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SUSTAINING THE SELF-CLEANING EFFECT OF A TORQUE-FLOW PUMP IN OFF-OPTIMAL MODES

This paper presents the results of a study of a torque-flow pump with a non-uniform blade system, whose design feature is the presence of expanded inter-blade channels that provide conditions for a self-cleaning effect. Unlike previous works, which confirmed the efficiency of this effect only at the optimal flow rate, this research analyzes the pump performance at off-optimal modes within the operating range – 0.8*Q*bep (100 m³/h) and 1.2*Q*bep (150 m³/h). Numerical simulations were carried out in ANSYS CFX using three-dimensional geometric models and unstructured computational grids. For each operating point, the complete hydraulic characteristics (head and efficiency) were determined, and the distributions of pressure and velocity in the inter-blade channels were analyzed. It was shown that, even under deviations from the optimal flow rate, the energy performance of the pump with a non-uniform blade system differs from the standard design by no more than 2.5 m in head and 1 % in efficiency. The most important result is the confirmation of the stability of the self-cleaning effect within the operating zone. An asymmetry of pressure distribution and local pulsations were detected in the inter-blade channels, which contribute to the removal of fibrous inclusions from the blade surfaces. It was found that at increased flow rates the intensity of pulsations grows, while at reduced flow rates they remain regular and ensure stable cleaning. Thus, the pump with a non-uniform blade system demonstrates a combination of acceptable energy performance and stable self-cleaning capability throughout the operating zone, which makes it promising for application in wastewater systems and industrial processes where reliability and durability are of critical importance.

Keywords: torque-flow pump; self-cleaning; CFD; ANSYS CFX; operating zone; off-optimal modes.

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ЗБЕРЕЖЕННЯ САМООЧИЩУЮЧОГО ЕФЕКТУ У ВІЛЬНОВИХРОВОМУ НАСОСІ НА ПОЗАОПТИМАЛЬНИХ РЕЖИМАХ РОБОЧОЇ ЗОНИ

Представлено результати дослідження вільновихрового насоса з нерівномірною лопатевою системою, конструктивною особливістю якого є наявність розширених міжлопатевих каналів, що створюють умови для прояву самоочищуючого ефекту. На відміну від попередніх робіт, де було підтверджено дієвість цього ефекту у точці оптимальної подачі, у даному дослідженні проаналізовано поведінку насоса на позаоптимальних режимах робочої зони – 0,8*Q*опт (100 м³/год) та 1,2*Q*опт (150 м³/год). Чисельне моделювання виконано у середовищі ANSYS CFX із використанням тривимірних геометричних моделей та неструктурованих розрахункових сіток. Для кожного режиму визначено повні гідравлічні характеристики (напір та коефіцієнт корисної дії), а також проаналізовано розподіли тиску й швидкості у міжлопатевих каналах. Показано, що навіть за відхилення від оптимальної подачі енергетичні показники насоса з нерівномірною лопатевою системою відрізняються від стандартної конструкції не більше ніж на 2,5 м за напором і 1 % за ККД. Найважливішим результатом є підтвердження стійкості самоочищуючого ефекту в робочій зоні. У міжлопатевих каналах фіксується асиметрія розподілу тиску та локальні пульсації, які сприяють зсуву волокнистих включень із поверхні лопатей. Виявлено, що при підвищеній подачі інтенсивність пульсацій зростає, тоді як при зниженій подачі вони зберігають регулярність і забезпечують стабільне очищення. Таким чином, насос із нерівномірною лопатевою системою демонструє поєднання прийнятних енергетичних показників та здатності до самоочищення у всій робочій зоні, що робить його перспективним для застосування у системах водовідведення та промислових процесах, де надійність і довговічність обладнання мають вирішальне значення.

Ключові слова: вільновихровий насос; самоочищення; CFD; ANSYS CFX; робоча зона; позаоптимальні режими.

Introduction. One of the main problems in the operation of torque-flow pumps is the rapid decrease in reliability while operating with fibrous and contaminated liquids [1]. Under such conditions, even a small accumulation of deposits on the impeller blades leads to a drop in head, a decrease in efficiency, and an increased risk of emergency failures [2]. Traditional maintenance measures and mechanical cleaning reduce this risk but are associated with additional time and resource costs [3]. Therefore, one of the key directions in the development of modern pumps is the creation of design solutions that ensure their ability to self-clean directly during the operating process [5].

In previous studies by the authors, it was proved that the use of an impeller with a non-uniform blade system in torque-flow pumps (Fig. 1) makes it possible to achieve this effect at the best efficiency point (BEP) [6]. It was shown that the asymmetry of the inter-blade channels generates pressure and velocity pulsations, which contribute to the removal of fibers from the blade surfaces. This opens up the possibility of significantly increasing pump reliability under difficult operating conditions [7].

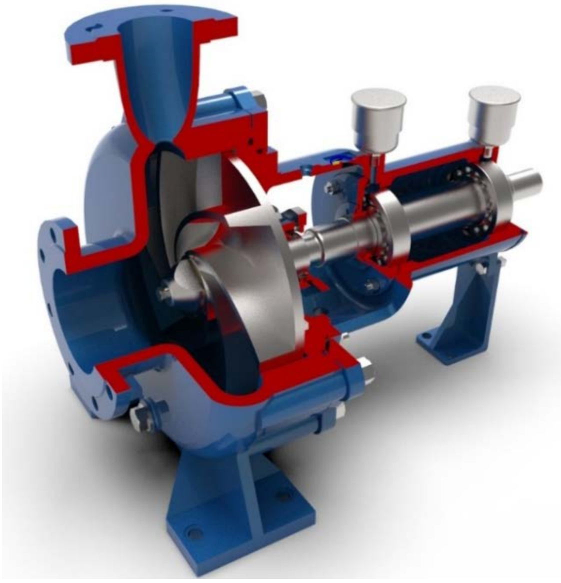


Fig. 1. Structural design of a torque-flow pump

At the same time, for practical applications it is important to confirm that the self-cleaning mechanism is not limited only to the BEP, but is also maintained when operating over a wider flow rate range [8]. The operating range, where the flow varies within ±20 % of the BEP, is typical for most pumping systems. Operation under these conditions determines the actual efficiency and durability of the equipment; therefore, studying the pump behavior at $0.8Q_{\mathrm{BEP}}$ and $1.2Q_{\mathrm{BEP}}$ is of particular importance [9].

Thus, this study aims to confirm the sustainability of the self-cleaning effect in a torque-flow pump with a non-uniform blade system within the operating range. This allows not only to evaluate the stability of hydraulic characteristics beyond the BEP but also to verify the suitability of the design for long-term operation with liquids containing fibrous inclusions.

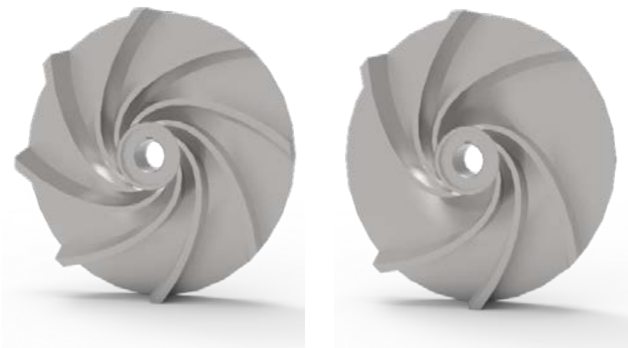
Literature review. Torque-flow pumps are traditionally used for pumping liquids with suspended, fibrous, and abrasive inclusions. Typical examples include suspensions, syrups, and liquids with household waste (wet wipes, hygiene products, etc.) [10]. Operation with such liquids creates a chronic problem of clogging in the flowing part and, as a consequence, the degradation of performance indicators, primarily energy efficiency. Therefore, effective self-cleaning mechanisms are required to ensure stable operation during the operating process, rather than only during maintenance downtime [11]. This need has been clearly formulated in recent studies, which emphasize that ensuring self-removal of contaminants is a prerequisite for maintaining head, efficiency, and cavitation resistance of pumps of this type [12].

The operating process in torque-flow pumps is twofold: a blade operating process, typical for dynamic pumps, and a vortex operating process with the formation of a toroidal vortex in the free chamber [13]. Energy is transferred both directly, through the interaction of the operating fluid with the impeller blades, and indirectly, through the vortex structure. This makes the hydrodynamics of the flowing part more complex compared to centrifugal machines and requires special approaches to design and operation [14].

Improving the energy efficiency of torque-flow pumps in the literature is mainly associated with modifications to the impeller and elements of the flowing part [15]. In particular, replacing radial blades with curvilinear ones makes it possible to increase pump efficiency by approximately 3–5 % [16], without the risk of inducing cavitation at the inlet [17]. For pumps of this type, a reduced need for separate anti-cavitation devices compared to centrifugal units has also been noted [18]. Other approaches include extending part of the blades into the free chamber and adding winglets on the blade edges [19]. Such solutions stabilize the flow before and after the pump and reduce additional hydraulic losses due to vortex formation [20], although alternative designs of deflector devices may complicate manufacturing and increase the final cost [21].

A key scientific shift in recent years has been the transition from purely "geometric" improvements to functional self-cleaning mechanisms that deliberately exploit the natural non-uniformity of pressure and velocity in the inter-blade channels [6]. Unlike the idealized Euler scheme with a uniform distribution of relative velocity, the real flow in the inter-blade channels is significantly non-uniform: the relative velocity is higher near the back side of the blade, while the pressure is higher near the working side [22]. For torque-flow pumps, where the outflow from the channels occurs mainly in the axial direction, this non-uniformity cannot be neglected [23]. Uniform blade spacing results in a cyclic but ultimately more "stable" pressure distribution in the free chamber, whereas a non-uniform pitch (channels doubled in angular coverage) generates significant pulsations of absolute pressure at the channel outlets (Fig. 2). As a result, the self-cleaning mechanism is realized as an operational property rather than a side effect.

The authors' previous research [6] experimentally and numerically demonstrated the effectiveness of this approach at the best efficiency point (BEP), showing that the amplitude of pulsations in the expanded channels with non-uniform blade spacing can exceed those of a "uniform" impeller by more than two times, thus creating the prerequisites for stable self-cleaning when operating with contaminated fluids. At the same time, the existing body of publications pays insufficient attention to the long-term reliability and energy efficiency of torque-flow pumps specifically within the operating range beyond the BEP, where in practice the transport of multiphase fluids with unpredictable content of solid and fibrous inclusions most often occurs. This research gap – verifying and ensuring the stability of self-cleaning under deviations from the BEP – defines the relevance of our study.



a *b*

Fig. 2. Torque-flow pump impellers:
a – with uniform; *b* – with non-uniform blade spacing

Finally, it is worth noting the widespread use of numerical simulation (ANSYS CFX) as a tool for rapid hypothesis testing and cost reduction at the design stage. This approach demonstrates reliable convergence with the results of bench hydraulic tests and has become an established practice for hydrodynamic problems of pumps of this type [24; 25]. Therefore, further verification of off-optimal modes of the operating range in this paper is based on CFD analysis, with an emphasis on pressure/velocity distributions and pulsation indicators [26], which are directly related to the self-cleaning mechanism.

Aim and objectives of the research. The aim of this research is to verify and confirm the stability of the self-cleaning effect in a torque-flow pump with a non-uniform blade system at operating range modes deviating from the best efficiency point ($0.8Q_{\text{BEP}}$ and $1.2Q_{\text{BEP}}$), as well as to provide a quantitative assessment of the impact of this design solution on the hydraulic characteristics of the pump.

To achieve this aim, the following objectives were formulated:

- to perform CFD simulations of the pump operation in the flow range of 100–150 m³/h for both the standard and modified impellers;
- to determine the complete hydraulic characteristics (head and efficiency) and evaluate their changes compared to the best efficiency point (BEP);
- to analyze the flow structure in the inter-blade channels and in the free chamber, with particular attention to the asymmetry of pressure and velocity;
- to identify the presence of pulsation phenomena that create conditions for fiber detachment from the blade surfaces and ensure self-cleaning;
- to formulate generalized conclusions regarding the efficiency of the non-uniform blade system within the operating range and its potential for practical application.

Research Methodology. The analysis of the torque-flow pump operation was carried out using computer simulation methods [27]. Two impeller configurations were considered: the standard design and a modified version with omitted blades, which create asymmetric inter-blade channels and provide conditions for self-cleaning.

The geometric models were created in SolidWorks and calculated in the ANSYS CFX software package [28]. To correctly reproduce the hydrodynamics, an unstructured computational grid with local refinement near the walls and within the inter-blade channels was applied. The total number of elements was about 1.5 million, which ensured an acceptable balance between accuracy and computational time.

Water at a temperature of 20 °C was used as the operating fluid. The flow was modeled in a turbulent regime using the k–ε turbulence model, which has proven effective for pumps of this type [29]. The calculations were performed until convergence of the main parameters (head, power, efficiency) was achieved, with a relative error not exceeding 0.05.

The study was conducted for three characteristic modes: $0.8Q_{\text{BEP}}$ (100 m³/h), Q_{BEP} (125 m³/h), and $1.2Q_{\text{BEP}}$ (150 m³/h). For each mode, the hydraulic characteristics and flow patterns in the inter-blade channels were determined, which made it possible to evaluate the manifestation and stability of the self-cleaning effect within the operating range of the pump [30].

Results. The numerical research of the torque-flow pump with a non-uniform blade arrangement confirms the preservation of operability and the self-cleaning effect within the operating range under deviations from the best efficiency point (BEP) (see Table 1).

In particular, at $0.8Q_{\text{BEP}}$ (100 m³/h), the total head of the pump with omitted blades is 65.46 m, while for the standard pump it is 65.87 m. Thus, the difference is only 0.41 m, which can be considered practically negligible. The overall efficiency of both designs at this mode is identical and equals 38.3 %, indicating full correspondence in energy performance. These results lead to the conclusion that introducing asymmetry into the blade system does not cause deterioration of pump characteristics when operating at reduced flow rates.

At the decreased flow rate ($0.8Q_{\text{BEP}}$ = 100 m³/h), some difference was observed. The total head of the pump with the self-cleaning mechanism was 65.44 m compared to 65.87 m for the standard design, which corresponds to a decrease of about 0.41 m. The efficiency in both cases confirms the absence of additional losses associated with the asymmetry of the inter-blade channels. Nevertheless, this difference is fully acceptable for practical operation, since the pump maintains stable performance and does not exceed the limits of operational characteristics.

At the best efficiency point (Q_{BEP} = 125 m³/h), which is traditionally considered the most favorable for hydraulic machines, the results also confirm the effectiveness of the self-cleaning mechanism. The total head of the pump with the non-uniform blade system is 59.44 m, while for the standard impeller it is 60.83 m. Thus, the difference of 1.39 m is moderate and remains within acceptable deviations for practical application. The efficiency in this case is 39.8 % for the impeller with omitted blades and 40.5 % for the standard one, indicating only a 0.7 % reduction in performance.

At the increased flow rate ($1.2Q_{\text{BEP}}$ = 150 m³/h), the general trend is maintained. The total head of the pump with omitted blades is 59.75 m, which is 2.25 m lower than the standard design (62.0 m). The overall efficiency at this mode is 38.7 % compared to 39.1 % for the standard impeller. The difference of 0.4 % indicates a moderate increase in hydraulic losses, which, however, is not decisive for technical efficiency.

Importantly, even at higher flow rates, the pump with the non-uniform blade arrangement maintains characteristics close to those of the standard analogue, confirming the operability of this design solution throughout the operating range.

In addition to quantitative indicators, a detailed analysis of flow patterns in the inter-blade channels of the studied impellers was carried out. For the $0.8Q_{\text{BEP}}$ mode, the appearance of local flow separation zones in the expanded channels (Figs. 3–5) is characteristic. They are accompanied by a decrease in velocity in the central part of the channel and an increase near the operating side of the blade. This leads to the formation of pulsations that act on the blade surface and promote the detachment of fibrous inclusions.

Table 1 – Results of simulation of the torque-flow pump with a standard impeller (traditional design) and a self-cleaning impeller (with omitted blades)

Operating range, $Q = kQ_{\text{BEP}}$	Standard pump		Self-cleaning pump		Difference	
	Head, m	Efficiency, %	Head, m	Efficiency, %	Head, m	Efficiency, %
$0.8Q_{\text{BEP}}$ (100 m³/h)	65.87	38.3	65.46	38.3	0.41	0
Q_{BEP} (125 m³/h)	60.83	40.5	59.44	39.8	1.39	0.7
$1.2Q_{\text{BEP}}$ (150 m³/h)	62.00	39.1	59.75	38.7	2.25	0.4

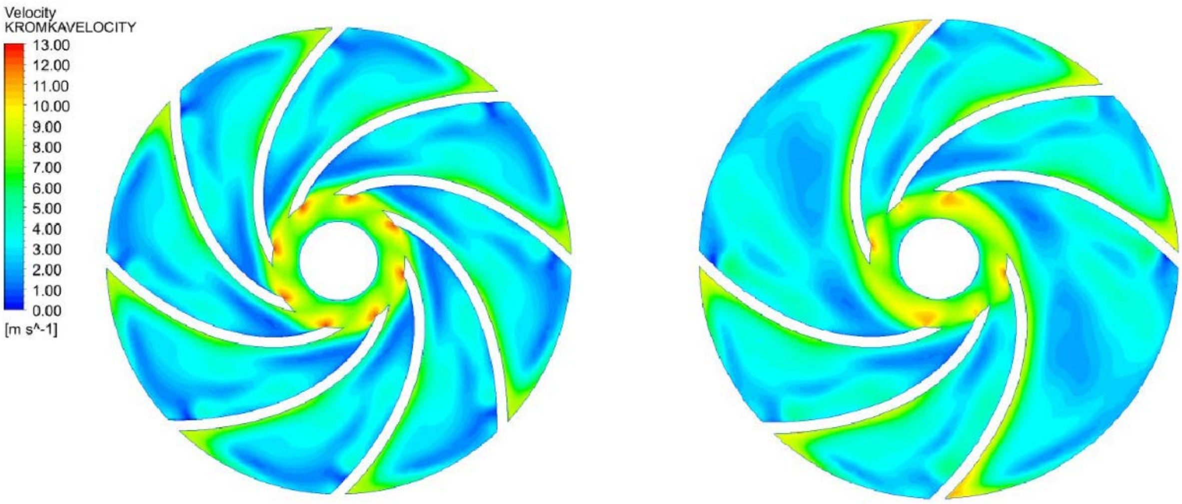


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Fig. 3. Distribution of relative velocity near the impeller edge (operating mode $Q = 0.8Q_{BEP}$):
a – standard impeller; *b* – impeller with self-cleaning effect

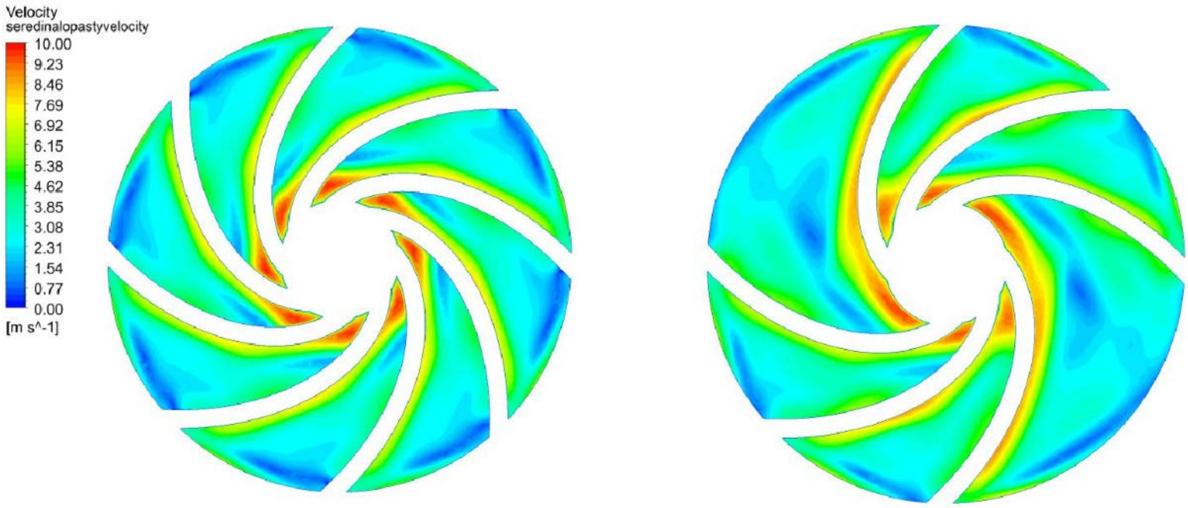

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Fig. 4. Distribution of relative velocity in the center of the inter-blade channels of the impeller (operating mode $Q = 0.8Q_{BEP}$):
a – standard impeller; *b* – impeller with self-cleaning effect

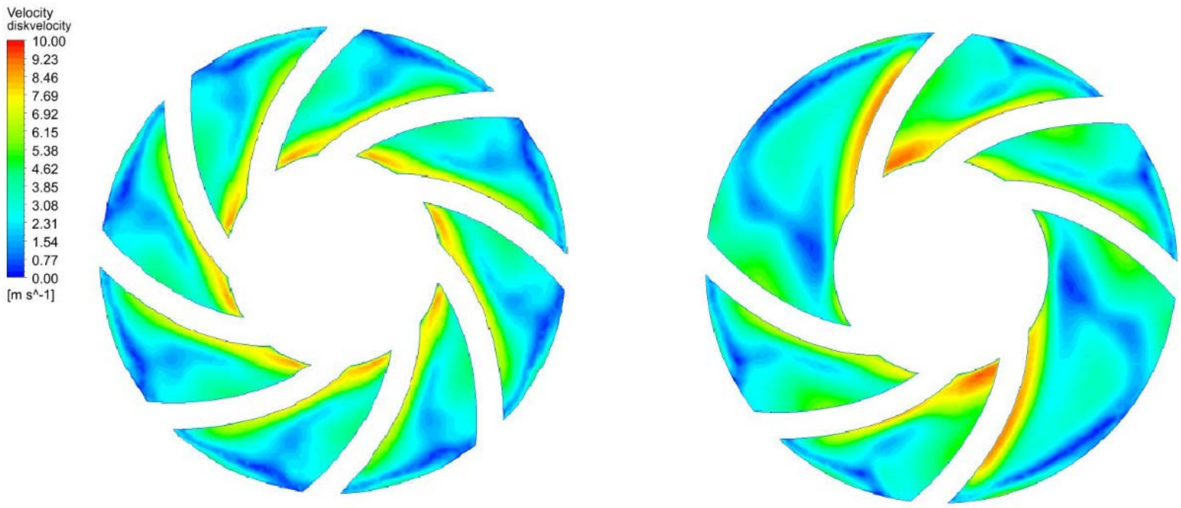

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Fig. 5. Distribution of relative velocity near the impeller disk (operating mode $Q = 0.8Q_{BEP}$):
a – standard impeller; *b* – impeller with self-cleaning effect

At the same time, at the BEP ($Q = Q_{BEP}$), the analysis of the relative velocity distribution in the inter-blade channels of the impeller (Figs. 6–8) reveals a characteristic asymmetry that leads to the formation of pulsations in the expanded channels. This confirms that the self-cleaning effect is not only present at the BEP but also represents an inherent part of the operating process. Thus, even at the point of optimum performance, the pump with non-uniform blade spacing demonstrates only minor differences in energy characteristics compared to the standard design, while offering a fundamental advantage in the form of self-cleaning capability, which significantly enhances reliability when pumping contaminated media.

With an increase in flow rate to $1.2Q_{BEP}$, the pulsation intensity rises: in the expanded channels of the impeller with omitted blades, a larger volume of liquid passes through, which causes a non-uniform velocity distribution and the formation of additional circulation zones in the free chamber (Figs. 9–11). As a result, conditions arise for more intensive fluid mixing, which also promotes self-cleaning.

The pressure diagrams (Figs. 12–14), constructed for the specified operating modes, confirmed the persistence of differences between the standard and expanded channels. At all researched modes, the pump with omitted blades shows alternating zones of increased and decreased pressure, which form the pulsation mechanism. This phenomenon, previously identified at the BEP, proved to be stable under off-optimal modes of the operating range. It is this mechanism that ensures the ability of the pump to self-clean, since fluctuating loads and local accelerations of the flow prevent the accumulation of fibrous inclusions on the blades.

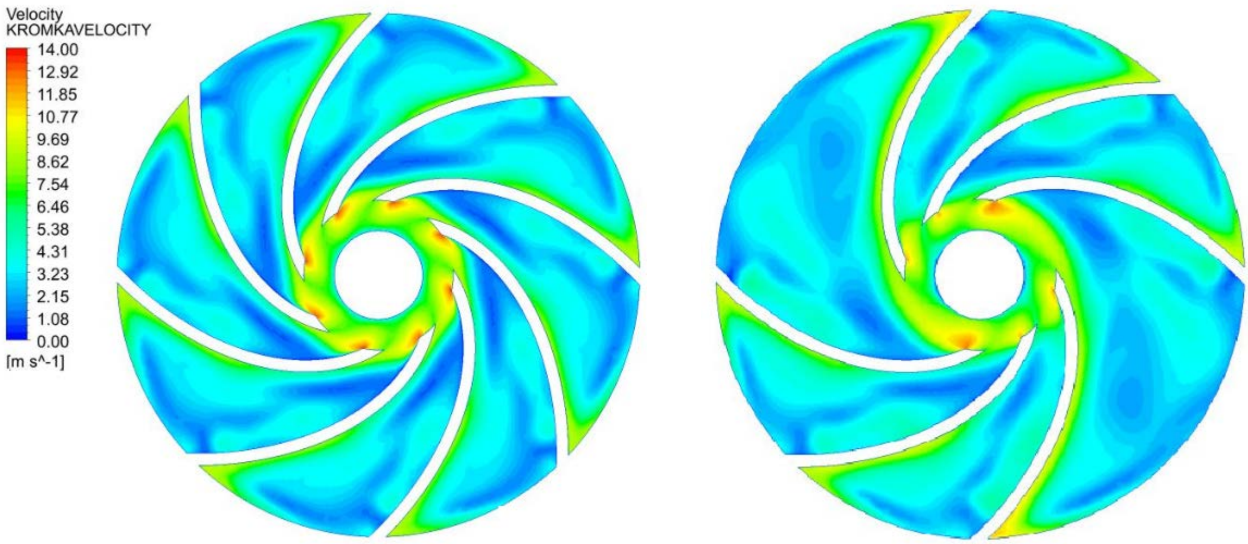

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Fig. 6. Distribution of relative velocity near the impeller edge (best efficiency point, $Q = Q_{BEP}$):
a – standard impeller; *b* – impeller with self-cleaning effect

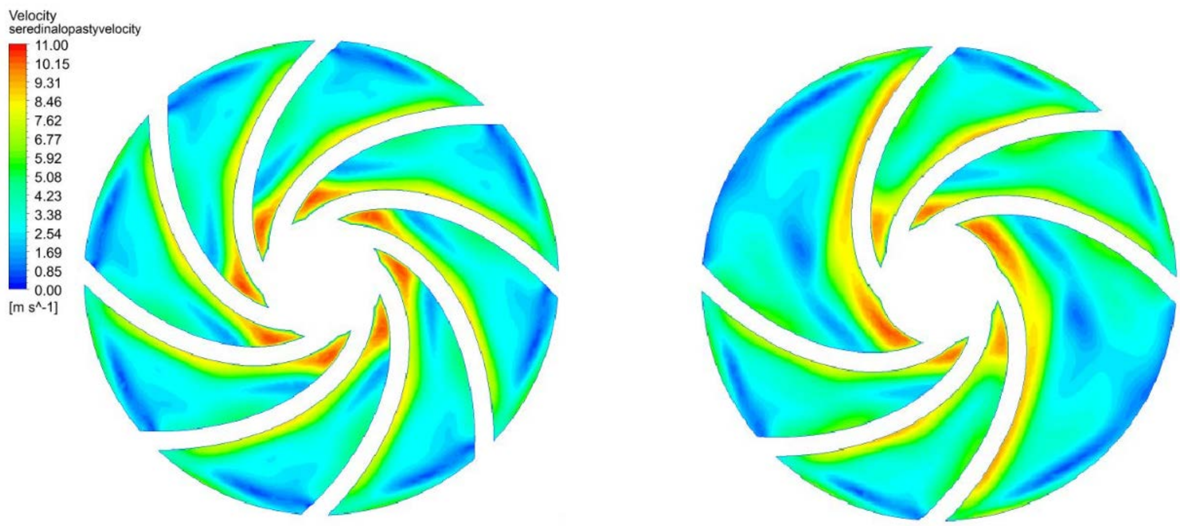

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Fig. 7. Distribution of relative velocity in the center of the inter-blade channels of the impeller (best efficiency point, $Q = Q_{BEP}$):
a – standard impeller; *b* – impeller with self-cleaning effect

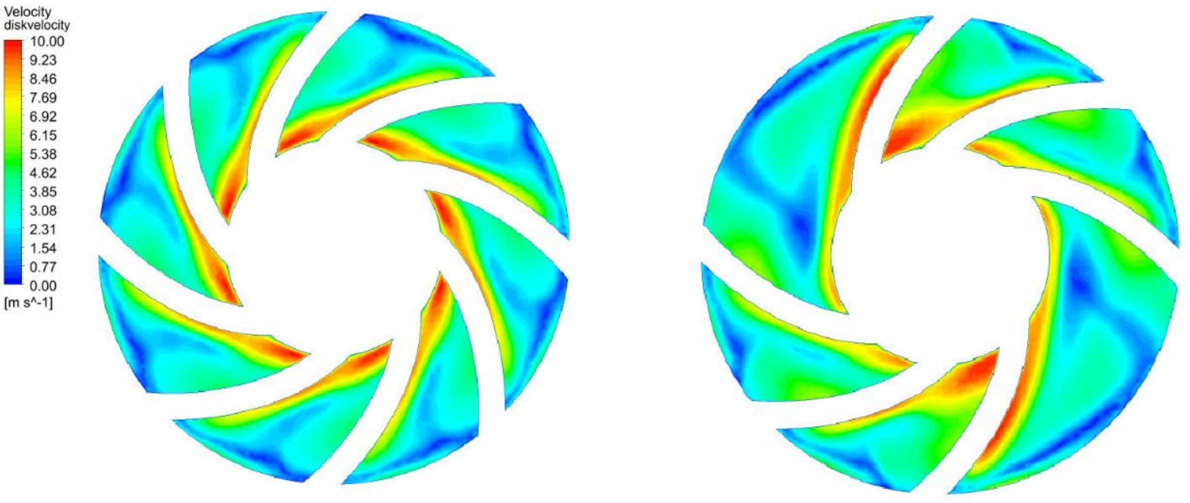

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Fig. 8. Distribution of relative velocity near the impeller disk (best efficiency point, $Q = Q_{\text{BEP}}$):
a – standard impeller; *b* – impeller with self-cleaning effect

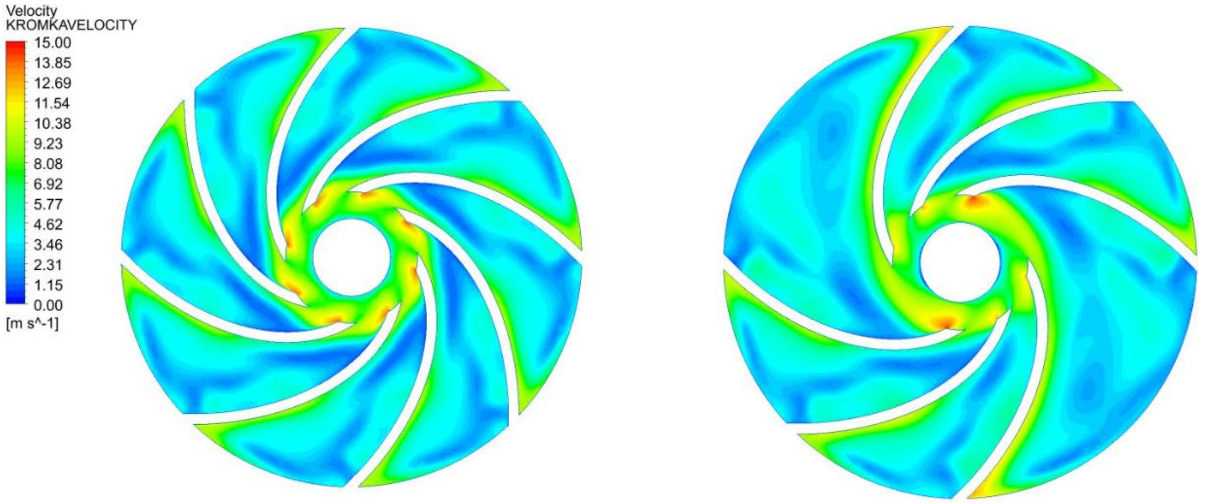

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Fig. 9. Distribution of relative velocity near the impeller edge (operating mode $Q = 1.2Q_{\text{BEP}}$):
a – standard impeller; *b* – impeller with self-cleaning effect

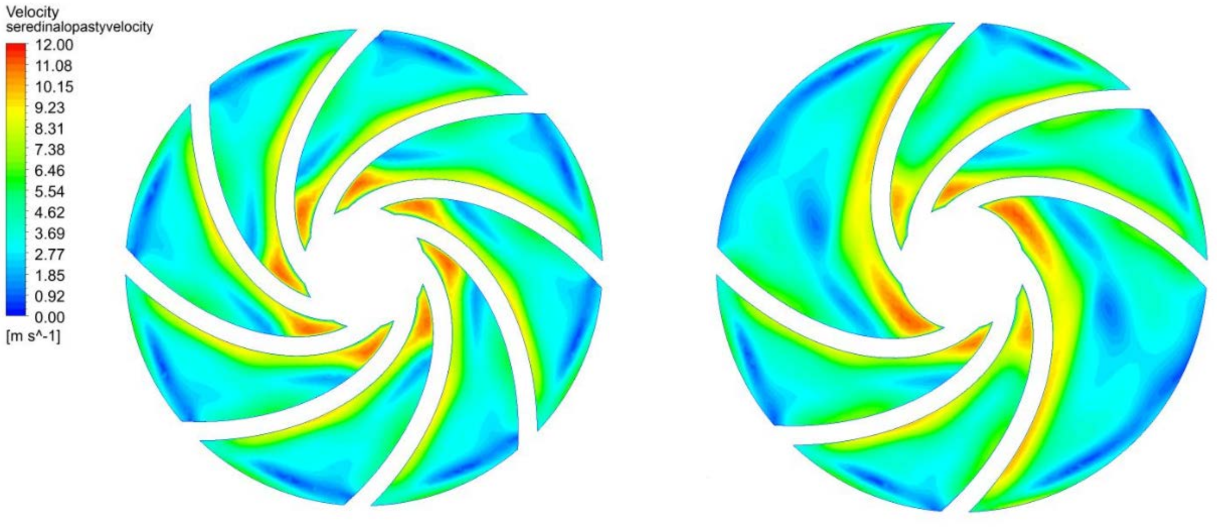

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Fig. 10. Distribution of relative velocity in the center of the inter-blade channels of the impeller (operating mode $Q = 1.2Q_{\text{BEP}}$):
a – standard impeller; *b* – impeller with self-cleaning effect

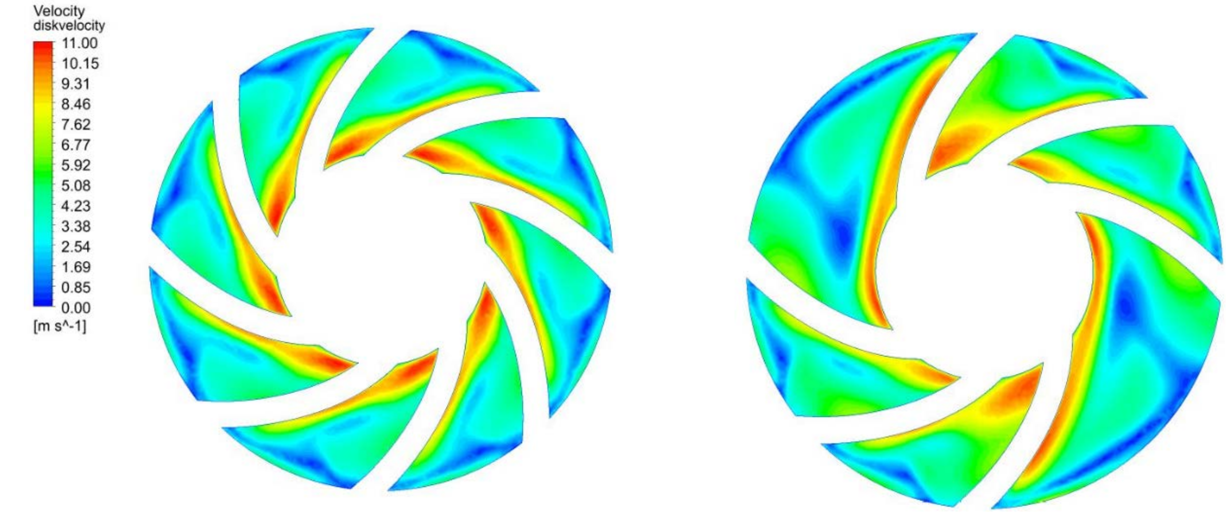

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Fig. 11. Distribution of relative velocity near the impeller disk (operating mode $Q = 1.2Q_{\mathrm{BEP}}$):
a – standard impeller; *b* – impeller with self-cleaning effect

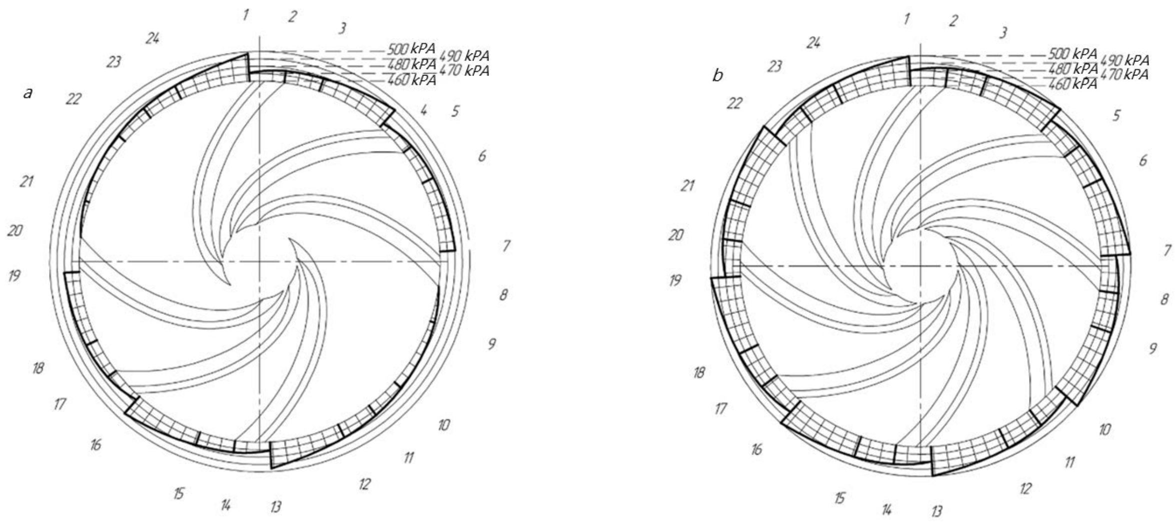

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Fig. 12. Pressure distribution diagrams near the impeller edge (best efficiency point, $Q = Q_{\mathrm{BEP}}$):
a – standard impeller; *b* – impeller with self-cleaning effect

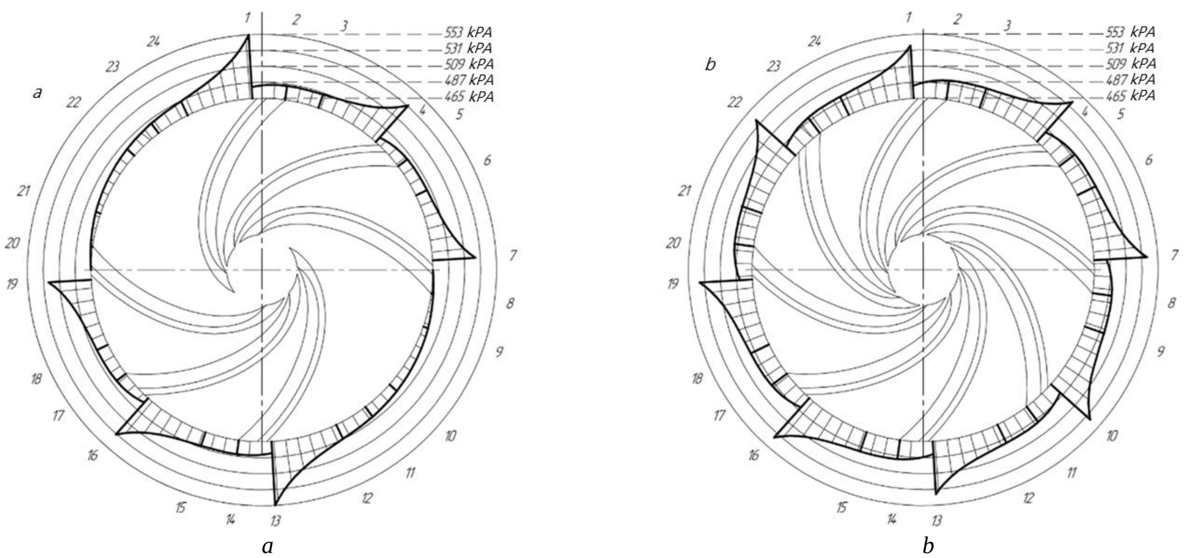

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Fig. 13. Pressure distribution diagrams in the center of the inter-blade channels of the impeller (best efficiency point, $Q = Q_{\mathrm{BEP}}$):
a – standard impeller; *b* – impeller with self-cleaning effect

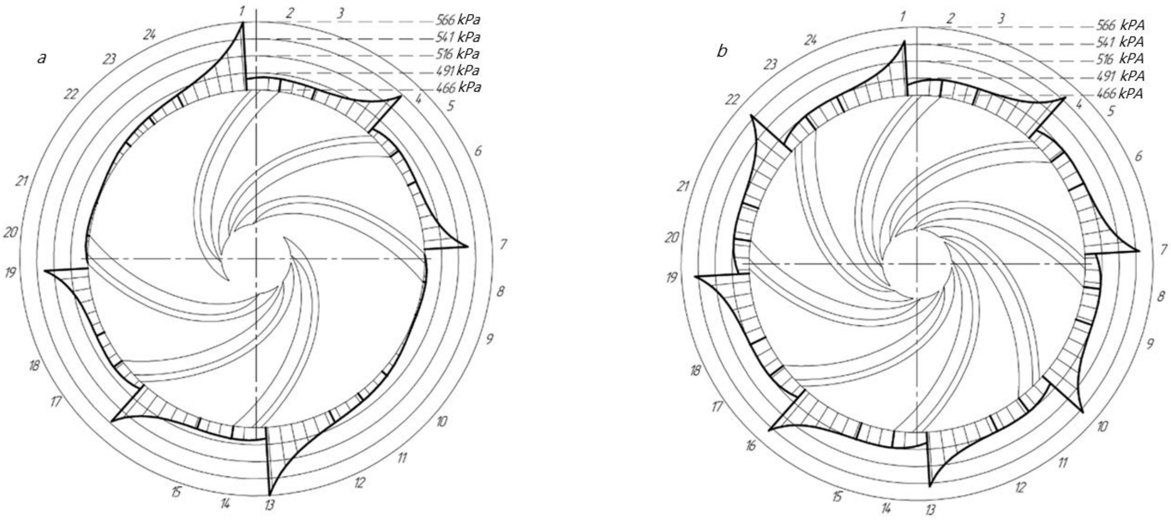

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Fig. 14. Pressure distribution diagrams near the impeller disk (best efficiency point, $Q = Q_{\mathrm{BEP}}$):
a – standard impeller; *b* – impeller with self-cleaning effect

Thus, the study confirms that the torque-flow pump with a non-uniform blade system is capable of operating within the operating range at flow rates of $0.8Q_{\mathrm{BEP}}$ and $1.2Q_{\mathrm{BEP}}$ without a significant decrease in energy performance. Moreover, at these modes the stability of the self-cleaning effect has been confirmed, which makes the proposed design suitable for long-term operation when pumping liquids with a high content of fibrous inclusions.

Discussion. The obtained CFD simulation results make it possible to draw several fundamental generalizations regarding the operation of a torque-flow pump with a non-uniform blade system. First, the analysis showed that deviations from the best efficiency point (BEP) within the operating range do not lead to a significant decrease in energy performance. Despite the presence of expanded inter-blade channels and asymmetry in the blade system, the differences in head and efficiency between the investigated pump and the standard design remain minor – within 1–2 m in head and less than 1 % in efficiency. This indicates that the proposed design maintains its effectiveness under real operating conditions, when the flow rate may vary over a wide range.

Second, the key finding is the preservation of the self-cleaning effect across all investigated modes of the operating range. In the inter-blade channels of the pump with omitted blades, a stable pressure asymmetry is observed, which generates local flow pulsations. At reduced flow ($0.8Q_{\mathrm{BEP}}$), these appear as zones of flow separation and reattachment, creating conditions for fiber detachment. At the BEP, the pulsations are less intense but remain regular, ensuring consistent cleaning of the blade surfaces. At increased flow ($1.2Q_{\mathrm{BEP}}$), the pulsation amplitude grows, leading to more intensive mixing of the liquid in the free chamber and a higher likelihood of fiber detachment from the blades. Thus, the self-cleaning mechanism is not an accidental phenomenon for a single operating point but has a systemic nature, embedded in the very geometry of the flowing part.

Third, the practical significance of the obtained results lies in confirming the reliability of such pumps in real operating conditions. Sewerage systems and industrial facilities often operate in modes far from the BEP, where conventional pumps quickly lose efficiency due to clogging. The proposed design demonstrates stable hydraulic characteristics and self-cleaning capability throughout the operating range, which provides grounds to recommend it as a more reliable solution for pumping liquids with a high content of fibrous and solid inclusions.

Overall, the conducted analysis confirmed that the developed torque-flow pump combines two critically important factors: the preservation of energy efficiency and the ability to self-clean. Such a balance opens prospects for the further application of this design in systems where reliability and durability of equipment are decisive.

Conclusions. In this research, the operation of a torque-flow pump with a non-uniform blade system was investigated at operating range modes deviating from the best efficiency point (BEP). Based on numerical simulation and analysis of hydraulic characteristics, a number of findings with both scientific and practical value were obtained.

It was shown that at reduced flow ($0.8Q_{\mathrm{BEP}} = 100$ m³/h) and increased flow ($1.2Q_{\mathrm{BEP}} = 150$ m³/h), the pump with omitted blades maintains operability at the level of the standard design. The differences in head do not exceed 2.5 m, and in efficiency do not exceed 1 %, which indicates a minimal impact of asymmetry on the energy performance of the unit. At the best efficiency point ($Q_{\mathrm{BEP}} = 125$ m³/h), a similar trend is observed: the reduction in head and efficiency is minor and does not exceed the limits of acceptable deviations.

The most important result is the confirmation of the stability of the self-cleaning effect throughout the operating range. In the inter-blade channels of the pump with omitted blades, pressure asymmetry is maintained, leading to the occurrence of local flow pulsations. These pulsations act as a mechanism for detaching fibrous inclusions from the blade surfaces, preventing their accumulation and clogging of the flowing part. It was found that at increased flow the pulsation intensity grows, while at reduced flow they remain regular and ensure stable cleaning. Thus, the self-cleaning effect is not accidental or confined to the best efficiency point, but has a systemic nature inherent to the entire operating range.

The obtained results confirm that the application of a non-uniform blade system in torque-flow pumps is an effective way to enhance their reliability when handling liquids containing fibrous inclusions. The combination of acceptable energy performance with the ability to self-clean makes this design promising for implementation in sewerage and industrial systems, where resistance to clogging and long-term reliable operation are of critical importance.

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