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Impact of the technical condition of main pumps on fuel consumption in a hydraulic excavator

M. G. Rakhutin[1], **V. H. Tran**[2], **A. E. Krivenko**[1] ✉, **Q. Kh. Giang**[3]
[1] *University of Science and Technology MISIS, Moscow, Russian Federation*
[2] *Le Quy Don Technical University, Hanoi, Vietnam*
[3] *Thanh Dong University, Hai Duong City, Vietnam*
✉ *Krivenko.ae@misis.ru*

Abstract
During the operation of hydraulic excavators, the technical condition of pumps deteriorates due to wear, leading to increased internal clearances, fluid leakage, a reduction in volumetric efficiency, and higher energy losses, ultimately resulting in excessive fuel consumption. The objective of this study was to determine the optimal service life of pumps, taking into account the growing fuel overconsumption during operation. The following tasks were addressed: developing a mathematical model for pump ownership costs, incorporating progressive fuel overconsumption; designing an algorithm and conducting computer simulations using Simulink-Matlab; and assessing the increase in fuel consumption. The study examines the impact of the technical condition of the main hydraulic pumps on fuel overconsumption using the Komatsu PC2000-8 hydraulic excavator as a case study. Based on the proposed pump operation cost model, which accounts for the increase in fuel consumption over time, dependencies between fuel overconsumption and pump wear were established. Computer modeling was performed in Simulink-Matlab and Excel based on the developed calculation methodology and software algorithm. Relationships between the excavator's fuel overconsumption and the technical condition of the pumps were identified. A mathematical model for pump ownership costs is presented, taking into account the progressive fuel overconsumption during operation, along with the resulting equation for determining the optimal service life of pumps to minimize total costs, including pump acquisition and fuel expenses. This expression considers the technical condition of the main pumps, their rate of deterioration, fuel costs, and pump replacement costs. A fuel overconsumption indicator was introduced, defined as the ratio of the difference between actual fuel consumption per 1 m^3 of excavated material and fuel consumption at nominal efficiency of the main pumps (nominal fuel consumption) to the nominal fuel consumption. The application of this criterion, in conjunction with the proposed equation for determining the optimal pump service life, allows for a data-driven selection of the critical wear threshold for the main pumps, reducing total ownership and fuel costs by up to 17%, depending on economic and mining-engineering conditions.

Keywords
mining machinery, hydraulic mining excavator, pump technical condition, hydraulics, pump, condition, operation, modeling, leakage, efficiency, wear, costs, algorithm, consumption, overconsumption, optimal service life

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ГОРНЫЕ МАШИНЫ, ТРАНСПОРТ И МАШИНОСТРОЕНИЕ

Научная статья

Влияние технического состояния главных насосов гидравлического экскаватора на расход топлива

М.Г. Рахутин[1], **В.Х. Чан**[2], **А.Е. Кривенко**[1] ✉, **К.К. Занг**[3]

[1] *Университет науки и технологий МИСИС, г. Москва, Российская Федерация*
[2] *Государственный технический университет им. Ле Куй Дона, г. Ханой, Вьетнам*
[3] *Университет Тхань Донг, г. Хайзыонг, Вьетнам*
✉ *Krivenko.ae@misis.ru*

Аннотация
В процессе эксплуатации гидравлических экскаваторов вследствие износа изменяется техническое состояние насосов. Увеличиваются зазоры, переток жидкости, снижается объемный КПД, возрастают потери энергии, что приводит к перерасходу топлива. Целью работы являлось определение рационального срока эксплуатации насосов с учетом перерасхода топлива, который возрастает в процессе эксплуатации. Решены задачи: создание математической модели затрат на владение насосом с учетом перерасхода топлива, возрастающего в процессе эксплуатации, разработка алгоритма и компьютерного моделирования в программе Simulink-Matlab, оценка увеличения расхода топлива. В статье на примере гидравлического экскаватора Komatsu PC2000-8 показано влияние технического состояния главных насосов гидравлического экскаватора на перерасход топлива. На основе предлагаемой модели затрат на эксплуатацию насоса с учетом повышения расхода топлива в процессе эксплуатации получены зависимости перерасхода топлива от технического состояния насосов. По разработанным методике расчета и программному алгоритму выполнено компьютерное моделирование в программах Simulink-Matlab и Excel. Получены зависимости перерасхода топлива гидравлического экскаватора от технического состояния насосов. Представлены математическая модель затрат на владение насосом с учетом перерасхода топлива, возрастающего в процессе эксплуатации, и полученное на ее основе выражение для определения рационального срока эксплуатации насосов для минимизации затрат на приобретение насосов и топлива, учитывающее техническое состояние главных насосов, скорость его изменения, стоимость топлива и замены насоса. Предложен показатель, характеризующий перерасход топлива, определяемый отношением разницы между фактическим расходом топлива на 1 м^3 экскавируемой горной массы и расходом топлива при номинальных значениях КПД основных насосов (номинальным расходом) к номинальному расходу. Использование предлагаемого критерия совместно с выражением для определения рационального срока эксплуатации насосов позволит обоснованно выбирать значение предельного состояния основных насосов и уменьшить суммарные затраты на владение насосом и на расход топлива до 17 % в зависимости от экономических и горнотехнических факторов эксплуатации с учетом экономических и горнотехнических факторов эксплуатации.

Ключевые слова
горные машины, карьерный гидравлический экскаватор, техническое состояние насосов, гидравлика, насос, состояние, эксплуатация, моделирование, утечки, КПД, износ, затраты, алгоритм, расход, перерасход, рациональный срок

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Introduction

Leakage of the working fluid in the discarge mechanism of positive displacement pumps in the hydraulic drive of mining excavators is inherent in the design phase and, on average, accounts for 5% of the operating flow rate at working pressure. A lower leakage volume results in deteriorated lubrication and cooling conditions for the components of the discharge mechanism, leading to overheating and eventual pump failure. The leakage volume is directly dependent on the clearance size in the pump discharge mechanism [1–3]. As the components wear, the clearances in the discharge mechanism increase, leading to higher leakage of the working fluid, a decrease in pump efficiency, and an increase in fuel consumption. The aim of the study was to determine the optimal service life of pumps, taking into account the excess fuel consumption that increases during operation. The impact of increasing leakage on the productivity of a mining excavator can be assessed through the volumetric efficiency of the hydraulic machine. As established in previous studies, the effect of pump wear on energy consumption occurs in two stages: 1. The power reserve of the drive fully compensates for the energy losses caused by increasing internal leakage in the pump. At this stage, the machine's productivity remains unchanged, but the specific energy consumption per cubic meter of mined material increases; 2. The power reserve of the drive is insufficient to compensate for the energy losses due to volumetric leakage in the pump, resulting in a decrease in machine productivity, while the specific energy consumption per cubic meter of mined material continues to rise. During operation, including in axial piston pumps of hydraulic excavators, component wear increases internal clearances, allowing fluid to leak through them. This leads to energy losses and increased (excess) fuel consumption. Replacing pumps based on the increase in excess fuel consumption can help reduce total fuel costs and ownership costs over the pump's operational lifetime. Establishing an optimal service interval for the pump will enable timely replacement planning and better forecasting of future expenses [4–6]. Determining the relationship between "excess" fuel consumption and the technical condition of the pump (leakage volume) will allow for defining the most optimal volumetric efficiency range, considering minimal productivity losses, excess fuel consumption, and ownership costs.

Methods

In a hydraulic excavator, all primary and auxiliary operations are performed using a hydraulic drive. The primary operations, which include digging, swinging to dump, bucket unloading, and swinging back to the face[1], are carried out using variable-displacement axial piston pumps, commonly referred to in technical literature[2] [7–9] as main or primary pumps. Wear of the converting and displacing mechanisms in high-pressure hydraulic pumps leads to increased clearances and distortion of the geometry of components operating in sliding or rolling contacts. As clearances increase, hydraulic fluid leakage rises, causing a decrease in the pump's volumetric efficiency and an increase in energy consumption for performing useful work, as confirmed by previous studies [10–12]. Ultimately, this process results in excess fuel consumption of the internal combustion engine. Replacing the pump resolves the issue of fuel overconsumption but entails additional costs. To achieve the objective of determining the optimal service life of pumps, the following tasks were formulated: developing a mathematical model for pump ownership costs, accounting for fuel overconsumption that increases over time, designing an algorithm and conducting computer modeling in Simulink-Matlab, evaluating the increase in fuel consumption over the pump's service life.

The study examined the impact of the technical condition of HPV375 axial piston pumps on the fuel consumption of the Komatsu PC2000-8 mining hydraulic excavator. Within the scope of the research, it was assumed that energy losses in the friction pairs of the excavator's mechanisms remain constant and were therefore not considered in the calculations.

The main pumps of the excavator's hydraulic system supply hydraulic fluid to the hydraulic motors of the working equipment and the swing mechanism. Depending on the phase of the excavator's work cycle, some hydraulic motors may remain idle or, conversely, operate under maximum load. The load on the excavator's mechanisms determines the working pressure in the hydraulic system, and, in turn, the magnitude of internal leakage and friction forces in the pump's discharge mechanism changes proportionally to pressure variations. Thus, to accurately assess energy losses in the main hydraulic pumps, it is necessary to consider the properties of the excavated rock mass, the temperature of the hydraulic fluid, the level of fluid leakage, as well as the velocities and accelerations of moving components [13, 14].

Leakage through the clearances of the axial piston pump mechanisms depends on several factors, the most significant being the pressure difference between the inlet and outlet of the clearance and the flow resistance of the clearance, which is determined by its shape and cross-sectional area. Under otherwise identical conditions, leakage increases with rising pressure differential. This occurs during the displacement of hydraulic fluid from the pump's working chamber. During the filling phase of the working chamber, leakage is nearly absent.

Leakage in the working chambers of the HPV375+375 pump's discharge mechanism can be represented as four main components: fluid bypass in the annular clearance between the plunger and the working chamber wall Q_{pc}, leakage in the spherical joint connecting the plunger base to the slipper pad, leakage through the flat clearance between the slipper pad and the swashplate, leakage at the contact surface between the cylinder block and the valve plate Q_{bp}.

[1] GOST R 55165–2012. Mining equipment. Open-pit single-bucket excavators with a bucket capacity exceeding 4 m^3. General technical requirements and test methods.

[2] Zang K.K. Substantiation and selection of hydraulic system cooler parameters for a mining hydraulic excavator operating in the Socialist Republic of Vietnam. [Author's abstract of the dissertation for the degree of Cand. Sci. (Eng.)]. Moscow: MISIS; 2021. 21 p.

These leakages are not only unavoidable by design but also essential, as the hydraulic fluid lubricates component surfaces subjected to forces generated by working pressure, thereby reducing wear.

When calculating fluid bypass through the clearance between the plunger and the working chamber wall, it is essential to consider that due to lateral forces arising during the transmission of torque from the drive shaft to the plunger group, the plunger assumes an eccentric position in the working chamber, despite tight tolerances and high manufacturing precision. The fluid flow rate in the eccentric annular clearance is determined by the following equation [15, 16]:

$$Q_{pc} = \frac{\pi d_p h_{pc}^3 (p_c - p_0)}{12\mu l}(1+1.5\lambda^2) - \frac{\pi d_p h_{pc} v}{2}, \qquad (1)$$

where d_p – pump plunger diameter, m; h_{pc} – average clearance between the plunger and the working chamber wall, m; p_c, p_0 – working pressure of the pump and casing pressure, respectively, Pa; μ – dynamic viscosity of the working fluid, Pa·s; $\lambda = e/h_{pc}$ – elative eccentricity of the plunger in the working chamber; e – plunger eccentricity relative to the cylinder walls, m; v – plunger velocity, m/s; l – length of the plunger section inside the cylinder at a given moment, m:

$$l = l_0 + R(1-\cos\omega t)\,\mathrm{tg}\,\gamma, \qquad (2)$$

where l_0 – average length of the plunger section inside the cylinder, m; R – radius of the working chamber axes, m; ω – angular velocity of the cylinder block, rad/s; γ – tilt angle of the swashplate, degrees.

The axial velocity of an individual piston relative to the cylinder is determined by:

$$v = \omega R\,\mathrm{tg}\,\gamma \sin\omega t. \qquad (3)$$

Leakage of the working fluid through the clearance between the piston and the slipper is calculated using the following expression [17]:

$$Q_{bp} = \frac{\pi h_{bp}^3 (p_1 - p_0)}{3\mu\left(\mathrm{tg}^2\beta_2 - \mathrm{tg}^2\beta_1 + 2\ln\left|\dfrac{\mathrm{tg}\,\beta_2}{\mathrm{tg}\,\beta_1}\right|\right)}, \qquad (4)$$

where h_{bp} – clearance between the piston and the slipper, m; p_1, p_0 – pressure in the slipper chamber and in the pump casing chamber, respectively, Pa; β_1, β_2 – design angles of the piston and slipper, rad.

Leakage calculations for other components of the axial piston pump follow a similar approach.

The current GOST 13823–78 standard specifies failure criteria only for fixed-displacement axial piston pumps and does not establish limits for variable-displacement pumps with a control system powered by the main flow. However, according to existing engineering practices, there comes a point when further operation of a variable-displacement axial piston pump becomes impractical, including due to excessive fuel consumption. For mining hydraulic excavators, the failure threshold of variable main pumps should be determined considering both mining-technical and economic operating conditions [18].

Results and discussion

A comprehensive mathematical model, incorporating the listed leakage formulas for the critical components of the fluid discharge mechanism in axial piston pumps of the hydraulic system in a mining excavator, was developed in Simulink-Matlab. In recent years, Simulink-Matlab, along with other popular CAD and CAE systems, has been widely and successfully used for digital prototyping of equipment operating processes in the mining industry [19]. Additionally, the model included constraints and conditions that directly and indirectly affect the leakage volume of the working fluid in the clearances. These include: pump working chamber cycle parameters, design parameters of the discharge mechanism, time and load parameters of the mining hydraulic excavator's duty cycle, temperature of the hydraulic fluid.

As part of the numerical experiment, the volumes of hydraulic fluid leakage were determined for high-pressure pumps in the hydraulic system of a mining hydraulic excavator, considering different levels of discharge mechanism wear: from a new pump (clearances $h_{pc} = h_{cv} = h_{ps} = h_{ss} = 5$ μm) to a pump in operation for several years (clearances $h_{pc} = h_{cv} = h_{ps} = h_{ss} = 20$ μm).

he fuel overconsumption values corresponding to pump leakage losses are presented in Table 1. The graphs showing the dependence of fuel overconsumption on hydraulic fluid temperature for four levels of discharge mechanism wear (Fig. 1) indicate that as clearances increase, fuel overconsumption rises exponentially. For example, at a hydraulic fluid temperature of 70 °C increasing the clearance size in the discharge mechanism of an axial piston pump by a factor of 2, 3, and 4 results in fuel overconsumption due to hydraulic fluid leakage increasing by factors of 8, 27, and 64, respectively. This relationship can be expressed by the function $x = y^3$.

The fuel overconsumption during working operations, depending on the clearance between the piston and the cylinder block at different hydraulic fluid temperatures, is shown in Fig. 2.

The impact of hydraulic fluid temperature on power losses in a hydraulic excavator was analyzed in [20]. However, that study did not consider the effect of pump technical condition on power losses.

It should be noted that a power loss of 1 kWh results in an excess fuel consumption of 207–218 g.

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Table 1

Fuel overconsumption during primary duty cycle operations depending on the clearance between the piston and cylinder block

HF temperature, °C	Fuel overconsumption, L/h ×10⁻³															
	Digging				Swing to dump				Bucket unloading				Swing to face			
	Clearance size, μm															
	5	10	15	20	5	10	15	20	5	10	15	20	5	10	15	20
20	46	98	226	448	24	28	36	52	28	34	50	78	18	18	22	30
40	82	208	510	1.036	36	44	66	102	42	58	94	156	26	30	38	54
60	138	406	1.040	2.146	48	66	110	186	60	90	164	294	34	42	60	92
80	224	720	1.896	3.946	64	98	178	316	80	138	274	510	44	58	92	152
100	342	1.178	3.156	6.604	82	138	272	506	104	200	428	826	56	80	136	234

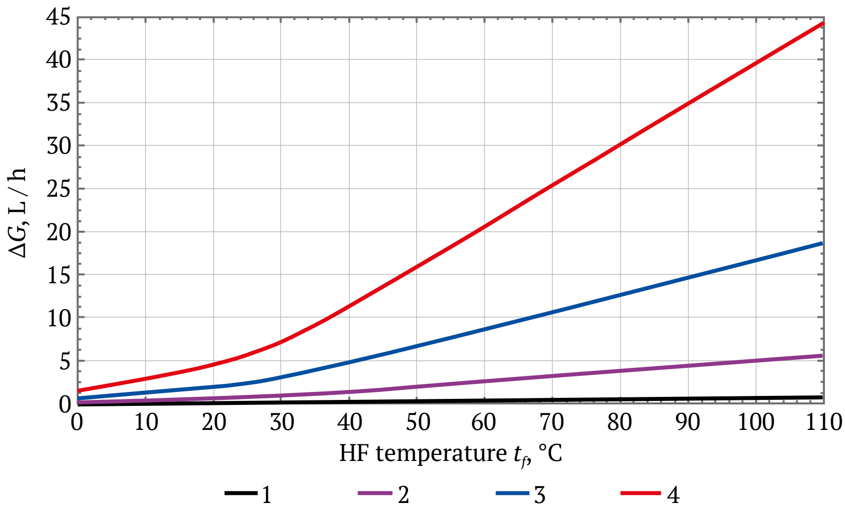

Fig. 1. Power losses at different clearance widths: *1* – 5 μm; *2* – 10 μm; *3* – 15 μm; *4* – 20 μm

In Chan V. H.'s study[3], a mathematical model was developed to calculate the ownership cost of the main hydraulic excavator pump and the expenses associated with excess fuel consumption:

$$V = Z_e + Z_g \left[\frac{v_\eta}{\eta_n} \frac{T}{2} + \frac{v_\eta^2}{\eta_n^2} \frac{T^2}{3} \right] + \frac{C}{T}, \tag{5}$$

where Z_e – pump operating costs, RUB/h; Z_g – fuel costs at the initial moment of operation, RUB/h C – pump replacement cost, RUB; η_n – volumetric efficiency of the pump at the initial moment of operation; v_η – rate of volumetric efficiency degradation, %/h; T – service life, h.

Based on the proposed model, an expression was derived to determine the replacement interval:

$$T_{opt} = \sqrt{\frac{2\eta_n C}{v_\eta Z_g}}. \tag{6}$$

[3] Chan V. H. Optimization of pump replacement intervals for mining hydraulic excavators operating in Vietnam. [Author's abstract of the dissertation for the degree of Cand. Sci. (Eng.)]. Tver; 2024. 21 p.

Using the calculated replacement interval will help minimize pump acquisition costs and fuel consumption throughout the pump's operational life until replacement.

From the equation, it is evident that the replacement interval increases proportionally to the square root of the pump replacement cost and decreases with lower fuel costs and higher volumetric efficiency degradation rates during operation.

Furthermore, the equation indicates that the fixed operating costs of the pump do not affect the optimal replacement interval (Fig. 3).

To evaluate fuel overconsumption, the study proposes the K_{ef} indicator, which characterizes excess fuel consumption and is determined by the ratio of the difference between the actual fuel consumption per cubic meter of excavated material G_f and the fuel consumption at the initial volumetric efficiency G_n to the fuel consumption at the initial volumetric efficiency:

$$K_{ef} = \frac{G_f - G_n}{G_n}.$$

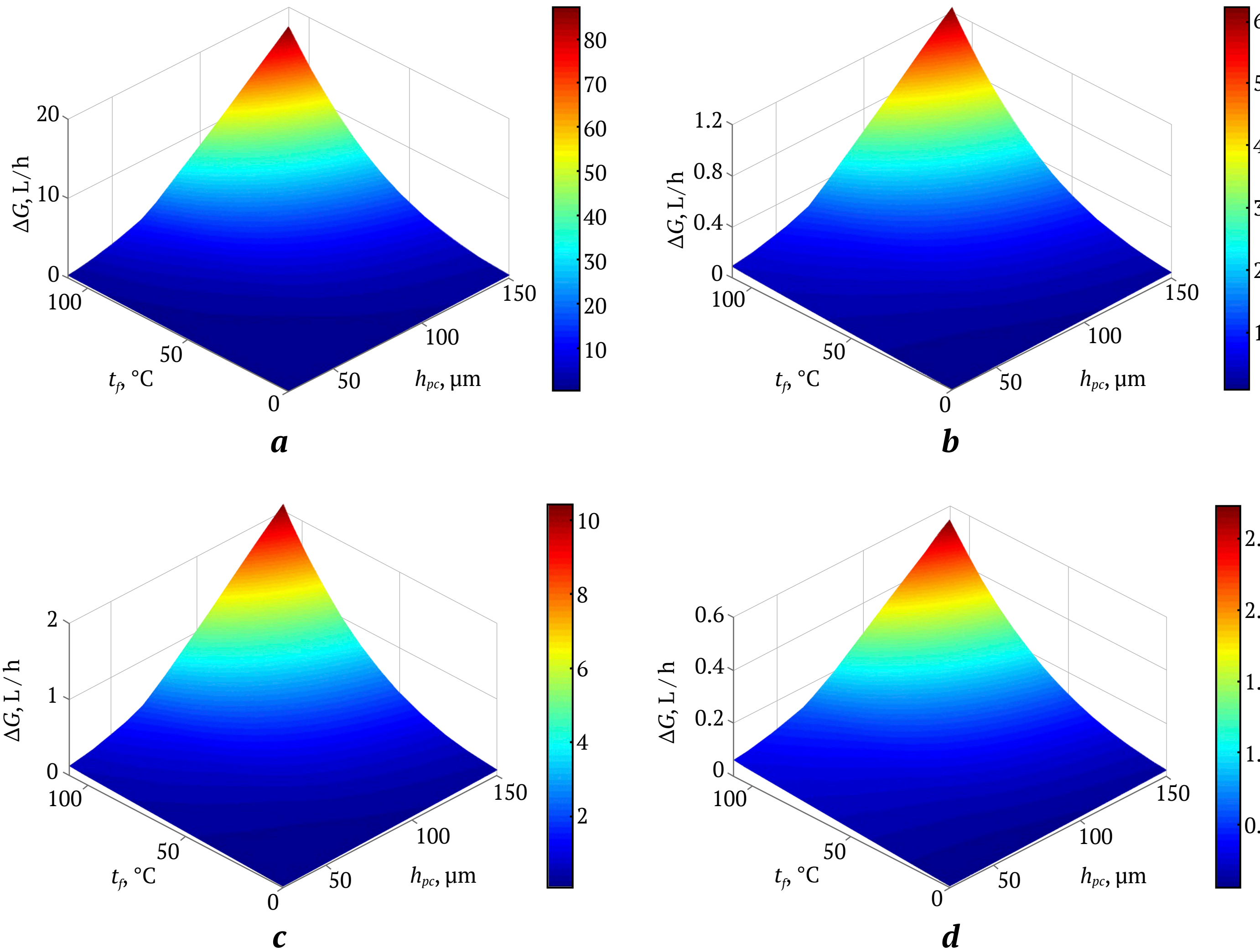

Fig. 2. Fuel overconsumption during working operations:
a – digging; *b* – swing to dump; *c* – bucket unloading; *d* – swing to face

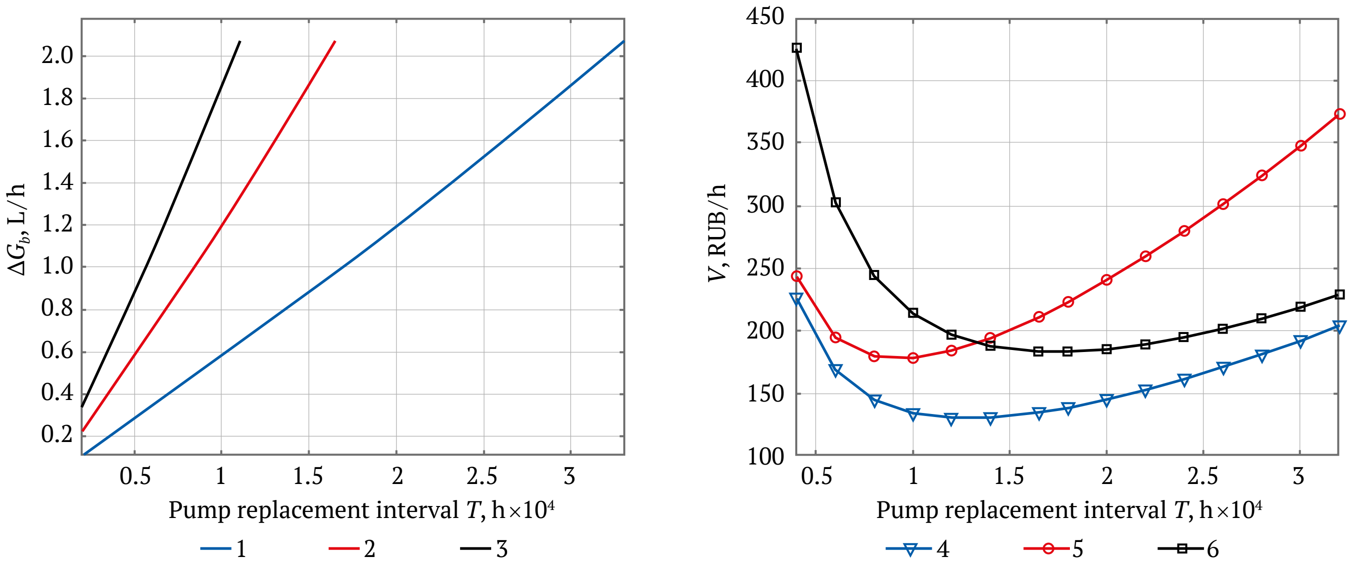

Fig. 3. Impact of the replacement interval for main pumps:
a – on fuel overconsumption; *b* – on fuel costs and pump replacement costs:
1 – $v_n = 0.5 \cdot 10^{-3}$ %/h; *2* – $v_n = 1 \cdot 10^{-3}$ %/h; *3* – $v_n = 1.5 \cdot 10^{-3}$ %/h; *4* – $v_n = 1 \cdot 10^{-3}$ %/h, C_{zn} = 800 000 RUB, D = 35 RUB/L; *5* – $v_n = 1 \cdot 10^{-3}$ %/h, C_{zn} = 800 000 RUB, D = 70 RUB/L; *6* – $v_n = 1 \cdot 10^{-3}$ %/h, C_{zn} = 1 600 000 RUB, D = 35 RUB/L

The K_{ef} value is zero when the nominal and actual fuel consumption are equal, i.e., at the initial moment of operation. If the actual fuel consumption becomes twice the nominal value (which is not permissible in operation), the coefficient reaches one.

Using the proposed fuel efficiency coefficient and the derived equation for pump replacement intervals will enable data-driven decisions regarding the definition of critical pump conditions and optimal replacement timing. This approach can reduce total pump ownership and fuel costs by up to 17%, depending on the economic and mining-technical operating conditions.

Conclusion

1. Using the developed algorithm and computer modeling in Simulink-Matlab, a relationship was established between fuel overconsumption, hydraulic fluid viscosity, and clearance size in the HPV375 axial piston pump of the Komatsu PC2000-8 excavator.

2. A mathematical model was developed for pump ownership costs, accounting for increasing fuel overconsumption over the pump's service life. Based on this model, an expression was derived to determine the optimal pump service life, aimed at minimizing pump acquisition and fuel costs, while considering the technical condition of the main pumps, its degradation rate, fuel price, and pump replacement costs.

3. A new indicator was proposed to characterize fuel overconsumption, defined as the ratio of the difference between actual fuel consumption per 1 m^3 of excavated material and the fuel consumption at the initial pump efficiency to the fuel consumption at initial efficiency.

4. Implementing the proposed fuel overconsumption indicator and the equation for pump replacement intervals will allow for more accurate planning of replacement timing and future expenditures. Additionally, this approach can reduce total pump ownership and fuel costs by up to 17%, depending on economic and mining-technical operating factors.

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Information about the authors

Maxim G. Rakhutin – Dr. Sci. (Eng.), Professor of the Department of Mining Equipment, Transport and Mechanical Engineering, University of Science and Technology MISIS, Moscow, Russian Federation; ORCID 0000-0001-5873-5550, Scopus ID 57200152323; e-mail rahutin.mg@misis.ru

Van Hiep Tran – Cand. Sci. (Eng.), Lecturer of the Mechanical Engineering Faculty, Le Quy Don Technical University, Hanoi, Vietnam; ORCID 0000-0003-0962-5835; e-mail hieptv@lqdtu.edu.vn

Alexander E. Krivenko – Cand. Sci. (Eng.), Associate Professor of the Department of Mining Equipment, Transport and Mechanical Engineering, University of Science and Technology MISIS, Moscow, Russian Federation; ORCID 0000-0001-7198-4447, Scopus ID 57210220257; e-mail Krivenko.ae@misis.ru

Quoc Khanh Giang – Cand. Sci. (Eng.), Dean of the Faculty of Mechanical Engineering, Thanh Dong University, Hai Duong City, Vietnam; ORCID 0009-0006-8589-5609; e-mail khanhgq@thanhdong.edu.vn

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