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Efficiency of electric drive of a centrifugal pump unit

Abstract. The study was carried out to analyse ways to improve the efficiency of the electric drive of a centrifugal pumping unit and to determine the optimal approaches to its energy-efficient operation. Efficiency analysis, experimental studies and theoretical models were employed to assess the impact of technologies on the energy consumption of pumping units. The study determined that the use of frequency control can significantly reduce energy consumption during the operation of a centrifugal pumping unit, especially under variable load conditions. The highest efficiency is achieved when the pump operates at optimum speeds, which can be achieved using variable frequency drives (VFDs). The study also determined that the correct selection of the pump impeller and its maintenance is essential to reduce energy losses. Losses in mechanical connections can be minimised by using high-quality components and regular maintenance of the equipment. The study confirmed that automated control systems significantly improve the efficiency of pump operation, ensuring timely correction of operating parameters following the operating conditions. The conclusion demonstrated the need to implement a comprehensive approach to optimise the energy consumption of pumping units. The study determined that reducing mechanical losses in drives and pumping units using modern technologies significantly increases system efficiency. The introduction of integrated monitoring systems to control pump operation can significantly reduce downtime and improve overall equipment reliability. Notably, the modernisation of electric drives has a positive impact on the energy efficiency of pumping systems through the introduction of innovative materials and design solutions. The study determined that the introduction of new models of electric motors with improved

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performance contributes to more rational use of energy. In addition, the study proved that regular diagnostics and preventive maintenance of equipment contribute to the stable operation of pumping units, reducing the likelihood of emergency stops and unforeseen repairs

Keywords: control systems; electric motor; mechanical costs; energy saving; energy consumption; optimal parameters; diagnostics

INTRODUCTION

The efficiency of the electric drive of a centrifugal pump unit is a key factor in determining the performance and energy efficiency of pumping systems in various industries. In the context of global changes associated with rising energy prices and tighter environmental requirements, the need to optimise the performance of pumping units is becoming increasingly important. Centrifugal pumps are central in many industrial processes, as they are used to pump liquids in areas such as water supply, wastewater, chemical, petrochemical, food processing, and cooling and heating systems.

The efficiency of centrifugal pumps directly depends on their design features, the choice of electric motors and operating conditions. For instance, choosing the right size and type of pump can have a significant impact on its performance and energy consumption. Modern technologies, such as variable frequency drive, allow pumps to adapt to changing load conditions, which can significantly reduce energy costs (Ratushnyak *et al.*, 2022). Automated control systems also enable real-time monitoring and control of pumping units, which increases their efficiency and reliability. Regular maintenance and modernisation of equipment is an important aspect of improving efficiency. Timely diagnostics and preventive maintenance identify and eliminate potential problems that could lead to reduced productivity or increased energy costs. The use of new technologies and materials, such as improved impellers or high-efficiency electric motors, further reduces energy losses and ensures the stable operation of pumping units (Golyshev & Mysak, 2012). Thus, a comprehensive approach to optimising pumping systems not only improves their energy performance but also helps to reduce their negative impact on the environment. Existing research on this topic already covers several aspects, such as the impact of variable frequency drives (VFDs), motor selection, maintenance, and new impeller materials. D. Kaya *et al.* (2021) demonstrated how VFDs can significantly improve the energy efficiency of centrifugal pumps. However, their study does not sufficiently consider the impact of different pump operating modes on the overall system performance, while J. Gómez *et al.* (2022) pointed out the importance of selecting motors with high efficiency to reduce energy costs. However, there is insufficient consideration of how motor models affect operating costs under different load conditions.

H. Dui *et al*. (2022) studied the role of regular maintenance of pumping systems in maintaining their efficiency, but their work does not cover the impact of different types of maintenance on reducing the risk of accidents, and Y. Hu *et al.* (2021) highlighted the use of new materials for impellers that reduce mechanical losses but did not consider the economic aspects of introducing such technologies into production. M. Christensen *et al*. (2021) investigated the automation of management processes to improve the stability of pump operations but did not sufficiently consider the integration of automated systems into existing infrastructure. C. Vering *et al*. (2021) highlighted the need to adapt pumping systems to changing operating conditions, but their study did not cover specific parameters that may be critical for regional conditions. W. Cai *et al*. (2021) addressed the economic benefits of new technologies, although omitting the long-term investment costs of their implementation. S. Angadi *et al*. (2021) noted the potential for alternative energy sources to power pumps but did not sufficiently consider their integration into existing systems. P. Brockway *et al*. (2021) described energy efficiency in the context of climate change, but do not focus on specific technologies that can reduce environmental impact. P. Das *et al*. (2021) addressed the integration of pumping systems into the overall energy management system but did not sufficiently address the aspects of interaction with other infrastructure elements.

However, despite these results, some gaps need to be further explored, such as the lack of attention to the integration of automated control systems, which could further optimise pump performance.

The study aimed to analyse the existing methods of improving the efficiency of the electric drive of a centrifugal pump unit and determine the optimal approaches to their energy-efficient operation. Research objectives:

1. To study the influence of VFDs on the energy efficiency of the electric drive of a centrifugal pump unit.
2. To investigate the optimal parameters of pump operation under variable load conditions to improve their performance.
3. To evaluate the effectiveness of various methods of pumping system maintenance to reduce energy costs.

MATERIALS AND METHODS

The study was carried out in 2023 based on the laboratory of energy-efficient technologies of NasosEnergo LLC to assess the efficiency of the electric drive of a centrifugal pump unit of the Wilo CronoNorm NHIL 65/250 type. The pump had a capacity of 120 m^3/h, a head of 55 m and was equipped with a 30-kW squirrel-cage induction motor. The equipment was manufactured by Wilo SE. This type of pump is widely used in water supply, wastewater treatment and industrial technologies. The following equipment was used for the experiments:

1. Asynchronous motor. The experimental setup used a 30 kW Siemens 1LE15032AA204FA4 AC squirrel-cage induction motor equipped with a Siemens Sinamics G120 VFD. The VFD allowed the motor speed to be changed from 1500 to 3000 rpm, which ensured adaptation to different load conditions. The speed control helped to increase the system's efficiency by optimising the pump's operation at partial load.

2. Sensors. Flow sensors: Siemens Sitrans F M MAG 6000 for measuring liquid volumetric flow with an accuracy of ±0.2%. Pressure sensors: WIKA A-10 for monitoring the pressure at the inlet and outlet of the system, with an accuracy of 0.1% of the measured value. Temperature sensors: RTD PT100 for monitoring the temperature of the working environment. Power sensors: Siemens Sentron PAC3200 to record power consumption.

3. Data collection system. Siemens Simatic WinCC software was used to analyse the unit's operating parameters, which automatically collected and stored data on the pump's operation. This was used to visualise and monitor indicators in real-time, as well as to analyse system performance in detail.

The use of a frequency-controlled induction motor has improved the energy efficiency of the pumping unit and ensured stable operation under variable loads. To assess the efficiency of the electric drive, a series of experiments were conducted with varying load conditions: from the minimum to the nominal performance level. The temperature conditions varied between 15-25°C, and the system pressure was maintained at 2.5 bar. Experimental data shows that the overall efficiency of the pump reached 85%, with the maximum efficiency value recorded at partial load when the VFD regulated the speed to 2400 rpm.

In the study of the efficiency of the electric drive of a centrifugal pump unit, the key factors affecting the performance and energy efficiency of pumping systems were identified. Particular attention was paid to the efficiency of electric motors, which convert electrical energy into mechanical energy. The total efficiency μ accounts for energy losses to overcome hydraulic, volumetric and mechanical losses during the transfer of energy to the fluid and is determined by three efficiencies (1):

$$\mu = \mu_m \times \mu_g \times \mu_v, \quad (1)$$

where μ_m – mechanical efficiency; μ_g – hydraulic efficiency; μ_v – volumetric efficiency.

Determining the value of each of these coefficients was critical to assessing the overall efficiency of a pumping unit (Moshnoriz *et al.*, 2021). During the study, experimental measurements were carried out to assess the actual efficiency of pumping systems under different load conditions and rotational speeds. One of the main tasks was to study the possibilities of regulating the speed of electric motors using VFDs. This helped to reduce energy consumption, especially in cases of partial load. Thanks to the use of VFDs, the power consumption of the pumps was reduced while maintaining the required performance. Formula (2) was used to determine the mechanical losses in the system:

$$P_m = P_{in} - P_{out}, \quad (2)$$

where P_m – mechanical losses; P_{in} – input power; P_{out} – output pump power.

The analysis of the research results was based on the study of design features, selection of electric motors and operating conditions of pumping systems. To evaluate the efficiency of the electric motor and the pumping unit with an asynchronous squirrel-cage motor, the formula for calculating the efficiency of the electric motor was used (3):

$$\mu = \frac{P_2}{P_1}, \quad (3)$$

where P_2 – useful mechanical power on the motor shaft; P_1 – electrical power consumed from the grid.

This formula determined how efficiently electrical energy is converted into mechanical energy, accounting for heating losses and other factors. Formula (4) is used to determine the pump power:

$$N = \frac{p \times g \times Q \times H}{\mu}, \quad (4)$$

where p – liquid density; g – acceleration of free fall; Q – volumetric flow rate; H – pressure; μ – overall efficiency.

This formula shows how much useful work a pump does to pump a liquid to a certain height. The following formula (5) is used to calculate the power of the electric motor when using a gearbox:

$$N_{mot} = \frac{N_{useful}}{\mu_e} \times k, \quad (5)$$

where N_{useful} – useful pump power; μ_e – gearbox efficiency; k – reliability factor.

This formula accounted for additional losses in the gearbox and possible overloads. The experiments determined the overall efficiency of the system at 85%, the maximum value of which was achieved at partial load with engine speed control up to 2400 rpm using a VFD. This significantly reduced energy consumption without diminishing pump performance.

RESULTS

The efficiency of an electric motor is one of the most important parameters that determine its performance. In the context of converting electrical energy into mechanical energy, efficiency is not only a performance indicator but also an important factor affecting energy consumption, equipment operation costs and environmental aspects of its use. Electric motors, in particular asynchronous motors, are central to modern industrial processes. They are used to power a variety of machines and mechanisms, including pumping units, fans and compressors. The efficiency of modern induction motors ranges from 90-95% (de Souza *et al.*, 2022). This means that most of the consumed electrical energy is converted into useful mechanical work. The IE1, IE2, and IE3 classes provide consumers with the opportunity to choose motors with different levels of energy efficiency (Zheng, 2022). The higher the class, the less energy is spent on conversion, which directly affects energy savings.

Electric motor with high efficiency not only reduces electricity costs but also contributes to the reduction of greenhouse gas emissions, as less energy consumption usually leads to lower emissions from power plants. The importance of electric motor efficiency is also emphasised in the context of global efforts towards energy efficiency and sustainable development. Reduction of energy consumption is an important challenge for industry, especially in the face of rising energy prices and global climate change. The use of high-efficiency electric motors can be an important step in this direction, as they not only reduce costs but also improve overall productivity. However, to maximise the efficiency of an electric motor, the selection of a high-efficiency model is not enough. The correct choice of operating parameters, including speed, load and operating conditions, are also important factors. For instance, the use of VFDs can significantly increase the overall efficiency of a system, as they can be used to adjust the motor speed according to demand, reducing energy losses during partial load operation. In summary, the efficiency of an electric motor is a key indicator that affects the efficiency and cost-effectiveness of its operation. Modern asynchronous motors with efficiencies of up to 90-95% open new opportunities for energy saving and reducing the environmental footprint. Given the growing demands for energy efficiency in all industries, choosing motors with high efficiency is not only economically viable but also necessary for the sustainable development of society. However, to accurately determine the overall efficiency of a pumping system, it is not only the efficiency of the motor that needs to be accounted for but also other important factors.

The mechanical efficiency depended on the quality of the components used in the system and their wear, while the hydraulic efficiency was determined by the pump design and operating conditions. Modern asynchronous electric motors can achieve efficiencies of up to 90-95%, which is an important factor in ensuring high efficiency in converting electrical energy into mechanical energy. At the same time, the energy efficiency of the pumps themselves varied, with typical efficiency values ranging from 60-85%. Design characteristics such as impeller type and size were found to have a significant impact on pump efficiency. The energy efficiency of the pumping unit was determined by key technical parameters that affected the overall performance of the system. Centrifugal pumps were characterised by a wide range of efficiencies, which depended on their design, size and impeller type. Typically, the efficiency of pumps varied between 60-85%, which was due to the specifics of the design elements and operating conditions.

The geometry and material of the impeller were one of the determining factors of efficiency. The quality of this component directly affects the energy loss as the fluid moves through the pump. An impeller that was incorrectly proportioned or made of poor-quality materials created additional drag, resulting in lower efficiency. In addition, pump size played an important role: large-displacement pumps demonstrated higher efficiency at high flow rates but could be less efficient at low flow rates. Operating conditions also had a significant impact on the efficiency of pumping units. High pressures and fluctuations in fluid flow contributed to energy losses as the pump operated at higher loads. To reduce these losses, VFDs were used to adjust the motor speed to the actual needs of the system, which reduced energy consumption and increased overall energy efficiency. Maintenance of the pumping units was an important aspect of ensuring their stable operation. Wear and tear of components such as bearings, seals or belt drives contributed to a decrease in efficiency due to increased mechanical losses. Preventive maintenance and timely replacement of worn parts helped to maintain optimal system performance. Thus, the energy efficiency of centrifugal pumps was improved by optimising design solutions, adjusting operating conditions and introducing speed control technologies, as well as regular maintenance.

The speed control of a centrifugal pump unit has become an important tool for optimising the energy efficiency of the system. The use of VFDs made it possible to adapt the operation of the electric motor to the actual needs of the pumping system by changing the motor speed. This was especially important in cases where the pump was operating at partial load or in conditions of variable fluid flow. The use of VFDs to control pump speeds is an effective method of optimising pump performance, as shown in Table 1. This reduces energy costs and improves overall pumping system performance in a variety of operating conditions.

Table 1. Controlling the speed of pumps with a VFD

Parameter	Description
Adjustment method	VFD for motor speed control
Advantages	Reduced energy consumption by adapting the speed to the load
Operation optimisation	Allows pumps to operate at partial load, which reduces energy costs
Conditions of use	Important in variable flow conditions and with variable system performance requirements
Impact on efficiency	Improves overall system efficiency by reducing energy losses
Adjustment range	Can provide a wide range of speed control, suitable for different pumps
Examples of use	Applications in water supply, irrigation, industrial systems, HVAC systems
Technical specifications	Depends on the type of VFD; and may include maximum and minimum frequencies, rated currents
Economic effect	Reduced operating costs due to lower energy consumption

Source: compiled by the author based on D. Bordeasu *et al*. (2023)

Classic systems, where the motor speed remained constant, resulted in excessive energy consumption as the pump continued to run at full capacity even when the pumping demand was reduced. The use of a VFD solved this problem. By regulating the motor's power frequency, the VFD allowed the speed to be precisely adjusted to the actual operating conditions, thereby reducing unnecessary energy consumption. An important feature of using VFDs was also the reduction of mechanical losses in the system, which occurred in mechanical connections such as couplings or belt drives. Formula (2) was used to estimate such losses. For instance, a pumping system received an input power , but the system provided only 90 kW of useful work at the output. In this case, the mechanical losses are calculated using formula (2):

$$P_m = 100_{kW} - 90_{kW} = 10_{kW}.$$

Consequently, power losses amounted to 10 kW, which indicated a decrease in the overall efficiency of the system. It was therefore important not only to optimise the operation of the pumps with the VFDs but also to minimise mechanical losses in the connections. By reducing energy losses through speed control, the overall efficiency of the system was improved, and energy costs were reduced. In cases where the pump operated at partial load or in variable flow conditions, the use of VFDs made it possible to flexibly adjust the motor operation, saving energy resources. The use of this technology was not only cost-effective but also contributed to increased reliability and service life of the equipment.

To evaluate the efficiency of the electric drive of a centrifugal pump unit with an asynchronous motor with a squirrel-cage rotor, the efficiency of the electric motor was calculated using formula (3). Electric power consumption $P_1 = 32$ kW, and the useful mechanical power at the pump shaft $P_2 = 27.2$ kW.

$$\mu = \frac{27.2}{32} = 0.85\ (85\%).$$

Thus, the efficiency of the induction motor was 85%. This indicates the efficient conversion of electrical energy into mechanical energy with minimal losses. The useful power of the pump was calculated using formula (4). For a pump with a volumetric flow rate $Q = 120$ m^3/year = = 0.0333 m^3/s, of pressure H = 55 m, and water density p = 1000 kg/m^3 calculation made:

$$N = \frac{1000 \cdot 9.81 \cdot 0.0333 \cdot 55}{0.85} = 21.23 \text{ kW}.$$

Therefore, the useful power of the pump is 21.23 kW at maximum head and capacity. The calculation of the required power of the electric motor with gearbox is calculated using formula (5). When connecting the pump via a gearbox with efficiency and reliability factor , the required motor power is determined as follows:

$$N_{mot} = \frac{21.23}{0.95} \cdot 1.15 = 25.7 \text{ kW}.$$

This value demonstrates that an electric motor of at least 25.7 kW is required to provide the required performance and compensate for the losses in the gearbox. Energy loss in mechanical connections is an important aspect that affects the overall efficiency of pumping units. The process of transferring mechanical energy from the electric motor to the pumping system was often accompanied by certain losses due to friction, wear and tear of components and inefficiencies in connecting components such as couplings and belt drives. These losses reduced the overall performance of the unit, lowered efficiency and increased energy costs. One of the main sources of losses is friction in mechanical joints. Couplings and belt transmissions transmit torque from the engine to the pump's working elements. This created significant friction forces that prevented efficient energy transfer (García Moreno, 2023). These forces depended on the condition of the components, the accuracy of their adjustment, and the operating conditions. Incorrect installation or wear of the connection elements led to an increase in friction and, as a result, additional energy losses. Another important loss factor was the loss of energy due to inefficient torque transmission. Couplings and belt drives can absorb some of the energy transferred from the motor to the pump. This is due to both the design features of these components and deformations or displacements during operation. High-quality materials and fine-tuning of mechanical connections could significantly reduce these losses, ensuring more stable and reliable operation of the pump unit. In addition, regular maintenance and component condition monitoring played a key role in reducing losses. Wear and tear on mechanical joints such as bearings or belts contributed to increased losses due to friction and improper power transmission. During the operation of the pumping units, it was important to replace worn parts on time and to carry out preventive maintenance to maintain high levels of efficiency.

In general, minimisation of losses in mechanical connections was achieved by using high-quality components, correct gearing and regular maintenance. Recommendations for minimising energy losses in mechanical connections of pumping systems are shown in Table 2. Optimisation of these factors has increased the efficiency of the pumping unit, reduced energy consumption and ensured stable operation of the system in various operating modes.

Table 2. Energy losses in mechanical connections of pumping systems and ways to minimise them

Aspect	Description	Recommendations
Type of mechanical connection	Couplings and belt drives	Use of high-quality and reliable components
Efficiency Impact	Energy loss due to friction and wear	Regular maintenance and replacement of worn parts
Settings	Incorrect settings can lead to losses	Correct belt tension and alignment settings

Continued Table 2.

Aspect	Description	Recommendations
Efficiency	Efficiency may decrease due to mechanical losses	Using technology to improve efficiency
Maintenance	Essential for maintaining efficiency	Regular inspections and maintenance
Potential losses	Loss of mechanical energy	Assessment and monitoring of mechanical losses

Source: compiled by the author based on K. Kan *et al*. (2022)

Based on the obtained dependencies, the characteristic of the efficiency of an induction motor with a squirrel-cage rotor is shown in Figure 1.

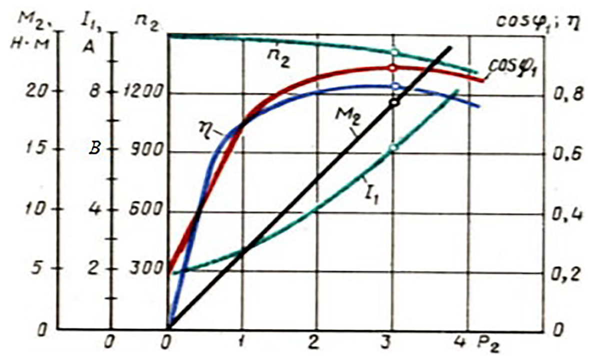

Figure 1. Characteristics of the efficiency of an induction motor with a squirrel-cage rotor

Source: compiled by the authors

This characteristic is in line with the engine's data sheet and has been confirmed by production tests. The efficiency of an induction motor has a parabolic shape and is described by the following equation (6):

$$\mu = E_1 + E_2 P + E_3 P^2, \quad (6)$$

where E_1, E_2, E_3 – approximation coefficients.

To determine these coefficients, three power values were substituted for the three values of efficiency, and a system of equations was solved. The resulting efficiency equation was as follows:

$$\mu = 0.75 + 0.012P - 0.0001P^2.$$

Based on this formula, a structural diagram was built to calculate the efficiency of an induction motor with a squirrel-cage rotor depending on the power at the motor shaft (Fig. 2).

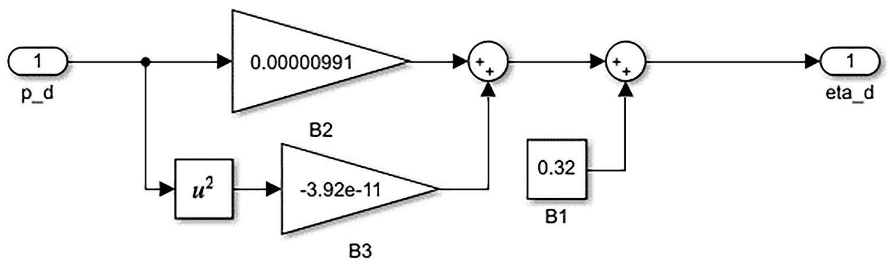

Figure 2. Block diagram for determining the efficiency of an asynchronous motor with a squirrel-cage rotor depending on the power at the shaft

Source: compiled by the authors

According to this scheme, the motor efficiency can be calculated by knowing the power at the shaft P_2 which is defined as the product of the electromagnetic torque M and the angular velocity ϑ. Thus, obtaining instantaneous values of torque and rotational speed made it possible to calculate the instantaneous value of the motor efficiency. Next, the efficiency characteristic of the Wilo CronoNorm NHIL 65/250 pump unit was plotted. This characteristic corresponds to the pump's passport data and has been confirmed by tests. The analytical dependence of the pump efficiency is parabolic. This characteristic is specified in the passport data of the pump series and confirmed by control tests of individual pumps from the production batch in production. The efficiency curve of an induction motor is parabolic and can be represented by the following analytical expression (8):

$$\mu(v, q) = A_1 \times v^2 + A_2 \times v \times q + A_3 \times q^2, \quad (8)$$

where A_1, A_2, A_3 – approximation coefficients; v – speed of rotation of the pump impeller, expressed as a relative value to the nominal speed.

By substituting three power values corresponding to three efficiency values into the efficiency equation, a system of three equations was obtained for the rated speed:

$$\begin{cases} 0.45 = A_1 + A_2 \times 0.014 + A_3 \times 0.014^2 \\ 0.65 = A_1 + A_2 \times 0.029 + A_3 \times 0.029^2 \\ 0.6 = A_1 + A_2 \times 0.039 + A_3 \times 0.039^2. \end{cases}$$

This system of equations was solved, and the values of the approximation coefficients were found. The equation for the pump's efficiency was therefore as follows:

$$\mu(v, q) = -0.027 \times v^2 + 44.494 \times (v \times q) - 729.351 \times q^2.$$

The total accounts for energy losses to overcome hydraulic, volumetric and mechanical losses during the transfer of energy to the fluid and is determined by the three components of efficiency according to formula (8). For instance, a pumping unit where the mechanical efficiency is 92% ($\mu_m = 0.92$), hydraulic – 85% ($\mu_d = 0.85$), and volumetric efficiency – 98% ($\mu_c = 0.98$). Using the formula (8), we calculated the total efficiency of the system:

$$\mu = 0.92 \times 0.85 \times 0.98 = 76.64\%.$$

That is, 76.64% of the total electrical energy supplied to the system is converted into useful mechanical work. The remaining 23.36% was lost through hydraulic, mechanical and other internal system resistance. Thus, the efficiency of the pumping unit depended largely on each of its components. Optimisation of each of these coefficients would significantly improve the overall energy efficiency of the system and reduce operating costs.

Automated pump control systems are key to ensuring the energy efficiency of pumping units. In dynamic operating conditions, when fluid volumes or system pressures change, traditional control methods are often not flexible enough. Automation makes it possible to respond to these changes in real-time, ensuring optimum energy use and maximum equipment performance. Automated systems analyse input data on fluid parameters such as volume, pressure, and flow rate and adjust the pump's operating mode accordingly (Hieninger *et al.*, 2021a). This mitigated unnecessary overloading or underloading of the system, which led to increased energy consumption or reduced efficiency. For example, when the volume of liquid being pumped decreased, the system automatically reduced the pump's power, reducing its electricity consumption while maintaining the required level of performance (Anisimov *et al.*, 2018). Automation ensured constant monitoring of the system. This included tracking temperature, vibration, pressure, and other indicators that could indicate possible malfunctions or reduced efficiency. In the event of deviations, the system could independently adapt the pump's operation to prevent breakdowns and maintain its optimal performance. This approach minimised equipment downtime and reduced repair and maintenance costs. In addition, automated control systems made it possible to integrate pumps with other components of the energy and industrial infrastructure, creating a single control platform. This contributed to more efficient coordination of the various elements of the system and ensured that their operation was consistent with current requirements. As a result, the pumps could work in harmony with other installations, which increased the overall energy efficiency of the system.

In general, the introduction of automated pump control systems has significantly contributed to the optimisation of energy consumption. These systems allowed for real-time demand response, ensuring stable and efficient operation of the pumping unit, which was especially relevant in conditions of variable flow or pressure.

The technical condition of equipment is substantial in ensuring efficiency and reliability. During the operation of pumping units and other machines, their performance can be significantly reduced due to wear and tear of individual components or deficiencies in overall maintenance. This phenomenon has a direct impact on overall energy consumption and operating costs, therefore highly necessary to maintain the proper technical condition of the equipment. Wear and tear of components such as bearings, couplings and motors are a normal process in prolonged operating cycles. Bearings, which support moving parts, can be subjected to high loads, which causes further wear and tear. This, in turn, can cause vibrations, noise, and increased friction, which negatively impacts the overall efficiency of the system. Replacing worn bearings at the proper time is essential to maintaining stable and effective operation of the equipment. Improper maintenance can also cause reduction in performance (Mohammadi *et al.*, 2023). Lack of regular checks and preventive maintenance can leave small problems unaddressed that eventually develop into serious damage. For instance, insufficient lubrication can cause increased friction, which in turn leads to overheating and additional wear and tear on components. Changing lubricants in a timely manner and regularly checking the system for leaks are critical to maintaining high efficiency. Monitoring the condition of the wiring is another important aspect of maintenance. Damaged or worn wiring can cause short circuits, further impeding operation of electronics (Chen *et al.*, 2022). This, in turn, increases energy consumption and reduces the operational life of electric motors. Regular inspections of electrical connections, their insulation and protection are necessary for preventing such problems and ensure stable operation of the entire system.

Therefore, maintenance of proper technical condition of the equipment is critical to effective operation. Regular preventive maintenance, timely bearing replacement and upkeep of the condition of electrical wiring help prevent performance degradation while maintaining the high efficiency and reliability of pumping units and other mechanical systems. Investing in maintenance reduces operating costs and extends the service life of the equipment.

DISCUSSION

In the course of studying the efficiency of the electric drive of a centrifugal pump unit, results were obtained that confirm the importance of efficiency as the main indicator of pumping system performance. The study determined that modern asynchronous electric motors can achieve an efficiency of 90-95%, which indicates a high efficiency of converting electrical energy into mechanical energy. This, in turn, reduces energy consumption and increases the overall performance of the pumping unit. This was also investigated by I. Husain *et al.* (2021), where the results confirmed that the efficiency of an electric drive depends on design characteristics such as power, motor type, and control system. Asynchronous electric motors are most efficient under constant load conditions, while synchronous motors demonstrate higher performance in variable modes. The introduction of modern control systems, such as VFDs, can reduce energy costs by 20-30%. B. Kim *et al.* (2022) also showed that the design parameters of pumping systems, such as the type of pump and the geometry of its impeller, have a significant impact on energy efficiency. Optimised pump designs can achieve energy savings of 15-25% compared to conventional designs. The choice of lightweight and durable materials also reduces mechanical losses and improves overall system efficiency, underlining the importance of the latest technology in pump design. It is worth noting that further research in this area could focus on the introduction of innovative technologies that will further improve the efficiency of electric drives and pumping systems. In particular, the integration of smart sensors and real-time monitoring systems can provide more accurate control over energy consumption and equipment performance. It is also important to consider environmental aspects and energy efficiency in the development of new technologies. The use of renewable energy sources and improvements to existing systems can not only reduce energy costs but also contribute to sustainable development and reduce the negative impact on the environment (Qawaqzeh *et al.*, 2020). These changes open new opportunities to reduce costs and improve overall efficiency in the industry.

The study also demonstrated that the energy efficiency of the pumps, which ranged from 60-85%, was highly dependent on design features. For instance, the type and size of the impeller, as well as the materials used to make the pump components, had an impact on the hydraulic efficiency of the pump. These results confirm that optimising the design of pumps can be a key factor in improving their efficiency. T. Capurso *et al.* (2022) concluded that key factors affecting the efficiency of pumping units include design features, operating conditions, and environmental conditions. The type of pump, its geometry, materials, and installation quality are important. The operating mode affects the ratio between flow and head, which can lead to overloading or underloading of the unit. External factors, such as fluid temperature and the presence of mechanical impurities, can also reduce pump efficiency. T. Hieninger *et al.* (2021b) determined that VFDs contribute to the efficiency of pumping units by allowing the motor speed and pump performance to be adjusted to meet actual needs. Their use reduces energy consumption, reduces mechanical wear and improves the reliability of the units by avoiding sudden load changes. Thus, VFDs are an important tool for achieving high efficiency in pumping systems, which reduces operating costs. These results confirm the above study, as they demonstrate a close link between pumping unit efficiency and the introduction of VFDs. The analysis showed that the use of these technologies can significantly reduce energy costs while maintaining system stability. The study found that under conditions of variable demand, VFDs optimise pump performance, ensuring that they operate at maximum efficiency. In addition, the results confirm that the correct choice of VFD parameters can reduce the risk of mechanical failures and extend the service life of pumping units. This approach not only improved efficiency but also increased the overall reliability and safety of the systems. These findings thus highlight the importance of integrating the latest technologies into traditional processes to achieve optimal performance in pumping systems.

The analysis showed that VFDs improved the efficiency of electric drives. The study found that controlling the motor speed with a VFD allows the pumps to adapt to changing operating conditions, which in turn reduces energy consumption. In situations of partial load, when the pump does not operate at full capacity, the use of VFDs has significantly reduced energy consumption (Panchenko *et al.*, 2018). It is worth noting the work of B. Kim *et al.* (2023), also found that the value of mechanical losses in pumping systems is a critical aspect that affects their overall efficiency. Mechanical losses occur due to friction between moving parts, as well as due to vibrations and unstable operation of the units. These losses can reduce the efficiency of pumps, as part of the energy consumed is converted into heat, resulting in reduced performance. Effective management of mechanical losses, including regular maintenance and design optimisation, can significantly improve the overall efficiency of pumping systems and reduce operating costs. In turn, A. Matiane *et al.* (2021) concluded that the impact of component quality on the overall performance of pumping systems is also a significant factor. High-quality materials used in the construction of pumps can reduce mechanical losses and improve the durability of the units. For example, the use of wear-resistant materials for bearings and seals ensures more efficient pump operation by reducing friction and increasing reliability (Filimonov & Bacherikov, 2022). In addition, high-quality components help pumping systems to better adapt to different operating conditions, which in turn increases their overall performance and efficiency. Thus, investing in quality materials and components is essential to achieving consistent and high performance in pumping systems. These findings are consistent with the findings in the previous section, as they highlight the importance of controlling mechanical losses to ensure high efficiency in pumping systems. The analysis of mechanical losses shows that reducing them can have a significant impact on overall efficiency. This is consistent with previous findings that regular maintenance and improvements in pump design can reduce energy losses, thereby increasing performance. Furthermore, the results confirm that the quality of components has a direct impact on the overall performance of pumping systems. High-quality materials not only reduce the risk of mechanical failures but also ensure stable operation under different conditions. This is in line with the previously mentioned points about the importance of investing in reliable and durable components to maintain system efficiency. As a result, the evidence suggests that increased attention to mechanical losses and component quality is key to optimising pumping system performance.

However, despite the high efficiency of modern electric motors, the study found that mechanical losses in the system also affect the overall efficiency of the pump unit. The study showed that energy losses in mechanical connections such as couplings and belt drives lead to a reduction in efficiency. Minimising these losses by using quality components and proper system setup is therefore an important aspect of improving performance. K. Abidov *et al.* (2023) also conducted a study that confirmed that automation of pumping unit control is an important aspect of modern water supply systems and industrial processes. It increases control accuracy, reduces the human factor, and provides a quick response to changes in operating conditions. The integration of sensors and modern controllers allows for real-time monitoring of pump parameters, fault detection and optimisation of operating modes, which reduces energy costs and increases the overall efficiency of systems. Y. Wang *et al.* (2021) also identified that adaptive control systems play a key role in ensuring the energy efficiency of pumping units. They automatically adjust to changes in operating conditions, which allows for optimised pump performance and reduced energy consumption. They also improve pump reliability by anticipating and adjusting parameters in response to changes. In this way, adaptive control systems contribute to the achievement of high standards of energy efficiency and environmental friendliness of pumping systems. By comparing the data obtained in the course of the research, it is possible to identify clear trends that indicate a significant impact of automation and adaptive control systems on the efficiency of pumping units. In particular, the analysis showed that the introduction of automated solutions can reduce energy consumption by up to 30%, while adaptive systems improve response to changes in operating conditions, which has a positive impact on the stability and reliability of the units. In addition, a comparison of the results shows that the combined use of automation and adaptive control systems can not only save resources but also reduce the negative impact on the environment. Such solutions can significantly reduce greenhouse gas emissions, which is particularly relevant in the context of global efforts to combat climate change. Thus, these results confirm the importance of implementing modern technologies to improve the energy efficiency of pumping systems in various industries.

Regular maintenance has also proved to be important in ensuring the high efficiency of electric drives. Wear and tear on components and improper maintenance have been shown to have a negative impact on the efficiency of pumping units. Timely preventive maintenance, replacement of worn parts, and monitoring of the wiring proved to be critical to maintaining stable system operation. M. Tan *et al.* (2021) concluded that regular maintenance is a key factor in improving the efficiency of pumping systems. This includes routine inspections, cleaning, replacement of worn components, and adjustment of operating parameters. Such maintenance allows problems to be detected and resolved at an early stage, preventing serious accidents and production stoppages. By managing the technical condition of pumps, their optimal performance is ensured, which directly affects the reduction of energy costs and the increase in system efficiency. Regular maintenance helps to maintain the stability of pumping units, extending their service life. M. El-Emam *et al.* (2022) found that wear and tear on pumping system components negatively affects their efficiency. Wear processes such as erosion, corrosion, and mechanical damage can lead to a decrease in pumping efficiency and an increase in energy consumption. For instance, wearing out bearings or seals leads to increased friction, which reduces pump performance and increases energy costs. Thus, monitoring wear and timely replacement of worn parts is critical to maintaining the high efficiency of pumping systems and ensuring their reliability in operation. When analysing the results of the study, regular maintenance was noted to have a direct impact on the efficiency of pumping systems. The study found that systematic inspections and maintenance can reduce the risk of failures and increase the overall performance of pumps. In cases where worn-out components were replaced on a scheduled basis, a significant increase in efficiency was recorded, indicating that investment in maintenance significantly improves the economic efficiency of the plants. In addition, the results show that wear and tear on pumping systems can be a critical factor limiting their performance. The analysis showed that even small defects, such as cracks in the casing or wear on the impellers, can lead to significant energy losses and reduced efficiency. Worn components were found to increase energy costs, which significantly affects the overall operating efficiency. Therefore, timely detection and remediation of wear problems are essential to maintaining a high level of efficiency in pumping systems.

In general, the study results highlighted that increasing the efficiency of the electric drive of a centrifugal pump unit is possible through the integration of technologies, optimisation of the design of pumps and electric motors, and the introduction of automation systems. All these measures can not only reduce energy costs but also ensure stable and reliable operation of pumping systems in various industrial conditions, which is an important task for modern industry.

CONCLUSIONS

As a result of the study of the efficiency of the electric drive of a centrifugal pumping unit, conclusions were obtained that indicate a significant potential for improving the energy efficiency of pumping systems. The study determined that the efficiency of electric motors, which reaches 90-95% in modern asynchronous motors, is a critical factor that directly affects the performance of pumping units. When analysing the study results, it became clear that improving the design characteristics of pumps and selecting the optimal types of electric motors significantly increase the overall efficiency of the system. This highlights the need to incorporate the specifics of component selection at the design stage. The study of mechanical losses has shown that the quality of the components used in the system and their proper configuration can significantly reduce energy losses. For example, the use of high-quality couplings and belt drives was found to significantly reduce mechanical losses. VFDs have proven to be an effective solution for optimising the speed of electric motors. This reduces energy consumption, especially under partial load conditions, which is typical in many industrial applications. The study also highlighted the importance of automated control systems, which allow pumps to adapt to changing operating conditions. Automation of control processes makes it possible to optimise operating parameters in real-time, which helps to achieve the most energy-efficient modes. Such systems reduce the likelihood of overloading pumps and help maintain their stability. Regular maintenance, timely replacement of worn components and monitoring of the equipment's condition have proven to be crucial to maintaining high efficiency. Bearing wear and other mechanical failures have been found to significantly reduce the overall efficiency of pumping systems. Therefore, regular inspections and preventive maintenance are essential to ensure the reliable operation of pumping units.

Thus, the results of the study confirmed that the integration of modern technologies and approaches to pumping systems management can significantly improve their energy efficiency. Implementation of the above measures will help reduce operating costs and improve environmental performance, which are important conditions for sustainable industrial development. Reducing energy consumption not only reduces the costs of enterprises but also has a positive impact on the environment. Thus, the study points to the need for continuous improvement of technologies in the pumping equipment industry to ensure their efficient and environmentally friendly operation.

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CONFLICT OF INTEREST

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Ефективність електричного привода відцентрового насосного агрегату

Анотація. Дослідження було проведено для аналізу способів підвищення ефективності електричного привода відцентрового насосного агрегату та визначення оптимальних підходів до його енергоефективної експлуатації. У дослідженні застосовувалися аналіз ефективності, експериментальні дослідження та теоретичні моделі для оцінки впливу технологій на енергоспоживання насосних агрегатів. Виявлено, що застосування частотного регулювання дозволяє суттєво знизити енерговитрати при роботі відцентрового насосного агрегату, особливо в умовах змінного навантаження. Найбільший коефіцієнт корисної дії (ККД) досягається при роботі насоса на оптимальних швидкостях обертання, що можна забезпечити завдяки використанню частотних перетворювачів (VFD). Також встановлено, що правильний вибір робочого колеса насоса і його технічне обслуговування мають важливе значення для зниження втрат енергії. Втрати в механічних з'єднаннях можна мінімізувати за рахунок використання високоякісних компонентів і регулярної профілактики обладнання. Було підтверджено, що автоматизовані системи керування значно підвищують ефективність експлуатації насосів, забезпечуючи своєчасну корекцію параметрів роботи відповідно до умов експлуатації. Висновок свідчить про необхідність впровадження комплексного підходу для оптимізації енергоспоживання насосних агрегатів. Дослідження виявило, що зниження механічних втрат у приводах та насосних агрегатах через застосування сучасних технологій значно підвищує ефективність системи. Впровадження інтегрованих систем моніторингу для контролю роботи насосів дозволяє значно зменшити час простою та підвищити загальну надійність обладнання. Зазначено, що модернізація електричних приводів позитивно впливає на енергетичну ефективність насосних систем завдяки впровадженню інноваційних матеріалів і конструктивних рішень. Виявлено, що впровадження нових моделей електродвигунів з покращеними характеристиками сприяє більш раціональному використанню енергії. Крім того, доведено, що регулярна діагностика та профілактичне обслуговування обладнання сприяють стабільній роботі насосних агрегатів, зменшуючи ймовірність аварійних зупинок і непередбачених ремонтів

Ключові слова: системи керування; електродвигун; механічні витрати; енергозбереження; витрати енергії; оптимальні параметри; діагностика