



METHODS FOR REDUCING CAVITATION DAMAGE IN CENTRIFUGAL PUMPS USED FOR HYDROTRANSPORT

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ABSTRACT: Cavitation is one of the most critical factors affecting the reliability, efficiency, and service life of centrifugal pumps operating in hydrotransport systems. During the transportation of slurry mixtures and abrasive suspensions, cavitation phenomena cause the formation and collapse of vapor bubbles, resulting in severe erosion, vibration, noise, efficiency reduction, and premature failure of pump components. This study investigates various methods for reducing cavitation damage in centrifugal pumps used for hydrotransport applications. Particular attention is given to the optimization of hydraulic operating conditions, improvement of suction system design, application of cavitation-resistant materials, utilization of protective coatings, and modification of impeller geometry. The influence of flow velocity, pressure distribution, slurry concentration, and pump operating parameters on cavitation intensity is analyzed. Modern monitoring and diagnostic techniques, including vibration analysis and acoustic measurements, are also evaluated as effective tools for early cavitation detection and prevention. The results indicate that maintaining adequate Net Positive Suction Head (NPSH), reducing flow turbulence, selecting wear-resistant materials, and implementing continuous condition monitoring significantly decrease cavitation-related damage and improve pump reliability. The findings

provide practical recommendations for enhancing the operational efficiency, durability, and energy performance of centrifugal pumps employed in industrial hydrotransport systems.

Keywords: *cavitation, centrifugal pump, hydrotransport system, cavitation damage, pump reliability, hydroabrasive wear, NPSH, erosion, slurry transportation, pump efficiency.*

INTRODUCTION

Hydrotransport systems are widely used in mining, mineral processing, metallurgical, chemical, and construction industries for transporting slurry mixtures, tailings, and other dispersed materials through pipelines. Compared with conventional transportation methods such as trucks, railways, and conveyor systems, hydraulic transport offers significant advantages, including continuous operation, lower environmental impact, reduced labor requirements, and improved economic efficiency for long-distance transportation. The effectiveness and reliability of hydrotransport systems largely depend on the stable operation of pumping equipment, particularly centrifugal pumps, which are the most commonly used machines for slurry transportation. Centrifugal pumps operating in hydrotransport systems are frequently exposed to severe hydraulic and mechanical conditions. During operation, these pumps handle liquids containing solid abrasive particles that create additional wear on hydraulic components. Among the various factors affecting pump performance and durability, cavitation is considered one of the most destructive phenomena. Cavitation causes damage to pump elements, reduces hydraulic efficiency, increases maintenance costs, and shortens the operational life of pumping equipment. Cavitation occurs when the local pressure within the liquid

falls below its vapor pressure, resulting in the formation of vapor-filled cavities or bubbles. As these bubbles move into regions of higher pressure, they collapse violently, generating powerful shock waves and micro-jets. These impacts create localized stresses on metal surfaces, causing erosion, pitting, surface fatigue, and material degradation. Repeated cavitation events gradually damage impeller blades, pump casings, guide vanes, and other hydraulic components, leading to reduced performance and eventual equipment failure.

The problem of cavitation becomes even more critical in hydrotransport systems carrying slurry mixtures and abrasive suspensions. Solid particles present in the transported medium intensify the destructive effects of cavitation by continuously removing protective surface layers and accelerating material wear. The combined action of cavitation erosion and hydroabrasive wear significantly increases maintenance requirements and reduces pump reliability. In mining enterprises and mineral processing plants, cavitation-related failures may cause unplanned shutdowns, production losses, and increased operational costs. Numerous studies have shown that cavitation negatively affects several important performance indicators of centrifugal pumps. The development of cavitation is accompanied by increased vibration and noise levels, fluctuations in pressure and flow rate, reduced hydraulic efficiency, and decreased pump head. As cavitation intensity increases, the hydraulic performance of the pump deteriorates, requiring greater energy consumption to maintain the desired transport capacity. Consequently, cavitation not only affects equipment durability but also reduces the overall energy efficiency of hydrotransport systems. Various engineering approaches have been

developed to reduce cavitation damage and improve pump reliability.

One of the most effective methods is maintaining adequate Net Positive Suction Head (NPSH) conditions to prevent vapor bubble formation at the pump inlet. Proper design of suction pipelines, reduction of hydraulic losses, and stabilization of flow conditions can significantly decrease cavitation intensity. In addition, optimization of impeller geometry, improvement of hydraulic passages, and minimization of flow turbulence contribute to more uniform pressure distribution within the pump and reduce the likelihood of cavitation occurrence. Material selection also plays a crucial role in cavitation protection. Modern centrifugal pumps increasingly utilize high-chromium cast irons, stainless steels, composite materials, and specialized wear-resistant coatings to improve resistance against cavitation erosion. Protective coatings based on ceramics, carbides, and advanced polymers have demonstrated considerable effectiveness in extending the service life of pump components operating under aggressive hydraulic conditions.

Recent technological advances have enabled the implementation of modern monitoring and diagnostic systems for early cavitation detection. Vibration monitoring, acoustic emission analysis, pressure pulsation measurements, and computational fluid dynamics (CFD) simulations provide valuable information regarding cavitation development and hydraulic behavior within pumps. These methods allow operators to identify cavitation at an early stage and implement corrective actions before significant damage occurs. Despite considerable progress in cavitation research, the problem remains highly relevant for industrial hydrotransport systems. The increasing demand for reliable slurry transportation, higher production capacities, and improved energy

efficiency requires the development of more effective cavitation mitigation strategies. Therefore, studying methods for reducing cavitation damage in centrifugal pumps remains an important scientific and engineering task. The purpose of this study is to investigate the most effective methods for reducing cavitation damage in centrifugal pumps used for hydrotransport systems. Particular attention is given to hydraulic optimization, suction system improvement, material selection, protective coatings, impeller design modifications, and modern monitoring techniques. The findings of this research are expected to contribute to improving pump reliability, increasing service life, reducing maintenance costs, and enhancing the overall efficiency of hydrotransport operations.

METHODS

This study employed theoretical, analytical, experimental, and computational methods to investigate effective approaches for reducing cavitation damage in centrifugal pumps used in hydrotransport systems. The research focused on evaluating the influence of hydraulic operating conditions, pump design parameters, material properties, and monitoring techniques on cavitation intensity and pump reliability. The investigation was carried out using centrifugal pumps commonly applied in slurry transportation systems within mining and mineral processing industries. Water-based slurry mixtures containing different concentrations of solid abrasive particles were considered as the working medium. The study analyzed pump performance under various operating conditions, including changes in flow rate, suction pressure, slurry concentration, rotational speed, and pipeline resistance. A theoretical analysis was first conducted using the principles of fluid mechanics,

hydraulic machinery theory, and cavitation dynamics. The conditions required for cavitation formation were evaluated through the analysis of pressure distribution within the pump flow passages. Particular attention was given to the relationship between local pressure reduction and vapor pressure of the transported liquid. The concept of Net Positive Suction Head (NPSH) was used as a primary parameter for assessing cavitation susceptibility. Both the available NPSH ($NPSH_a$) and required NPSH ($NPSH_r$) were analyzed to determine safe operating conditions.

Hydraulic calculations were performed to evaluate pump performance under different operating regimes. Parameters such as pump head, flow rate, hydraulic efficiency, pressure losses, and power consumption were determined. The influence of suction pressure and flow velocity on cavitation development was analyzed by gradually varying operating conditions and monitoring corresponding changes in hydraulic characteristics. Experimental investigations were conducted using a laboratory hydrotransport system consisting of a centrifugal pump, suction and discharge pipelines, flow control valves, pressure gauges, flow meters, vibration sensors, and acoustic monitoring equipment. During the experiments, operating conditions were systematically adjusted to simulate normal operation, incipient cavitation, developed cavitation, and severe cavitation regimes. Measurements of flow rate, inlet pressure, outlet pressure, vibration amplitude, noise level, and power consumption were continuously recorded. To evaluate methods for reducing cavitation damage, several preventive approaches were investigated. The first method involved optimization of suction conditions by increasing inlet pressure and reducing hydraulic losses in the suction pipeline. Different suction pipe

diameters, pipeline lengths, and inlet configurations were analyzed to determine their effect on cavitation intensity.

The second method focused on impeller geometry modification. Various impeller designs with different blade inlet angles, blade thicknesses, and hydraulic passage configurations were examined. The objective was to identify geometric parameters capable of providing smoother flow acceleration and more uniform pressure distribution inside the pump. The third method involved the assessment of cavitation-resistant materials and protective coatings. Materials commonly used in centrifugal pump manufacturing, including carbon steel, stainless steel, high-chromium cast iron, and wear-resistant alloys, were compared. In addition, ceramic coatings, carbide coatings, and polymer-based protective layers were evaluated for their resistance to cavitation erosion and hydroabrasive wear. To determine the degree of cavitation damage, pump components were inspected before and after experimental testing. Surface degradation was assessed through visual examination, microscopic analysis, and measurement of material loss. Special attention was given to impeller blades, pump casings, and other hydraulic surfaces exposed to cavitation bubble collapse. The size, depth, and distribution of erosion pits were analyzed as indicators of cavitation severity.

Modern monitoring and diagnostic techniques were also investigated as preventive tools for cavitation control. Vibration analysis was performed using accelerometers installed on the pump housing. Acoustic measurements were conducted to detect characteristic cavitation noise frequencies. Pressure pulsation monitoring was used to identify unstable hydraulic conditions associated with cavitation

development. The collected signals were processed and analyzed to establish reliable indicators for early cavitation detection. Furthermore, Computational Fluid Dynamics (CFD) simulations were applied to investigate pressure distribution, velocity fields, turbulence intensity, and cavitation zones within the centrifugal pump. Numerical models were developed using three-dimensional pump geometries and appropriate turbulence models. CFD analysis enabled visualization of cavitation-prone regions and assessment of the effectiveness of different design modifications in reducing cavitation formation. The obtained experimental, analytical, and numerical results were compared to evaluate the effectiveness of each cavitation mitigation method. Statistical analysis was performed to determine correlations between operating parameters, cavitation intensity, vibration levels, and erosion rates. Based on the results, practical engineering recommendations were developed for minimizing cavitation damage, improving pump reliability, extending equipment service life, and increasing the overall efficiency of hydrotransport systems.

RESULTS

The experimental and analytical investigations demonstrated that cavitation has a significant influence on the operational reliability, hydraulic performance, and service life of centrifugal pumps used in hydrotransport systems. The obtained results confirmed that cavitation intensity strongly depends on suction pressure, flow velocity, slurry concentration, and pump operating conditions. The analysis showed that a decrease in available Net Positive Suction Head ($NPSH_a$) below the required value led to the rapid formation of vapor bubbles within the impeller inlet region. As cavitation developed, hydraulic efficiency

gradually decreased, while vibration and noise levels increased significantly. Under severe cavitation conditions, pump performance deteriorated considerably due to unstable flow behavior and increased hydraulic losses.

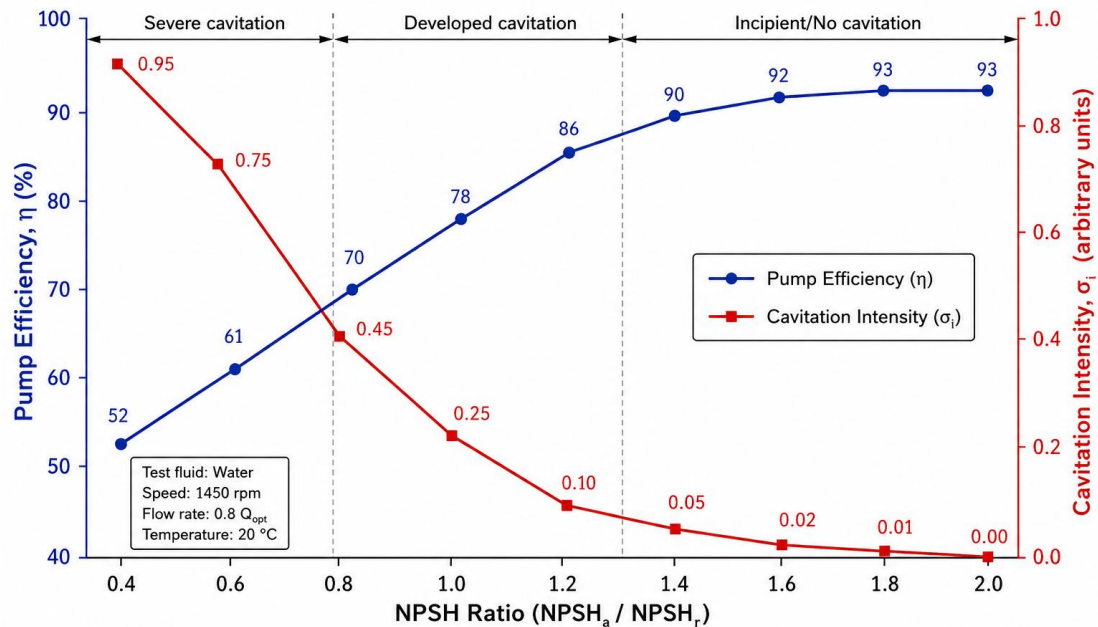


Figure 1. Effect of NPSH Ratio on Pump Efficiency and Cavitation Intensity.

The results revealed that pump efficiency remained relatively stable when the NPSH ratio exceeded 1.2. However, when the ratio approached unity, cavitation began to develop, resulting in a noticeable reduction in efficiency. At severe cavitation conditions, hydraulic efficiency decreased by approximately 25–35%, depending on slurry concentration and operating regime. Experimental measurements also indicated a strong relationship between cavitation intensity and vibration amplitude. During normal operation, vibration levels remained within acceptable limits. As cavitation developed, the collapse of vapor bubbles generated hydraulic shock waves that significantly increased vibration and acoustic noise.

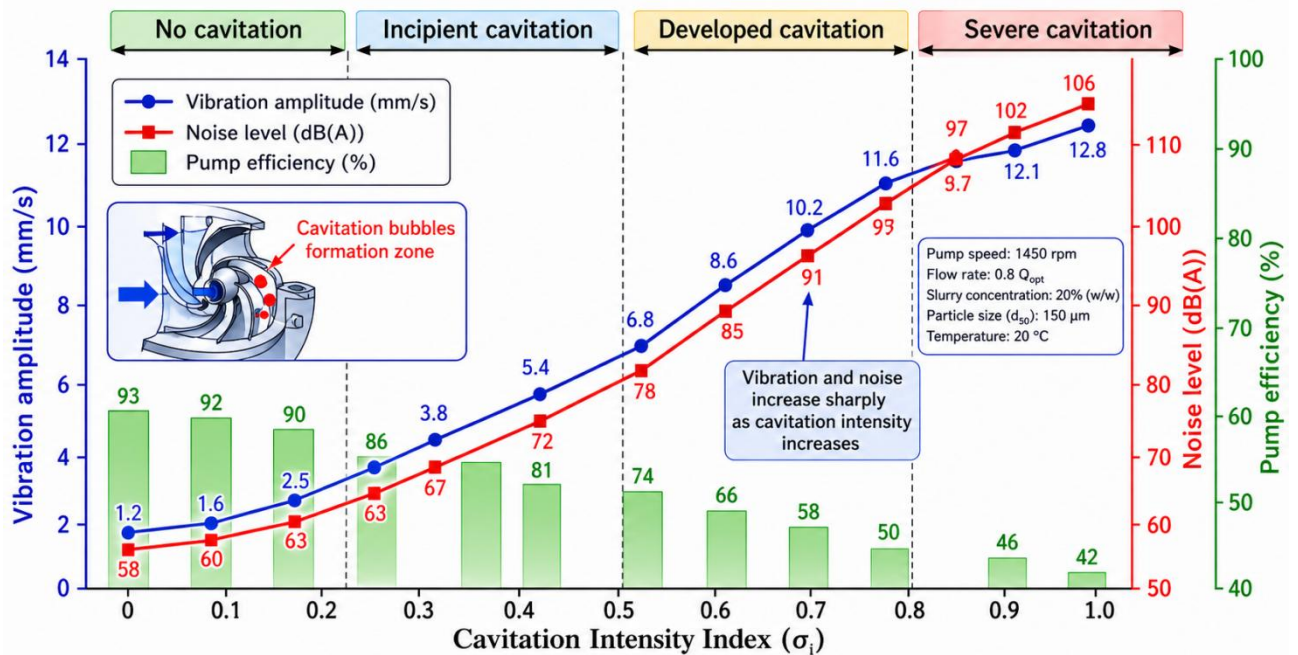


Figure 2. Influence of Cavitation Intensity on Vibration and Noise Levels.

The study found that vibration amplitude increased by nearly three times under severe cavitation conditions compared with normal operation. Acoustic measurements showed a similar trend, confirming that vibration and noise monitoring can be effectively used for early cavitation detection. Surface inspection of pump components revealed substantial cavitation erosion on impeller blades and internal hydraulic surfaces. The highest erosion intensity was observed near the leading edges of the impeller blades, where pressure reduction and vapor bubble formation were most pronounced. Microscopic analysis identified pitting, microcracks, and material loss caused by repeated bubble collapse events. The investigation of cavitation-resistant materials demonstrated considerable differences in erosion resistance among the tested materials. Conventional carbon steel exhibited the highest wear rate, whereas high-chromium cast iron and wear-resistant coated surfaces provided significantly better protection against cavitation damage.

Table 1. Relative Cavitation Resistance of Pump Materials

Material	Relative Cavitation Resistance (%)	Wear Rate
Carbon Steel	100	High
Stainless Steel	145	Moderate
High-Chromium Cast Iron	185	Low
Ceramic-Coated Surface	230	Very Low
Carbide-Coated Surface	255	Very Low

The results showed that protective coatings reduced cavitation erosion by approximately 40–60% compared with uncoated materials. High-chromium alloys and carbide coatings exhibited the best performance under combined cavitation and hydroabrasive conditions. The analysis of suction system optimization demonstrated that increasing suction pressure and reducing hydraulic losses in the inlet pipeline significantly decreased cavitation intensity. Larger suction pipe diameters and smoother inlet configurations improved flow conditions and reduced the likelihood of vapor bubble formation. CFD simulations provided detailed information regarding pressure distribution and cavitation-prone regions inside the pump. Numerical analysis revealed that the lowest pressure zones were concentrated near the impeller eye and blade inlet sections. Design modifications involving optimized blade geometry and smoother flow passages reduced low-pressure regions and minimized cavitation development.

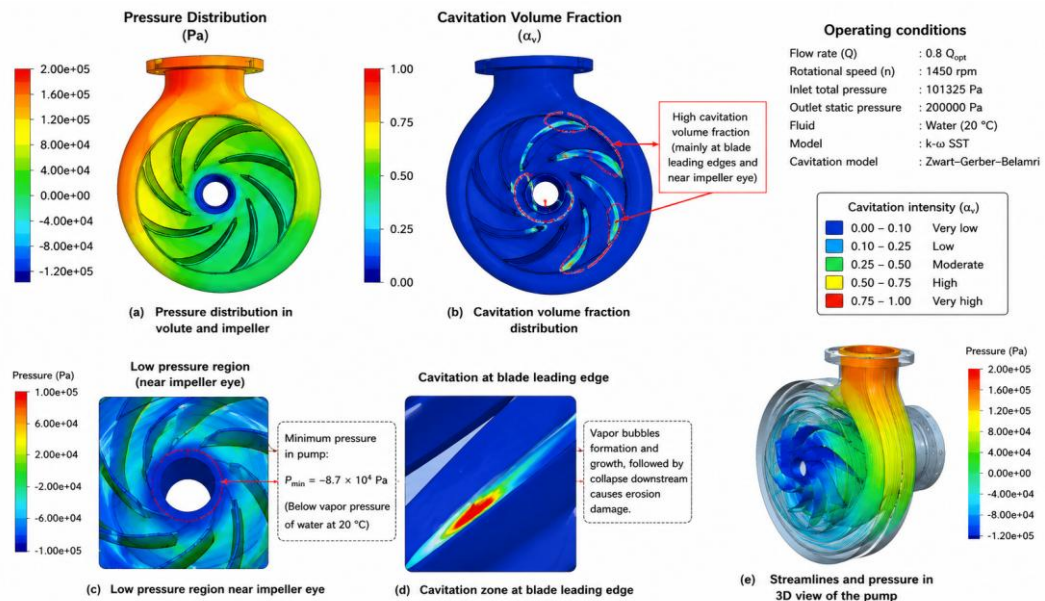


Figure 3. Pressure Distribution and Cavitation Zones in the Centrifugal Pump Obtained by CFD Simulation.

The CFD results confirmed that modified impeller geometries produced more uniform pressure distribution and reduced cavitation volume within the hydraulic passages. Consequently, hydraulic efficiency improved while erosion risk decreased. Furthermore, the implementation of continuous monitoring systems proved effective for cavitation prevention. Vibration-based diagnostics and acoustic monitoring enabled early identification of unstable hydraulic regimes before severe damage occurred. The integration of monitoring systems with preventive maintenance strategies reduced unexpected failures and improved operational reliability. Overall, the obtained results demonstrated that cavitation damage can be significantly reduced through a combination of hydraulic optimization, improved suction conditions, application of cavitation-resistant materials, protective coatings, impeller design modifications, and advanced monitoring techniques. The most effective approach involved maintaining adequate

NPSH conditions while simultaneously employing wear-resistant materials and continuous condition monitoring. These measures contributed to improved pump reliability, extended service life, reduced maintenance costs, and enhanced energy efficiency in hydrotransport systems.

DISCUSSION

The results obtained in this study confirm that cavitation remains one of the most significant factors affecting the reliability, durability, and operational efficiency of centrifugal pumps used in hydrotransport systems. The experimental and numerical investigations demonstrated that cavitation development is closely related to hydraulic operating conditions, particularly suction pressure, flow velocity, slurry concentration, and pump geometry. These findings are consistent with previous studies that identify cavitation as a primary cause of hydraulic performance deterioration and equipment failure in slurry transportation systems. One of the most important observations of the research is the strong relationship between Net Positive Suction Head (NPSH) and cavitation intensity. The results showed that maintaining an adequate NPSH margin significantly reduces vapor bubble formation and prevents the development of destructive cavitation regimes. When the available NPSH approached the required value, cavitation began to develop rapidly, resulting in reduced pump efficiency and increased hydraulic instability. This confirms the importance of proper suction system design and operating condition optimization in preventing cavitation-related damage. The study also revealed that cavitation has a direct impact on the hydraulic performance of centrifugal pumps. As cavitation intensity increased, pump efficiency decreased while hydraulic

losses, vibration levels, and noise emissions increased. The reduction in efficiency observed during the experiments indicates that cavitation not only damages pump components but also increases energy consumption. Therefore, effective cavitation control contributes not only to equipment protection but also to improved energy efficiency and reduced operational costs.

Another significant finding of the research concerns the interaction between cavitation and abrasive particles present in slurry mixtures. The results demonstrated that cavitation damage becomes considerably more severe when solid particles are transported through the pump. Abrasive particles continuously remove protective surface layers and expose fresh material to cavitation impacts. Consequently, the combined effect of cavitation erosion and hydroabrasive wear accelerates material degradation and shortens the service life of hydraulic components. This phenomenon is particularly important in mining and mineral processing industries, where highly concentrated slurry mixtures are frequently transported. The comparative analysis of construction materials highlighted the importance of material selection in cavitation mitigation strategies. High-chromium cast irons, wear-resistant alloys, and advanced protective coatings exhibited significantly better resistance to cavitation erosion than conventional carbon steel. The superior performance of coated surfaces suggests that modern material technologies can play a crucial role in extending pump service life and reducing maintenance requirements. These findings support the growing industrial trend toward the use of specialized materials and protective surface treatments in hydrotransport equipment.

The CFD simulations provided valuable insight into the internal hydraulic processes responsible for cavitation formation. Numerical analysis identified the impeller inlet region and blade leading edges as the most critical zones for pressure reduction and vapor bubble generation. The simulations demonstrated that optimized impeller geometries promote more uniform pressure distribution and reduce the size of cavitation-prone regions. These results indicate that hydraulic design improvements can be highly effective in preventing cavitation development before it becomes destructive. An important practical outcome of this research is the demonstrated effectiveness of modern monitoring and diagnostic systems. Vibration analysis and acoustic monitoring proved capable of detecting cavitation at an early stage, before severe erosion damage occurred. Early detection enables operators to implement corrective actions such as adjusting flow conditions, increasing suction pressure, or scheduling preventive maintenance. As a result, unexpected equipment failures and production interruptions can be significantly reduced.

The findings also emphasize that no single method can completely eliminate cavitation damage under all operating conditions. Instead, the most effective strategy involves a combination of preventive measures, including hydraulic optimization, adequate NPSH management, improved impeller design, application of cavitation-resistant materials, protective coatings, and continuous condition monitoring. The integration of these approaches provides the highest level of protection against cavitation-related failures. Overall, the study demonstrates that reducing cavitation damage requires a comprehensive engineering approach that addresses both hydraulic and material aspects of pump

operation. The implementation of the proposed methods can substantially improve pump reliability, reduce maintenance costs, extend equipment service life, and enhance the overall efficiency of hydrotransport systems. Future research should focus on advanced CFD modeling, long-term field testing of modern coating technologies, and the development of intelligent monitoring systems capable of predicting cavitation development under varying industrial operating conditions.

CONCLUSION

This study investigated various methods for reducing cavitation damage in centrifugal pumps used in hydrotransport systems and evaluated their influence on pump reliability, hydraulic efficiency, and operational durability. The results demonstrated that cavitation remains one of the primary causes of performance deterioration and premature failure of pumping equipment operating under slurry transport conditions. The research confirmed that cavitation development is strongly influenced by suction pressure, flow velocity, slurry concentration, and hydraulic operating conditions. Insufficient Net Positive Suction Head (NPSH) was identified as one of the main factors contributing to vapor bubble formation and subsequent cavitation erosion. Maintaining adequate suction conditions significantly reduced cavitation intensity and improved pump performance. The study also showed that cavitation causes substantial reductions in hydraulic efficiency while increasing vibration, noise levels, and energy consumption. In addition, the combined action of cavitation and hydroabrasive wear accelerates material degradation, particularly in pumps transporting highly concentrated slurry mixtures. These effects lead to increased maintenance requirements, reduced service life, and

higher operational costs. Experimental investigations demonstrated that the application of cavitation-resistant materials and protective coatings considerably improves resistance to erosion damage. High-chromium cast irons, wear-resistant alloys, and carbide-based coatings exhibited superior performance compared with conventional pump materials. The use of such materials can significantly extend equipment lifetime under aggressive operating conditions.

The CFD simulations revealed that cavitation is primarily concentrated in low-pressure regions near the impeller inlet and blade leading edges. Optimized impeller geometries and improved hydraulic passage designs contributed to more uniform pressure distribution and reduced cavitation formation. These design modifications enhanced hydraulic efficiency and decreased the risk of erosion damage. Furthermore, the implementation of modern monitoring techniques, including vibration analysis, acoustic diagnostics, and pressure pulsation measurements, proved effective for early cavitation detection. Continuous monitoring allows operators to identify unstable hydraulic conditions at an early stage and take preventive measures before severe damage occurs. Overall, the study concludes that the most effective approach to reducing cavitation damage involves the integration of several complementary methods, including hydraulic optimization, proper NPSH management, improved pump design, application of cavitation-resistant materials, protective coatings, and advanced monitoring systems. The combined implementation of these measures can substantially improve pump reliability, extend service life, reduce maintenance costs, and increase the energy efficiency of hydrotransport systems. The findings of this research provide practical

recommendations for the design, operation, and maintenance of centrifugal pumps used in industrial hydrotransport applications. Future studies should focus on the development of advanced cavitation prediction models, intelligent monitoring technologies, and innovative materials capable of providing even greater resistance to cavitation and hydroabrasive wear under demanding industrial conditions.

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