

Article

Axial-Flow Pump with Enhanced Cavitation Erosion Resistance

Aleksandr Zharkovskii ¹, Dmitry Svoboda ¹, Igor Borshchev ¹, Arsentiy Klyuyev ^{1,*}, Evgeniy Ivanov ¹
and Sergey Shutsky ²

¹ The World-Class Research Center “Advanced Digital Technologies”, Peter the Great St. Petersburg Polytechnic University, 195251 Saint Petersburg, Russia

² JSC “Central Design Bureau of Mechanical Engineering”, 190020 Saint Petersburg, Russia

* Correspondence: arsentiyklyuyev@gmail.com

Abstract: Axial-flow pumps, in addition to providing high anti-cavitation properties, must have high anti-erosion properties to ensure the required lifetime of the pump. Erosion damage of surfaces occurs when the net positive suction head (NPSH) significantly exceeds its critical value. The object of the study in this article is the axial-flow pump with a specific speed of 600 in two alternatives: № 1 and № 2. By analysis of the flow in the impeller blade systems, the ratio value between the NPSH, which ensures the absence of erosion, and the NPSH₃, at which pump operational failure occurs, was determined. Impeller variant № 1 did not provide the required ratio. Impeller variant № 2 had higher cavitation qualities, and the required ratio was achieved for it. Energy, cavitation, and erosion characteristics of the axial-flow pump with impeller № 2 in rotational frequency $n = 2000$ rpm were investigated. Easily breakable paint coatings were used for the accelerated study of cavitation erosion. The experiment was carried out at three different flow rates and confirmed the assumptions made—the pump with impeller № 2 was not affected by cavitation erosion at the optimum flow rate. Patterns of erosion zones were accompanied by calculations of vapor zones in the impeller. At flow rates less than the optimum, cavitation disruptions occurred and appeared behind the vapor region. As a result, the condition of ensuring erosion-free flow in the impeller of an axial pump with a specific speed of 600 was obtained, ensuring the ratio $NPSH/NPSH_3 > 2.5$. Recommendations on designing of erosion-free flow part of the axial pump impeller were also obtained.



Citation: Zharkovskii, A.; Svoboda, D.; Borshchev, I.; Klyuyev, A.; Ivanov, E.; Shutsky, S. Axial-Flow Pump with Enhanced Cavitation Erosion Resistance. *Energies* **2023**, *16*, 1344. <https://doi.org/10.3390/en16031344>

Academic Editor: Carlo Roselli

Received: 6 December 2022

Revised: 10 January 2023

Accepted: 22 January 2023

Published: 27 January 2023



Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

Keywords: axial-flow pump; cavitation flow; erosion; flow passage; NPSH; vapor-filled cavities

1. Introduction

Cavitation is the process of the generation of vapor cavities in a liquid, which can be compared to boiling due to an increase in temperature at constant pressure, but in the case of cavitation, the effect appears when there is a local decrease in pressure, which leads to a discontinuity in the liquid flow [1]. This effect can be used positively, for example, as intensification technology in water treatment or chemical processing, using cavitation reactors, such as Venturi-type cavitation reactors [2]. The influence of temperature effects on the hydrodynamic cavitation process was deeply studied by the authors in the articles [3, 4]. However, for most hydraulic machines, cavitation is negative and leads to negative consequences. First, the pump performance must be predicted with a sufficient degree of accuracy, and cavitation can lead to a dramatic reduction in pump performance. Second, cavitation itself is a source of vibrations and noise due to the non-stable nature of the cavitation process. Third, cavitation can cause erosion of the materials of which the flow passage is made. Cavitation erosion, as well as being associated with the presence of solid inclusions in the fluid flow [5], leads to lower efficiency in both turbines [6,7] and pumps [8,9]. Cavitation erosion of pump impellers also may be caused by the resonance of torsional vibrations of centrifugal pump shafts [10].

There are several methods for observing and evaluating cavitation erosion. Image processing methods for quantifying cavitation structure and cavitation erosion were es-

established by the authors in [11]. These methods are based on statistical principles and can be used to analyze the distribution characteristics of the cavitation structure. An image-processing technique for the experimental images also was proposed in [12], which obtained the mean and standard deviation of the grey level of the cavitation structure images on the hydrofoil surface in the flow field. A high-speed photography method was used in [13] to observe the positions of the cavitation erosion pits. The positions of the cavitation erosion pits were analyzed by combining the images recorded by high-speed photography. In the study [14], a large eddy simulation method is applied to simulate the unsteady cavitating flows, and an energy approach is developed to estimate the cavitation erosion area. This approach is modified by considering hydrodynamic efficiency, which is deduced from the perspective of a shock wave. The authors in [15] proposed a method to detect cavitation collapse based on the velocity divergence field and used the maximum pressure as an index to estimate cavitation erosion risk.

In addition to ensuring the high-cavitation properties of dynamic pumps, especially axial-flow pumps, it is also necessary to achieve high resistance to erosion that can occur because of the cavitation process. This will prevent the flow passages of the pump from being destroyed by cavitation erosion and will provide the necessary durability during the pump's lifetime cycle.

As experimental studies have shown, erosion degradation of streamlined surfaces occurs at the value of net positive suction head (NPSH), significantly exceeding its critical value. Cavitation erosion initiates from the appearance of the first cavitation bubbles and when there is still no influence of cavitation on the main integral performance characteristics of the pump (head, efficiency). In [16], the research results on cavitation fracture of inducers for centrifugal pumps were presented. It was obtained that at the optimum flow rate (best efficiency point), cavitation damage is eliminated at $\text{NPSH}/\text{NPSH}_3 > 6$ (where NPSH_3 is the net positive suction head available to a pump under test at a constant rate of flow when the pump head is decreased by 3 percent because of cavitation caused by a decreasing available suction head). In works [17–20], issues of prevention from cavitation erosion in the flow passage of centrifugal pumps were considered.

The validity of the existing recommendations is investigated in this paper by means of a physical experiment and computational simulation of the two-phase medium flow in the axial-flow pump.

2. Materials and Methods

The object on which the phenomenon of cavitation erosion was investigated is the axial-flow pump with the specific speed $n_s = (3.65 \times n \times Q^{1/2})/H^{3/4} \approx 600$. Four versions of pump flow passage were investigated: blade system № 1 with 6 impeller blades (rimmed, Figure 1a, and rimless, Figure 1b) and blade system № 2 with 4 impeller blades (rimmed, Figure 1c, and rimless, Figure 1d). The number of diffuser vanes in all cases was 11. All flow passages had smoothly falling characteristics, high efficiency, and low NPSH_3 value. For blade system № 1 $\text{NPSH}_3 = 1.7$ m and for blade system № 2 $\text{NPSH}_3 = 1$ m [21].

2.1. Experimental Setup

For the study of cavitation erosion on models of flow passages, easily breakable paint coating can be applied. In [22], a coating of the blade system of the Francis hydraulic turbine with liquid-metallic lead was used. In [23–26], for experimental detection of places and timing of cavitation destruction, the method of laying easily breakable coatings on the inner surface of the flow passage components of the pump was applied. Using the accelerated express method, instead of time-consuming and expensive full-scale experiments, makes it possible to quickly check the presence or absence of cavitation erosion on the pump model. In this work, the method of applying easily breakable paint coatings was used.

Experiments took place in the Research Experimental and Computational Complex of Hydromechanical Engineering Laboratory, located at the Peter the Great St. Petersburg Polytechnic University. Studies were conducted to determine the energy, cavitation, and

erosion tests of the investigated axial-flow pump. The experimental complex for testing axial-flow pumps is shown in Figure 2.

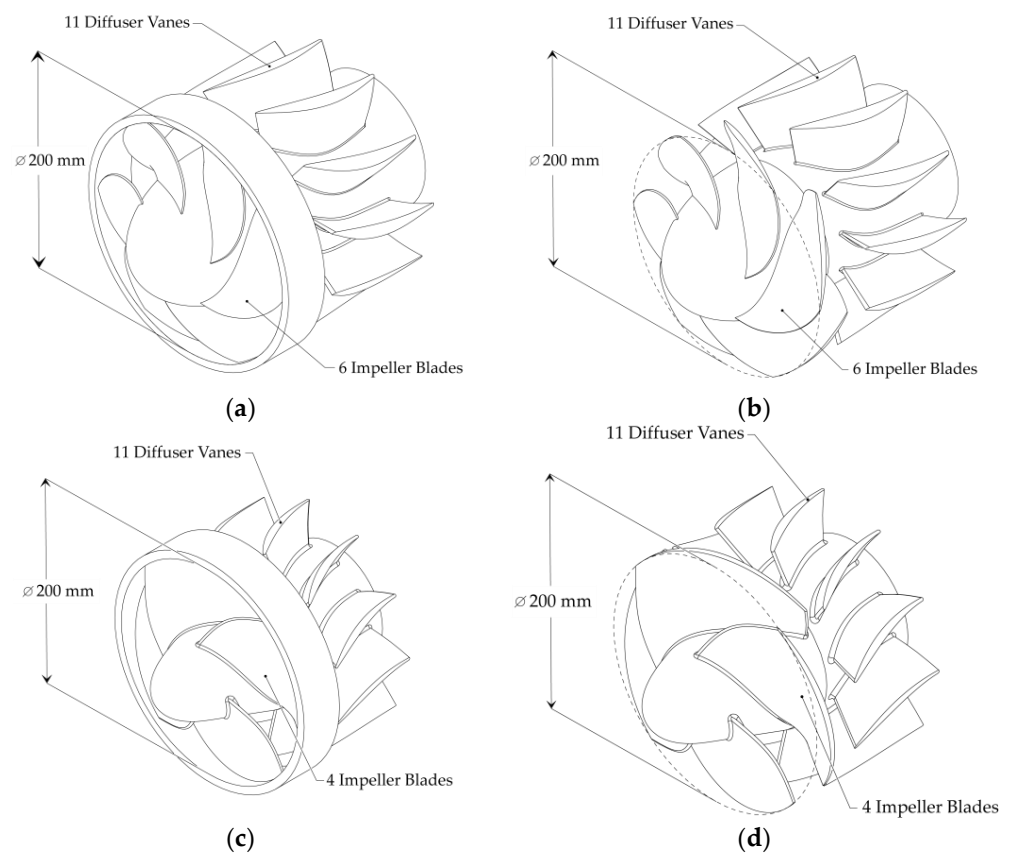


Figure 1. Axial-flow impeller variants: № 1: (a) Impeller № 1 with rim; (b) Impeller № 1 without rim; (c) Impeller № 2 with rim; (d) Impeller № 2 without rim.

Axial Flow Pump with Transparent Chamber

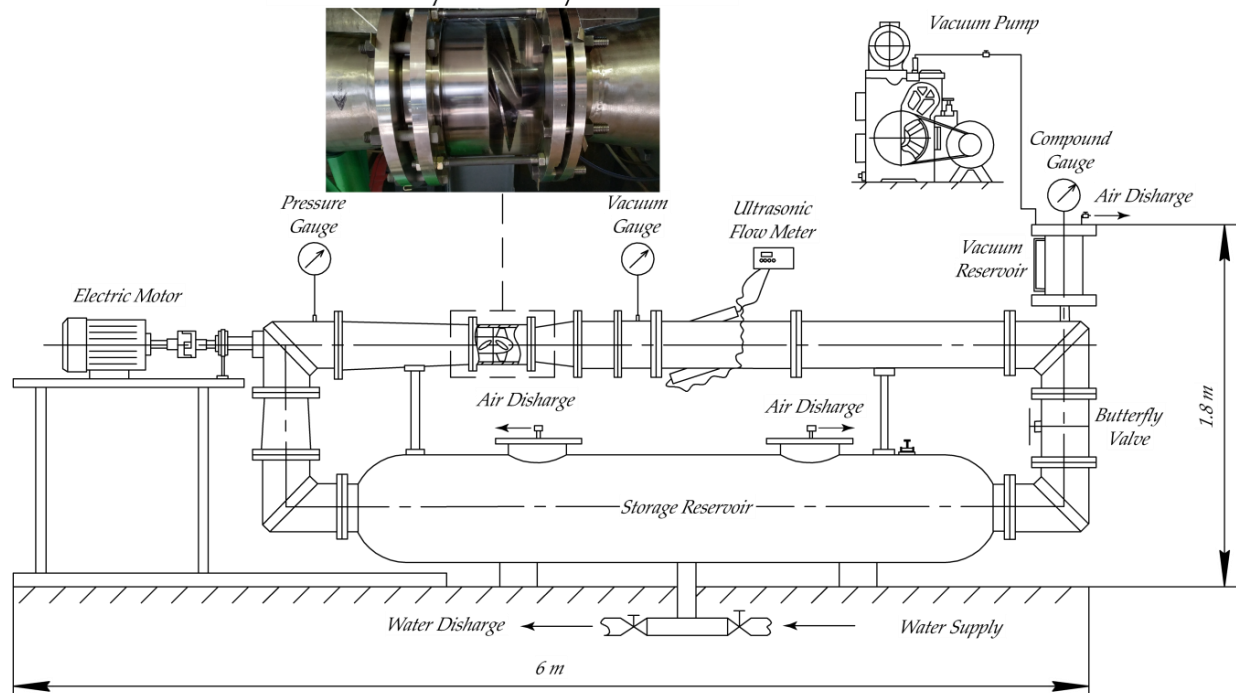


Figure 2. Experimental complex for testing axial-flow pumps.

The experimental complex allows to test the axial impellers with and without rim, with rotational speed up to 2500 rpm, flow rate up to 410 m³/h, head up to 10 m, and power consumption of up to 15 kW.

The method of the experiment for cavitation erosion accelerated study with the laying easily breakable paint coating is as follows. The impeller, pre-coated with an easily breakable paint coating, is installed in a transparent axial-flow pump chamber. The experimental complex is filled with water; the air is discharged through special valves. The desired operating mode ($1.2 \times Q_{BEP}$; $1.0 \times Q_{BEP}$ and $0.3 \times Q_{BEP}$, controlled with an ultrasonic flow meter) is set using the butterfly valve. The vacuum pump reduces the pressure at the pump inlet (controlled by the vacuum gauge), and the required NPSH value is reached. The time is recorded, and the appearance of coating destruction on the blades due to the cavitation process is visually monitored with a stroboscopic tachometer. When the first signs of fracture appear, the experiment is stopped, the experimental complex is emptied, the impeller chamber is dismantled, and the impeller is removed and photographed. Then, the procedure is repeated. The experiment makes it possible to evaluate the degree of destruction of the coating, depending on the time of exposure.

2.2. Numerical Calculation Method

CFD methods, based on numerical multiphase flow calculations, are now widely used to investigate cavitation in the flow passages of hydraulic machines [27–30]. Methods for calculating the wear of streamlined surfaces by fluid flows with solid inclusions have been developed. These methods are well known and are included in commercial software packages, such as Ansys CFX and Ansys FLUENT [31,32]. Several methods exist for the theoretical calculation of cavitation erosion [33–35]. These methods are based on the calculation of the collapse energy of the streamlined surface arising from the collapse of cavitation bubbles that enter the high-pressure region of the flow. Most of the mentioned authors note that to verify and refine these methods, it is necessary to have more experimental data than is currently available.

In this paper, the simulation of cavitation flow and its characteristics was carried out in the Ansys CFX software package. The calculation model (Figure 3) included the entire hydraulic path of the Experimental complex.

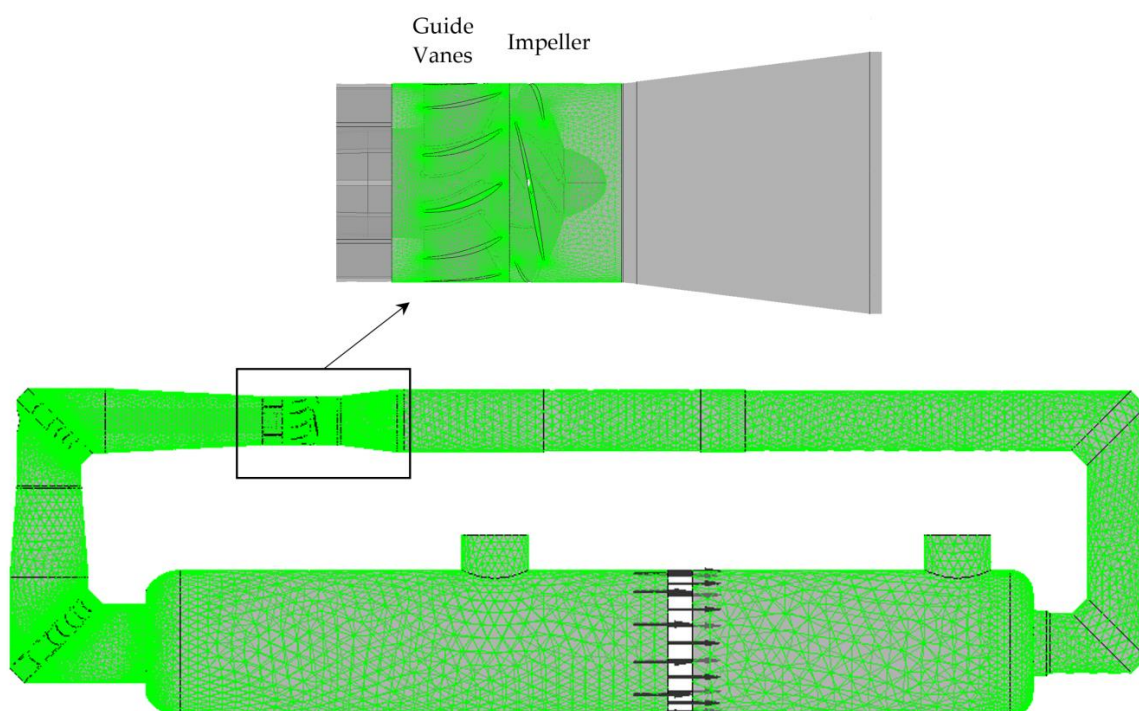


Figure 3. Calculation model of the experimental complex for testing axial-flow pumps.

The grid density in the blade system domains was increased to 1.9 million elements for the impeller area and 2.8 million elements for the guide vanes area. The total number of elements of the entire computational domain was 10 million elements.

The Y^+ parameter on the impeller blades, according to the calculation results, does not exceed 200 (Figure 4). This means that the first grid cells are in the logarithmic boundary sublayer. Such grid parameters are correct for a high-Reynolds k -epsilon turbulence model with an included wall function.

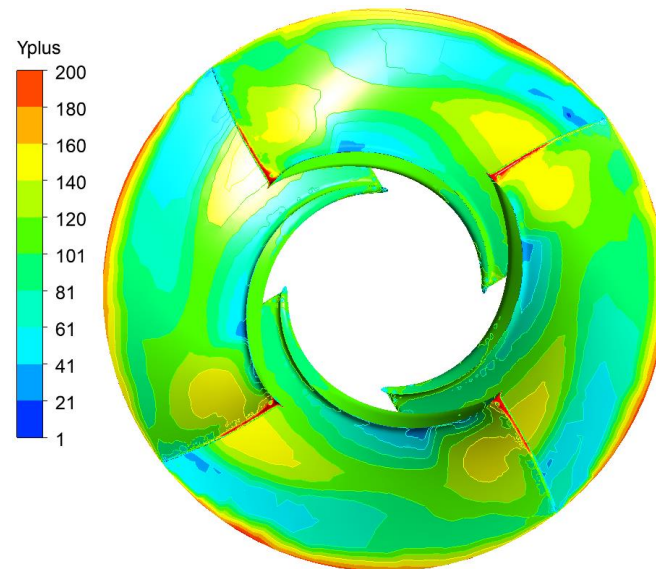


Figure 4. The distribution of the Y^+ parameter on the blade's surfaces.

The Eulerian Multiphase Mixture Model was used to simulate cavitation phenomena. This model assumes that the working fluid in the calculation area consists of liquid and its vapor, released when the pressure in the flowing passage drops below the pressure of saturated vapor at the calculation temperature. The saturation vapor pressure was set for temperature $T = 18\text{ }^{\circ}\text{C}$ equal to 2065 Pa. The morphology of both phases was a continuous fluid with the homogeneous model, whose physical properties were the same throughout the volume. The phases could mix with each other; that is, they are mutually penetrating mediums and do not form a free surface. Thus, it was assumed that the vapor particles are relatively small and light, so their velocity does not differ much from the velocity of the carrying fluid—water—in magnitude and direction. Therefore, to model the flow of both phases, one continuity equation, one set of equations of motion, and one energy equation, written with respect to the mass-averaged values of velocity and density of the mixture, were used. The Rayleigh–Plesset equation was used to describe the dynamics (growth and collapse) of a single bubble. Inclusion of the mass transfer mechanism allowed to add the condition of simulation of the cavitation process.

At the inlet boundary, the total pressure was set to 1 atm; it was also assumed that only the liquid phase was present there. Then, the inlet pressure was reduced to 0.37 atm, which corresponds to the $\text{NPSH} = 3.67\text{ m}$, at which the experimental studies were conducted. At the outlet boundary, the bulk mass flow rate was set, corresponding to the operating mode of the pump. It was assumed that cavitation caverns would appear in those areas of the blades where the static pressure drops to the saturation pressure. The calculation results were used to build a cavitation characteristic, visualize velocity and pressure distributions, and identify flow passage surfaces where cavitation erosion may occur (where the vapor phase accumulates).

3. Results

Experimental tests of model axial-flow pump with impeller № 1 and № 2 (cavitation, cavitation erosion) were carried out on three flow modes: $Q = 1.2 \times Q_{BEP}$; $1.0 \times Q_{BEP}$, and

$0.3 \times Q_{BEP}$, where Q_{BEP} corresponds to the best efficiency point of the pump. The cavitation erosion tests were carried out with the NPSH value of the model unit corresponding to the $NPSH = 3.65$ m.

By calculation of multiphase flow in a model impeller № 1, it was found that with $NPSH = NPSH_3 = 1.7$ m, the vapor-filled cavity takes the most part of the back surface of the blade. This cavity is located across the blade from the periphery to the hub and, thus, disrupts the blade flow kinematics and causes a reduction of the pump's energy parameters. A further decrease in NPSH results in a complete pump performance failure.

A computational evaluation of possible erosion damage on the impeller surfaces was made by analyzing the volumetric vapor distribution areas at the back of the impeller blade. Figure 5 shows the calculated vapor-filled cavities at different NPSH values for a blade system № 1.

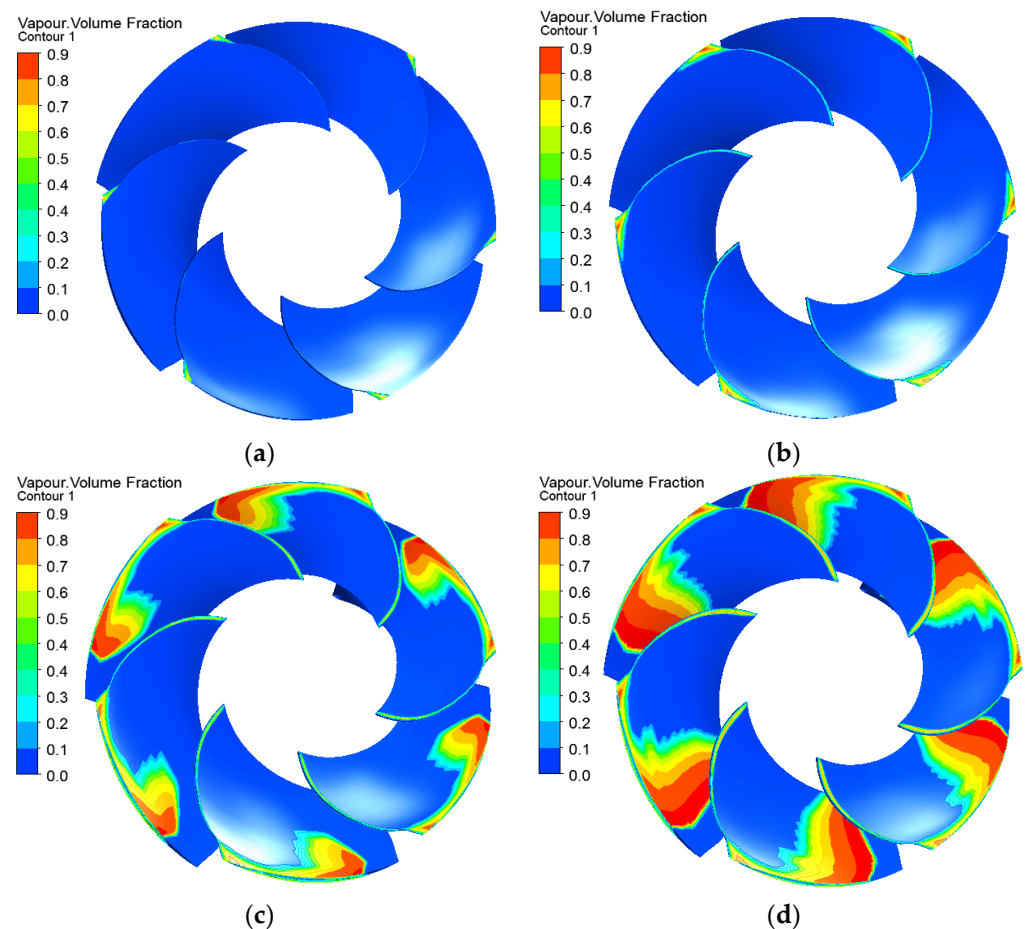


Figure 5. Vapor-filled cavities on the backside of impeller blades at different NPSH values (CFD calculation, blade system № 1, $Q = Q_{BEP}$): (a) $NPSH = 4.8$ m; (b) $NPSH = 2.74$ m; (c) $NPSH = 1.9$ m; (d) $NPSH = NPSH_3 = 1.7$ m.

It follows from the analysis of Figure 5a that at $NPSH = 4.8$ m, the vapor cavities are practically absent. This value corresponds to $NPSH = NPSH_i$, which represents the net positive suction head required for the cavitation inception, but does not yet affect the pump parameters. This mode can only be detected during the observation of the flow passage through the transparent chamber during the experiment or by numerical calculation.

At $NPSH = 2.74$ m (Figure 5b), vapor caverns were found in the peripheral area at the leading edges of the impeller. Still, no effect on the pump characteristic has been observed. At $NPSH = 1.9$ m (Figure 5c), the vapor caverns already occupied a quarter of the area at the back of the blade. In this mode, cavitation begins to affect the head characteristic of the pump. $NPSH = 1.7$ m corresponds to the critical one, at which the pump performance drops

significantly. As can be seen in Figure 5d, the vapor caverns occupy ~40% of the blade's back surface and interfere with the flow around the blade, which leads to a complete decrease of the pump head and an inability to deliver the required flow rate because of cavitation.

Thus, the $NPSH/NPSN3 = NPSHi/NPSN3 = 4.8/1.7 = 2.8$ ratio obtained by CFD agrees with the experimental data presented in [16–18].

Based on the results of the calculations, it was decided to focus on the condition $NPSH/NPSN3 \geq 2.5$ to design the axial-flow pump with enhanced cavitation erosion resistance. From this ratio and the available NPSH of the pump unit, it follows that the required NPSH3 for this pump should be $NPSH3 = 1$ m.

In accordance with the information received, an impeller with the blade system № 2 was created. The new impeller has four blades (instead of six), reduced hub coefficient, reduced blade angles, another blade curvature, and increased blade coverage angle; the blade thickness was chosen to be minimal that satisfied the strength conditions, the angle of attack at the leading edge of the blade was zero. As a result, the calculated value of the NPSH3 of the impeller with blade system № 2 was $NPSH3 = 1$ m, which satisfied the requirements.

Figure 6 depicts experimental energy characteristics for the axial-flow pump № 2 with a specific speed of $n_s \approx 600$, at rotation speed $n = 2000$ rpm, for both rimmed and rimless impellers.

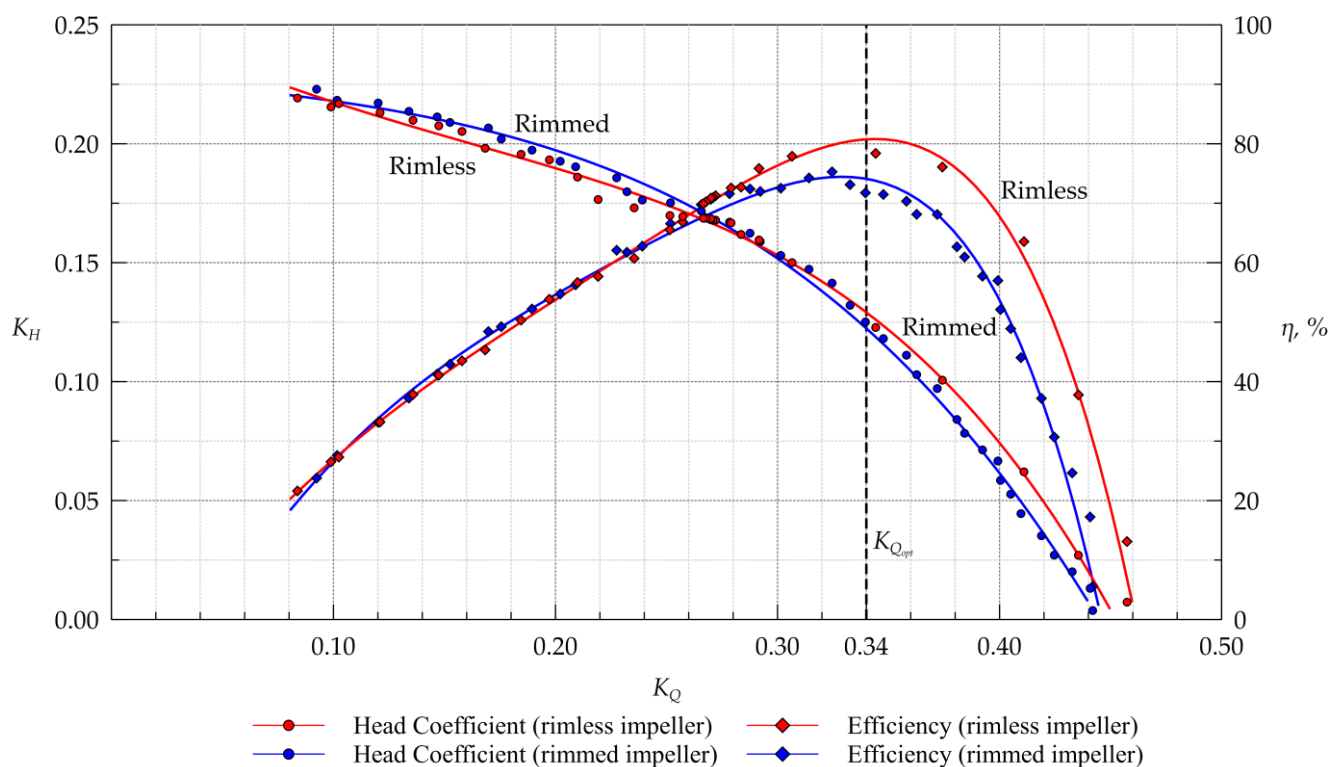


Figure 6. Experimental energy characteristics of the axial pump № 2 with rimmed and rimless impellers.

K_Q and K_H coefficients from Figure 6 are calculated as follows:

$$K_Q = \frac{Q}{n \cdot D^3}; \quad (1)$$

$$K_H = \frac{H}{n^2 \cdot D^2} \quad (2)$$

where Q is the volumetric flow rate, H is the pump head, n is the rotation speed of the shaft, and D is the outer diameter of the impeller.

From Figure 6, it follows that the head characteristics of both variants are continuously decreasing, but the characteristic of the rimmed impeller is steeper. The hydraulic efficiency of the pump at part load conditions is identical, but at the optimal ($0.34 \times K_Q$ and $0.125 \times K_H$) and high flow rates, there is a difference: the efficiency of the rimmed impeller is about 5% lower than of the rimless one. The same difference is retained at high flow rates. The lower hydraulic efficiency of the rimmed impeller is explained by increased hydraulic friction losses in the blade system with a larger area (due to the presence of the rim) of interaction between the flow and the impeller. These losses are proportional to the flow velocity, so they appear at high-flow rates.

On the Experimental complex for testing axial-flow pumps, cavitation characteristics were obtained at flows of $1.2 \times Q_{BEP}$, $1.0 \times Q_{BEP}$, and $0.3 \times Q_{BEP}$. NPSH3 for an axial pump with a rimmed impeller was lower than for an impeller without a rim.

After taking the energy and cavitation characteristics, cavitation erosion studies were carried out for the axial-flow pump with the rimmed and rimless impeller at the available NPSH of the pump unit $NPSH = 3.65$ m. The tests were carried out at a pump speed of $n = 2000$ rpm. The research of impeller № 2 on cavitation erosion was performed with $NPSH = 3.65$ m, respectively, at each flow rate of $1.2 \times Q_{BEP}$, $1.0 \times Q_{BEP}$, and $0.3 \times Q_{BEP}$. Table 1 shows some results of the tests of the axial pump with a rimless impeller, and Table 2 is for an impeller with a rim.

Table 1. Research results for the rimless impeller № 2 ($n = 2000$ rpm, $NPSH = 3.65$ m).

Q/Q_{BEP}	Time (s)	Cavitation Erosion
1.2	4800	No
1.0	4800	No
0.3	300–960	Yes

Table 2. Research results for the impeller № 2 with the rim ($n = 2000$ rpm, $NPSH = 3.65$ m).

Q/Q_{BEP}	Time (s)	Cavitation Erosion
1.2	–	No
1.0	–	No
0.3	3950	Yes

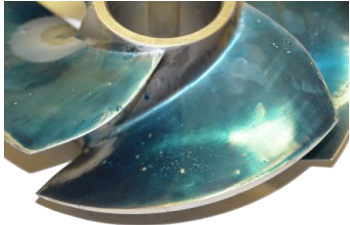
It follows from Tables 1 and 2 that at flow rates $1.2 \times Q_{BEP}$ and $1.0 \times Q_{BEP}$ and $NPSH = 3.65$ m, no cavitation damage of easily breakable paint coatings was observed in the impeller (as expected). Vapor-filled cavities at these flow rates and $NPSH = 3.65$ m have also not been obtained by CFD calculations. Thus, impeller № 2 provides the required high-erosion resistance at the optimum flow rate (best efficiency point). At the flow rate of $Q = 0.3 \times Q_{BEP}$, cavitation erosion was detected.

Table 3 shows the development over time of the cavitation erosion zone in the rimless impeller on the flow rate $Q = 0.3 \times Q_{BEP}$ and $NPSH = 3.65$ m.

From the photos in Table 3, one can see that the pitting areas on all impeller blades are equally spaced. Pitting begins to appear when the blades are exposed to cavitation over 300 s. At an exposure time of 960 s, the final appearance of the pitting areas is observed.

Figure 7 shows the calculated isovolume of the vapor phase at the suction surfaces of the blades combined with the static pressure field distribution.

Table 3. Development of cavitation erosion zone in the rimless impeller ($Q = 0.3 \times Q_{BEP}$, NPSH = 3.65 m).

Cavitation Exposure Time (s)	Impeller Front View	Blade View
300		
480		
840		
960		

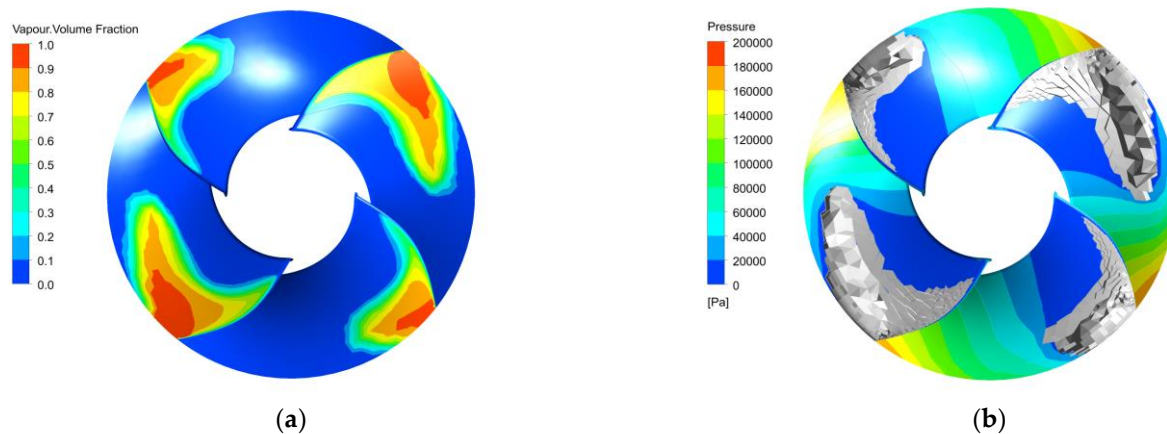


Figure 7. Visualization of CFD calculation results on the suction surface of rimless impeller № 2 ($Q = 0.3 \times Q_{BEP}$, NPSH = 3.65 m): (a) Vapor-filled cavities; (b) Isovolume of vapor with a concentration of more than 10%.

Figure 8 shows the area of cavitation erosion on the blade obtained during the physical experiment on the experimental complex for testing axial-flow pumps, also at $Q = 0.3 \times Q_{BEP}$.



Figure 8. Cavitation erosion zones on the suction surface of rimless impeller № 2 ($Q = 0.3 \times Q_{BEP}$, $NPSH = 3.65$ m).

The analysis of Figures 7 and 8 shows that cavitation destructions of the easily breakable paint coating appear behind the vapor region in the area, where the static pressure exceeds the atmospheric pressure and the bubbles collapse. Cavitation erosion at non-optimal flow $Q = 0.3 \times Q_{BEP}$ is accompanied by a calculated vapor zone occupying about 20% of the blade area. At the same flow rate $Q = 0.3 \times Q_{BEP}$, but with $NPSH = NPSH_3 = 2$ m, cavitation failure of pump parameters occurs. This failure corresponds to a vapor area occupying almost the whole surface of the blade (Figure 9).

Figure 9a shows a visualization of the volume fraction of vapor on the back side of the impeller blade. In Figure 9b, the static pressure distribution, limited by the saturation pressure, corresponds to the design temperature (2065 Pa for equal to $T = 18$ °C). In Figure 9c, the blade system of the impeller and diffuser vanes shows the volume of vapor with a concentration greater than 30%.

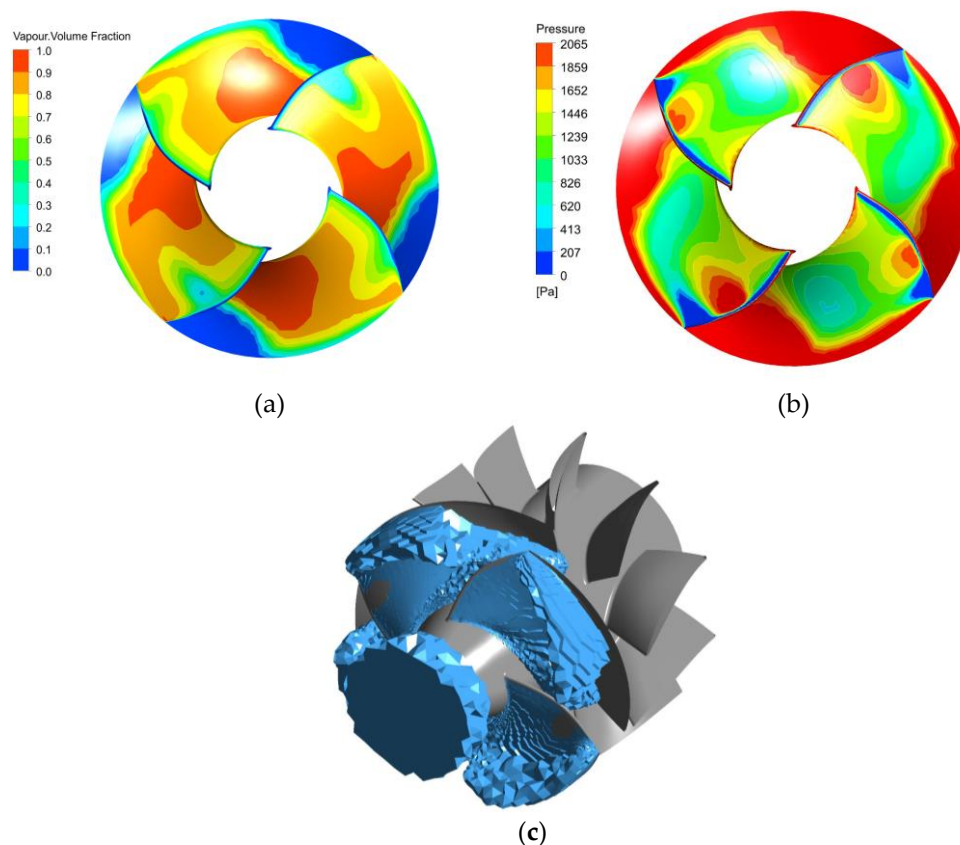


Figure 9. Visualization of CFD calculation results on the suction surface of rimless impeller № 2 ($Q = 0.3 \times Q_{BEP}$, $NPSH_3 = 2$ m): (a) Vapor volume fraction distribution; (b) Pressure distribution (c) Isovolume of vapor with a concentration of more than 30%.

4. Conclusions

The design process of dynamic hydraulic machines, in particular pumps, often requires the knowledge of the condition under which there will be no cavitation erosion in them. Pump head decrease due to the cavitation process can be predicted adequately by CFD calculation from the value of the $NPSH_3$. Cavitation erosion occurs with the inception, and then, the implosion of the first cavitation bubbles appears in the flow passage. The process of cavitation inception occurs much before the cavitation impairs the performance of the pump. In this paper, for the axial-flow pump with a specific speed of 600, the quantitative relationship between the $NPSH_i$, at which the first cavitation bubbles incept (the beginning of cavitation erosion), and $NPSH_3$, at which the head of the suction impeller drops by 3%, was found. The condition of cavitation erosion absence in this axial-flow pump is written in the form of the inequality— $NPSH/NPSH_3 > 2.5$. This condition can be used further for this class of pumps. The conducted calculation studies showed that to achieve high anti-cavitation and anti-erosion properties, it is necessary to reduce the hub diameter, blade installation angles, blade curvature, the angle of attack on the inlet edge should be close to zero, the angle of blade coverage should be increased, the thickness of blades should be minimal, but with the observance of conditions for strength. The blade system № 2, designed in consideration of these recommendations, received a reduced value of $NPSH_3$ and high anti-erosion performance, which was then confirmed experimentally.

An axial-flow pump with a rimmed impeller has better cavitation properties than a rimless impeller. This is because the wheel with a rim does not have the slot cavitation inherent in an impeller without a rim. The impeller with a rim also has greater strength but a slightly lower efficiency than an impeller without a rim. The efficiency of the rimmed impeller is about 5% less than that of the rimless one. The lower hydraulic efficiency of the rimmed impeller is explained by increased hydraulic friction losses in the blade system with

a larger area (due to the presence of the rim) of interaction between the flow and the impeller. The presence of the rim enhances structural rigidity, increases natural oscillation frequency, and prevents leakages of the fluid from the pressure side to the suction side of the blade. A radial clearance, length of the rim, the volume of leakage amounts, and surface roughness can have effects on the energy characteristics of an axial pump. The degree of these effects will be different for pumps with different specific speeds. For axial-flow pumps with a specific speed of $n_s \approx 600$ in terms of energy qualities, the rimless impeller is better—it has a higher head and efficiency. In terms of strength qualities, the rimmed impeller is better. In terms of cavitation qualities, both impellers meet the requirements—there is no cavitation erosion on the best efficiency point. The distribution of erosion zones under part-load conditions is comparable in both impellers.

A full-scale experiment to study cavitation erosion is expensive and time-consuming. The method of the cavitation erosion accelerated study with laying easily breakable paint coatings was used. The performed experiment confirmed the calculated conclusions about the absence of cavitation erosion at the nominal operating point in the impeller with the improved blade system № 2. This research method for studying cavitation erosion can be recommended in all kinds of dynamic hydraulic machines; for example, in hydraulic turbines.

Author Contributions: Conceptualization, A.Z. and S.S.; methodology, D.S.; software, D.S. and E.I.; validation, A.K., I.B., and E.I.; formal analysis, S.S.; investigation, A.K.; resources, I.B.; data curation, A.K.; writing—original draft preparation, D.S.; writing—review and editing, A.Z. and A.K.; visualization, A.K.; supervision, A.Z.; project administration, I.B.; funding acquisition, I.B. All authors have read and agreed to the published version of the manuscript.

Funding: The research was partially funded by the Ministry of Science and Higher Education of the Russian Federation as part of the World-Class Research Center Program: Advanced Digital Technologies (contract no. 075-15-2022-311 dated 20 April 2022).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The results of the work were obtained using computational resources of the supercomputer center in Peter the Great Saint-Petersburg Polytechnic University Supercomputing Center (www.spbstu.ru, accessed on 1 December 2022).

Conflicts of Interest: The authors declare no conflict of interest.

References

- Ge, M.; Petkovšek, M.; Zhang, G.; Jacobs, D.; Coutier-Delgosha, O. Cavitation dynamics and thermodynamic effects at elevated temperatures in a small Venturi channel. *Int. J. Heat Mass Transf.* **2021**, *170*, 120970. [CrossRef]
- Ge, M.; Sun, C.; Zhang, G.; Coutier-Delgosha, O.; Fan, D. Combined suppression effects on hydrodynamic cavitation performance in Venturi-type reactor for process intensification. *Ultrason. Sonochem.* **2022**, *86*, 106035. [CrossRef] [PubMed]
- Ge, M.; Zhang, G.; Petkovšek, M.; Long, K.; Coutier-Delgosha, O. Intensity and regimes changing of hydrodynamic cavitation considering temperature effects. *J. Clean. Prod.* **2022**, *338*, 130470. [CrossRef]
- Ge, M.; Manikkam, P.; Ghossein, J.; Subramanian, R.K.; Coutier-Delgosha, O.; Zhang, G. Dynamic mode decomposition to classify cavitating flow regimes induced by thermodynamic effects. *Energy* **2022**, *254*, 124426. [CrossRef]
- Rakibuzzaman, M.; Kim, H.-H.; Kim, K.; Suh, S.-H.; Kim, K.Y. Numerical Study of Sediment Erosion Analysis in Francis Turbine. *Sustainability* **2019**, *11*, 1423. [CrossRef]
- Tiwari, G.; Kumar, J.; Prasad, V.; Patel, V.K. Derivation of cavitation characteristics of a 3MW prototype Francis turbine through numerical hydrodynamic analysis. *Mater. Today Proc.* **2020**, *26*, 1439–1448. [CrossRef]
- Jian, W.; Yong, W.; Houlin, L.; Qiaorui, S.; Dular, M. Rotating Corrected-Based Cavitation Model for a Centrifugal Pump. *J. Fluids Eng.* **2018**, *140*, 111301. [CrossRef]
- Qiu, N.; Zhu, H.; Long, Y.; Zhong, J.; Zhu, R.; Wu, S. Assessment of Cavitation Erosion in a Water-Jet Pump Based on the Erosive Power Method. *Scanning* **2021**, *2021*, 5394782. [CrossRef]
- Zhu, H.; Qiu, N.; Wang, C.; Si, Q.; Wu, J.; Deng, F.; Liu, X. Prediction of Cavitation Evolution and Cavitation Erosion on Centrifugal Pump Blades by the DCM-RNG Method. *Scanning* **2021**, *2021*, 6498451. [CrossRef] [PubMed]

10. Adamkowski, A.; Henke, A.; Lewandowski, M. Resonance of torsional vibrations of centrifugal pump shafts due to cavitation erosion of pump impellers. *Eng. Fail. Anal.* **2016**, *70*, 56–72. [\[CrossRef\]](#)
11. Lv, D.; Lian, Z.; Zhang, T. Study of Cavitation and Cavitation Erosion Quantitative Method Based on Image Processing Technique. *Adv. Civ. Eng.* **2018**, *2018*, 5317578. [\[CrossRef\]](#)
12. Dular, M.; Bachert, B.; Stoffel, B.; Širok, B. Relationship between cavitation structures and cavitation damage. *Wear* **2004**, *257*, 1176–1184. [\[CrossRef\]](#)
13. Sato, K.; Shimojo, S. Detailed Observations on a Starting Mechanism for Shedding of Cavitation Cloud. In Proceedings of the Fifth International Symposium on Cavitation, Osaka, Japan, 1–4 November 2003.
14. Zhang, S.; Qian, Z.; Ji, B. Estimation of cavitation erosion area in unsteady cavitating flows using a modified approach. *Ocean Eng.* **2022**, *262*, 112229. [\[CrossRef\]](#)
15. Mihatsch, M.S.; Schmidt, S.J.; Thalhamer, M.; Adams, N. Numerical Prediction of Erosive Collapse Events in Unsteady Compressible Cavitating Flows. In *MARINE 2011, IV International Conference on Computational Methods in Marine Engineering*; Springer: Dordrecht, The Netherlands, 2013; pp. 187–198. [\[CrossRef\]](#)
16. Zhukov, V.M. Investigation of Cavitation Destruction of Pre-Engineered Wheels of Centrifugal Pumps for Power Engineering. Ph.D. Thesis, Chalmers University of Technology, Göteborg, Sweden, 1975; p. 24.
17. Babin, V.A. Prevention of Cavitation Erosion of Sodium Pumps Flow-Through Parts. In Proceedings of the International Conference on Cavitation in Pumps with Sodium Coolant, Vienna, Austria, 10–11 October 1985.
18. Babin, V.A. Accounting for Cavitation Phenomena in Designing Individual Units and Equipment of Fast Neutron Reactors. In Proceedings of the Soviet-French Seminar, Cadarache, France, 1978.
19. Zhukov, V.M. On the effect of flow rate on cavitation fractures. *Hydraul. Mach.* **1982**, *16*, 73–78.
20. Ramamurthy, B. A Stepped Dependence of Cavitation Erosion and Noise on Flow Rate. Theoretical Foundations of Engineering Calculations. *Trans. ASME. Ser. D J. Basic Eng.* **1979**, 188–195.
21. Svoboda, D.G.; Zharkovskii, A.A.; Ivanov, E.A.; Shchutskii, S.Y.; Dyagilev, P.Y. High-Efficiency Axial Pumps for Reactor Use. *Russ. Eng. Res.* **2019**, *39*, 556–560. [\[CrossRef\]](#)
22. Staritsky, V.G. *Technique of Research of Cavitation Erosion on Models of Hydraulic Turbines*; LPI: New Berlin, WI, USA, 1965; Volume 246.
23. Trifonov, E.V. Determination of cavitation by brittle coatings. *Energomashinostroenie* **1955**, 25–26.
24. Lunatsi, E.D. Domestic method of predicting cavitation erosion using easily destructible materials and characteristics of their relative resistance. *Eng. Her.* **2015**, 53–65.
25. Veremeenko, I.S. Method of experiment and analysis of erosion studies of hydraulic turbines. *Hydraul. Mach.* **1984**, *18*, 115–125.
26. Svoboda, D.; Ivanov, E.; Zharkovskii, A.; Borshchev, I. Calculated and experimental determination of erosion zones in the flow part of the vane type pump. *E3S Web Conf.* **2019**, *121*, 01002. [\[CrossRef\]](#)
27. Bernsten, G.; Kjeldsen, M.; Muller, R. Cavitation induced dynamics in hydraulic machinery. In Proceedings of the 10th IAHR WG Meeting on the Behavior of Hydraulic Machinery under Steady Oscillatory Conditions, Tokyo, Japan, 2001; pp. 1–8.
28. Bouziad, Y.A. Physical Modelling on Leading Edge Cavitation: Computational Methodologies and Application to in Hydraulic Machinery. Ph.D. Thesis, Ecole Polytechnique Federale de Lausanna, Lausanne, Switzerland, 2005.
29. Tsujimoto, Y.; Horiguchi, H.; Yonezawa, K. Cavitation instabilities in turbopump inducers. Analyses in 1–3 Dimensions. *Int. J. Fluid Mach. Syst.* **2010**, *3*, 170–180.
30. Alexenskii, V.A.; Zharkovskii, A.A.; Pugachev, P.V. Calculated determination of cavitation characteristics of centrifugal pumps. *Izv. Samara Sci. Cent. Russ. Acad. Sci.* **2011**, *13*, 411–414.
31. Lin, P.; Hu, D.; Lu, J.M.; Wang, S. CFD Numerical Simulation of Sand-Contained Cavitation Characteristics of Axial-Flow Pump. *Adv. Mech. Eng.* **2021**, *13*, 16878140211032785. [\[CrossRef\]](#)
32. Zhang, D.S.; Pan, Q.; Zhang, H.; Shi, W.D.; Zhang, R.J.; Xing, J. Numerical Simulation and Optimization of Solid-Liquid Two-Phase Flow in a Back-Swept Axial Flow Pump. *Therm. Sci.* **2017**, *21*, 1751–1757. [\[CrossRef\]](#)
33. Thiruvengaram, A. A unified theory of cavitation damage. *Trans. ASME. Ser. D* **1963**, *85*, 365–373. [\[CrossRef\]](#)
34. Gulich, J.F.; Pace, S. Quantitative prediction of cavitation erosion in centrifugal pumps. In Proceedings of the 13th IAHR Symposium, Montreal, Canada, 2–5 September 1986; pp. 1–17.
35. Sedlař, M.; Soukal, J.; Krátký, T.; Vyroubal, M. Numerical prediction of impacts of cavitation in pumps for power generation. *Therm. Eng.* **2015**, *62*, 408–413. [\[CrossRef\]](#)

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.