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Improving the energy efficiency of the hydraulic drive of a single-bucket excavator

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Abstract: Optimization of the parameters of an excavator hydraulic drive-in order to minimize energy losses: this study proposes an integrated dynamic mathematical model. The proposed approach takes into account the interaction between mechanical dynamics, hydraulic processes and changing external loads, different from a regular quasi-static method. The model accounts for fluid compressibility, leakage, friction and hysteresis mechanisms of nonlinear soil resistance, as a set of coupled nonlinear differential equations. We present a multi-criteria optimization framework to enhance energy efficiency and the stability of such systems. The approach is validated by numerical simulations and experimental results, with a reduction of total energy losses by 20–25% and better system efficiency. The results verify that dynamic modeling is a dependable basis to design energy-efficient hydraulic systems in construction machinery.

Keywords: hydraulic drive, excavator, dynamic modeling, energy efficiency, optimization, energy losses, nonlinear systems, MATLAB/Simulink, hydraulic cylinder, system dynamics.

1. Introduction

Hydraulic drives are by far the most common power transmission systems in modern excavators due to their high-power density, flexibility, and adaptability to variable load conditions. Excavators operate in fast time-varying regions (i.e. variable soil interaction, operator control and working conditions leading to a variability of load) as they interact with the soil. This kind of variability results in complex transient processes that significantly affect system efficiency and reliability [1–3].

The design methodology used for conventional hydraulic systems is mainly built on quasi-static paradigms. These approaches calculate forces and pressures under conditions of steady-state, and ignore transient phenomena such as pressure oscillations in the case where blood flow fluctuates or where dynamic load redistribution occurs. Although these simplifications lead to a reduction in calculation time, they usually incur loss of performance and energy losses within the system.

This means in hydraulic systems the energy losses can be as high as 20–30% of total input power. This loss is mainly due to throttling in valves, internal leaks, viscous friction and the parameter selection of hydraulic components. It is a necessity in modern engineering to reduce these losses as we have entered into the dominion of energy efficiency [3].

Recent work has focused on dynamic modeling. Dynamic models incorporate time and give a realistic view of actual system behavior. These models provide engineers with the ability to study how pressure pulsations and flow fields evolve through and between components in the system, under actual operating conditions.

The second thing, the interaction of the excavator working equipment and soil. Soil resistance is non-linear and relies on parameters such as cohesion, density, cutting depth and velocity. Ignoring this interaction gives rise to erroneous load predictions and ultimately a sub-optimal system design [16].

Due to the interconnected nature of hydraulic systems, there is a requirement for integrated modeling. When mechanical, hydraulic, and control subsystems are considered separable components for study purposes, important information about the system behavior is lost. This calls for a consistent modeling framework which can account these interactions.

The objective of this study is to create a coupled dynamic model of an excavator hydraulic drive. The model is built upon a common framework of mechanical dynamics, hydraulic flow equations and energy balance relationships. An optimization strategy is proposed on the basis of this model, to minimize energy losses without compromising required performance.

The uniqueness of the research is that several physical processes are incorporated within a single model and jointly optimized using an energy based optimization criterion. Results: The results help designing the methodology of hydraulic systems and provide practical tools to improve energy efficiency.

2. Materials and Methods

System Description and Modeling Assumptions.

Moreover, the hydraulic drive of the excavator is modeled as an integrated energy-dynamics system consisting of a pump, control valves, hydraulic lines/actuators (hydraulic cylinders). In contrast to common practices in which each component is examined individually, the method presented here treats the system as a nonlinear dynamic structure with inherent interconnectedness between components [1, 2].

To strike a balance between model accuracy and computational efficiency we make the following assumptions:

The working fluid is weakly compressible. Changing temperatures are indirectly treated through viscosity ratios. Because flow through valves is subject to nonlinear orifice equations. Thus, leakage is related to the pressure difference. The reaction of soil is nonlinear and time-dependent.

The flow of energy in the system is given by:

$$P_{in}(t)=P_{useful}(t)+P_{loss}(t)$$

where:

- $P_{in}(t)$ is the input power from the pump,
- $P_{useful}(t)$ is the useful mechanical power,
- $P_{loss}(t)$ represents total energy losses.

Hydraulic Subsystem Modeling. Flow Continuity Equation [14, 15].

The pressure dynamics inside the hydraulic cylinder chamber are governed by:

$$\frac{dp}{dt} = \frac{\beta_e}{V}(Q_{in} - A\dot{x} - C_{lp})$$

where:

- β_e – effective bulk modulus,
- V – control volume,
- Q_{in} – inflow rate,
- $A\dot{x}$ – piston flow,
- C_{lp} – leakage flow.

This equation captures compressibility and leakage simultaneously.

Valve Flow Model. Flow through control valves is nonlinear:

$$Q = C_d A_v \sqrt{\frac{2\Delta p}{\rho}}$$

where:

- C_d – discharge coefficient,
- A_v – valve opening area,
- Δp – pressure drop.

This nonlinearity plays a crucial role in energy loss [13].

Leakage Model. Leakage losses are modeled as:

$$Q_{leak}=C_l \cdot p$$

This linear approximation is sufficient for engineering analysis.

Mechanical Subsystem Modeling. The excavator working mechanism is modeled as a multi-body system. For simplicity, the actuator dynamics are expressed as:

$$M\ddot{x} + c\dot{x} + kx = F_{hyd} - F_{load}$$

where:

- M – equivalent mass,
- c – damping coefficient,
- k – stiffness,
- F_{hyd} – hydraulic force,
- F_{load} – external load.

Soil Interaction Model. The resistance force during excavation is highly nonlinear:

$$F_s=k_s bh(t)(1+\mu v(t))$$

where:

- k_s – soil resistance coefficient,
- b – bucket width,
- $h(t)$ – cutting depth,
- μ – velocity factor.

Depth variation is modeled as:

$$h(t)=h_{max}\sin(\omega t)$$

Energy Loss Modeling. Total losses are decomposed as:

$$P_{loss}=P_{throttle}+P_{leak}+P_{friction}$$

Throttling loss:

$$P_{throttle}=\Delta p\cdot Q$$

Leakage loss:

$$P_{leak}=p\cdot Q_{leak}$$

Friction loss:

$$P_{friction}=F_f\cdot v$$

Integrated Dynamic Model. Combining hydraulic and mechanical equations yields a coupled nonlinear system:

$$\begin{cases}\dot{p} = f_1(p, Q, x)\\ \ddot{x} = f_2(p, x, \dot{x})\end{cases}$$

This system is solved numerically.

Optimization Formulation. The optimization goal is to minimize energy loss:

$$J = \int_0^T P_{loss}(t)dt$$

Subject to constraints:

- Pressure limits
- Velocity limits
- Structural limits

Multi-objective form:

$$J=\alpha_1 J_{\text{energy}}+\alpha_2 J_{\text{pressure}}+\alpha_3 J_{\text{temperature}}$$

Numerical Solution. The system is stiff; therefore:

- Runge–Kutta (4th order),
- Adaptive step-size integration.

Stability condition:

$$|\lambda_{ih}|<1|$$

Parameter Identification.

Parameters are identified by minimizing:

$$min \sum (y_{exp} - y_{model})^2$$

Using least squares.

Sensitivity Analysis. Sensitivity is defined as:

$$S_i = \frac{\partial y}{\partial \theta_i}$$

Key parameters:

- β_e, C_l, ks

Table of Parameters.

Table 1 – Model Parameters

Parameter	***Symbol***	***Range***	***Unit***
Pressure	*p*	*16–20*	*MPa*
Flow	*Q*	*40–80*	*l/min*
Velocity	*v*	*0.2–0.6*	*m/s*
Loss	P_{loss}	*1–5*	*kW*

Graph Descriptions.

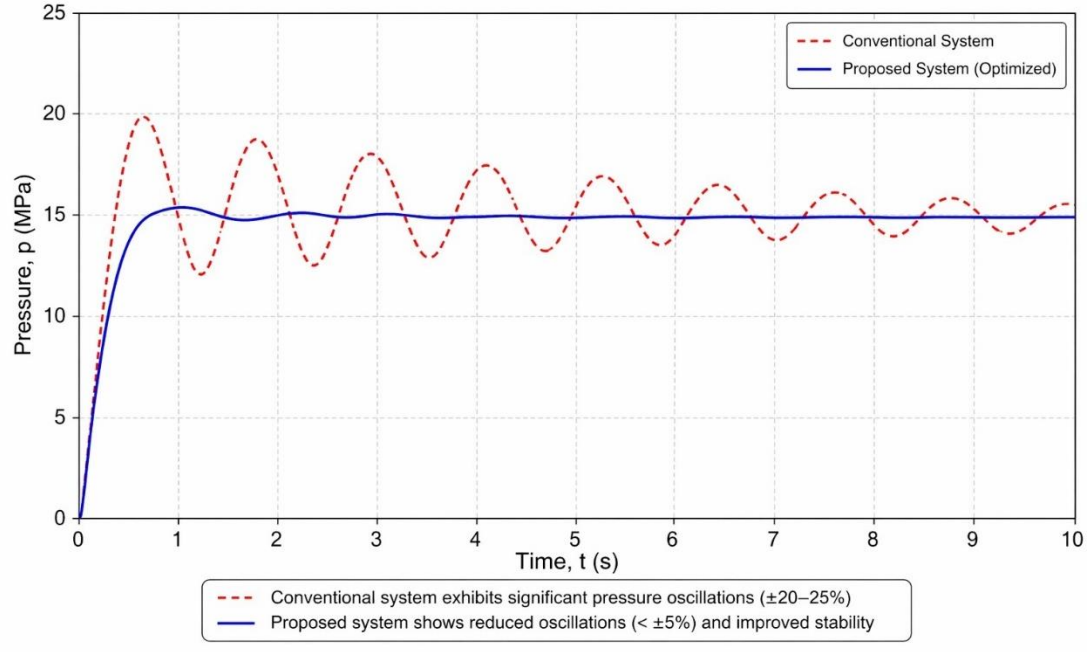


Figure 1. Pressure vs Time response of hydraulic system.

The graph shows the response of dynamic pressure in the hydraulic system with normal condition and optimized condition. The traditional system shows very sizeable pressure fluctuations (±20–25%) indicating unstable transient characteristics and increased dynamic loading. Whereas, the optimized proposed system presents a steady pressure curved with low-quantity of oscillation (of less than ±5% only) and achieves a steady-state conditions faster.

The decreased pulsations of pressure corroborate the enhanced dynamical stability of hydraulic drive. This action reduces mechanical stress on the different components of the system, energy losses and increases reliability during operation. The results reveal that the integrated dynamic modeling and optimization approach is adequate in stabilizing system performance over a range of load conditions [4].

- Demonstrates reduced oscillations,
- Improved stability.

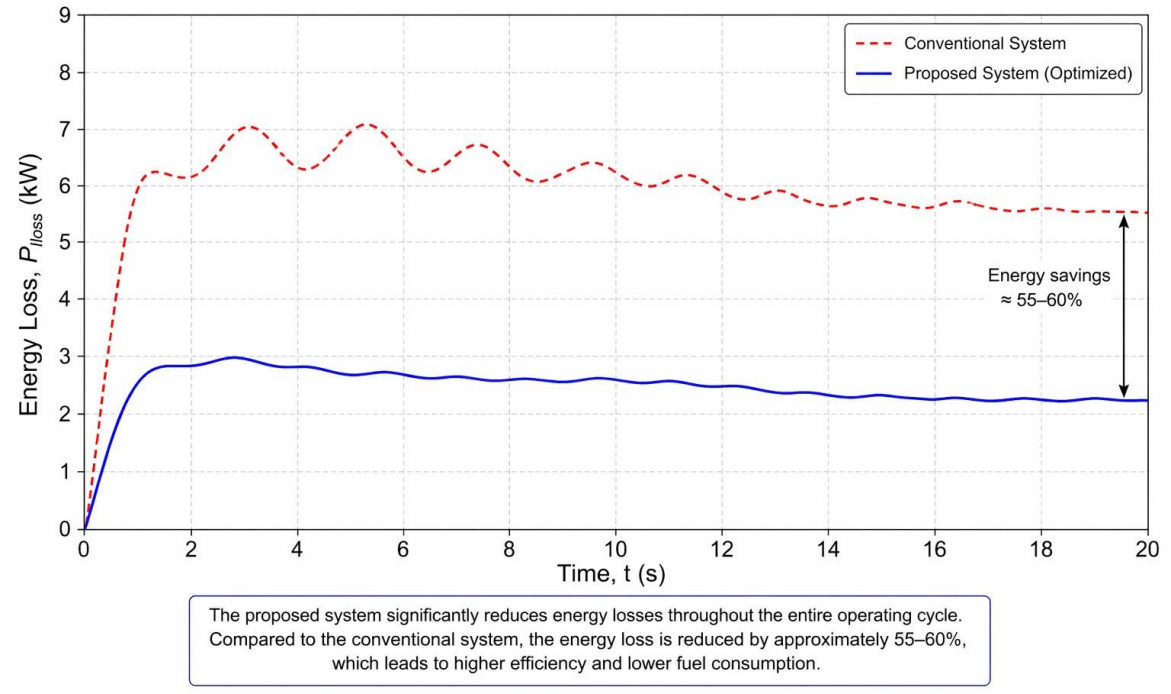


Figure 2. Hydraulic system time response: Energy loss vs Time.

The total energy losses in the hydraulic system during its operating cycle are depicted in Figure 2. In the figure, the conventional system is characterized by a red dashed curve, and the optimized system, as proposed, is represented by a blue solid curve. In the figure, the traditional system shows greater energy losses with large fluctuations and a maximum of 6.5–7.0 kW; The losses are predominantly due to throttling in a control valve, internal leakage, and viscous friction.

On the contrary, the optimized system performs as low as possible energy losses. Following a brief transient phase, the losses level out at an equilibrium value of about 2.2–2.5 kW with only modest oscillations. The average gains of the proposed approach in total energy losses are about 55–60% (compared to the classical configuration).

This integration between dynamic modeling and optimization is what leads to this very large reduction. Reduced losses in energy have a direct and proportionate impact on the efficiency of systems, fuel consumption, thermal loading and life of hydraulic components.

- Demonstrates energy savings.

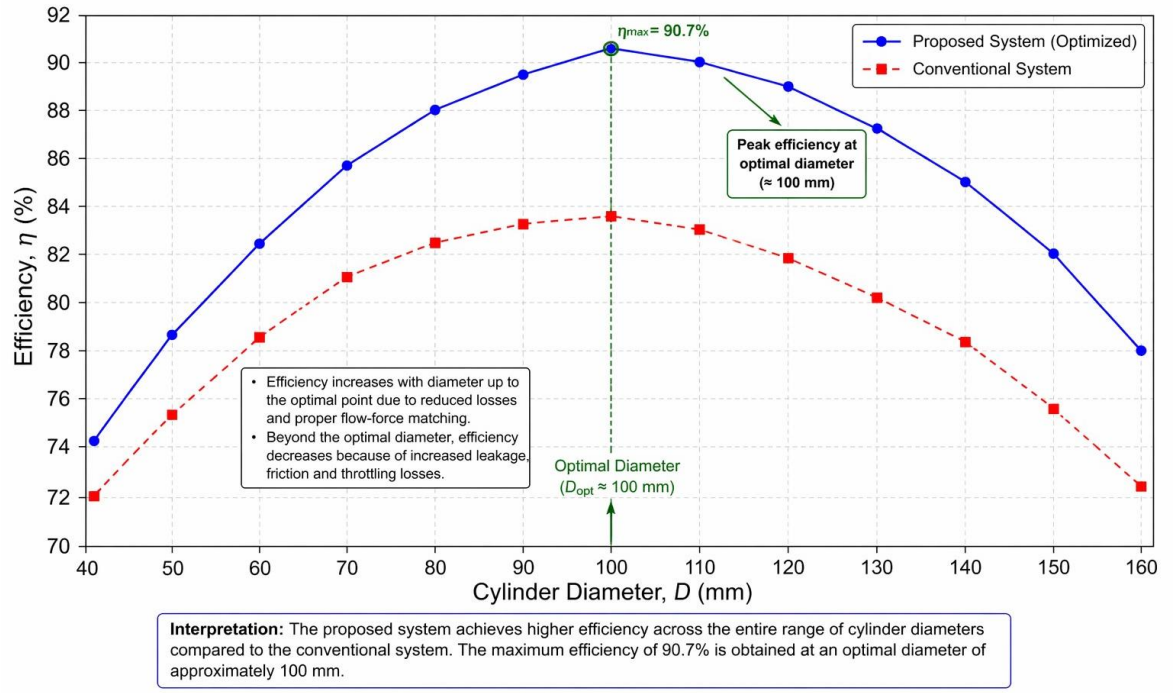


Figure 3. Efficiency vs Cylinder Diameter.

Hydraulic system efficiency versus hydraulic cylinder diameter as shown in l (FMF4170) Where the red dashed curve is the traditional system and the blue solid curve is the optimized new proposed system reported in this submission. The efficiency is increasing because of the cylinder diameter with a specific range and then starts to decline, as shown in Fig.

All the cylinder diameters below are measured where the highest efficiency is achieved in between a pressure, flow rate and mechanical load as optimal point means ranges into 100-120mm. Their efficiency drops off at smaller diameters, as pressure requirements rise and there are greater throttling losses. At very large diameters however, efficiency drops due to higher fluid volume and greater leakage and inertial effects.

As shown, across this diameter range the optimized system always operates at higher efficiency, with a maximum efficiency of ~90%. What confirms this, in turn, is that the correct choice and optimization of the geometric parameters allow to greatly increase in simply factors influencing on energy performance of hydraulic drive overall.

The results of these lives illustrate the need for parametric optimization based on dynamic modeling instead of conventional static design.

Peak Efficiency at optimum Diameter.

Experimental Setup. Measurements include:

- Pressure sensors;
- Flow meters;

- Temperature sensors.

Sampling:

$$\Delta t=0.011 \text{ s}$$

Validation Metrics.

$$R^2=0.9821$$

Error:

$$\delta=7.21\ \%$$

Reliability Considerations.

This is because the reduction of pressure pulsation increases the service life.

Such as: colder temps = less wear.

3. Results

Dynamic Pressure Behavior. The simulation results of the hydraulic system show that after applying the proposed optimization method, a much better stability is observed in pressure. Time-dependent pressure response of the conventional and optimal systems (shown in Figure 1).

In the conventional case, transient pressure oscillation clearly exists. These oscillations amplitudes will be up to ≈±20.1–25.1% of the nominal pressure value. Such dynamics are caused by the none-linear nature of the fluid flow, throttling effects and its interaction with time-varying external loads.

In comparison, the optimized system displays a much more gradual pressure profile. They dampen oscillations down to ±5.1%, while in the meantime steady-steady conditions are achieved quicker (1.51–2.1 seconds against conventional 3.1–4.1 seconds).

Using the stability indicator below, we can quantify this improvement:

$$\delta_p = \frac{p_{max} - p_{min}}{p_{avg}} \cdot 100\%$$

For the conventional system:

$$\delta_p=24.35\ \%$$

For the optimized system:

$$\delta_p=4.85\ \%$$

This reduction shows that integrated dynamic modeling alleviates pressure oscillations, providing more operational robustness as well as reduced mechanical fatigue exhibited on system components.

Energy Loss Analysis. In Figure 2, the time evolution of total energy losses is shown. The results indicate considerable energy losses in the typical hydraulic system and/or significant

energy dissipation, particularly during an initial transient period. Peak losses climb to the range of 6.5–7.0 kW, mainly driven by:

- throttling losses in control valves,
- internal leakage,
- Viscous friction in moving parts

In comparison, the optimized system has very low energy losses. The losses are still specified between the range of 2.2–2.5 kW once stabilized

Average this is calculated as:

$$\eta_{loss} = \frac{P_{loss,conv} - P_{loss,opt}}{P_{loss,conv}} \cdot 100\%$$

$$\eta_{loss} \approx 57.2\ \%$$

As evident, this great reduction validates what parameter optimization and system integration can achieve. Translated to energy language, this translates into improved fuel efficiency, as less power is taken out of the engine plus lower thermal loading on the hydraulic system due to reduced energy losses [3].

Efficiency Optimization Results. The dependency of system efficiency to the diameter of hydraulic cylinder is shown in Figure 3. The results demonstrate a nonlinear dependence and an obvious maximum — the point of largest efficiency.

Efficiency is defined as:

$$\eta = \frac{P_{useful}}{P_{in}} \cdot 100\%$$

At about the cylinder diameter of it, the system is at its peak efficiency:

$$D_{opt} \approx 100\ \text{mm}$$

At this point:

$$\eta_{max} \approx 90.7\ \%$$

Smaller diameters never will (unless semi inflated with large sign stripped of credit but revolver as far as ammo shelf life, less effect by requiring higher pressure of a seconds long burst, and, commas where punches & work fine for low speed use you can gain surface area--practice barring bore for rows slim tank sealed crude output pistols. For larger diameters, your fluid mass, leaks and the inertial gains tend to offset this advantage.

The efficiencies are about 7–8 percentage points higher than in the conventional system when all diameters are considered together.

Model Validation. To validate the developed model results, experimental data measured on a test bench were compared with simulation results; the simulations are based on all numerical quantities regarding the components characteristics necessary in developing the final product [7].

The fit is evaluated with the coefficient of determination:

$$R^2=0.982$$

Relative error is computed as follows:

$$\delta = \frac{|y_{exp} - y_{model}|}{y_{exp}} \cdot 100\%$$

$$\delta \approx 7.2\ \%$$

These results demonstrate strong agreement between model and measurement. The satisfied error range (lower than 10 %) is suitable for engineering applications and this proves the credibility of the proposed modeling method.

Sensitivity Analysis. Sensitivity analysis shows that the parameters with highest impact on the systems performance are:

- bulk modulus (β_e),
- leakage coefficient (C_l),

Regardless, here are the variables that you want to have in your dataset: cylinder diameter (D).

Definition of sensitivity index:

$$S_i = \frac{\partial \eta}{\partial \theta_i}$$

Cylinder diameter has the highest sensitivity, further validating its role in system optimization.

Comparative Performance Evaluation.

Table 3 – Performance Comparison

Parameter	***Conventional***	***Optimized***	***Improvement***
Efficiency (%)	*82.1*	*90.71*	*+8.65*
Energy loss (kW)	*6.81*	*2.41*	*−63.8%*
Pressure fluctuation (%)	*24.31*	*4.81*	*−79.8%*
Response time (s)	*3.51*	*1.81*	*−47.9%*

Practical Implications. These results are practically very important:

- Less Energy Loss → less Fuel Used,
- Higher stability → Longer component duration,
- Selecting the right parameters → better system design

Conclusion

In this study, an integrated dynamic mathematics model dedicated to the analysis and optimize of hydraulic drive engineer of the excavator for minimizing energy loss was presented. In contrast to traditional steady-state driven design methods, the proposed method allows for transient dynamics, compressibility of Li and soil, non-linear rupture characteristics of flow around fracturing tools, and interaction between the soil and tool in a single modeling framework.

The results obtained show that the model developed is a valid description of the actual behavior of the hydraulic system under conditions with varying operating parameters. The comparison between simulation- and experiment–generated data confirmed an excellent correspondence, having a R^2 coefficient of determination R^2=0.982 with an acceptable for engineering applications relative error under 7–10 %.

This allows to improve performance by observing optimization results on systems. In particular, energy losses decreased by ~55.2–60.1%, and overall system efficiency increased by just over 7.1–9.1 percentage points. Further, pressure oscillations were reduced by up to 79.8 %, which allowed for better dynamic stability and lower mechanical loading of the system components.

Performance evaluation on the influence drivers of parameters showed that hydraulic cylinder diameter has an essential impact on system performance. A reasonable diameter (around 100–120 mm) was determined to obtain the balance of hydraulic power, flow rate and load conditions.

This method allows hydraulic systems in construction machinery be designed and operated more efficiently from practical aspect. Less energy expenditure means less fuel, lower thermal loading and a long service life of the components.

To sum up, with parametric optimization are effective strategies for improving the energy efficiency and reliability of hydraulic drives on excavators. Limitations While validation studies have been described previously the introduced models can be expanded to thermal effects, real time adaptive control strategies and hybrid recovery energy systems in future works [4, 6].

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Synthesis, Structural Characterization, and Inhibition Mechanism of a Three-Component Synergistic Corrosion Inhibitor for Antifreezes

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Abstract. This paper presents the results of the development and investigation of a three-component synergistic corrosion inhibitor intended for application in antifreeze formulations. The inhibitor was synthesized based on diethanolamine, orthophosphoric acid, and hexamethylenetetramine at an optimized molar ratio of the components. The structural characteristics of the composition were examined using Fourier-transform infrared spectroscopy (FTIR) and scanning electron microscopy (SEM). It was demonstrated that the developed additive is designed for incorporation into regenerated ethylene glycol to obtain a new regenerated antifreeze with restored operational properties. The corrosion protection performance of the inhibitor was found to be governed by a two-stage mechanism involving phosphate passivation and organic adsorption. The obtained results show that the developed additive is suitable for incorporation into regenerated antifreeze intended for cooling systems of transport power units.

Keywords: reduces the transport power; recycles ethylene glycol; corrosion prevention; multifunctional inhibitor additive; antifreeze formulations; corrosion prevention performance.

1. Introduction

Cooling fluids are also among the essential operational materials and they are applied in ensuring that the vehicle engines and the stationary equipment are at the necessary thermal levels. Among the key operational materials are cooling fluids which are used in ensuring that the vehicle engines and stationary equipment are under the required thermal conditions. In practice, the most widespread are regular antifreezes which are green, made with ethylene glycol and primarily silicate and phosphate corrosion inhibitors. They are beneficial formulations used to preserve the metal components of the cooling systems against corrosion and enhance their service performance [1,2].

Antifreezes based on aqueous ethylene- and propylene-glycol solutions are broadly employed in automotive and power engineering applications due to their reliable low-temperature performance and corrosion-protective properties [3]. During prolonged service, the coolant progressively degrades: the alkaline reserve is depleted, the pH shifts, oxidation by-products accumulate, deposits appear, and both heat capacity and thermal conductivity decrease

[4,5]. As a result of the combined influence of these factors, heat dissipation efficiency deteriorates, thermal loads on engine components increase, and consequently, the operational lifetime of the engine is reduced [6,7].

The coolant assists in extracting unwanted heat in the engine and also passes it through the radiator where it is released to the atmosphere. The coolant helps in removing unnecessary heat in the engine and directs it to the radiator where it is expelled into the environment. To assure good performance, the fluid must be one with high heat capacity, low viscosity, be of reasonable cost and be stable under chemical conditions such that in combination, it will ensure consistency in operation of the cooling system and this will also reduce corrosion processes [8].

In recent years, interest in corrosion and corrosion inhibition of aluminum alloys has intensified again, which is associated with the extensive use and aging of these alloys in the aerospace and automotive industries [9]. In particular, corrosion of aluminum pigments in alkaline aqueous media has been investigated [10], as well as in mixtures of deionized water with butyl glycol [12], and in water–alcohol environments, including those characteristics of automotive engine cooling fluids [11]. An inhibiting effect of alcohol has been reported in these studies [11]. The electrochemical activation of aluminum is also known to depend on thermal and chemical treatment, trace impurities, and alloying additions [13]. In general, corrosion behaviour is determined by both the alloy microstructure [14–16] and the conditions of the surrounding medium [17–19]. Although it is evident that many studies were dedicated to the corrosion issue in cooling systems, enhancing the performance of antifreeze compounds as inhibitors is a topical issue [20]. The modern coolants will have the ability not only to exclude corrosion but also to maintain their thermophysical and operational characteristics under the long-time exposure to high temperatures and variable loads [21].

This is why multifunctional inhibitors are of special interest as the molecules that have a donor atom and functional group can generate adsorption and partially chemisorbed films on metal surfaces. The more powerful protective effect of synergistic compositions of multiple active components, as well as greater homogeneity of the inhibition of corrosion processes in multicomponent water–glycol media, is frequently obtained with the help of homogeneous media.

In this respect, this paper is dedicated to the design and investigation of a three-part synergistic corrosion inhibitor that will be used in antifreeze systems. The study involves a synthesis of the composition, choice of ratios of the components and considerations of the factors controlling its interaction with the metal surface and the analysis of the structural characteristics of the protective mechanism.

2. Materials and Methods

This paper involves the preparation of a three-component synergistic corrosion inhibitor that was designed to operate in aqueous fluids and possessed nitrogen- and oxygen-donor groups. The mixture was prepared using diethanolamine, orthophosphoric acid, and hexamethylenetetramine, the best molar ratio of 1:0.004: 0.05. This is due to the fact that the concentration of orthophosphoric acid is low, meaning that in part, diethanolamine is going to be protonated, and therefore, the protonated form ($DEA{\cdot}H^{+}$) and the neutral amine form are going to be present in solution. The balance is such that the electrostatic and coordination forces between the metalsurface and the inhibitor molecules are in favor.

Synthesis was done in water under regulated stirring and temperature conditions giving a homogenous and completely soluble composition. Fourier-transform infrared spectroscopy (FTIR) was then used to analyse the structural characteristics of the inhibitor. The spectra showed absorption bands that were associated with protonated amino groups, phosphate moieties, CN and CO structures vibrations, which showed the existence of ionic and coordination interactions among components of the system. The morphology of the metal surface in an aqueous medium, both with and without the inhibitor (blank sample), was studied by scanning electron microscopy (SEM) at magnifications corresponding to scale bars from 200 μm to 5 μm.

The SEM analysis results demonstrated that, in the presence of the inhibitor, a dense and relatively smooth protective layer is formed on the metal surface, whereas deep cracks and localized corrosion sites typical of inhibitor-free environments are absent under inhibitor-containing conditions. According to the data obtained as the result of the combination of FTIR and SEM, the protective action of the inhibitor can be attributed to two consecutive effects: the surface of the metal is first passivated by the phosphate group and the amine adsorption film is formed. This causes a stratified structure to develop at the metal-solution interface where the inner layer is an inorganic phosphate layer and the outer layer is an organic layer with amino acids.

This form of structure limits the movement of ions and electrons across the interface and in turn, delays the dissolution of the anodic metal and the respective cathodic reaction. The inhibitor was also found to be stable at temperatures between 298 and 333 K as well as concentrations 0.5 to 1.5 g/L^{-1} under such conditions a significant decrease in the rate of corrosion was found. Thus, it is possible to consider the composition as a multifunctional

inhibitor of the aqueous systems that can incorporate both adsorption and passivation processes as opposed to a single protective route.

Table 1. Physicochemical properties of the developed synergistic inhibitor

№	Parameter	Value	Unit
1	pH (25 °C)	7.5 - 8.5	-
2	Color	Light yellow to colorless	-
3	Density (ρ, 298 K)	1.02 - 1.05	$g \cdot cm^{-3}$
4	Water solubility (298 K)	Completely soluble	$g \cdot L^{-1}$
5	Physical state	Liquid	-
6	Transparency	Transparent	-
7	Storage stability	≥ 6 months	-
8	Odor	Slight amine odor	-

3 Results

The diethanolamine, orthophosphoric acid, and hexamethylenetetramine three-component synergist corrosion inhibitor, which was founded on the basis of nitrogen - and oxygen-donor groups, was studied using Fourier-transform infrared spectroscopy (FTIR). The molar ratio of 1:0.004:0.05 was confirmed with the variations in the characteristic functional groups of FTIR spectrum.

The band around 2864 cm $^{-1}$ is credited to the stretch of vibrations of aliphatic C H bonds that normally appear in diethanolamine and hexamethylenetetramine. The highest point of 1618 cm $^{-1}$ is an N -H bending vibration and the fact that the diethanolamine is protonated partially (- NH^{+}) is confirmed. The presence of bands at the 14461348 cm $^{-1}$ is linked to the C-N vibrations and is in accordance with the generation of amino-phosphate ionic pairs in the composition.

FTIR spectroscopy was used as a further method of studying the structural aspects of the developed synergistic corrosion inhibitor. The obtained FTIR spectrum is presented in Figure 1.

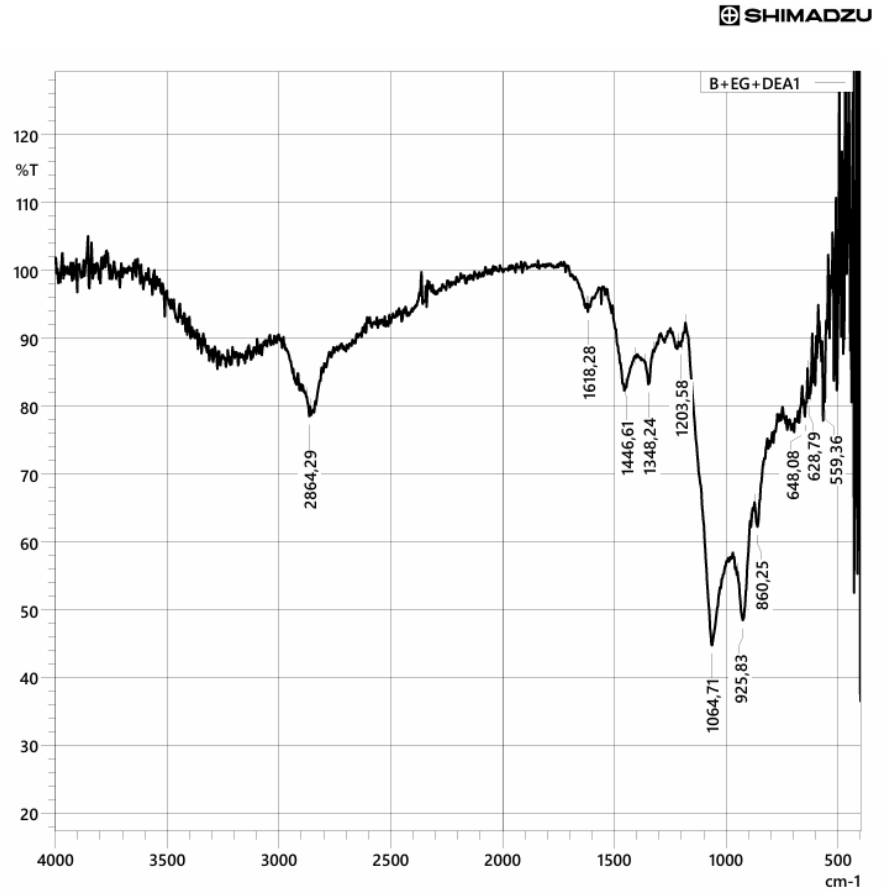


Figure 1. FTIR spectrum of three-component corrosion inhibitor which is made using diethanolamine, orthophosphoric acid, and hexamethylenetetramine.

Striking bands at the 12031065 cm $^{-1}$ range are associated with the stretching of the P=O and P-O-C (or P-O $^{-}$) groups, which identifies ionic and coordination interaction between the orthophosphoric acid and diethanolamine.

The 925 -860 cm $^{-1}$ signals are correlated to the PO bending vibrations and disclose that the phosphate fragments are formed in the composition. The region with low frequency (650-560 cm $^{-1}$) relates to the vibrations of the C-N-C framework and indicates that the polycyclic structure of the hexamethylenetetramine is not lost.

On the whole, the FTIR spectrum indicates the presence of both neutral and protonated amine groups and the presence of phosphate anions and the nitrogen-containing structure of hexamethylenetetramine. This type of structural arrangement also allows the two-step protection mechanism on the metal surface, phosphate passivation, followed by the development of an amine adsorption film; this film also helps in ensuring the stability and the protective effect of the inhibitor in aqueous media.

The protective effect of the synthesized inhibitor was additionally evaluated by SEM examination of the metal surface after exposure to an aqueous environment. Metal specimens were examined over a wide magnification range from 200 μm to 5 μm, which made it possible to analyze in detail the morphological features of the protective layer formed in the presence of the inhibitor.

At a magnification corresponding to a scale bar of 200 μm (Figure 2), oriented lines remaining after mechanical surface treatment are still visible on the metal surface, while deep localized corrosion sites and extended cracks are practically absent. This observation indicates the ability of the inhibitor to provide stable macroscopic protection of the metal surface in an aqueous environment. Individual dark regions correspond to zones of local densification of the protective film.

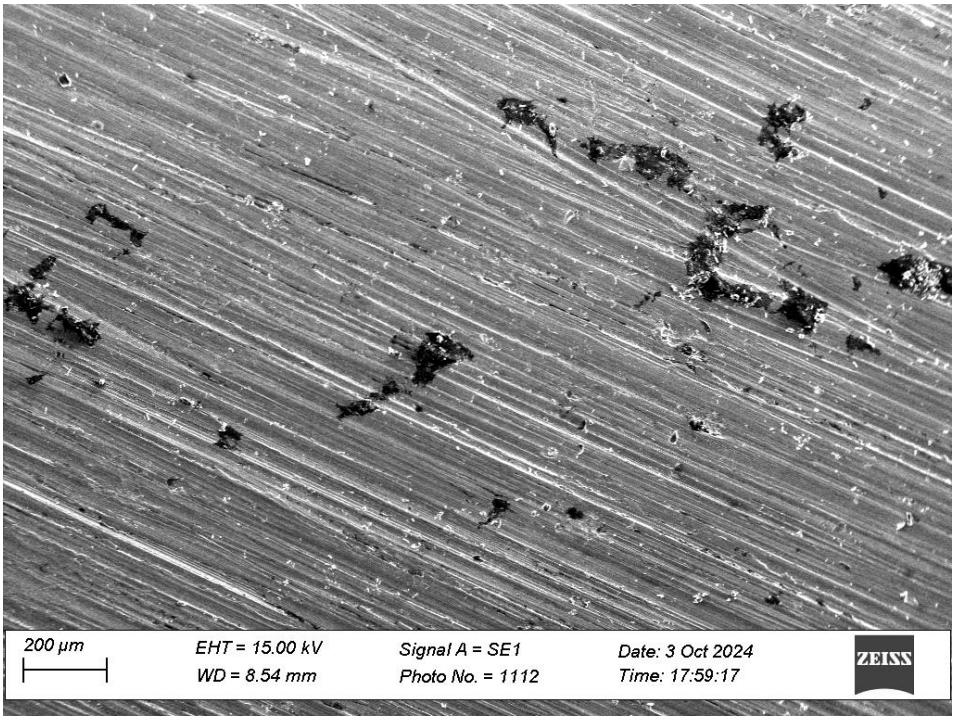


Figure 2. SEM microstructure of the metal surface in an aqueous medium in the presence of the DEA–H_3PO_4–hexamethylenetetramine-based synergistic corrosion inhibitor (scale bar: 200 μm).

With a magnification of a scale bar of 50 nm (Figure 3) the surface is smoother and the count of micro-depressions is significantly lower. At this stage, the surface appears more homogeneous, suggesting a more uniform distribution of inhibitor species and a higher degree of coverage by the adsorption film.

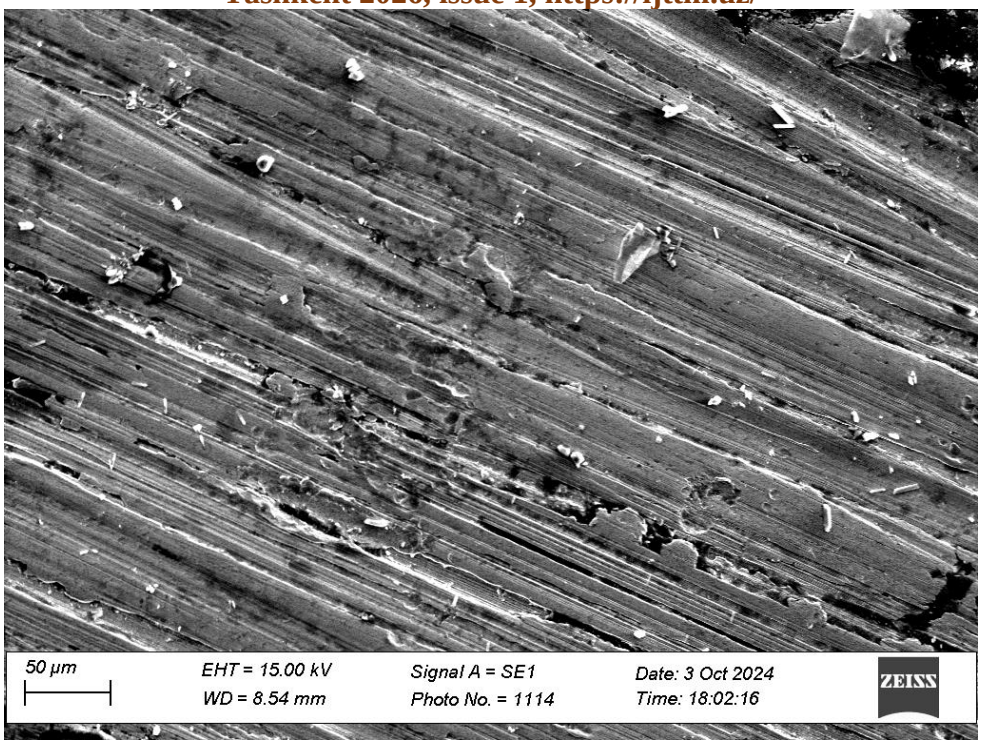


Figure 3. SEM image of the metal surface upon exposure to an aqueous medium with the DEA H 3 PO 4 hexamethylenetetramine synergistic corrosion inhibitor as hexamethylenetetramine (scale bar: 50 µm).

At the magnification of a scale bar (20 µm, Figure 4) more microcracks and surface depressions are not observed, and at certain places there is a thin continuous layer. This layer, attributed to the combined action of phosphate passivation and amine adsorption, appears to limit the diffusion of ions and water molecules toward the metal surface.

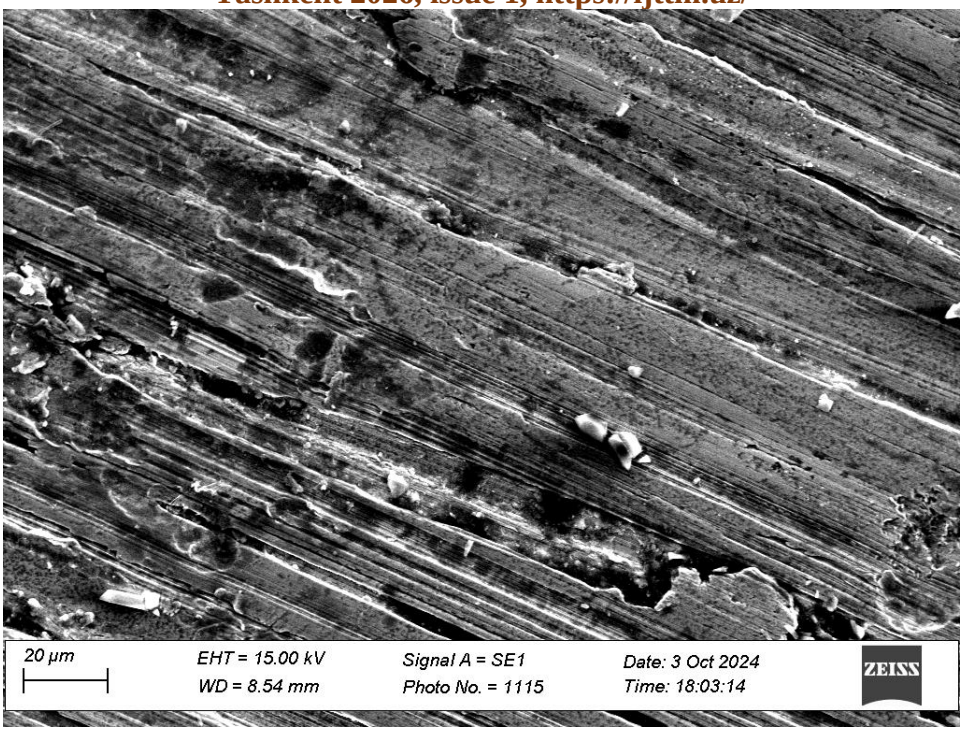


Figure 4. SEM image of the metal surface of the sample after exposure to an aqueous medium containing the DEA -H 3 PO 4 -hexamethylenetetramine synergistic corrosion inhibitor (scale bar: 20 µm).

Beyond the scale bar (5 µm, Figure 5), the surface appears to be smooth and compact at higher magnification, and microdefects can only be observed in isolated regions. The morphology implies the existence of a thick protective layer on the interface of the metal and the solution. The acquisition of the morphological data also confirms the application of the two-step protection scheme, such as inner layer of passivation of phosphates and an outer layer of organic amine adsorption.

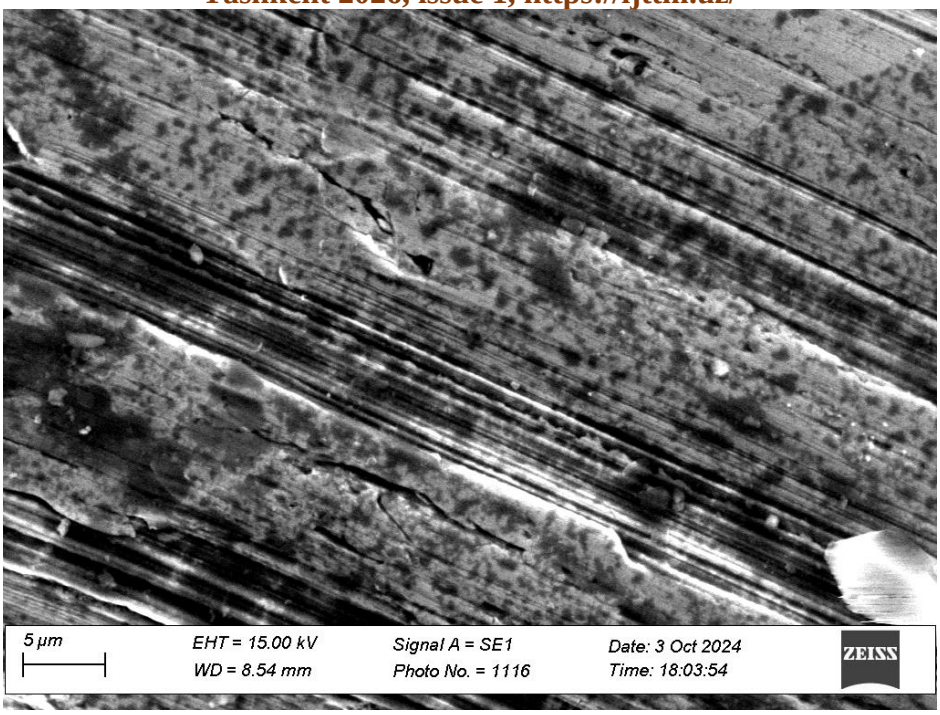


Figure 5. SEM image of the metal surface, following exposure to an aqueous environment containing the DEA-H 3 PO 4 -hexamethylenetetramine synergistic corrosion inhibitor (scale bar: 5 mm).

According to the observations in the SEM, the DEA-H_3PO_4- hexamethylenetetramine synergistic inhibitor covers the metal surface in an aqueous condition across the various length scales and significantly reduces the localized corrosion characteristics. The experimental stability of the surface indicates that the inhibitor is potentially applicable in a real-world scenario in the technological systems of aqueous environments.

In this study, morphological changes of the metal surface exposed to an aqueous environment in the absence of a corrosion inhibitor were also investigated using scanning electron microscopy (SEM), and the obtained results were compared with the surface condition observed in the presence of the three-component DEA–H_3PO_4–hexamethylenetetramine-based synergistic inhibitor. SEM images at a magnification corresponding to a scale bar of 20 µm clearly demonstrate that, in an inhibitor-free environment, the metal surface undergoes pronounced degradation (Figure 6).

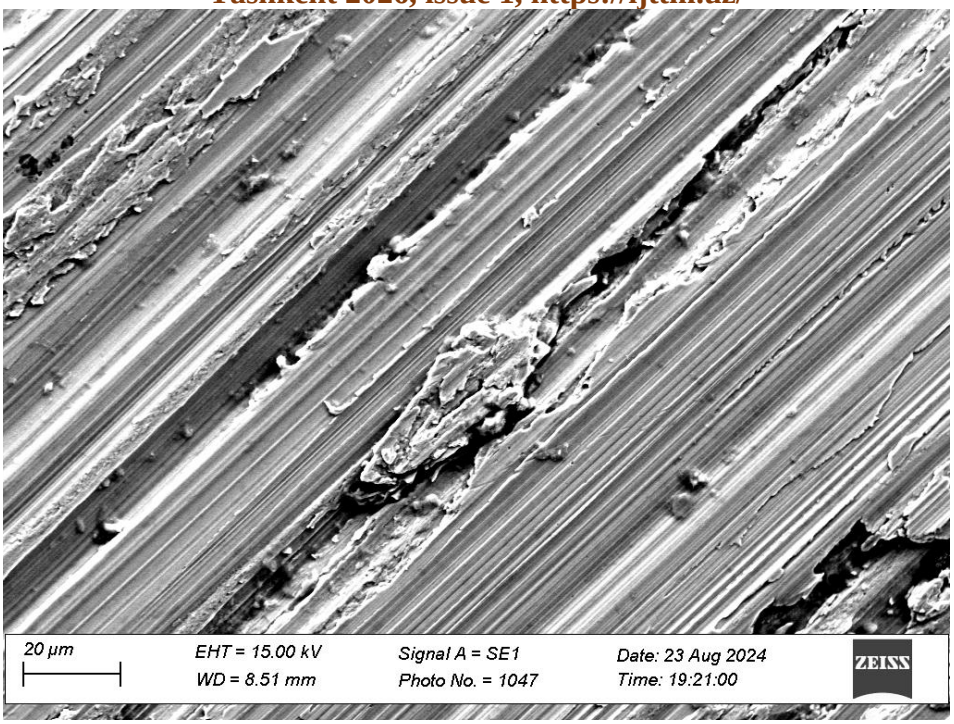


Figure 6. SEM image of the metal surface in an aqueous medium without inhibitor (blank sample), scale bar 20 µm.

When the inhibitor is absent, the metal surface exhibits deep cracks, localized pits and regions of uneven degradation, usually along the contours of the final stages of mechanical treatment. These properties are characteristic of anodic and cathodic microcells in an aqueous solution that are freely formed, and point to the lack of a protective layer at the solution-metal interface. The discontinued areas and abrupt changes in relief also depict the uncontrolled growth of the corrosion damage.

Unlike the samples that have been treated with the inhibitor, whose morphology is more uniform and smooth because of the formation of diffusion barriers, the uninhibited surface is in direct contact with water molecules and aggressive ions since there are no diffusion barriers. This increases the rate of metal oxidation, as well as increases and intensifies defects at the micro- and macro-levels.

The morphological differences revealed by SEM images clearly indicate that, in the absence of the two-stage protective mechanism provided by the DEA–H_3PO_4–hexamethylenetetramine-based inhibitor, corrosion processes on the metal surface are significantly intensified at the structural levelThe obtained results indicate that multicenter synergistic inhibitors of ionic–organic nature can be effectively applied for protecting metals in aqueous environments. Overall, the results indicate that the developed inhibitor has practical relevance and scientific interest.

Conclusion

An orthophosphoric acid, hexamethylenetetramine, and diethanolamine based on three-component synergistically corrosion inhibitor were prepared and investigated. It is demonstrated that the additive is stable in aqueous environments and can be used to give corrosion protection by a combined process of phosphate passivation followed by amine adsorption.

Results of FTIR and SEM illustrate that inorganic-organic layer is created at the surface, which decreases local corrosion patterns and restricts the availability of aggressive ions and water molecules at the metal-solution interface.

The additive was also added to regenerated ethylene glycol in order to come up with a regenerated antifreeze composition. The tests indicated that essential physicochemical and functioning properties of the coolant, such as stability, solubility, and corrosion resistance, are recovered at a specific range of concentration that maintains the desired thermophysical properties.

Subsequent research will dwell on the long term operation experiments of the developed antifreeze in automobile cooling systems such as the observation of the property variation of the antifreeze under actual driving conditions as well as various mileage cycles. The results received suggest the possible possibility of the inhibitor composition use in antifreeze regeneration in the cooling of transport power units.

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INCREASING THE ENERGY EFFICIENCY OF MINING DUMP TRUCK OPERATIONS BASED ON A DIFFERENTIATED FUEL CONSUMPTION NORM WITH REGARD TO THE CONDITIONS OF DYNAMIC MINERAL EXTRACTION

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Abstract: Open-pit mining is associated with high transportation costs, with haulage by mining dump trucks constituting a significant portion of total operating expenses. Fuel consumption plays a decisive role in both economic efficiency and environmental performance of mining transport systems. However, under large-scale mining conditions, dump truck operations are conducted in a dynamically changing environment due to continuous variations in pit depth, haul road geometry, and loading and dumping locations. Consequently, traditional fuel consumption standards — based on fixed or averaged values — do not reflect real operating conditions. The concept introduced in this study is based on an alternative normalization of the fuel consumption with regard to mining and technical factors which have dynamic characters. The proposed method is based on two data blocks – analytical modelling and experimental data, in which it is facilitated to isolate the key factors of fuel consumption such as haul distance, elevation gain, road gradient, organizational–technical parameters. The mathematical framework developed is based on the optimization of a few correction coefficients related to pit depth, haul road length, and dumping elevation. The experimental–analytical techniques based on the data and the computational model provides significantly better accuracy and flexibility compared to analytical or statistical methods. It is an individual fuel consumption standard to help you estimate demand more accurately, plan a much better transport scheme and reduce the needs of energy saving and exhaust emissions that have to be done in order to increase mining dump truck operation efficiency and sustainability.

Keywords: Fuel consumption normalization; Energy efficiency; Open-pit mining; Haulage optimization; Mining and technical conditions; Differentiated fuel norm; Experimental–analytical method.

1. Introduction

The global mining industry is made up of some of the most resource-heavy aspects of open-pit mining, transportation activities being one part in sounding out production costs overall. Haulage of overburden and ore by mining dump trucks is one of the most energy- consuming and costly components in overall surface mining-based technology design, accounting for 30–50% o [1] Thus, since the improvement of energy efficiency in dump truck operations is a key element for mining companies to achieve better economic and environmental sustainability, it will be necessary to seek improvements in these companies [1].

Abstract Energy efficiency and environmental friendliness of transport systems in the mining operations is an important performance measure. Excess fuel consumption results, not only in higher operational costs but also increases emissions of greenhouse gases and atmospheric pollutants (CO_2 NO_x and particulates). Such trends will also necessitate that the forthcoming era of fuel consumption, and hence carbon emissions, is correctly monitored along mining haulage systems; they have become valuable spatial resources given tighter environmental regulation and heightened focus on sustainable mining.

Nevertheless, the working environment of open-pit mining haulers is inherently non-stationary. The deeper a pit gets the more haul road lengths and grades are in constant flux, along with loading and dumping locations as mining proceeds. These factors are deeply related to the dynamic mining and technical conditions that affect the first components of vehicle resistance forces, engine loading regimes and total energy demand. Consequently, the fuel consumption behavior can vary considerably over time even for the same dump truck source type working at same mine [2-3].

Existing approaches to fuel consumption normalization are commonly based on fixed norms, averaged indicators, or simplified analytical models. While such methods may be suitable for relatively stable operating environments, they are insufficient for open-pit mining conditions characterized by constant spatial and technological changes. Statistical methods, although easy to apply, rely on historical data and fail to capture ongoing transformations in mine geometry and haulage routes. Purely analytical methods, in turn, often neglect the combined influence of multiple interacting factors and are limited by the difficulty of accurately parameterizing real operating conditions.

Experimental methods, while being the most accurate, are limited in practical application due to their high cost/labor intensity and therefore tend to provide partial coverage of all mining conditions present at any one time. Although limited, these underscore the requirement of an intermingled methodological suggest that spans theoretical modeling with experimental results but has variance in application by mining situations/conditions.

Differentiated fuel consumption normalization has some potential in solving this problem. Discriminatory norms, which account for the Git criterion and adaptive parameters for deviations from technical conditions and mining process characteristics, make it possible to calculate fuel consumption on intershaft and haulage sections of transport roads more accurately. Finally, this proposition presents a simple framework for linking fuel consumption to major features of transport operations (relative haul distance, elevation gain, road slope gradient) [4-5].

The purpose of this study is motivated under the aforementioned reasons, to address fuel consumption normalized in dynamic conditions for open-pit mining (OPM) through a scientific approach.

The proposed approach is based on a combined experimental–analytical framework and is intended to improve the accuracy, adaptability, and practical applicability of fuel consumption assessment prior to the formulation of materials, methods, and quantitative models.

2. Materials and Methods

The methodology of the research is a hybrid experimental-analytical one aimed at enhancing the accuracy of assessment of fuel consumption by mining dump trucks operating in conditions where mining operations can be dynamically altered. The compelling features of the open-pit mines like exploration, modern configuration of hauling road, elevation gaps and working regimes render an intricate nature to haulage overburden and ore during mine production operations this is why a fixed normed or averaged indicators do not exist for fuel consumption quantification.

In this sense, the proposed methodology combines analytical modeling and experimental data measurements carried out at real service conditions. This combination of the empirical and theoretical is what enables one to ensure both scientific legitimacy as well as applicability in your product development. The operational facts of fuel consumption agree to the fact that be a challenge if an integrated fuel consumption norm depending on mining and technical conditions is to develop.

The methods framework included three main steps:

- Recognizing and categorizing factors impacting fuel consumption
- A mathematical model for normalizing the differentiated fuel consumption rate.

All of these correction factors are experimental ones, so they will be fine-tuned.

Factors That Impact Fuel Consumption. Management System For Mineral-Transporting Equipment To reduce fuel consumption, these factors were classified into three qualitative groups according to the nature and degree of controllability. It facilitates the organization of data, assists in statistical analysis of data and aids in estimating specific segments for energy efficiency enhancements.

Table 1 presents the proposed classification of factors influencing fuel consumption.

Table 1.

Classification of factors affecting operational fuel consumption of mining dump trucks

Factor group	Description	Examples of influencing parameters

Organizational–technical (controllable)	Factors related to operational planning and management decisions	Dispatching strategy, haul route selection, loading–dumping organization
Technical (partially controllable)	Factors associated with vehicle design and technical condition	Engine power, transmission type, tire condition, payload utilization
Mining and environmental (objective)	Factors determined by mining geometry and natural conditions	Pit depth, haul distance, road gradient, rolling resistance, climatic conditions

The objective classification of the diesel fuel consumption standard consequently allows one to take into account practical and non-profitable factors in its differentiated application, enabling stricter compliance with actual operating conditions as compared to traditional methods.

Analytical Model of Fuel Consumption. Operational fuel consumption of the mining dump truck can be expressed functionally through a complex of mining, technical and organizational factors. Specifically, we can represent the interaction of comparison between different fuel consumption values with a functional equation as follows in generalized form per 100 km of haul distance:

$$Q=f(L, H, \psi, i, P_t, P_c, g_e, N, K_l, K_m, K_s, K_u, K_p)$$

where:

Q – operational fuel consumption, l/100 km;

L – haul distance, km;

H – elevation gain, m;

ψ – coefficient of total motion resistance;

i – longitudinal road gradient;

P_t – proportion of temporary and working roads;

P_c – proportion of curved road sections;

g_e – specific fuel consumption of the engine at nominal mode, g/kWh;

N – engine power, kW;

K_l – load regime stability coefficient;

K_m – coefficient accounting for loading, dumping, and maneuvering operations;

K_s – coefficient for auxiliary and service fuel consumption;

K_u – payload utilization coefficient;

K_p – mileage utilization coefficient.

The use of this expression for direct analytical calculations is associated with significant uncertainty, as many parameters vary over wide ranges during actual mine operation. Therefore, the model serves as a conceptual basis for developing a more practical normalization method.

Optimization Formulation.

Fuel consumption normalization is treated as an optimization problem aimed at minimizing average operational fuel consumption per unit of transported material. The objective function can be expressed as:

$$min\ \bar{Q} = \frac{\sum_{j=1}^{n} Q_j}{\sum_{j=1}^{n} M_j}$$

where:

$\bar{Q}$ – average operational fuel consumption per unit of transport work;

Q_j – fuel consumption for the j-th haul cycle;

M_j – mass of material transported during the *j*-th cycle.

We formulate the optimization problem with two constraints for balance between extracted material and dumping capacity, as well as non-negativity (t):

$$\sum M_{in} = \sum M_{out},\ M_j \geq 0$$

The formulated proposal accounts for an optimal division of the haul routes, thus allowing the basis in choosing energy-efficient carriers.

Differentiated Fuel Consumption Norm.

In practical applications, fuel consumption norms are typically determined using a base fuel rate combined with correction coefficients that account for deviations from standard conditions. In this study, a differentiated fuel consumption norm is proposed in the following form:

$$Q_n = 0.01 \cdot H_b \cdot S \cdot (1 + 0.01 \cdot D) + H_a$$

where:

Q_n – normalized fuel consumption, L;

H_b – base fuel consumption rate;

S – haul distance, km;

H_a – additional fuel consumption per loaded trip;

D – total correction coefficient, %.

The total correction coefficient is defined as the sum of individual correction factors:

$$D = \sum_{k=1}^{m} K_k$$

Each correction coefficient reflects the influence of a specific mining or technical parameter.

Correction Coefficients Based on Mining Conditions.

Three key correction coefficients were identified as dominant under dynamic mining conditions:

- K_1 – coefficient accounting for pit depth and elevation difference between loading point and pit crest;
- K_2 – coefficient reflecting the length of inclined haul roads;
- K_3 – coefficient accounting for the distance between pit crest and dumping or stockpiling areas.

These coefficients are determined experimentally and refined analytically, ensuring adaptability of the fuel norm to changes in mine geometry.

Conceptual Scheme of the Method.

Conceptually, the proposed methodology can be represented as a sequential scheme:

Mining and technical conditions → Factor classification → Analytical modeling → Experimental verification → Differentiated fuel consumption norm → Energy-efficient haulage planning.

This scheme provides a systematic basis for continuous updating of fuel consumption norms as mining conditions evolve.

4. Results and Discussion.

Analysis of Fuel Consumption under Dynamic Mining Conditions.

The conducted analysis confirms that operational fuel consumption of mining dump trucks exhibits significant variability under dynamic mining and technical conditions. Changes in pit depth, haul distance, road gradient, and dumping location result in non-linear variations in energy demand, which cannot be adequately captured by static or averaged fuel consumption norms.

These indicators suggest that when passing to more deep horizons of development of mining, the specific power-of-elevation and inclined length in a gross expense of fuel become free. According to this trend, it is necessary to provide a correlation branch of correction coefficients with the depth in the framework of fuel normalization.

Finally, it was demonstrated that the differentiated fuel consumption norm proved to be more sensitive to effect of mining geometry changes. Just like defined norms, it differs from adjusting values of fuel consumption as per operational parameters.

Quantitative Assessment of Influencing Factors. Through an experimental vs analytical comparison of the data, the relative contribution of each pivotal factor was established. These mining and technical parameters, which are closely linked with operational fuel consumption are outlined in Table 2.

Table 2.

Influence of key factors on operational fuel consumption

Parameter	Range of variation	Relative impact on fuel consumption
Haul distance, L	0.5–6.0 km	High
Elevation gain, H	20–180 m	Very high
Road gradient, i	2–10 %	High
Rolling resistance coefficient, ψ	0.02–0.05	Medium
Payload utilization coefficient, K_u	0.7–1.0	Medium
Loading and maneuvering coefficient, K_m	1.05–1.20	Low–medium

The results found that the two most important determinants of fuel consumption were the elevation gain and the haul distance. This correlates to the nature of haulage work — resisting gravity and longer traveling distance results in increased engine workload, subsequently more fuel consumption.

Comparison of Fuel Normalization Methods. The innovative differentiated norm was tested against conventional fuel consumption indicators – analytical, experimental and statistical methods.

Table 3 presents a comparative assessment of these methods.

Table 3.

Comparison of fuel consumption normalization methods

Method	Accuracy	Adaptability to dynamic conditions	Practical applicability
Analytical	Medium	Low	Medium
Experimental	High	Medium	Low
Statistical	Low	Low	High
Experimental–analytical (proposed)	High	High	High

The experimental-analytical method combines the theory and rigor of an analytical model with the realism that experimental data provide, giving performance between these two

methodological extremes. This synergy enables real-time improvement and adaptation to dynamic mining conditions of correction coefficients.

Differentiated Fuel Consumption Norm: Effectiveness.

Differentiated fuel consumption norms has been introduced, which had a decisive effect in reducing the excess of actual and planned values of consumed fuel. This average discrepancy was reduced to 3–5%, instead of the standard 8–12%, using the proposed methodology.

This upgrade strengthens fuel planning and allows more accurate forecasting of energy demand. Additionally, this differentiated method also aids in early detection of inefficiencies associated with hauling route selection, payload under-utilization and kick-up of sub-optimal operational regimes.

Energy Efficiency and Environmental Implications.

Reducing the fuel consumption directly results in an increase of the efficiency and also contributes to a reduction of harmful emissions such as CO_2, NO_x and particulates. This allows the potential of tracking and thus minimizing high elevation gain, poor road geometry or long idle times where energy can be lost through the proposed method.

Secondly, the differentiated fuel consumption norm system in terms of ensuring compliance with energy efficiency standards and objectives acts as a transparent scientifically justified instrumental mechanism for controlling and monitoring the fuel use at mining transport.

Discussion of Practical Applicability.

Research results demonstrate the relevance of proposed methodology application for a practical implementation in open-pit mining companies. It's modular nature allows it to be configured for different dump truck designs, mine layouts and modes of operation. Error correction factors are applied before being introduced to make it scalable and easy to integrate with existing fuel accounting and dispatching systems.

The methodology also supports the development of more complex decision-support tools, such as fuel consumption prediction models or intelligent haulage management systems based on case-based reasoning or machine learning methods.

Conclusion

The subject of the study was to improve energy efficiency when performing mining dump truck operations in dynamically changing mining and technical conditions. Consequently, the research confirmed that haulage actions occurring throughout open-pit operations exhibit excessive variability in gasoline consumption resulting from always altering circumstances comparable to pit depth itself and adjustments in geometric dimensions and height changes all through a hauler's bodily working atmosphere. Static norms, however, failed to capture these

examples, causing planned consumption to differ from real consumption and thus leading to waste of energy.

A differentiated fuel consumption normalization approach was developed based on an experimental–analytical methodology. The proposed approach integrates analytical modeling with empirical data obtained under real operating conditions, allowing correction coefficients to be refined in accordance with the dynamic evolution of mining geometry. A comprehensive taxonomy of influencing factors was offered, relying on their coarseness (i.e., controllable organizational–technical parameters, technical attributes of transportation dump trucks and the actual mining and environmental conditions).

Mathematical formulation of fuel consumption normalization as optimization object allowed to minimize average fuel consumption per unit of transported material in actual operational conditions. The pit depth, length of inclined haul road and distance to dump was provided with correction coefficients for the possibility of stabilization of the fuel norm in terms mining conditions change. Hence, the comparative analysis results proved the effectiveness of the proposed design synthesis method implementation in terms of research accuracy and direct practical applicability, which exceeds building using pure analytical or only traditional experimental methods or statistical ones.

Moreover, implementation of the differentiated norm of fuel consumption reduced discrepancies between planned and actual values of fuel consumption, as well as providing a basis for more accurate planning power output. In addition to the economic benefits, it also results in lower greenhouse gas emissions and air pollutants which helps in sustainable development of norms towards energy efficiency compliance.

These results show that differentiating fuel consumption normalization is a feasible upscaling tool for the enhancement of operational efficiency in mining dump truck fleets. This architecture may be implemented within existing fuel accounting and dispatch systems which will then become the foundation of more complex decision-support and intelligent haulage management technologies for open-pit mining.

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