pump

The object of the study is a serial TFP 125-50 torque-flow pump equipped with a base impeller and a modernized impeller (Fig. 3).

Fig. 3. Impeller of the TFP 125-50 torque-flow pump: a – base impeller; b – proposed impeller

The base configuration employs a standard TFP 125-50 impeller with straight blades, while the proposed configuration uses an impeller with profiled blades. Water was used as the working fluid during the experiments; its physical properties were determined according to the temperature, which was monitored throughout the experimental investigations.

The experimental tests were conducted to determine the main operating parameters of the pump, including flow rate, head, power consumption, and efficiency, as well as to construct the head and energy characteristics.

Description of the Test Bench and Measuring Equipment

The developed experimental test bench (Fig. 4) consists of the test pump, an electric motor equipped with a motor-balance system, a sealed tank, a system of discharge and suction pipelines, as well as a set of measuring and control devices. The schematic layout of the test bench provides the capability to regulate the pump flow rate and to monitor the main parameters of the operating process.

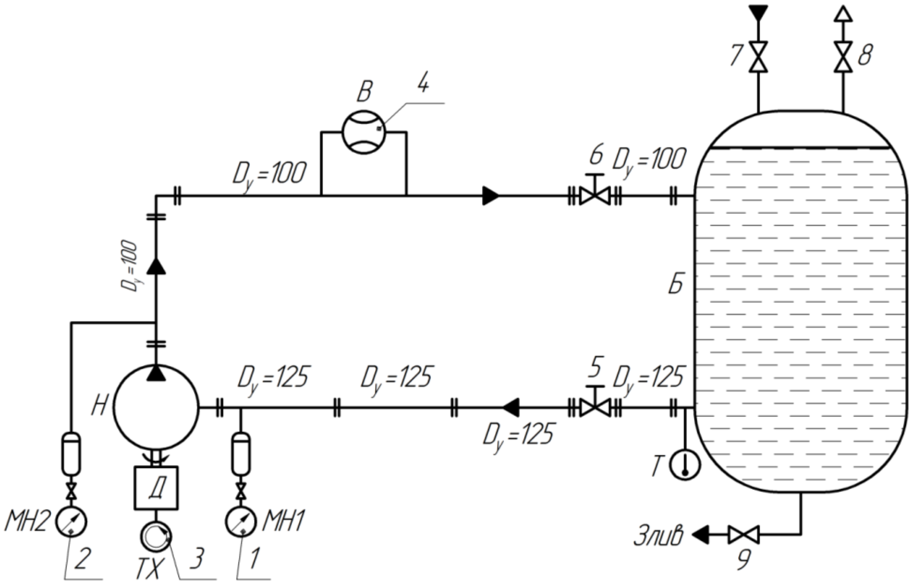

Fig. 4. Schematic diagram of the experimental test bench

The flow rate was measured using an ultrasonic flow meter, which ensures the required accuracy of flow determination within the specified measurement range. Pressure in the discharge and suction pipelines was measured using pressure gauges of the appropriate accuracy class. The rotational speed of the electric motor shaft was monitored using a tachometer.

The torque on the electric motor shaft was determined using the motor-balance system by measuring the force applied at the lever arm with the use of standard weights. This approach allowed direct determination of the mechanical power at the shaft and contributed to a reduction in the overall measurement uncertainty.

Method for Determining Operating Parameters

The pump head was determined based on the readings of pressure gauges installed in the discharge and suction pipelines, taking into account the density of the working fluid and the kinetic component of the flow velocity:

$$H = 0.102 \cdot \frac{p_d - p_s}{\rho} + 0.0827 \cdot Q^2 \cdot \left(\frac{1}{d_d^4} - \frac{1}{d_s^4} \right), \quad (1)$$

where p_d, p_s are the pressure gauge readings in the discharge and suction pipelines, kgf/sm^2; ρ is the fluid density; Q is the pump flow rate; d_d, d_s are the internal diameters of the discharge and suction pipelines at the pressure measurement locations, m.

The shaft power of the electric motor was determined from the measured torque and the rotational speed of the shaft:

$$N = M \cdot \frac{\pi \cdot n}{30} = \frac{\pi \cdot n \cdot l \cdot (F - F_0)}{3000}, \ kW, \quad (2)$$

where M is the torque on the motor shaft; n is the rotational speed of the motor shaft; l (1492 mm) is the lever arm length; F –is the force measured at the lever arm; F_0 is the initial force acting on the lever arm.

The pump efficiency was calculated as the ratio of hydraulic power to mechanical power at the shaft. The operating characteristics were constructed based on the results of a series of measurements performed while varying the flow rate within the specified operating range:

$$\eta = \frac{\rho \cdot g \cdot Q \cdot H}{N}, \quad (3)$$

where H is the pump head; g = 9,81 m/s^2 is the gravitational acceleration.

Method for Evaluating Experimental Uncertainty

The accuracy of experimental measurements was evaluated using a generalized error analysis that considers uncertainties arising during the measurement of the main operating parameters of the pump [10]. Both systematic and stochastic error components were taken into account, and their combined effect was determined according to the following relationship:

$$\sigma = \sqrt{\sigma_S^2 + \sigma_R^2}, \quad (4)$$

where σ_S is the systematic measurement error; σ_R is the random measurement error.

Statistical processing of the experimental results was performed based on series of repeated measurements, which made it possible to quantitatively assess the variability of the measured quantities and to reduce the influence of random deviations. The formation of the random error component was determined by the accuracy of the applied measuring instruments and the conditions of reading the measurements, which was taken into account using the following relationship:

$$\sigma_S = \sqrt{\sigma_A^2 + \sigma_O^2}, \quad (5)$$

where σ_A is the instrument error; σ_O is the reading error.

For each investigated parameter, a generalized statistical characterization of the experimental data was carried out, including the determination of the most probable value, the dispersion of results, and the interval range of their variation. The errors of derived quantities were calculated using the formal apparatus of error propagation, which ensures correct consideration of the influence of primary measurements.

The reliability of the obtained results was verified by comparing the calculated limiting errors with the permissible values specified by relevant standards, which allowed conclusions to be drawn regarding the correctness of the experimental procedure and the adequacy of the selected measurement methodology.

The size of the experimental sample was determined based on the requirements for statistical reliability. At a confidence level of α = 0,95 and with the relative error limited to no more than 5%, the number of repeated measurements at a given operating point was set to at least five.

The random error component was characterized using the reproducibility variance, which describes the degree of scatter of the results in a measurement series and is determined by the following expression:

$$\sigma_R = \sqrt{\frac{\sum_{i=1}^{n}\left(\bar{y}-y_i\right)^2}{(n-1)\cdot n}}, \tag{6}$$

where $\bar{y}$ is the most probable value of the measured parameter; y_i is the value of the i-th measurement; n is the number of measurements.

The most probable value of the investigated parameter was calculated using the expression:

$$\bar{y} = \frac{\sum_{i=1}^{n} y_i}{n}. \tag{7}$$

After which the magnitude of statistical dispersion was evaluated according to:

$$S = \sqrt{\frac{\sum_{i=1}^{n}\left(\bar{y}-y_i\right)^2}{n-1}}. \tag{8}$$

Interval estimation of the measurement results was performed using confidence intervals determined by the following relationship:

$$\Delta\bar{y} = t_{a,n}\cdot\sigma_R^2. \tag{9}$$

where $t_{a,\,n}$ is the Student’s t-coefficient.

The final values of the parameters were presented in interval form according to:

$$y = \bar{y} + \Delta\bar{y}. \tag{10}$$

The accuracy of determining the pump flow rate was evaluated by considering the errors in measuring the flow rate and the rotational speed of the electric motor shaft according to:

$$\Delta Q = \sqrt{\delta Q^2 + \delta n^2}, \tag{11}$$

where δQ is the relative limiting error of flow rate measurement; δn is the relative limiting error of rotational speed measurement.

The errors in determining the rotational speed and the flow rate were calculated using relationships (12) and (13), respectively:

$$\delta n = \frac{\Delta n}{n}\cdot 100, \tag{12}$$

$$\delta Q = \frac{\Delta Q}{Q}\cdot 100, \tag{13}$$

where Δn is the absolute limiting error of rotational speed measurement; ΔQ is the absolute limiting error of flow rate measurement.

The limiting error of pump head determination was calculated using the following expression:

$$\Delta H = \sqrt{\delta H^2 + 4\delta n^2}\ , \tag{14}$$

where δH is the relative limiting error of pump head measurement.

The components of the limiting head error were determined by considering the accuracy of pressure measurements in the discharge and suction pipelines and the error in determining the working fluid density, according to:

$$\delta H = \frac{1}{H}\left[\left(\frac{0.102}{\rho}\right)^2 \cdot \left[\left(\delta_d p_d\right)^2 + \left(\delta_s p_s\right)^2\right] + \left(\frac{0.102}{\rho}\right)^2 \cdot \left(p_d - p_s\right)^2 \cdot \delta\rho^2 + \right.$$
$$\left. + 0.1654^2 \cdot \left(\frac{1}{d_d^4} - \frac{1}{d_s^4}\right) \cdot Q^4 \cdot \delta Q^2\right], \tag{15}$$

where δ_{pd} i δ_{ps} are the relative limiting errors of the pressure gauges in the discharge and suction pipelines, respectively; $\delta\rho$ is the relative limiting error in determining the fluid density.

The error in determining the power consumption at the pump shaft was calculated using a relationship that accounts for the combined influence of the accuracy of force measurement, lever arm length, rotational speed, and sensitivity of the balancing device:

$$\Delta N = \sqrt{\left(\frac{100 \cdot \psi_F}{F}\right)^2 + 4\delta n^2 + \delta F^2 + \delta l^2}\ , \tag{16}$$

where ψ_F is the sensitivity threshold of the balancing machine; F is the measured force value; δF is the relative limiting error of force measurement using weights; δl is the relative limiting error of measuring the lever arm length.

The total error in determining pump efficiency was evaluated using the following relationship:

$$\Delta\eta = \sqrt{\Delta N^2 + \Delta Q^2 + \Delta H^2}\ . \tag{17}$$

The generalized root-mean-square relative error of direct and indirect measurements was determined according to:

$$\sigma_\varepsilon = \frac{\varepsilon}{2'}\ , \tag{18}$$

where ε is the relative limiting error of the measured parameter.

Results of the Study.

The experimental investigations were carried out using base and modernized impellers of the torque-flow pump. For each design variant, based on the results of a series of measurements, the main statistical characteristics of the measured parameters were determined, including the mean value, standard deviation, reproducibility variance, and confidence intervals.

The results of statistical processing of the experimental data for the base and modernized impellers are presented in Tables 1 and 2, respectively. Analysis of the obtained data indicates the stability of the measured parameters and the absence of systematic deviations, which confirms the correctness of the selected experimental methodology and sufficient reproducibility of the results.

Table 1. Random measurement errors obtained using the base impeller

Measured parameter	Absolute pressure in discharge pipeline p_d, kPa	Absolute pressure in suction pipeline p_s, kPa	Flow rate Q, m^3/h	Rotational frequency n, rpm
Measured value	693.8	168.67	125.2	1 471
	690.39	163.97	125.7	1 469
	691.45	163.18	125.4	1 470
	687.25	164.75	125.3	1 472
	687.84	165.04	124.8	1 474
Mean value	690.146	165.122	125.28	1471.2
Standard deviation	2.684	2.111	0.327	1.924
Reproducibility variance	1.200	0.944	0.146	0.860
Confidence interval	4.034	2.496	0.060	2.072

Table 2. Random measurement errors obtained using the proposed impeller

Measured parameter	Absolute pressure in discharge pipeline p_d, kPa	Absolute pressure in suction pipeline p_s, kPa	Flow rate Q, m^3/h	Rotational frequency n, rpm
Measured value	671.45	167.25	124.1	1 470
	672.17	165.98	125.3	1 465
	671.74	168.17	124.6	1 468
	672.32	163.64	125.2	1 467
	673.17	164.78	125.9	1 473
Mean value	672.17	165.964	125.02	1468.6
Standard deviation	0.657	1.825	0.691	3.050
Reproducibility variance	0.294	0.816	0.309	1.364
Confidence interval	0.242	1.865	0.267	5.208

Based on the evaluation of indirect uncertainties, it was established that the relative limiting errors in determining the flow rate, head, and power consumption do not exceed the permissible values specified by relevant standards (Tables 3 and 4). In particular, it should be noted that the relative limiting error in determining the pump efficiency for both impeller variants remains below 2%, which is sufficient for a reliable comparative analysis of energy characteristics.

Table 3. Indirect measurement errors obtained using the base impeller

Measured parameter	Mean value	Relative limiting error, %	Permissible limiting error, %
Flow rate Q, m^3/h	125.28	0.38	3.0
Head H, m	53.52	0.62	3.0
Power N, kW	18.27	0.71	3.0
Efficiency η, %	41.7	1.89	5.0

A comparison of the mean values of the main operating parameters shows that the application of the modernized impeller is accompanied by a reduction in pump head together with a decrease in power consumption. Such changes indicate a redistribution of energy losses in the flowing part of the pump and a more efficient utilization of the supplied mechanical energy.

Table 4. Indirect measurement errors obtained using the proposed impeller

Measured parameter	Mean value	Relative limiting error, %	Permissible limiting error, %
Flow rate Q, m^3/h	125.02	0.69	3.0
Head H, m	51.6	0.48	3.0
Power N, kW	17.58	1.14	3.0
Efficiency η, %	45.4	1.83	5.0

Based on the experimental data, the head and energy characteristics of the pump were constructed for both impeller variants (Fig. 5). Comparative analysis of these characteristics demonstrated that, over the entire investigated flow rate range, the modernized impeller provides higher efficiency values. The maximum increase in efficiency amounts to approximately 4–5% in the operating flow rate region, which is a significant result for torque-flow pumps, whose efficiency is traditionally limited by the features of the vortex operating process.

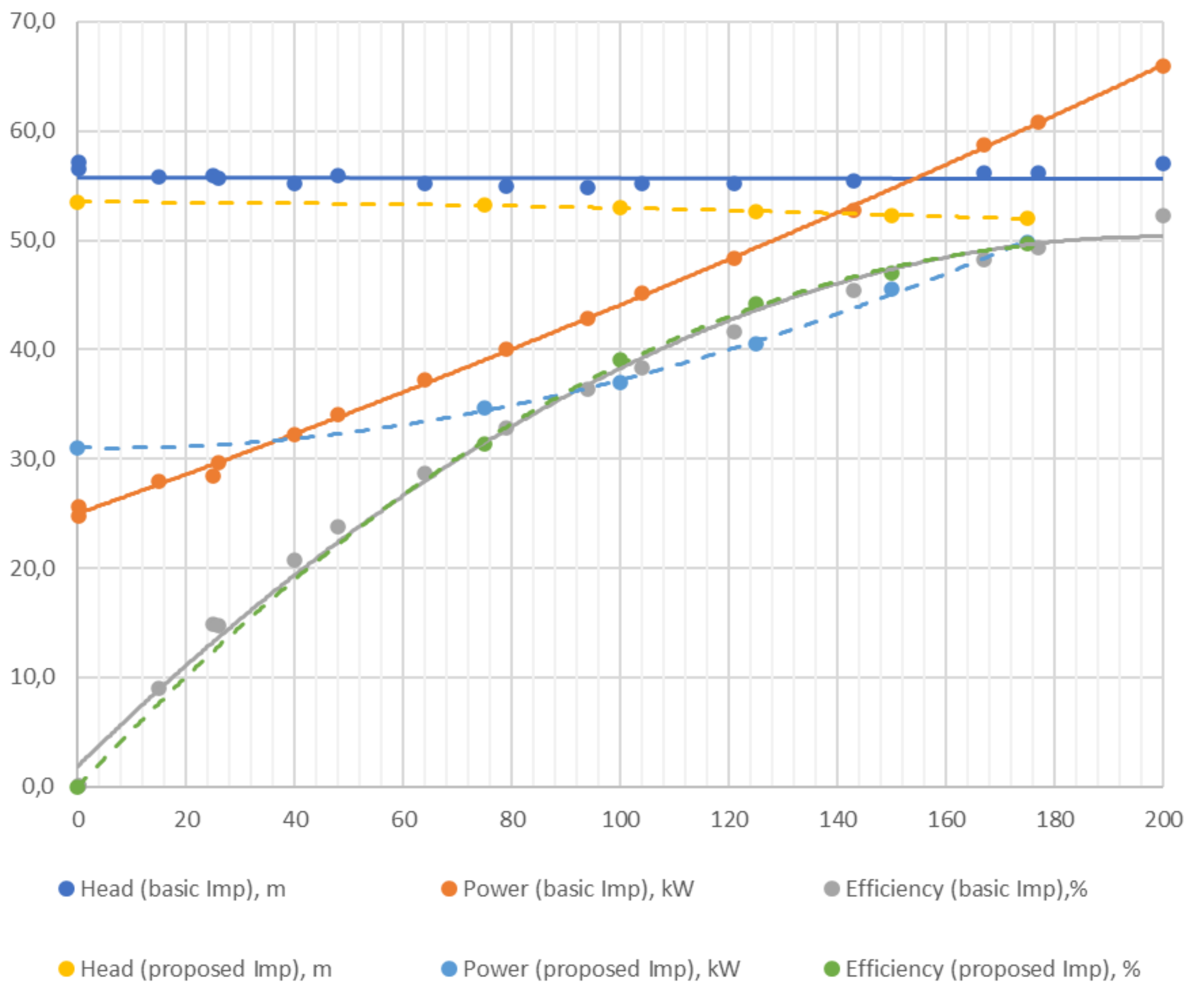

Fig. 5. Integral characteristics of the TFP 125-50 pump with base and proposed impellers

To assess the adequacy of the numerical model, the experimental pump characteristics were compared with the results of numerical simulations performed using Ansys CFX software. Both qualitative and quantitative agreement between the experimental and calculated head and energy characteristics was obtained over the entire range of investigated operating modes. The differences between the values determined by numerical and experimental methods do not exceed the limiting errors of the experimental measurements.

Thus, the results of the physical experiment confirm the effectiveness of the proposed impeller design modifications and the adequacy of the applied numerical model. The developed experimental test bench provides reliable verification of CFD calculations and can be used for further research and optimization of torque-flow pumps with regard to energy efficiency requirements.

Conclusions.

A specialized experimental test bench for investigating torque-flow pumps in a closed hydraulic loop was developed and validated. The test bench ensures stable operating modes, reproducibility of experimental conditions, and comprehensive determination of the main pump operating parameters, including flow rate, head, power consumption, and efficiency.

The proposed methodology for experimental testing and statistical processing of results, based on the theory of small samples and the propagation of errors of indirect measurements, provides control of both systematic and random error components and makes it possible to achieve relative limiting errors of the main operating parameters within the permissible values specified by applicable standards.

The experimental results demonstrate that the application of the modernized impeller in the TFP 125-50 torque-flow pump leads to a reduction in power consumption accompanied by a decrease in head within the operating flow rate range. This behavior indicates a redistribution of energy losses in the flowing part of the pump and a more efficient utilization of the supplied mechanical energy.

The constructed head and energy characteristics show that, over the entire investigated flow rate range, the modernized impeller provides higher efficiency values compared to the base design. The maximum efficiency increase amounts to approximately 4–5%, which is a significant result for torque-flow pumps, whose efficiency is traditionally limited by the features of the operating process.

The obtained results confirm the suitability of the developed experimental test bench for verification of CFD calculations and for further investigations and optimization of torque-flow pump designs, taking into account the requirements for improved energy efficiency and reliable operation under conditions involving the pumping of complex fluids.

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ЕНЕРГЕТИЧНІ ХАРАКТЕРИСТИКИ ВІЛЬНОВИХРОВОГО НАСОСА TFP 125-50: РЕЗУЛЬТАТИ ЕКСПЕРИМЕНТАЛЬНОГО ДОСЛІДЖЕННЯ

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Анотація. У роботі наведено результати експериментального дослідження вільновихрового насоса типу TFP 125-50, виконаного з використанням спеціалізованого випробувального стенда із замкнутим гідравлічним контуром. Розроблено та апробовано методику експериментальних випробувань, що забезпечує визначення основних робочих параметрів насоса, зокрема подачі, напору, споживаної потужності та коефіцієнта корисної дії, з урахуванням систематичних і випадкових похибок вимірювань. Експериментальні дослідження проведено для базового та модернізованого робочих коліс у широкому діапазоні подач. За результатами статистичної обробки встановлено, що відносні граничні похибки визначення основних параметрів не перевищують нормативно допустимих значень. Побудовано напірні та енергетичні характеристики насоса і виконано їх порівняльний аналіз. Показано, що застосування модернізованого робочого колеса забезпечує підвищення коефіцієнта корисної дії на 4–5 % у робочому діапазоні подач. Проведено верифікацію результатів фізичного експерименту шляхом порівняння з даними чисельного моделювання, що підтвердило адекватність застосованої CFD-моделі. Отримані результати можуть бути використані для подальших досліджень та оптимізації конструкцій вільновихрових насосів.

Ключові слова: вільновихровий насос, експериментальний стенд, робоче колесо, енергетичні характеристики, напірна характеристика, похибки вимірювань, чисельне моделювання, CFD-верифікація.