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ENHANCING THE ENERGY EFFICIENCY AND OPERATIONAL RELIABILITY OF CENTRIFUGAL PUMP SYSTEMS THROUGH THE IMPLEMENTATION OF DIGITAL CONTROL AND INTELLIGENT MANAGEMENT TECHNOLOGIES

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Abstract. This article examines approaches to improving the energy efficiency and operational reliability of centrifugal pump installations used in industrial systems. Particular attention is given to the monitoring and regulation of key operational parameters such as electric motor rotational speed, pressure, power consumption, and liquid flow rate. The study highlights the role of modern sensor technologies, automated control systems, and digital monitoring platforms in optimizing pump performance. The integration of pressure, flow, temperature, energy consumption, and corrosion sensors into a unified control system enables continuous monitoring of equipment condition and the implementation of predictive diagnostics.

Keywords: centrifugal pump, energy efficiency, automated control systems, digital monitoring, predictive maintenance, industrial safety, SCADA systems, pump diagnostics.

Аннотация. В статье рассматриваются вопросы повышения энергоэффективности и надежности работы центробежных насосных установок, широко применяемых в промышленных системах. Особое внимание уделено контролю и регулированию основных эксплуатационных параметров, таких как скорость вращения электродвигателя, давление, потребляемая мощность и расход перекачиваемой жидкости. Рассматривается роль современных датчиков, автоматизированных систем управления и цифровых технологий мониторинга в оптимизации работы насосного оборудования. Интеграция датчиков давления, расхода, температуры, энергопотребления и коррозии в единую систему управления обеспечивает непрерывный контроль технического состояния оборудования и позволяет реализовать элементы предиктивной диагностики.

Ключевые слова: центробежный насос, энергоэффективность, автоматизированные системы управления, цифровой мониторинг, предиктивная диагностика, промышленная безопасность, системы SCADA, насосное оборудование.

Аннотация. Мақолада саноат тизимларида кенг қўлланиладиган марказдан қочма насос қурилмаларининг энергия самарадорлиги ва ишончлилигини ошириш масалалари кўриб чиқилган. Асосий эътибор электр двигателининг

ISSN 3030-3907

айланиш тезлиги, босим, қувват сарфи ва суюқлик сарфи каби асосий эксплуатацион параметрларни назорат қилиш ва бошқаришга қаратилган. Насос ускуналарининг ишлашини оптималлаштиришда замонавий датчиклар, автоматлаштирилган бошқарув тизимлари ҳамда рақамли мониторинг технологияларининг аҳамияти ёритилган. Босим, сарф, ҳарорат, энергия истеъмоли ва коррозия датчикларини ягона бошқарув тизимига интеграция қилиш ускунанинг техник ҳолатини узлуксиз назорат қилиш ва прогностик диагностика элементларини жорий этиш имконини беради.

Калит сўзлар: марказдан қочма насос, энергия самарадорлиги, автоматлаштирилган бошқарув тизими, рақамли мониторинг, прогностик диагностика, саноат хавфсизлиги, SCADA тизимлари, насос ускуналари.

INTRODUCTION

The mining industry relies heavily on pumping equipment, which plays a fundamental role in maintaining the continuity of many technological operations. A wide range of industrial processes cannot function effectively without the use of pumping units. These include water removal from underground and surface mining areas, hydraulic transportation of materials, pulp transfer in mineral processing plants, technological water supply, and the operation of circulating water systems. Consequently, the performance and reliability of pumping stations significantly influence the overall productivity, operational safety, and stability of mining enterprises.

Continuous water removal from underground deposits is essential for maintaining geotechnical stability and preventing flooding in active working zones. Efficient drainage systems help ensure safe working conditions and protect mining infrastructure from water-related damage. In such systems, multi-stage centrifugal pumps are commonly applied because they are capable of generating high pressure and sustaining long-term continuous operation under demanding conditions.

In open-pit mining operations, high-capacity pumping systems are required to remove accumulated quarry water and maintain the necessary working conditions within the pits. Similarly, in mineral processing and enrichment plants, pumping equipment forms an essential component of the technological process. Pumps are used to transport mineral pulp, deliver chemical reagents required for processing, and circulate technical water throughout various stages of production.

More broadly, centrifugal pump installations have found widespread application not only in mining but also in other key industrial sectors such as oil and gas production, chemical manufacturing, power generation, metallurgy, and municipal infrastructure. These pumping systems ensure the reliable transportation, circulation, transfer, and storage of various liquid media, including water,

ISSN 3030-3907

petroleum products, chemical solutions, and other technological fluids required for industrial operations.Pump equipment is one of the largest consumers of electricity in mining enterprises. In practice, pumping units can account for up to 20-40 percent of a company's total electricity consumption, and in some cases, this figure is even higher. Energy consumption depends on the following factors:

1. pump operating mode and load level;
2. Hydraulic resistance and the condition of pipelines;
3. technical condition of the unit (friction, wear, cavitation);
4. efficiency of the electric motor;
5. control method (drossing or frequency control).

In many cases, the pumps operate under conditions that do not correspond to the nominal operating mode. If there is a discrepancy between the pump characteristics of the operating point and the hydraulic system characteristics, excessive energy consumption occurs. The practice of reducing consumption through throttling reduces energy efficiency, as excess pressure is lost in the pipeline.

The high degree of involvement of pump units in technological processes makes them critical elements of production infrastructure. The reliability and stability of pump operation directly affect the enterprise's productivity, the quality of technological operations, and the level of industrial safety.

In modern conditions, improving the operating modes of pumping units is of particular importance, as their operational efficiency is determined by a combination of hydraulic, energy, mechanical, and operational factors. Unoptimal operating modes lead to excessive energy consumption, accelerated wear of assemblies, and an increased likelihood of accidents.

Improvement of the operating modes of pumping units

Optimizing the operating modes of centrifugal pumps requires comprehensive monitoring of key operating parameters. Effective operation is possible only if the relationship between productivity, energy consumption, and the technical condition of the equipment is systematically analyzed.

1. Electric motor rotation speed

The rotational speed of the asynchronous electric motor is one of the determining factors of the centrifugal pump's performance. A change in rotational speed directly affects the fluid supply, the created pressure, and the power consumed [1-10].

With an increase in rotational speed, the pump's productivity increases, but at the same time, the energy consumption and the load on the mechanical elements

ISSN 3030-3907

increase significantly. Working at high speeds can lead to increased vibrations, accelerated wear of bearing assemblies and seals.

Modern frequency control systems allow adapting the engine's rotational speed to the current requirements of the technological process. This ensures the pump's operation within optimal load ranges, reduces starting currents, decreases mechanical stresses, and contributes to energy savings [11-22].Thus, determining and maintaining the optimal rotational speed is the most important condition for energy-efficient and reliable operation of the pump unit.2.

Pump pressure and power

The stability of the pump system's operation largely depends on maintaining a balance between the operating pressure and the actual output. Changes in the network's hydraulic resistance, fluid level fluctuations, or variable technological loads lead to a shift in the pump's operating mode.

If the pump operates outside the optimal operating zone, additional hydraulic losses occur, the load on the electric motor increases, and energy consumption increases. Prolonged operation under such conditions can lead to overheating, cavitation phenomena, and a decrease in equipment life [23-29].

Constant monitoring of pressure and power consumption allows for the timely detection of deviations from the nominal regime. Modern automatic control systems are capable of adjusting the pump's operating parameters in real time, ensuring the stability of the technological process and reducing operating costs.

3. Systematic monitoring and automated management

One of the main directions for improving the efficiency of pumping units is the implementation of automatic monitoring and control systems. Such systems ensure continuous monitoring of the unit's technical condition and analysis of operational indicators in real time [23-29].

The pump's hydraulic efficiency is determined by the ratio between the volume of pumped liquid and the energy consumed. Automated systems allow tracking this ratio, identifying trends in declining efficiency, and taking corrective measures.

ISSN 3030-3907

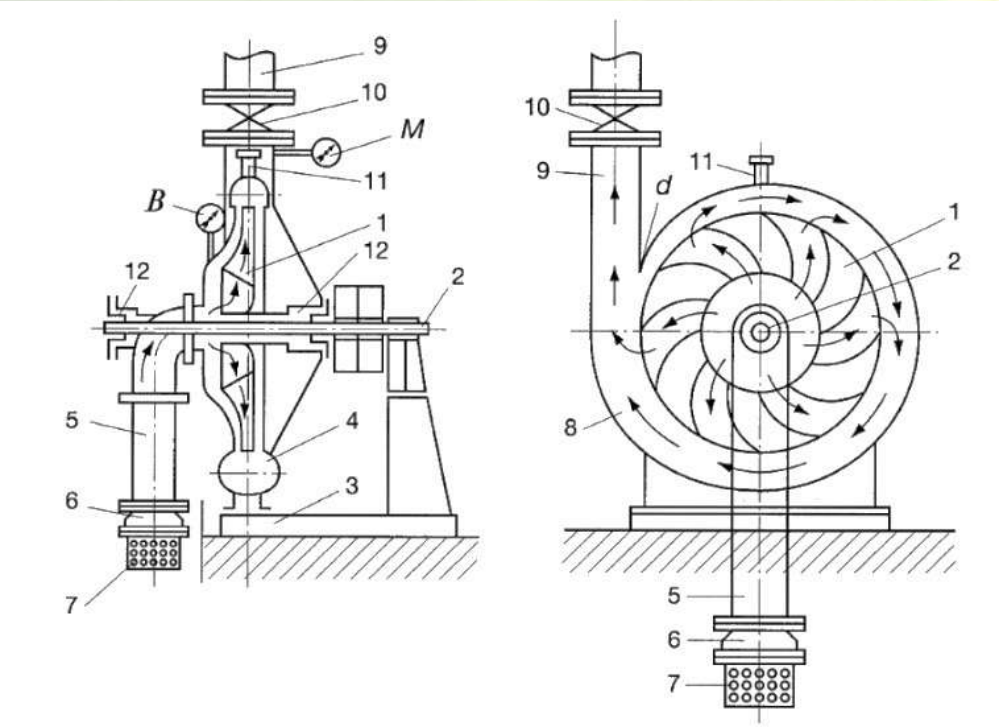


Fig.2. Principal diagram of a centrifugal pump unit.
1-Pump; 2-electric motor; 3-starting unit; 4-suction pipeline; 5-discharge pipeline; 6- reservoir; 7-protective mesh and check valve; 8, 11, 14 - gate valves; 9-reverse valve; 10-reserve pipeline; 12-filler;13-drainage pipe; 15-vacuum gauge;16-manometer;17- pump exhaust valve; H6-suction pipeline; HH - discharge pipeline; Hg - geodetic height.

To ensure intelligent and automated control of pumping equipment, a wide range of sensing devices is applied to monitor key operational parameters. These sensors play a crucial role in collecting real-time data about the functioning of the pump unit and allow the control system to respond promptly to any deviations from normal operating conditions.

Pressure sensors are installed at the inlet and outlet sections of the pumping system to continuously monitor pressure levels within the pipeline network. Their readings make it possible to detect abnormal pressure fluctuations, overload conditions, and potential instability in the operating regime of the pumping installation. Flow sensors are used to measure the quantity of liquid transported through the system. By analyzing flow rate data, operators can evaluate the actual productivity and efficiency of the pump and determine whether the equipment is functioning within the designed performance parameters.

Liquid level sensors represent another important component of the monitoring system. These devices help prevent the pump from operating in a so-called “dry running” mode, which may occur when the working fluid is absent or insufficient. Such conditions can lead to severe damage to internal components and

ISSN 3030-3907

significantly reduce the service life of the equipment. Temperature sensors are also widely used to monitor the thermal condition of critical elements such as the pump casing, bearings, and electric motor windings. An abnormal increase in temperature often serves as an early indicator of excessive load, friction, lubrication failure, or mechanical wear.

In addition, energy consumption sensors provide detailed information about electrical parameters, including power usage and current characteristics. These measurements allow engineers to evaluate the energy efficiency of the pumping unit and identify potential opportunities for reducing energy losses during operation. In environments characterized by high humidity or aggressive chemical conditions, corrosion and moisture sensors are installed to monitor the physical state of structural elements. These devices help prevent premature degradation of equipment materials and increase the reliability and durability of the pumping system.

The integration of all these sensors into a unified automated control system enables comprehensive monitoring and analysis of the technical condition of the pumping unit. Such an approach not only helps maintain optimal operating conditions but also creates the foundation for predictive diagnostic methods aimed at preventing equipment failures before they occur.

Modern industrial standards related to energy efficiency, reliability, and occupational safety require a transition from traditional periodic inspection methods toward continuous monitoring of pumping equipment. Conventional maintenance practices based solely on scheduled inspections are often insufficient, as they may fail to identify hidden defects in a timely manner and do not provide rapid responses to sudden changes in operating conditions.

Systematic monitoring involves the continuous collection, processing, and analysis of operational data in real time. Information from various measuring instruments is transmitted to a centralized control platform, where it is visualized, stored in databases, and subjected to analytical evaluation. This allows engineers and operators to track performance trends and detect deviations from normal operating parameters at an early stage.

A key component of modern automated control systems is the integration of pumping units into the enterprise’s unified digital infrastructure. Within this framework, programmable logic controllers (PLCs), supervisory control and data acquisition (SCADA) systems, and industrial communication modules are widely used. The application of these technologies provides several important advantages, including:

centralized monitoring and control of technological parameters;

ISSN 3030-3907

automatic maintenance of predetermined operating regimes;
generation of emergency warnings and alarm signals;
recording and analysis of deviations from normal operating conditions;
remote supervision and control of equipment operation.

The implementation of closed-loop control systems is particularly important for ensuring stable pump operation. In such systems, actual operating parameters—such as pressure, flow rate, and temperature—are continuously compared with predefined reference values. Based on the difference between these parameters, the control system generates corrective actions that influence actuating mechanisms. For example, the rotational speed of the electric motor can be adjusted using a frequency converter. This approach makes it possible to maintain a stable technological process even when external loads and operating conditions change.

Another important direction in the development of automated pumping systems is the integration of intelligent data analysis methods. The accumulation of operational data over long periods makes it possible to identify patterns in equipment behavior, analyze trends in parameter variation, and forecast the probability of future failures. Such analytical capabilities support the concept of predictive maintenance, where repair and maintenance activities are scheduled based on the actual technical condition of the equipment rather than fixed service intervals. As a result, enterprises can significantly reduce downtime, optimize maintenance costs, and increase the overall reliability and efficiency of pumping systems.

Additionally, automated control systems contribute to:

1. reduction of the influence of the human factor;
2. minimization of the probability of emergencies;
3. increasing the overall reliability of the technological chain;
4. reduction of equipment downtime;
5. optimization of energy consumption in dynamic modes.

In conditions of aggressive or explosive environments, automated monitoring is of particular importance, as it allows for monitoring critical parameters without the constant presence of service personnel. This significantly increases the level of industrial and environmental safety.

Thus, systematic monitoring and automated control are integral components of modern pump infrastructure. Their implementation ensures the transition from a reactive operating model to an intelligent model focused on optimization, stability, and long-term reliability of equipment.

CONCLUSION

ISSN 3030-3907

Improving the operational efficiency of centrifugal pump installations remains one of the key challenges in modern industrial engineering. The effective functioning of pumping systems largely depends on the continuous monitoring and regulation of critical operational parameters such as the rotational speed of the electric motor, pressure levels within the pipeline system, power consumption, and the flow rate of the transported fluid. Careful supervision of these parameters, combined with the application of advanced monitoring technologies and automated control systems, allows industrial enterprises to significantly enhance the overall performance of pumping equipment.

The integration of modern automation tools provides the opportunity to optimize pump operation under varying load conditions and technological requirements. By utilizing digital monitoring platforms, sensors, and intelligent control algorithms, operators can obtain accurate real-time information about the state of the pumping system and quickly respond to any deviations from normal operating conditions. Such an approach not only improves energy efficiency but also increases the reliability and safety of equipment during long-term operation.

The implementation of intelligent control systems also contributes to reducing operational and maintenance costs. Through automated regulation and predictive diagnostics, it becomes possible to prevent emergency failures, extend the service life of pumping units, and reduce the frequency of unplanned shutdowns. As a result, industrial enterprises can ensure greater stability and continuity of technological processes.

Therefore, the further development of automated control methods and optimization techniques for centrifugal pump operating modes represents a promising direction for both scientific research and the practical modernization of industrial infrastructure. The introduction of innovative digital solutions in pumping systems will continue to play an essential role in improving energy efficiency, reliability, and sustainability in modern industry.

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ISSN 3030-3907

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ISSN 3030-3907