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TRIBOTECHNICAL ANALYSIS OF ENERGY-EFFICIENT MIXERS FOR MINERAL SUSPENSIONS

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Abstract. Improving the energy efficiency and wear resistance of mixing devices is one of the priority challenges in geological, chemical, and processing industries. Under conditions of intensive abrasive action of mineral suspension particles on the working elements, a rapid decrease in performance and service life is observed. The nonuniform distribution of velocity and pressure within the flow leads to increased energy consumption and premature blade wear, making the optimization of impeller geometry and operating parameters highly relevant. Addressing this problem contributes to process stability and reduces operational costs. This study presents the results of numerical modeling and tribological analysis of an energy-efficient three-blade mixer designed for liquid–solid systems. Modeling was carried out using the finite element method (APM FEM) and hydrodynamic analysis in the KOMPAS-3D environment with the APM Flow module, followed by tribological simulation in MSC Marc. The integrated use of these tools provided a reliable representation of the velocity and pressure fields, as well as the distribution of local

contact stresses on the blade surfaces. It was found that an impeller with a 45° blade inclination generates a stable axial flow that prevents solid particle sedimentation and ensures homogeneous suspension mixing. The proposed modeling approach enables a comprehensive evaluation of tribological characteristics, improves calculation accuracy, and supports optimization of energy-efficient impeller design. The results can be used in developing resource- and energy-saving systems for geological and metalworking industries.

Key words: tribotechnical analysis; numerical modeling; KOMPAS-3D; APM Flow; three-blade mixer; hydrodynamics; energy efficiency; mineral suspension

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МИНЕРАЛДЫ СУСПЕНЗИЯЛАРҒА АРНАЛҒАН ЭНЕРГИЯНЫ ТИІМДІ ПАЙДАЛАНАТЫН АРАЛАСТЫРҒЫШТАРДЫҢ ТРИБОТЕХНИКАЛЫҚ ТАЛДАУЫ

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Аннотация. Энергия тиімділігін және тозуға төзімділікті арттыру геологиялық-техникалық, химиялық және қайта өңдеу өнеркәсібіндегі араластырғыш құрылғылар үшін басым бағыттардың бірі болып табылады.

Минералдық суспензия бөлшектерінің жұмыс органдарына қарқынды абразивтік әсер етуі жабдықтың өнімділігін және қызмет ету мерзімін айтарлықтай қысқартады. Ағын ішіндегі жылдамдық пен қысымның біркелкі таралмауы энергия шығынын арттырып, қалақтардың мерзімінен бұрын тозуына әкеледі. Сондықтан олардың геометриялық параметрлері мен жұмыс режимін оңтайландыру өзекті ғылыми-техникалық міндет болып табылады. Бұл мәселені шешу технологиялық процестердің тұрақтылығын арттырып, пайдаланудың энергетикалық және материалдық шығындарын азайтуға мүмкіндік береді. Зерттеу жұмысында «сұйықтық–қатты дене» типті жүйелерге арналған энергия үнемдейтін үш қалақты араластырғыштың сандық модельдеуі мен триботехникалық талдауының нәтижелері келтірілген. Модельдеу ақырлы элементтер әдісі (APM FEM) және КОМПАС-3D ортасындағы APM Flow модулі арқылы гидродинамикалық талдау әдісімен, сондай-ақ MSC Marc бағдарламасында кейінгі триботехникалық талдау арқылы орындалды. Бұл бағдарламалық құралдарды кешенді қолдану қалақ беттеріндегі жылдамдықтардың, қысымдардың және жергілікті жанасу кернеулерінің сенімді үлестірілуін анықтауға мүмкіндік берді. Зерттеу нәтижелері бойынша, қалақтарының көлбеу бұрышы 45° болатын араластырғыш тұрақты осьтік ағын түзіп, қатты бөлшектердің түбіне шөгуіне жол бермейтіні және суспензияның біркелкі араласуын қамтамасыз ететіні анықталды. Жүктемелердің таралуын талдау соққы-абразивтік, сырғымалы және құйындық үйкеліс аймақтарын көрсетті, бұл металкескіш аспаптардың кесу қырларындағы тозу шарттарына ұқсас. Ұсынылған модельдеу әдістемесі конструкцияның беріктік және триботехникалық сипаттамаларын кешенді бағалауға, есептеу дәлдігін арттыруға және энергия тиімді араластырғыштардың құрылымын оңтайландыруға мүмкіндік береді. Алынған нәтижелер геологиялық-техникалық және металл өңдеу салаларында ресурсты және энергияны үнемдейтін жүйелерді жобалау мен жетілдіруде пайдаланылуы мүмкін.

Түйін сөздер: триботехникалық талдау; сандық модельдеу; КОМПАС-3D; APM Flow; үш қалақты араластырғыш; гидродинамика; энергия тиімділігі; минералды суспензия

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ТРИБОТЕХНИЧЕСКИЙ АНАЛИЗ ЭНЕРГОЭФФЕКТИВНЫХ МЕШАЛОК ДЛЯ МИНЕРАЛЬНЫХ СУСПЕНЗИЙ

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Аннотация. Повышение энергоэффективности и износостойкости перемешивающих устройств является одной из ключевых задач в геолого-технической, химической и перерабатывающей промышленности. Частицы минеральных суспензий вызывают интенсивное абразивное воздействие на рабочие органы, что приводит к снижению производительности и сокращению срока службы оборудования. Неравномерность распределения скоростей и давлений в потоке усиливает энергозатраты и ускоряет износ лопастей, что актуализирует необходимость оптимизации их геометрии и режимов работы. В статье представлены результаты численного моделирования и триботехнического анализа энергоэффективной трёхлопастной мешалки, применяемой в системах типа «жидкость–твёрдое тело». Расчёты выполнены методом конечных элементов (APM FEM) и гидродинамического анализа в КОМПАС-3D с использованием модуля APM Flow, а также триботехнического анализа в MSC Marc. Комплексное применение инструментов позволило получить детализированные карты распределения скоростей, давления и локальных контактных напряжений на лопастях. Установлено, что мешалка с углом наклона лопастей 45° формирует устойчивый осевой поток, предотвращающий оседание твёрдых частиц и обеспечивающий равномерное перемешивание суспензии. Анализ напряжений выявил зоны ударно-абразивного, скользящего и вихревого трения, характерные для условий износа режущих кромок металлорежущих инструментов. Предложенная методика моделирования обеспечивает комплексную оценку прочностных и триботехнических характеристик, повышает точность расчётов и позволяет оптимизировать конструкцию энергоэффективных мешалок. Полученные результаты могут быть использованы при проектировании ресурсо- и энергосберегающих систем для геолого-технических и металлообрабатывающих.

Ключевые слова: триботехнический анализ; численное моделирование; КОМПАС-3D; APM Flow; трёхлопастная мешалка; гидродинамика; энергоэффективность; минеральная суспензия

Introduction

Mixing devices are widely used in the chemical, petrochemical, metallurgical,

food, pharmaceutical, and geological engineering industries, as they ensure the production of suspensions and solutions with a high degree of homogeneity throughout the entire volume of the apparatus. The efficiency of technological processes and the quality of the resulting substances depend on the uniform distribution of solid particles within the liquid. The energy consumed by mixing devices is one of the key factors determining the technical and economic performance of the installation. The mixing process can be carried out using impellers of various types. The choice of impeller design depends on the specific objectives of the technological process: preventing solid particle sedimentation, ensuring suspension homogeneity, or intensifying mass transfer. The most common designs are propeller-type impellers with different numbers of blades, installed at a distance from the bottom of the apparatus equal to the impeller diameter (Stelmach, 2023: 13; Wang, 2022: 4561; Stelmach, 2022: 585; Baba, 2022: 10). Among them, three-blade impellers with inclined blades are considered the basic and most versatile configurations.

Studies analyzing the parameters of three-blade impellers emphasize that the blade inclination angle is a critical parameter influencing both mixing efficiency and power consumption. Compared with the basic design, experimental results show that optimizing the blade inclination angle can reduce energy consumption by 10–35% and shorten the mixing time by 20–30% (Wu, 2024: 11; Hong Jian-Hao, 2013: 9; Martinetz, 2021: 880). Traditionally, the calculation of impeller parameters has been carried out using data from specialized literature. However, such an approach does not meet modern requirements for calculation accuracy and optimization of geometric parameters, since it does not take into account the actual distribution of velocities and pressures in the liquid, nor the tribotechnical processes occurring on the surfaces of the blades.

To improve the technological and energy efficiency of mixing devices, several studies have examined the influence of impeller type on the sedimentation of suspension particles in the bottom layer of the apparatus. Eleven types of impellers were tested, including hydrofoil impellers, standard pitched-blade turbines with blade angles of 24°, 35°, and 45°, as well as impellers designed according to the CVS 69 1043 standard (Nikiforov, 2018: 60). The efficiency of the tested impellers was compared based on the power required to prevent solid particles of the suspension from settling on the bottom. It was found that hydrofoil impellers are the most efficient, while the CVS 69 1043 designs are characterized by the greatest geometric simplicity. Power consumption is practically independent of the number of turbine blades, and the blade inclination angle has a minimal effect on the mixing efficiency of fine particles in the bottom layer (Nikiforov, 2018: 60).

According to the research by (Heidari, 2020: 13), the influence of four pitched-blade impellers (15°, 30°, 45°, and 60°) on the mixing performance in a gas–liquid vessel was analyzed using the Computational Fluid Dynamics (CFD) method. The behavior of the multiphase flow was modeled using the Euler–Euler multiphase approach. Based on the standard deviation criterion, it was observed that the axial gas-phase distribution for the 30° impeller was approximately 55% better than that

of the other configurations. In addition, the results showed that the 30° impeller provided uniform radial distribution and maximum gas-phase retention within the vessel. The energy consumption analysis revealed that the 30° impeller exhibited the highest power demand among the investigated designs; however, it also ensured the best mixing quality (Heidari, 2020: 13).

In the current investigation, the KOMPAS-3D software package with the APM Flow module was used for hydrodynamic analysis, while MSC Marc was applied to calculate contact interactions and tribotechnical characteristics. The combined use of these systems provided a comprehensive assessment of the impeller's energy efficiency and wear resistance.

According to the research by (Ding Xia, 2023: 11), the problem of flow nonuniformity and inefficient utilization of mixing energy in a stirred tank with two impellers was investigated. Using the Sobol method (Monte Carlo numerical techniques), an approximate model was developed, which reduced energy consumption by 15.6% compared with the prototype. Experimental tests conducted before and after optimization confirmed the reliability of the obtained results.

When operating mixers, it is important to consider changes in drive load during the filling and emptying stages of the apparatus. An increase in energy consumption and the potential risk of drive failure were reported in the research by (Stelmach J., 2021: 341), which investigated variations in mixing power during tank emptying for propeller-type impellers. For impellers with wide blades, the mixing power can be up to three times higher than that of a fully filled tank. The phenomenon of power increase during emptying is observed only for axially acting impellers. The instantaneous rise in power for two impellers mounted on a common shaft may exceed the calculated value by more than 50%, which can lead to motor overload (Stelmach, 2021: 341; Kassenov, 2022: 15; Mashekov et al., 2018: 12).

To determine the optimal parameters of a mixer and to predict its performance during the design stage, a calculation method for propeller-type impellers used for mixing non-Newtonian fluids is applied (Reviol, 2018: 16). The proposed method is based on the principle of inverse calculation and allows determining the complete set of impeller characteristics for fluids with different properties. Furthermore, the design and optimization of mixers are often carried out using internal flow field modeling. In the research by (Wang, 2023: 1808), single-factor numerical simulations and analysis of the influence of structural parameters were performed. The use of Latin Hypercube Sampling made it possible to design 100 sets of test configurations varying in impeller installation height and baffle angle, which improved mixing uniformity by 10% and reduced power consumption by 8.3%.

Thus, the analysis of scientific literature in the field of mixer design and optimization has made it possible to identify the following key points:

- Three-blade impellers with inclined blades represent the basic design configuration.

- The blade inclination angle has a significant influence on the uniform distribution of particles in the liquid and on the energy efficiency of the apparatus.

- The use of mathematical modeling and calculations in the KOMPAS-3D + APM Flow environment significantly reduces design time and increases calculation accuracy. In addition, the use of the APM FEM module within the KOMPAS-3D software suite allows for strength analysis of the mixer structure and assessment of its stress–strain state under various operating conditions.

- There is no consensus regarding the optimal inclination angles and geometric parameters of the blades.

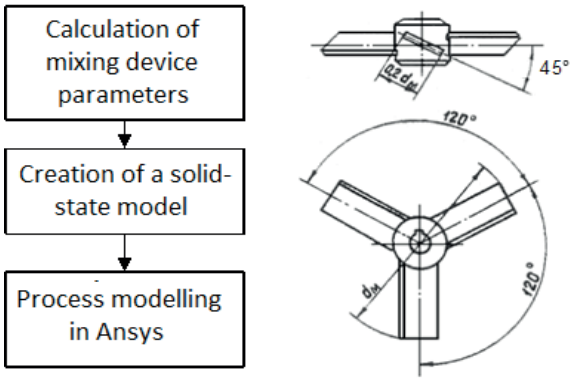
At the same time, during the mixing of mineral suspensions, the working surfaces of the impeller blades are subjected to intense abrasive action from solid particles, leading to gradual wear and changes in the hydrodynamic characteristics of the flow. These processes are tribotechnical in nature and are similar to the wear mechanisms of cutting edges in metal-cutting tools operating in contact with abrasive chips. Therefore, the study of the tribotechnical characteristics of impeller working surfaces is of both engineering and scientific-practical interest for increasing the service life and energy efficiency of the equipment.

The purpose of this research is to conduct numerical modeling and tribotechnical analysis of an energy-efficient three-blade impeller designed for the preparation of mineral suspensions, with a comparison of friction and wear conditions to similar processes typical of metal-cutting tools.

Materials and methods.

All experiments were carried out at Toraighyrov University. The dimensions of the tank, with a capacity of 1 m^3, are as follows: height H = 1270 mm and diameter D = 1000 mm. The experimental setup is shown in Figure 1a.

The object of the study is an energy-efficient three-blade impeller designed for the preparation of mineral suspensions used in geological and technical processes. The impeller consists of a hub with an inner diameter d, to which three flat blades are welded along the outer diameter d_o at an angle of 45° to the plane of rotation. The blade inclination angle is 45°. The impeller diameter is d□ = 0.7D, where D is the internal diameter of the vessel. The blade width is selected as 0.2d□ (Figure 1b).



a) b)

Figure 1 – Experiment procedure (a), parameters of a three-bladed agitator (b)

The circumferential velocity at the impeller blade tip, depending on the viscosity of the mixed medium, ranged from 1 to 3 m/s. The impeller parameters were determined in accordance with the recommendations of RD 26-01-90-85 (Absolyamova, 2025: 11). When mixing suspensions in a liquid-solid (L:S) system, a blade-type impeller without additional internal components was used, providing the possibility of generating a turbulent hydrodynamic regime (Absolyamova, 2025: 11).

The rated power of the drive unit was selected taking into account the starting conditions and amounts to 100% for vessels without internal components, at Reynolds numbers greater than 500 and when $G_D \leq 1,5$

$$Re = \frac{N \cdot d_м^2 \cdot \rho}{\mu}, \quad (1)$$

where N – the rotational speed of the impeller, rev/s;

$d_м$ – the impeller diameter, with a tank diameter of 1m, $d_м$=0,7 m;

ρ – the liquid density (water), ρ=1000 kg/m^3;

μ – the dynamic viscosity of the liquid (water), μ= 0,001 Pa·s.

In the calculations, the influence of the structural features of the impeller was taken into account using two coefficients: the impeller resistance coefficient ξ□ = 0.56 and the circulation flow coefficient K_2=0,0028. The values of these coefficients remain constant under turbulent flow conditions (Absolyamova, 2025: 11).

After calculating the impeller parameters, a solid-phase model was constructed in the KOMPAS software. The solid model was analyzed in the KOMPAS-3D environment using the APM Flow module, which performs finite element and hydrodynamic analysis with an adaptive mesh in the rotation zone. To verify the strength and stability of the structure, the APM FEM module was used; it applies the finite element method to calculate stresses and deformations in the blade nodes and hub.

To refine the stress–strain state and simulate tribotechnical contacts, the results of the hydrodynamic analysis were exported to the MSC Marc software package, where the distribution of contact pressures and the areas of increased wear on the working surfaces were analyzed. The physical properties of the liquid corresponded to those of water at T = 21°C, ρ = 1000 kg/m^3, and μ = 0.001 Pa·s.

To evaluate the hydrodynamic and tribotechnical loads, the obtained distributions of pressure and velocity along the blade surfaces were used to determine the contact stresses and the local zones of increased friction.

Results and discussion.

The results of the calculated geometric parameters of the impeller are presented below. The internal diameter of the vessel was taken as D = 1 m, and the height H = 1.27 m, corresponding to a tank capacity of 1 m^3. Based on these values:

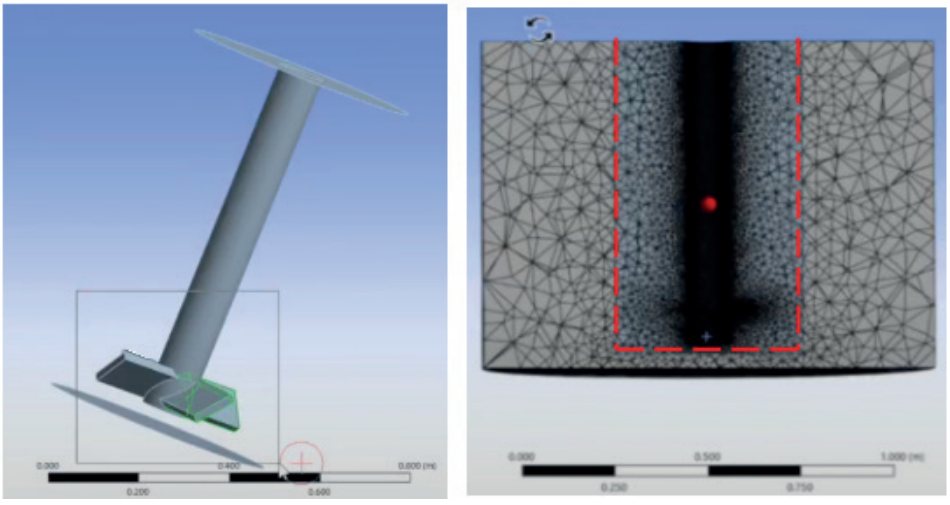
- impeller diameter d□ = 700 mm;
- blade width h = 140 mm;
- diameter d_o = 120 mm;

- drive power N = 3.2 kW (Absolyamova D.R., 2025: 11);
- rotational speed 60 and 90 rpm (Absolyamova D.R., 2025: 11).

Considering all parameters, it was found that the Reynolds number falls within the range corresponding to the turbulent mixing regime. The Reynolds number makes it possible to use experimental data for known impeller designs to determine the Kn coefficient, which in turn is required to calculate the rotational speed of the impeller. Based on the specified parameters, a solid model of the apparatus was constructed and imported into the KOMPAS-3D + APM Flow software environment for simulation. Figure 2 shows the solid model of the mixing apparatus (Figure 2a) and a cross-section of the model with a finite element mesh. The data preparation and mesh generation algorithm in APM Flow follows the procedure described in the KOMPAS-3D (APM Flow) user manual. The internal volume of the vessel was separated from the rotation plane at the outermost points of the impeller blades (indicated by a red dashed line in Figure 2b).

After inputting the physical characteristics of water at a temperature of 21°C, the solver was initiated to determine the optimal rotation parameters that ensure a turbulent regime without foam formation caused by air entrainment.

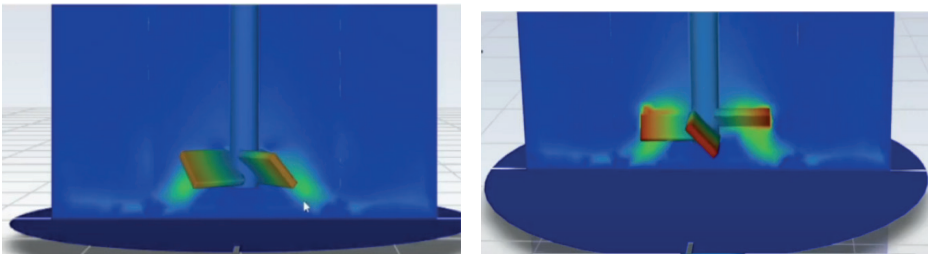
The simulation made it possible not only to determine the flow structure but also to identify regions of increased pressure and velocity, which served as the basis for evaluating local contact loads and analyzing the tribotechnical condition of the blade surfaces. The obtained load distributions were further analyzed in the APM FEM module, allowing identification of stress concentration zones at the blade attachment points and confirmation of the structural reliability. To refine the contact stress distribution and wear zones, the calculated data were additionally processed in MSC Marc.



(a) (b)

Figure 2 – Solid model of the mixing apparatus (a) and cross-section of the model with a finite element mesh (b)

The simulation results are shown in Figure 3. In the KOMPAS-3D + APM Flow environment, the liquid flow distribution during mixer operation was determined at a drive power of 3.2 kW and rotational speeds of 60 and 90 rpm. From Figure 3, the flow patterns clearly indicate that mixing occurs in the turbulent regime, yet without foam formation due to the entrainment of gases from the surrounding air. At 60 rpm, the flow pressure generated by the impeller is directed mainly sideways, whereas at 90 rpm, it is directed toward the bottom, ensuring better suspension mixing.



(a) (b)

Figure 3 – Solid model of the mixing apparatus at a rotational speed of 60 rpm (a) and 90 rpm (b)

The presence of a 45° blade inclination promotes the formation of an axial flow that effectively draws solid particles into the overall liquid volume and prevents them from settling at the bottom. The obtained results confirm the correctness of the chosen impeller design and parameters, which ensure an optimal balance between energy efficiency and mixing quality.

From a tribotechnical perspective, it was observed that the blade surfaces experience different types of contact interactions depending on the flow direction. In the area of the leading edge, the flow exerts increased hydrodynamic pressure, accompanied by impact–abrasive interaction of particles with the metal surface. In the middle section, a sliding mode of particle motion along the surface is observed, while in the trailing part, the flow weakens, forming zones with reduced friction. Such a distribution of loads makes it possible to assess surface wear resistance in a manner similar to that used in analyzing contact stresses and wear on the cutting edges of metal-cutting tools.

Thus, the simulation results obtained in KOMPAS-3D + APM Flow confirm that a three-blade impeller with a blade inclination angle of 45° is both structurally and energetically efficient for working with mineral suspensions. The identified flow distribution patterns and contact interaction characteristics can be applied to the selection of materials and coatings for working elements, as well as to the development of resource- and energy-saving systems, including in the design of metal-cutting equipment operating under similar mechanical and abrasive loading conditions.

Conclusions. The proposed design of the three-blade impeller demonstrated high efficiency in mixing liquid-solid systems. The optimal blade inclination angle

of 45° ensures uniform flow distribution and prevents solid particles from settling in the bottom zone. Under the specified operating conditions – drive power of 3.2 kW and rotational speeds of 60 and 90 rpm – the impeller can be powered by conventional energy sources such as the vehicle-mounted power system or a battery unit, which makes the design both energy-efficient and technologically adaptable.

The developed calculation and modeling methodology, implemented using the APM Flow and APM FEM modules within the KOMPAS-3D environment, as well as subsequent tribotechnical analysis in MSC Marc, proved to be fully effective. It enabled the identification of hydrodynamic load distributions and zones of potential particle friction against the blade surfaces. The nature of the contact interactions on the working surfaces is comparable to the abrasive wear processes observed on the cutting edges of metal-cutting tools. This confirms the feasibility of applying a tribotechnical approach in the design and optimization of such equipment.

Future work is planned to expand the range of investigated power levels from 3.2 to 15 kW and rotational speeds from 95 to 750 rpm, as well as to analyze the behavior of solid particles in the flow for various suspension types and impeller geometries. The obtained results will be used to refine the criteria for wear resistance and energy efficiency of the working elements in apparatuses used in geological, technical, and metalworking processes.

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