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Original study article

Modeling of the operation of a disc pump with the wall roughness consideration

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ABSTRACT

BACKGROUND: At present, a small number of studies of disk pumps operating with a low-viscosity liquid have been conducted. In addition, among the existing papers, numerical calculations are presented, which have a serious discrepancy with the experiments carried out. This article is devoted to numerical simulation of the operation of a disk pump with water, comparison of the calculation results with the experimental data.

AIMS: Determination the factors affecting the convergence of the main indicators with experimental data when performing CFD simulation with a low-viscosity liquid.

METHODS: In this paper, the numerical modeling method based on the solution of discrete analogs of the basic equations of fluid dynamics is used. In order to compare the *CFD* simulation with the experiment, a test bench on which two configurations of the impeller were studied was created.

RESULTS: It is shown that it is important to take into account the influence of the roughness of solid walls for this type of dynamic machines when modeling their operation with a low-viscosity liquid, since it has a significant effect on the indicators of the disk pump. Comparison of the obtained indicators a with the experimental data, as well as flow patterns in the flow part are given.

CONCLUSIONS: Based on the results of the article, it can be stated that consideration of roughness in numerical calculations of a dynamic pump has a positive effect on convergence with experimental data.

Keywords: *disc pump; numerical simulation; turbulence; CFD; roughness.*

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Оригинальное исследование

Учет влияния шероховатости при моделировании работы дискового насоса

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АННОТАЦИЯ

Обоснование. На данный момент проведено небольшое количество исследований дисковых насосов, работающих на маловязкой жидкости. К тому же среди существующих работ представлены численные расчёты, которые имеют серьёзное расхождение с проведёнными экспериментами. Данная статья посвящена численному моделированию работы дискового насоса на воде, сравнению результатов расчёта с экспериментальными данными.

Цель — определить факторы, влияющие на сходимость основных характеристик с экспериментальными данными при проведении *CFD* расчёта на маловязкой жидкости.

Методы. В данной работе применяется метод численного моделирования, основанный на решении дискретных аналогов базовых уравнений гидродинамики. Для сравнения *CFD* расчётов с экспериментом был создан испытательный стенд, на котором исследовались две конфигурации рабочего колеса.

Результаты. Показано, что для данного типа динамических машин важен учёт влияния шероховатости твёрдых стенок при моделировании их работы на маловязкой жидкости, поскольку она оказывает существенный эффект на характеристики дискового насоса. Приведено сравнение полученных характеристик с экспериментальными данными, а также картин течения в проточной части.

Заключение. На основании результатов статьи можно утверждать, что учёт шероховатости при численных расчётах динамического насоса положительно влияет на сходимость с экспериментальными данным.

Ключевые слова: *дисковый насос; численное моделирование; турбулентность; CFD; шероховатость.*

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BACKGROUND

Dynamic disk pumps, unlike their centrifugal counterparts, do not feature profiled blades within their impellers (Fig. 1). Instead, the impeller of a classic disk pump consists of a package of two or more smooth disks. These pumps are particularly suited for applications that involve pumping high-viscosity liquids [1, 2]. However, the use of disk pumps in handling low-viscosity media has also been noted, sparking interest in calculating and predicting their characteristics under such conditions [3].

Research on this subject is scarce, with some studies focusing on theoretical descriptions and their comparison with experimental results [4], while others examine these pumps through numerical hydrodynamic modeling [5]. Theoretical approaches to modeling flow with developed turbulence encounter significant limitations, which cause discrepancies in the obtained characteristics.

In studies that employ numerical modeling to explore disk pump flows, a frequent observation is the absence of experimental data for validation or significant discrepancies in such comparisons [6]. Given the extremely widespread use of *CFD* packages in engineering, validating the results from these models has become particularly interesting scientifically and practically.

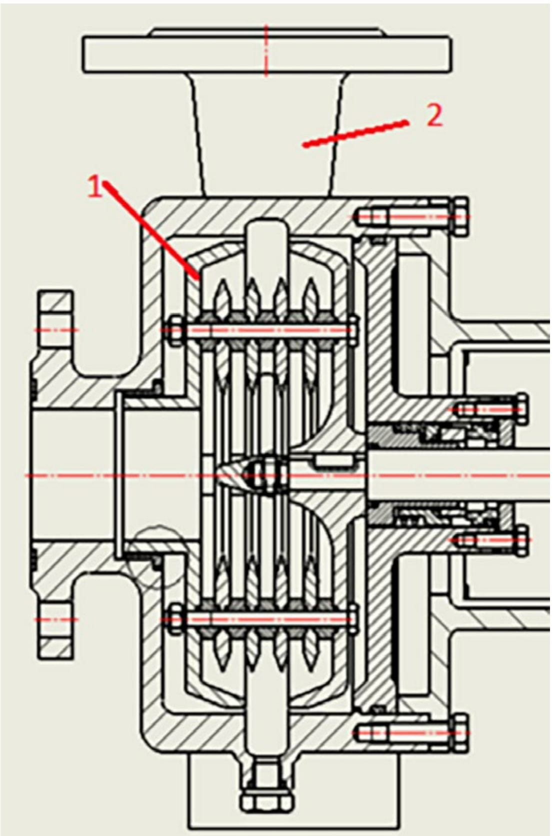

Fig. 1. A disc pump.
Рис. 1. Дисковый насос.

This paper presents the results of numerical modeling and experimental research into disk pumps operating on water. A key finding has been the significant influence that flow path element roughness has on the characteristics of this type of hydraulic machine, which must be considered when formulating the *CFD* calculation problem.

AIM

The objective of this study was to determine the factors influencing the convergence of the main characteristics with experimental data when performing *CFD* calculations of a disk pump operating with low-viscosity fluids.

DESCRIPTION OF THE MATHEMATICAL MODEL

The numerical modeling method used in this study relies on solving distinct analogs of the basic hydrodynamic equations. For an incompressible fluid (ρ = const), these equations are expressed as follows [7]:

1) mass conservation equation (continuity equation):

$$\frac{\partial \tilde{u}_j}{\partial x_j} = 0,$$

where $\tilde{u}_j$ is the average value of the fluid velocity in projection onto the *j*-th axis (*j* = 1,2,3);

2) equation for conservation of momentum (Reynolds averaging):

$$\rho\left[\frac{\partial U_i}{\partial t} + U_j\frac{\partial U_i}{\partial x_j}\right] = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_i}\left[\tilde{T}_{ij}^{(v)} - \rho u_i u_j\right];$$

where U and P are the average speed and pressure, respectively; $\tilde{T}_{ij}^{(v)} = 2\mu\tilde{s}_{ij}$ is the viscous stress tensor for an incompressible fluid; $\tilde{s}_{ij} = \frac{1}{2}\left[\frac{\partial \tilde{u}_i}{\partial x_j} + \frac{\partial \tilde{u}_j}{\partial x_i}\right]$ is the strain rate tensor; and $\rho u_i u_j$ is the Reynolds stress.

To complete the given system of equations, the semi-empirical turbulence model k-ω *SST* was used, demonstrating satisfactory convergence with the experimental data when simulating dynamic pumps [8, 9, 10].

To simulate flow near solid walls, a high-Reynolds version of the turbulence model is used. This approach involves using wall functions to describe the velocity profile instead of solving the equations of momentum conservation. In the logarithmic domain, these functions take the following form:

$$u^+ = \frac{1}{K}\ln\left(\frac{E}{f}y^+\right),$$

where $y^+ = \frac{\mathrm{yu}^*}{\nu}$ is the dimensionless distance from the wall; K and E are constants; and f is the roughness function.

In this approach, roughness is described by a function that directly affects the wall function in the logarithmic region, effectively reducing the velocity magnitude relative to the solid wall. The roughness function is described as follows:

$$f = \begin{cases} 1 & \text{if } R^+ < R^+_{smooth} \\ \left[B\cdot\left(\frac{R^+ - R^+_{smooth}}{R^+_{rough} - R^+_{smooth}}\right)\right]^a & \text{if } R^+_{smooth} < R^+ \quad < R^+_{rough}; \\ B + CR^+ & \text{if } R^+ > R^+_{rough} \end{cases}$$

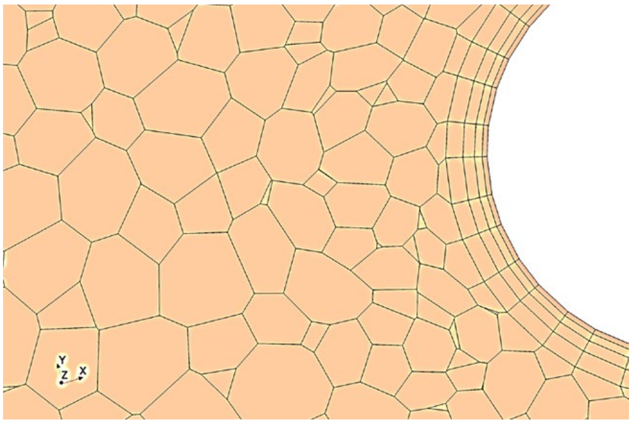

Fig. 2. The simulation mesh in the section of the flow part.
Рис. 2. Расчётная сетка в сечении проточной части.

Fig. 3. The test bench.
Рис. 3. Испытательный стенд.

where $R^+ = \frac{ru^*}{\nu}$; r is the value of equivalent roughness; ν is kinematic viscosity; $u*$ is the characteristic velocity near the wall, determined depending on the turbulence model used; $a = \sin\left[\frac{\pi}{2}\frac{\log\left(R^+ / R^+_{smooth}\right)}{\log\left(R^+_{rough} / R^+_{smooth}\right)}\right]$; R^+_{smooth} is the R^+ value characterizing the roughness corresponding to smooth walls; and R^+_{rough} is value for roughness corresponding to a rough wall.

The computational mesh comprises polyhedral cells in the flow core and prismatic layers near the solid walls (Fig. 2).

EXPERIMENTAL STUDY

A disk pump featuring a replaceable impeller configuration was tested (the test bench is presented in Fig. 3).

The impeller consists of two metal disks and plastic elements produced using additive manufacturing technologies, namely a shaft bushing, fastening blockings (possibly with blades), and a front (end) groove seal bushing seal. The impeller is shown in Fig. 4.

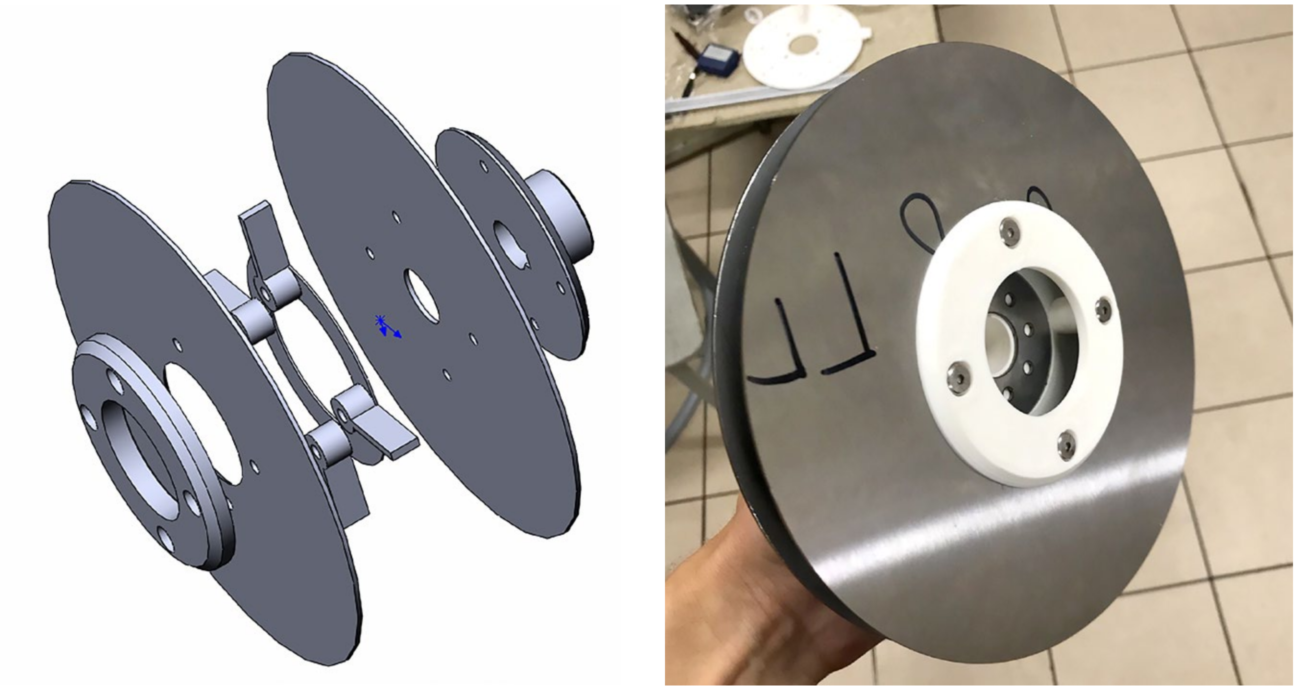

Fig. 4. A collapsible impeller.
Рис. 4. Разборное рабочее колесо.

RESULTS OF THE CALCULATIONS AND EXPERIMENTS

Figure 5 compares the obtained characteristics of a pump with a 13-mm-wide disk impeller with the results of numerical simulations (*CFD*) with and without considering surface roughness.

The parameters established for incorporating roughness in the simulation of a 13-mm-wide impeller were also applied to an 18-mm-wide impeller. The results are presented in Fig. 6.

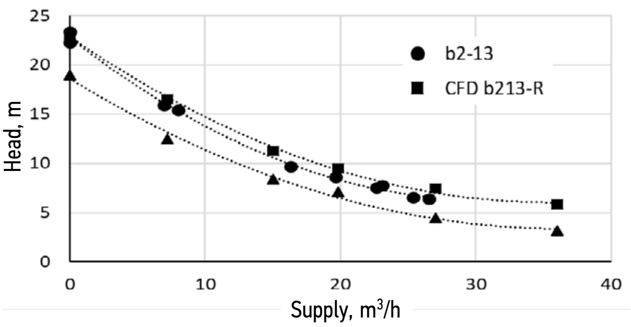

Fig. 5. Characteristic curves of a pump with a 13 mm wide disc impeller: experimental (b2-13), calculated with roughness considered (CFD b213-R) and without consideration (CFD b213).
Рис. 5. Характеристики насоса с дисковым рабочим колесом шириной 13 мм: экспериментальная (b2-13), расчётные с учётом шероховатости (CFD b213-R) и без (CFD b213).

For a qualitative comparison of the flow dynamics, Figs. 7 and 8 presents the velocity fields in the meridional section of the flow path (including the impeller, outlet, and lateral hollows) for an 18-mm-wide impeller.

ANALYSIS OF THE CALCULATION RESULTS

Based on the given characteristics and value distribution patterns, the following conclusions can be drawn:

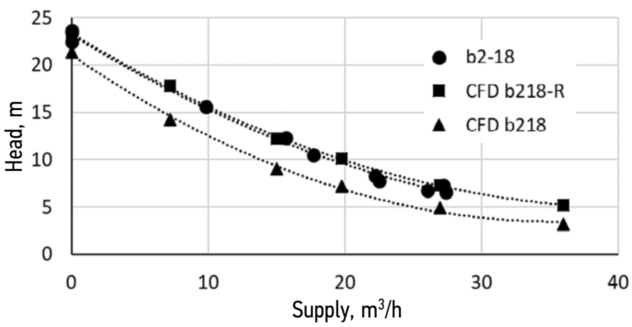

Fig. 6. Characteristic curves of a pump with a 18 mm wide disc impeller: experimental (b2-18), calculated with roughness considered (CFD b218-R) and without consideration (CFD b218).
Рис. 6. Характеристики насоса с дисковым рабочим колесом шириной 18 мм: экспериментальная (b2-18), расчётные с учётом шероховатости (CFD b218-R) и без (CFD b218).

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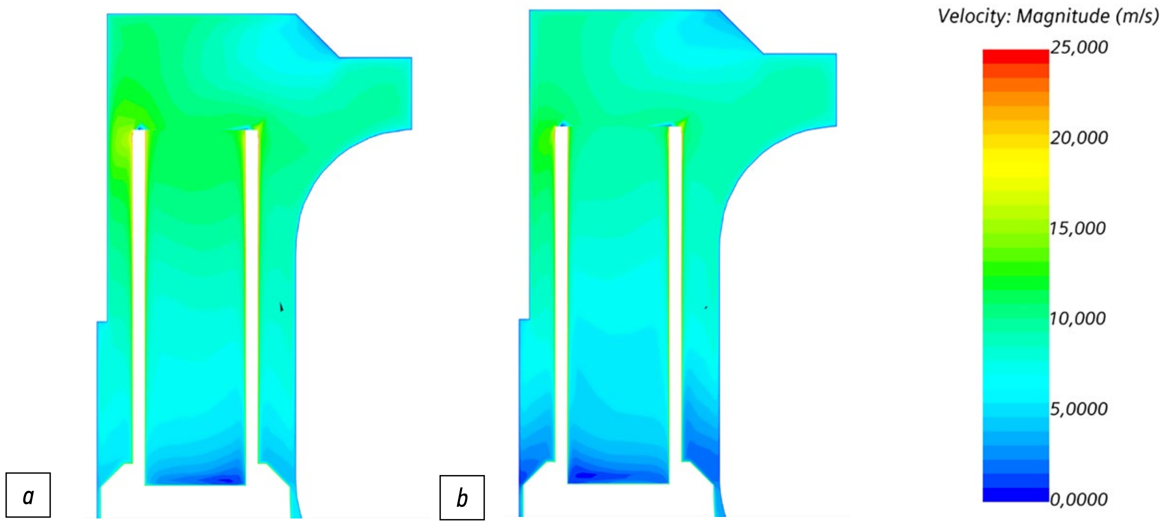

Fig. 7. Field distribution of the velocity amplitude at a supply of 15 m^3/h: *a*) with roughness; *b*) without roughness.
Рис. 7. Поле распределение амплитуды скорости при подаче 15 $м^3$/ч: *a*) с учётом шероховатости; *b*) без учёта шероховатости.

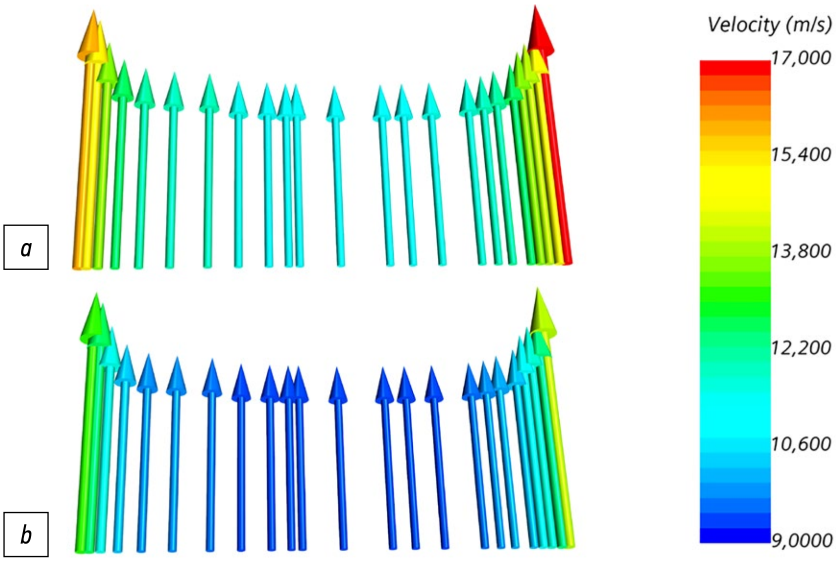

Fig. 8. The circumferential velocity of the fluid at the outlet of the impeller at a supply of 15 m^3/h: *a*) with roughness; *b*) without roughness.
Рис. 8. Окружная скорость жидкости на выходе из рабочего колеса при подаче 15 $м^3$/ч: *a*) с учётом шероховатости; *b*) без учёта шероховатости.

1. Numerical simulations of dynamic pumps with disk impellers with smooth surfaces for the flow path elements lead to a considerable discrepancy (up to 30% for both impellers) when calculating pressure.
2. Incorporating the influence of roughness into the numerical models significantly improves the convergence of the simulated results with the experimental data. The maximum error was 9% for an impeller width of 13 mm and 7.5% for an impeller width of 18 mm. The maximum errors were observed in the extreme right part of the pressure characteristic, which may be associated with an inaccurate estimation of roughness values.

The velocity distribution fields clearly show a decrease in fluid velocity near solid walls, which is attributed to the consideration of roughness. This results in additional acceleration in the impeller. Consequently, the average exit speed from the impeller increased by 17.7% (from 10.2 m/s to 12.4 m/s) at 15 m^3/h.

ADDITIONAL INFORMATION

Authors' contribution. V.A. Cheremushkin — numerical modeling and experimental research, preparation and writing of the text of the article; V.O. Lomakin — expert support of the experiment, collection and analysis of literary sources, preparation and writing of the article. The authors confirm that their authorship complies with the international ICMJE criteria (all authors made a significant contribution to the development of the concept, research and preparation of the article, read and approved the final version before publication).

Competing interests. The authors declare that they have no competing interests.

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ДОПОЛНИТЕЛЬНО

Вклад авторов. В.А. Черемушкин — выполнение численного моделирования и экспериментального исследования, подготовка и написание текста статьи; В.О. Ломакин — экспертное сопровождение эксперимента, сбор и анализ литературных источников, подготовка и написание статьи. Авторы подтверждают соответствие своего авторства международным критериям *ICMJE* (все авторы внесли существенный вклад в разработку концепции, проведение исследования и подготовку статьи, прочли и одобрили финальную версию перед публикацией).

Конфликт интересов. Авторы декларируют отсутствие явных и потенциальных конфликтов интересов, связанных с проведённым исследованием и публикацией настоящей статьи.

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REFERENCES

1. Misyura VI, Ovsyannikov BV, Prisnyakov VF. *Disc pumps.* Moscow: Mashinostroenie; 1986. (In Russ.).

2. Benderovich VA, Lunatsi ED. Dynamic laminar (disc) friction pumps. Areas of application of ONL pumps. *Hydraulics of Bauman Moscow State Technical University.* 2022;14:10–33. (In Russ.).

3. Zharkovsky AA, Ivanov OA, Klyuev AS. About the possibility of using disk impellers in low-flow oil pumps. *AIP Conference Proceedings.* 2020;2285. doi: 10.1063/5.0026592

4. Chernyavsky AM, Ruzmatov TM, Fomichev AV, et al. Experimental model of a disk pump to support blood circulation. *Bulletin of Transplantology and Artificial Organs.* 2016;18(4):93–101. (In Russ.). doi: 10.15825/1995-1191-2016-4-93-101

5. Stenina TV, Elizarova TG, Kraposhin MV. Regularized equations of hydrodynamics in the disk pump modeling problem and their implementation within the OpenFOAM package software package. *Preprints of M.V. Keldysh IPM.* 2020;66:1–30. (In Russ.). doi: 10.20948/prepr-2020-66

6. Petrova EN, Slabozhaninov MV. The use of disc pumps in LRE. *Aerospace engineering, high technologies and innovations.* 2021;2:154–157.

7. Loitsyansky LG. *Mechanics of liquid and gas.* Moscow: Drofa; 2003. (In Russ.).

8. Petrov AI, Lomakin VO. Numerical simulation of flow parts of pump models and verification of simulation results by comparing experimentally obtained values with calculated ones. *Science and Education. Bauman Moscow State Technical University. Electron. Journal.* 2012;5. (In Russ.). Accessed: Available from: http://old.technomag.edu.ru/doc/356070.html

9. Lomakin VO, Petrov AI. Verification of calculation results in the package of hydrodynamic modeling zvezda-CMS+ flow part of the centrifugal pump AH 50-32-200. *News of higher educational institutions. Sociology. Economy. Politics.* 2012:6. (In Russ.).

10. Lomakin V, Cheremushkin V, Chaburko P. Investigation of vortex and hysteresis effects in the intake device of a centrifugal pump. In: 2018 *PhD Symposium of the Global Society of Hydropower, GFPS.* Samara: IEEE, 2018. doi: 10.1109/GFPS.2018.8472374

СПИСОК ЛИТЕРАТУРЫ

1. Мисюра В.И., Овсянников Б.В., Присняков В.Ф. Дисковые насосы. М.: Машиностроение, 1986.

2. Бендерович В.А., Лунаци Э.Д. Динамические ламинарные (дисковые) насосы трения. Области применения насосов ОНЛ // Гидравлика МГТУ им. Н.Э. Баумана. 2022. № 14. С. 10–33.

3. Zharkovsky A.A., Ivanov O.A., Klyuev A.S. About the possibility of using disk impellers in low-flow oil pumps // AIP Conference Proceedings. 2020. Vol. 2285. doi: 10.1063/5.0026592

4. Чернявский А.М., Рузматов Т.М., Фомичев А.В. и др. Экспериментальная модель дискового насоса для поддержки кровообращения // Вестник трансплантологии и искусственных органов. 2016. Т. 18, №4. С. 93–101. doi: 10.15825/1995-1191-2016-4-93-101

5. Стенина Т.В., Елизарова Т.Г., Крапошин М.В. Регуляризованные уравнения гидродинамики в задаче моделирования дискового насоса и их реализация в рамках программного комплекса OpenFOAM // Препринты ИПМ им. М.В. Келдыша. 2020. №66. С. 1–30. doi: 10.20948/prepr-2020-66

6. Петрова Е.Н., Слабожанинов М.В. Применение дисковых насосов в ЖРД // Аэрокосмическая техника, высокие технологии и инновации. 2021. Т. 2. С. 154–157.

7. Лойцянский Л.Г. Механика жидкости и газа. М.: Дрофа, 2003.

8. Петров А.И., Ломакин В.О. Численное моделирование проточных частей макетов насосов и верификация результатов моделирования путем сравнения экспериментально полученных величин с расчетными. // Наука и образование. МГТУ им. Н.Э. Баумана. Электрон. журн. 2012. № 05. Дата обращения: Режим доступа: http://old.technomag.edu.ru/doc/356070.html

9. Ломакин В.О., Петров А.И. Верификация результатов расчета в пакете гидродинамического моделирования STAR-CCM+ проточной части центробежного насоса АХ 50-32-200 // Известия высших учебных заведений. Социология. Экономика. Политика. 2012. С. 6.

10. Lomakin V., CheremushkinV., Chaburko P. Investigation of vortex and hysteresis effects in the inlet device of a centrifugal pump // 2018 Global Fluid Power Society PhD Symposium, GFPS. Samara: IEEE, 2018. doi: 10.1109/GFPS.2018.8472374

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