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Original study article

Investigation of cavitation properties of a mobile pumping unit

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ABSTRACT

INTRODUCTION. In the introduction to the article, a review of publications on cavitation, vibration and noise in centrifugal pumps, including the issues of cavitation erosion of impellers, is carried out.

AIM. Comparison of cavitation properties of a centrifugal pump of a mobile pumping unit with and without a pre-engineered screw by computational fluid dynamic (CFD) modeling.

MATERIALS AND METHODS. The calculation of the flow part of a pre-injected impeller stage is described and the CFD model of its hydrodynamic simulation is described. In the CFD model, Navier-Stokes equations averaged over the Reynolds number and the working fluid continuity equation were used. A two-phase fluid model was used to simulate cavitation.

RESULTS. The final results of the calculations carried out in the above models are presented. Calculations were obtained for a pump with impeller with and without an upstream stage (screw). For the impeller without a screw, the cavitation margin of 4.7 m was obtained, which is critical for such a pump. For a pump with an impeller with an upstream auger the cavitation margin is 1,7 m, that is much better and allows to show efficiency of such solution.

CONCLUSION. The requirement of hydrodynamic modeling for selection of optimal flow part of centrifugal pump to improve its cavitation characteristics is formulated.

Keywords: *pumping unit; cavitation qualities; cavitation; pre-excited screw; hydrodynamic modeling.*

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Оригинальное исследование

Исследование кавитационных качеств передвижной насосной установки

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АННОТАЦИЯ

Введение. Во введении к статье обсуждаются публикации по теме кавитации, вибрации и шума в центробежных насосах, включая вопросы кавитационной эрозии рабочих колес.

Цель исследования — сравнение кавитационных свойств центробежного насоса передвижной насосной установки с предвключенным шнеком и без него методами гидродинамического моделирования (CFD).

Методы исследования. Рассмотрен расчет проточной части предвключенной ступени рабочего колеса, а также описана CFD-модель его гидродинамического моделирования. В CFD-модели использовались уравнения Навье-Стокса, осредненные по числу Рейнольдса, и уравнение неразрывности рабочей жидкости. Для моделирования кавитации применялась модель двухфазной жидкости.

Результаты. Представлены итоговые результаты расчетов, проведенные в указанных выше моделях. Были получены расчетные данные для насоса с рабочим колесом с предвключенной ступенью (шнеком) и без нее. Для рабочего колеса без шнека получен кавитационный запас 4,7 м, что является критическим для такого насоса. Для насоса с рабочим колесом с предвключенным шнеком получен кавитационный запас 1,7 м, что значительно лучше и позволяет продемонстрировать эффективность такого решения.

Заключение. Сформулированы требования о необходимости гидродинамического моделирования для подбора оптимальной проточной части центробежного насоса, для улучшения его кавитационных характеристик.

Ключевые слова: *насосная установка; кавитационные качества; кавитация; предвыключенный шнек; гидродинамическое моделирование.*

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INTRODUCTION

One of the main problems at operation of centrifugal pumps [1–9], entailing reduction of parameters, occurrence of noise and vibration, destruction of impellers is cavitation [10–14]. It is a process of formation and subsequent collapse of steam bubbles with simultaneous condensation of steam in liquid flow and is accompanied by acoustic noise and hydraulic shocks.

Proceeding from the above, when designing any pump, it is necessary to consider the possibility of cavitation. There are many options to combat the phenomenon of cavitation: changing the meridional cross-section of the impeller, increasing the diameter of the inlet to the impeller, changing the position of the inlet edge of the blades, the use of a pre-injected screw, etc.

The problem of cavitation is especially urgent for pumps operating in a wide range of flow rates and with large shaft speeds. To such pumps belongs the developed mobile pump unit with a drive from the internal combustion engine through the multiplier (pump shaft rotation frequency up to 5000 rpm), pressure at the pump inlet of which can vary within a wide range depending on the general operating mode of the whole pipeline and the operating modes of the previous units in the chain. For uninterrupted operation of such unit, it is required to consider options for increasing its cavitation qualities.

AIM OF THE STUDY

Comparison of the cavitation properties of a centrifugal pump of a mobile pumping unit with and without a pre-engineered screw by fluid dynamic simulation (CFD) methods.

RESEARCH METHODS

In order to compare cavitation properties of mobile pumping unit with and without auger with the use of computational fluid dynamic (CFD) modeling, auger was calculated. The screw is a pre-injected axial stage in a centrifugal pump, designed to create a boost at the inlet to the centrifugal impeller [15–22]. When designing the axial stage, it was decided to develop a screw of constant pitch, which simplifies the calculation process and the manufacturing process, in this case, the angle of installation of blades is constant along the length of the screw:

$$\beta_{2L} = \beta_{1L} .$$

Taking into account the angle of attack of the auger blade, the calculated setting angle of the inlet edge turned out:

$$\beta_{1c} + i_{1c} = 18° .$$

When designing and calculating the auger, the impeller blade installation angles at the inlet were assumed to be equal:

$$\beta_{1a} = 21°; \quad \beta_{1c} = 18°; \quad \beta_{1e} = 16° .$$

Based on the calculation performed and geometrical parameters obtained according to the method [22], a 3D model of the screw stage was built (Fig. 1).

To verify the cavitation characteristics of the pump [19–20], hydrodynamic modeling of two-phase fluid flow in the flow area of the first pump stage with a pre-entry screw was performed in the STARCCM+ software package and cavitation characteristics of the impeller without and with a pre-entry screw were built.

Calculation was carried out at nominal operating mode (liquid flow rate 80 m^3/h), to simulate the experiment, pressure at the inlet to the flowing part of the impeller decreased smoothly (in steps of 5–10 kPa) to the onset of stalling mode (sharp decrease of head). The second critical mode, due to labor intensity of its exact determination by this method, was determined approximately by the method described in the literature [22].

A two-phase fluid model was used to simulate cavitation. The approach known as VOF (Volume of Fluid) was used as a physical model.

When calculating by the VOF method, the multiphase medium is represented as a single fluid medium whose properties change proportionally in accordance with the volume fraction of each of the phases present in it — liquid and its vapor:

$$\alpha_i = \frac{V_i}{V},$$

where V_i is the volume of each of the phases, V is the volume of the calculation cell.

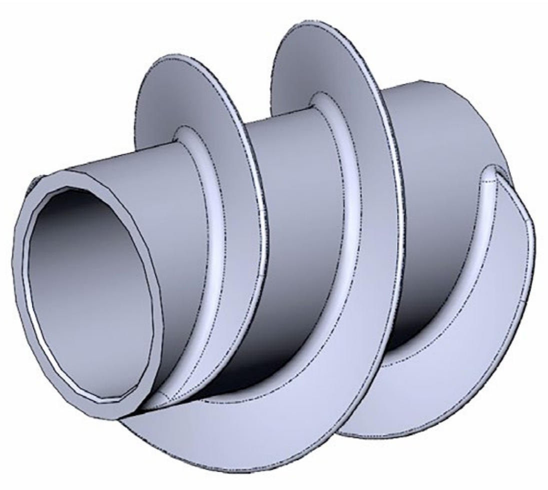

Fig. 1. 3D model of the auger.
Рис. 1. 3D-модель шнека.

The equation for the mass concentration of each of the phases is as follows:

$$\frac{\partial(\alpha_i \rho_i)}{\partial t} + \nabla \cdot (\alpha_i \rho_i V) = 0 .$$

Liquid cavitation was modeled based on a simplified Rayleigh-Plesset model. The simplification of the model consists in the fact that this model does not take into account the surface tension of the gas bubble and the effect of liquid viscosity on its growth rate. The cavitation bubble growth rate in the selected model is calculated as

$$\left(\frac{dR}{dt}\right)^2 = \frac{2}{3}\left(\frac{p_{\text{нп}} - p}{\rho}\right),$$

where R — bubble radius, m; $p_{\text{нп}}$ — saturated vapor pressure of liquid, Pa; p — surrounding liquid pressure, Pa; ρ — liquid density, kg/m^3.

In this case, the minimum cavitation bubble size and the minimum gas concentration in any of the calculated cells are strictly limited to sufficiently small, but nevertheless non-zero, values.

Since the turbulence model from the RANS (Reynolds averaged turbulence models based on Navier-Stokes equations) was used to model the turbulent flow in this paper, all calculated quantities are time-averaged.

In the case of the incompressible fluid model $(p = \text{const})$ these equations can be written in the form:

- the continuity equation for a liquid medium:

$$\frac{\partial \overline{u_x}}{\partial x} + \frac{\partial \overline{u_y}}{\partial y} + \frac{\partial \overline{u_z}}{\partial z} = 0 ,$$

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

- equation of change of momentum averaged over time:

$$\rho\left[\frac{\partial \overline{u_i}}{\partial t} + \overline{u_j}\frac{\partial \overline{u_i}}{\partial x_j}\right] = -\frac{\partial \overline{p}}{\partial x_i} + \frac{\partial}{\partial x_i}\left[T_{ij}^{(v)} - \rho\left\langle u_i u_j \right\rangle\right],$$

where $\overline{u_i}, \overline{p}$ — averaged velocity and averaged pressure; $\tilde{T}_{ij}^{(v)} = 2\mu \tilde{s}_{ij}$ — viscous stress tensor for incompressible fluid; $\tilde{s}_{ij} = \frac{1}{2}\left[\frac{\partial \overline{u_i}}{\partial x_j} + \frac{\partial \overline{u_j}}{\partial x_i}\right]$ — strain rate tensor; $\rho\left\langle u_i u_j \right\rangle$ — Reynolds stress.

The introduction of the Reynolds averaged Navier-Stokes equation [21] makes the system of equations unclosed, since it introduces the unknown Reynolds stresses. In order to close this system in this problem, the semiempirical k-ω SST model of turbulence was used, which introduces the necessary additional equations:

- turbulence kinetic energy transfer equation

$$\frac{\partial k}{\partial t} + U_j \frac{\partial k}{\partial x_j} = P_k - \beta k \omega + \frac{\partial}{\partial x_j}\left[\left(v + \sigma_k v_T\right) \cdot \frac{\partial k}{\partial x_j}\right];$$

- equation of the relative rate of dissipation of turbulence energy

$$\frac{\partial \omega}{\partial t} + U_j \frac{\partial \omega}{\partial x_j} =$$
$$= \alpha \cdot S^2 - \beta \cdot \omega^2 + \frac{\partial}{\partial x_j}\left[\left(v + \sigma_\omega v_T\right) \cdot \frac{\partial \omega}{\partial x_k}\right] + .$$
$$+ 2 \cdot \left(1 - F_i\right) \cdot \sigma_{\omega 2} \cdot \frac{1}{\omega} \cdot \frac{\partial k}{\partial x_j} \cdot \frac{\partial \omega}{\partial x_j}$$

The pump flow was modeled on a volumetric grid consisting of 2,335,845 cells. Multifaceted cells were generated in the flow core and prismatic cells near the solid walls, which allows to simulate the flow in the boundary layer more accurately. The computational grid is shown in Fig. 2.

The time step was chosen based on the speed of the impeller so that there would be at least 20 time steps per blade step, but so that the machine time for the calculation would not be too long for the calculation. The time step was chosen to be 0.0001s. The number of internal iterations for each time step was chosen to be 10, as the most optimal in terms of convergence and computation time.

The main parameters of the computational grid:

- The base size is 3 mm;
- stretch of the prismatic layer — 1.3;
- the thickness of the prismatic layer is 33.3% of the base size;
- the number of prismatic layers is 5.

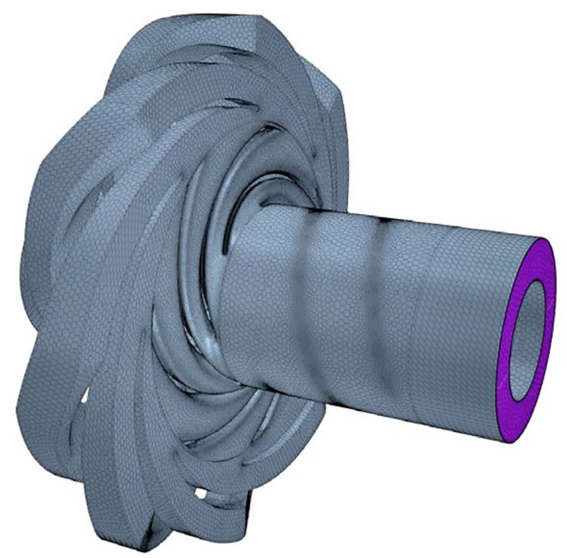

Fig. 2. Calculation grid.
Рис. 2. Расчетная сетка.

RESULTS

As a «starting point» of the calculation, two-phase calculation of the impeller without a screw stage was made, and the value of cavitation margin of 4.7 m was obtained, which is insufficient for operation of the pump unit (taking into account resistance in the suction piping) without additional boost at its inlet (Fig. 3, 4).

In order to check the quality of profiling, a wheel with a screw stage was calculated (Fig. 5, 6, 7) and a significant reduction of cavitation margin (up to 1.7 m) was obtained, which indicates the high cavitation qualities of the developed pump.

CONCLUSIONS

As a result of calculation by hydrodynamic simulation methods of a screw stage installed at the inlet of a high-speed multistage pump of a mobile pumping unit, a significant reduction of the allowable cavitation margin from 4.7 m to 1.7 m was obtained.

The study shows that the cavitation performance of such multistage pumps is often worse than required, indicating the need for a more detailed consideration of this issue on a case-by-case basis.

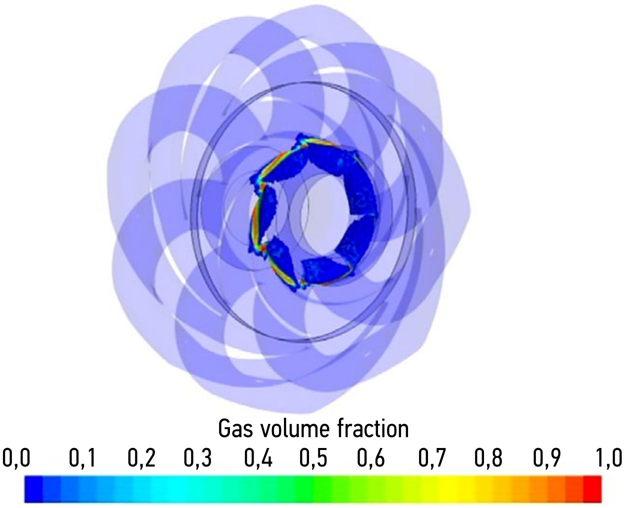

Fig. 3. Gas volume fraction. Distribution of the vapor phase at an inlet pressure of 50 kPa.
Рис. 3. Распределение паровой фазы при давлении на входе 50 кПа.

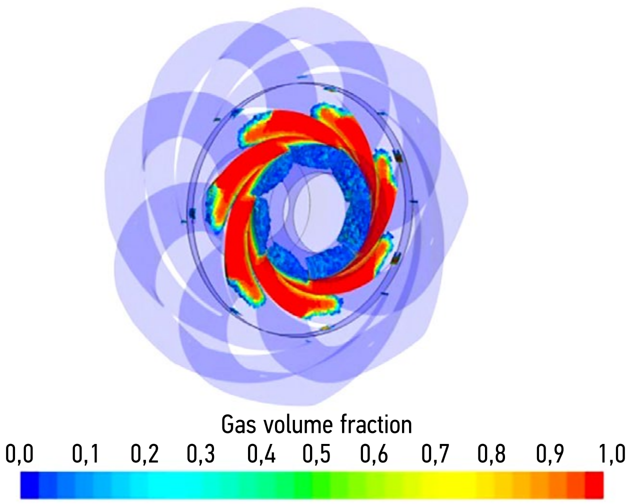

Fig. 4. Gas volume fraction. Distribution of the vapor phase at an inlet pressure of 40 kPa.
Рис. 4. Распределение паровой фазы при давлении на входе 40 кПа.

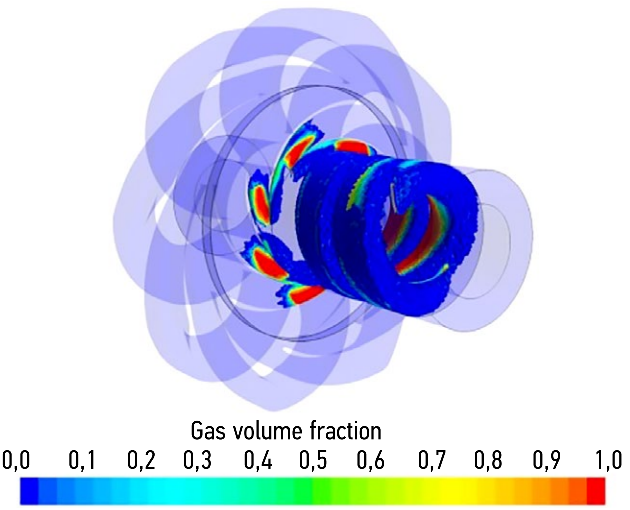

Fig. 5. Gas volume fraction. Distribution of the vapor phase at an inlet pressure of 20 kPa.
Рис. 5. Распределение паровой фазы при давлении на входе 20 кПа.

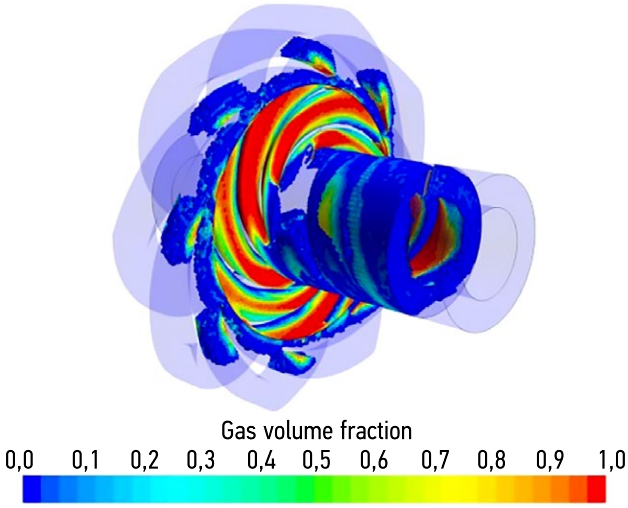

Fig. 6. Gas volume fraction. Distribution of the vapor phase at an inlet pressure of 12 kPa.
Рис. 6. Распределение паровой фазы при давлении на входе 12 кПа.

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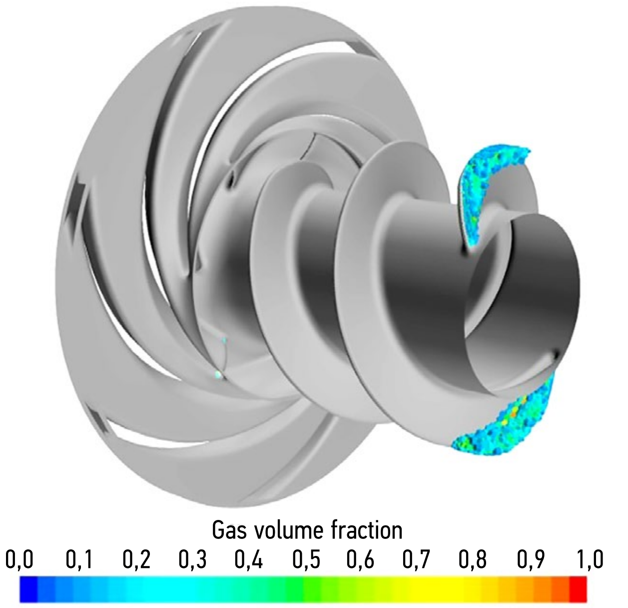

Fig. 7. Impeller with pre-engineered screw at atmospheric inlet pressure 101 kPa.
Рис. 7. Рабочее колесо с предвключенным шнеком при атмосферном давлении на входе 101 кПа.

ADDITIONAL INFORMATION

Authors' contribution. D.S. Konshin — calculations and graphs, writing part of the text of methods and results; E.M. Konkeev — calculation and graphs, writing part of the text of methods and results; A.I. Petrov — general scientific guidance, writing conclusions, editing text; A.A. Protopopov — writing annotations and introductions, search and review of literary sources, editing text and formulas. The authors confirm the compliance of their authorship with the international ICMJE criteria (all authors have made a significant contribution to the development of the concept, research and preparation of the article, read and approved the final version before publication).

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Источник финансирования. Авторы заявляют об отсутствии внешнего финансирования при проведении исследования.

REFERENCES

1. Handal I, Tkachuk V, Petrovand A, et al. Traditional methods for the design of radial-axial hydraulic turbines with verification in CFD simulation. *IOP Conference Series: Materials Science and Engineering.* 2020;779(1):012002. doi: 10.1088/1757-899X/779/1/012002

2. Petrov A, Sinitsyna A. Obtaining the maximum permissible gas content at the inlet to the ESP by computational fluid dynamics modeling. *IOP Conference Series: Materials Science and Engineering.* 2020;779(1):012006. doi: 10.1088/1757-899X/779/1/012006

3. Teplov O, Lomakin V. Improving the performance of a centrifugal vane pump by installing vortex generators on the suction surfaces of blades. *IOP Conference Series: Materials Science and Engineering.* 2020;779(1):012012. doi: 10.1088/1757-899X/779/1/012012

4. Kalinkin S, Petrov A. Investigation of the influence of the front end clearance on the parameters of a centrifugal pump with an open type impeller. *IOP Conference Series: Materials Science and Engineering.* 2020;779(1):012014. doi: 10.1088/1757-899X/779/1/012014

5. Saprykina M, Lomakin V. The calculation of multiphase flows in flowing parts of centrifugal pump. *IOP Conference Series: Materials Science and Engineering.* 2020;779(1):012037. doi: 10.1088/1757-899X/779/1/012037

6. Chaburko P, Kuznetsov A. Method for leakage measurement in the recirculation path of a hermetic pump. *IOP Conference Series: Materials Science and Engineering.* 2020;779(1):012039. doi: 10.1088/1757-899X/779/1/012039

7. Lomakin V, Valiev T, Chaburko P. Application of optimization algorithms to improve the vibroacoustic characteristics of pumps. *IOP Conference Series: Materials Science and Engineering.* 2020;779(1):012044. doi: 10.1088/1757-899X/779/1/012044

8. Aksenova E, Lomakin V, Cheremushkin V. Experimental study of cavitation resistance of restoring coatings. *IOP Conference Series. Materials Science and Engineering.* 2020;779(1):012045. doi: 10.1088/1757-899X/779/1/012045

9. Kasatkin M, Petrov A. Hydrodynamic modeling of cavitation in a multistage centrifugal pump during its operation in the constant feed mode with a change in the rotor speed of the pump. *IOP Conference Series:*

Materials Science and Engineering. 2020;779(1):012047. doi: 10.1088/1757-899X/779/1/012047

10. Kang YZ, Feng C, Liu LZ, et al. Comparison of three kinds of sensors used to identify the incipient cavitation. *Sensor Review.* 2018;38(1):13–20. doi: 10.1108/SR-05-2017-0078

11. Khoo MT, Venning JA, Pearce BW, et al. Nucleation effects on hydrofoil tip vortex cavitation. In: *Proceedings of the 21st Australasian Fluid Mechanics Conference, AFMC 2018.* Adelaide: Australasian Fluid Mechanics Society; 2018.

12. Wan W, Liu B, Raza A. Numerical prediction and risk analysis of hydraulic cavitation damage in a high-speed-flow spillway. *Shock and Vibration.* 2018;2018(1). doi: 10.1155/2018/1817307

13. Li H, Li S. Research on the cavitation in the pilot stage of flapper-nozzle hydraulic servovalve with fluid-strnctnre interaction. *IET Conference Publications.* 2018:783–786. doi: 10.1049/cp.2018.0106

14. Bai F, Saalbach K, Wang L, et al. Investigation of impact loads caused by ultrasonic cavitation bubbles in small gaps // IEEE Access. 2018;6:64622–64629. doi: 10.1109/ACCESS.2018.2877799

15. Tkachuk V, Navas H, Petrov A, et al. Hydrodynamic modelling of the impact of viscosity on the characteristics of a centrifugal pump. *IOP Conference Series: Materials Science and Engineering.* 2019;589(1):012007. doi: 10.1088/1757-899X/589/1/012007

16. Morozove E, Belov N, Cheremushkin V. Optimization of the radial chann of a centrifugal pump. *IOP Conference Series: Materials Science and Engineering.* 2019;589:012008. doi: 10.1088/1757-899X/589/1/012008

17. Martynyuk O, Petrov A. Optimization of the flow part of the pump for abrasive-containing liquids by hydrodynamic modeling methods. *IOP Conference Series: Materials Science and Engineering.* 2020;963(1):012005. doi: 10.1088/1757-899X/963/1/012005

18. Isaev N, Valiev T, Morozova E, et al. Optimization of a radial guide device with a no-vane transfer channel. *IOP Conference Series: Materials Science and Engineering.* 2019;589(1):012009. doi: 10.1088/1757-899X/589/1/012009

19. Boyarshinova A, Lomakin V, Petrov A. Comparison of various simulation methods of a two-phase flow in a multiphase pump. *IOP Conference Series: Materials Science and Engineering.* 2019;589(1):012028. doi: 10.1088/1757-899X/589/1/012014

20. Saprykina M, Lomakin V. The evaluation of the effect of gas content on the characteristics of a Centrifugal Pump. *IOP Conference Series: Materials Science and Engineering.* 2019;589(1):012017. doi: 10.1088/1757-899X/589/1/012017

21. Protopopov A, Bondareva D. On the issue of starting-up overheating of electric motors of centrifugal pumps. *IOP Conference Series: Materials Science and Engineering.* 2019;492(1):012002. doi: 10.1088/1757-899X/492/1/012002

22. Petrov AI, Protopopov AA. *Cavitation tests of a centrifugal pump: textbook.* Moscow: Izd-vo MGTU im NE Baumana; 2022.

СПИСОК ЛИТЕРАТУРЫ

1. Handal I., Tkachuk V., Petrovand A., et al. Traditional methods for the design of radial-axial hydraulic turbines with verification in CFD simulation // IOP Conference Series: Materials Science and Engineering. 2020. Vol. 779, N 1. P. 012002. doi: 10.1088/1757-899X/779/1/012002

2. Petrov A., Sinitsyna A. Obtaining the maximum permissible gas content at the inlet to the ESP by computational fluid dynamics modeling // IOP Conference Series: Materials Science and Engineering. 2020. Vol. 779, N 1. P. 012006. doi: 10.1088/1757-899X/779/1/012006

3. Teplov O., Lomakin V. Improving the performance of a centrifugal vane pump by installing vortex generators on the suction surfaces of blades // IOP Conference Series: Materials Science and Engineering. 2020. Vol. 779, N 1. P. 012012. doi: 10.1088/1757-899X/779/1/012012

4. Kalinkin S., Petrov A. Investigation of the influence of the front end clearance on the parameters of a centrifugal pump with an open type impeller // IOP Conference Series: Materials Science and Engineering. 2020. Vol. 779, N 1. P. 012014. doi: 10.1088/1757-899X/779/1/012014

5. Saprykina M., Lomakin V. The calculation of multiphase flows in flowing parts of centrifugal pump // IOP Conference Series: Materials Science and Engineering. 2020. Vol. 779, N 1. P. 012037. doi: 10.1088/1757-899X/779/1/012037

6. Chaburko P., Kuznetsov A. Method for leakage measurement in the recirculation path of a hermetic pump // IOP Conference Series: Materials Science and Engineering. 2020. Vol. 779, N 1. P. 012039. doi: 10.1088/1757-899X/779/1/012039

7. Lomakin V., Valiev T., Chaburko P. Application of optimization algorithms to improve the vibroacoustic characteristics of pumps // IOP Conference Series: Materials Science and Engineering. 2020. Vol. 779, N 1. P. 012044. doi: 10.1088/1757-899X/779/1/012044

8. Aksenova E., Lomakin V., Cheremushkin V. Experimental study of cavitation resistance of restoring coatings // IOP Conference Series. Materials Science and Engineering. 2020. Vol. 779, N 1. P. 012045. doi: 10.1088/1757-899X/779/1/012045

9. Kasatkin M., Petrov A. Hydrodynamic modeling of cavitation in a multistage centrifugal pump during its operation in the constant feed mode with a change in the rotor speed of the pump // IOP Conference Series: Materials Science and Engineering. 2020. Vol. 779, N 1. P. 012047. doi: 10.1088/1757-899X/779/1/012047

10. Kang Y.Z., Feng C., Liu L.Z., et al. Comparison of three kinds of sensors used to identify the incipient cavitation // Sensor Review. 2018. Vol. 38, N 1. P. 13–20. doi: 10.1108/SR-05-2017-0078

11. Khoo M.T., Venning J.A., Pearce B.W., et al. Nucleation effects on hydrofoil tip vortex cavitation // Proceedings of the 21st Australasian Fluid Mechanics Conference, AFMC 2018. Adelaide: Australasian Fluid Mechanics Society, 2018.

12. Wan W., Liu B., Raza A. Numerical prediction and risk analysis of hydraulic cavitation damage in a high-speed-flow spillway // Shock and Vibration. 2018. Vol. 2018, N 1. doi: 10.1155/2018/1817307

13. Li H., Li S. Research on the cavitation in the pilot stage of flapper-nozzle hydraulic servovalve with fluid-strnctnre interaction // IET Conference Publications. 2018. P. 783–786. doi: 10.1049/cp.2018.0106

14. Bai F., Saalbach K., Wang L., et al. Investigation of impact loads caused by ultrasonic cavitation bubbles in small gaps // IEEE Access. 2018. Vol. 6. P. 64622–64629. doi: 10.1109/ACCESS.2018.2877799

15. Tkachuk V., Navas H., Petrov A., et al. Hydrodynamic modelling of the impact of viscosity on the characteristics of a centrifugal pump // IOP Conference Series: Materials Science and Engineering. 2019. Vol. 589, N 1. P. 012007. doi: 10.1088/1757-899X/589/1/012007
16. Morozove E., Belov N., Cheremushkin V. Optimization of the radial chann of a centrifugal pump // IOP Conference Series: Materials Science and Engineering. 2019. Vol. 589. P. 012008. doi: 10.1088/1757-899X/589/1/012008
17. Martynyuk O., Petrov A. Optimization of the flow part of the pump for abrasive-containing liquids by hydrodynamic modeling methods // IOP Conference Series: Materials Science and Engineering. 2020. Vol. 963, N 1. P. 012005. doi: 10.1088/1757-899X/963/1/012005
18. Isaev N., Valiev T., Morozova E., et al. Optimization of a radial guide device with a no-vane transfer channel // IOP Conference Series: Materials Science and Engineering. 2019. Vol. 589, N 1. P. 012009. doi: 10.1088/1757-899X/589/1/012009
19. Boyarshinova A., Lomakin V., Petrov A. Comparison of various simulation methods of a two-phase flow in a multiphase pump // IOP Conference Series: Materials Science and Engineering. 2019. Vol. 589, N 1. P. 012028. doi: 10.1088/1757-899X/589/1/012014
20. Saprykina M., Lomakin V. The evaluation of the effect of gas content on the characteristics of a Centrifugal Pump // IOP Conference Series: Materials Science and Engineering. 2019. Vol. 589, N 1. P. 012017. doi: 10.1088/1757-899X/589/1/012017
21. Protopopov A., Bondareva D. On the issue of starting-up overheating of electric motors of centrifugal pumps // IOP Conference Series: Materials Science and Engineering. 2019. Vol. 492, N 1. P. 012002. doi: 10.1088/1757-899X/492/1/012002
22. Петров А.И., Протопопов А.А. Кавитационные испытания центробежного насоса: Учебно-методическое пособие. М.: Изд-во МГТУ им. Н. Э. Баумана, 2022.

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