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Development of the optimal design option for reducing energy losses in sucker rod pumps

Opracowanie optymalnej opcji konstrukcyjnej w celu zmniejszenia strat energii w pompach żerdziowych

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ABSTRACT: This article addresses efficiency challenges in sucker rod pumps (SRPs), particularly those arising from back leakage at the plunger–cylinder interface. Such leakage leads to pressure drops, reduced volumetric efficiency, and overall energy loss during oil production. To mitigate these issues, this research investigates various design modifications – including the integration of plungers with cuffs, grooved and checkerboard-patterned surfaces, and the application of visco-plastic fluids at the interface. These configurations aim to reduce fluid backflow and improve lubrication, thereby extending component life and improving pump efficiency. A comprehensive theoretical framework was developed, incorporating the resistance coefficients, Reynolds number, and surface roughness parameters to model leakage behavior. An empirical formula was derived to optimize flow velocity and pipe diameter, enhancing oil transportation efficiency within the system. Simulations based on the developed models were performed to evaluate the wear distribution along the plunger surface under different loading and friction conditions. The results revealed that the most significant wear occurs at the top and bottom extremities of the plunger, aligning with known failure zones in SRP operation. The novelty of this work lies in the integration of geometric surface features (grooves, screw holes, and textured patterns) with fluid-structure interaction modeling to strategically control leakage and minimize localized wear. Unlike existing studies that rely on isolated analytical or experimental approaches, this research introduces a holistic simulation-backed design optimization strategy. It is shown that such design improvements can increase oil recovery efficiency by 3–12%, with even a 1% gain translating into considerable economic benefits at field scale. Ultimately, the findings provide actionable insights for improving sucker rod pump design and operation, contributing to more energy-efficient and cost-effective oil extraction processes.

Key words: liquid and gas, resistance coefficient, piping, plunger, cylinder, sucker rod pump, metric thread.

STRESZCZENIE: Niniejszy artykuł porusza problemy, związane z efektywnością pracy pomp żerdziowych, w szczególności tych spowodowanych cofaniem się płynu między tłokiem a cylindrem. Prowadzą one do spadków ciśnienia i zmniejszenia sprawności objętościowych pompy oraz ogólnych strat energetycznych podczas wydobycia ropy. Aby ograniczyć te problemy, w badaniach przeanalizowano różne modyfikacje konstrukcyjne, takie jak: stosowanie tłoków z mankietem uszczelniającym, rowkowanych powierzchni, otworów gwintowanych oraz cieczy lepkoplastycznych na styku elementów. Celem tych konfiguracji jest zmniejszenie cofania się cieczy oraz poprawa smarowania, co prowadzi do wydłużenia trwałości komponentów i poprawy efektywności pompy. Opracowano modele matematyczne, uwzględniające współczynnik oporu, liczbę Reynoldsa oraz względną chropowatość powierzchni, w celu skutecznego kontrolowania natężenia wycieków. Dodatkowo, wyprowadzono wzór empiryczny służący do wyznaczania optymalnej średnicy rur i prędkości przepływu, co pozwala zwiększyć efektywność transportu ropy. Przeprowadzono symulacje oparte na opracowanych modelach, aby ocenić rozkład zużycia powierzchni tłoka, uwzględniając współczynniki tarcia oraz obciążenia. Wyniki wykazały, że największe zużycie występuje w górnych i dolnych partiach tłoka, co jest zgodne ze znanymi strefami zużycia pomp żerdziowych. Innowacyjność tej pracy polega na integracji cech geometrycznych (rowki, otwory gwintowane, wzory teksturowane) z modelowaniem oddziaływania płyn-struktura, aby móc kontrolować cofanie się płynu i minimalizować lokalne zużycie. W odróżnieniu do istniejących badań, które opierają się na indywidualnych podejściach analitycznych lub eksperymentalnych, to badanie przedstawia kompleksową strategię optymalizacji projektowania wspartą symulacjami. Wykazano, że takie modyfikacje mogą skutkować zwiększeniem wydobycia ropy o 3–12%. Nawet 1% wzrost odzysku ropy może przynieść znaczne korzyści finansowe. Uzyskane wyniki dostarczają użytecznych wskazówek do ulepszania konstrukcji i eksploatacji pomp żerdziowych, przyczyniając się do bardziej energooszczędnych i opłacalnych procesów wydobycia ropy.

Słowa kluczowe: ciecz i gaz, współczynnik oporu, rurociągi, tłok, cylinder, pompa żerdziowa, gwint metryczny.

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Introduction

The efficiency of sucker rod pumps, essential components in artificial lift systems for oil production, is commonly hindered by back leakage occurring in the annular partitions between the plunger and cylinder, which reduces the system's overall energy balance. This issue, well documented in studies on hydraulic performance, results in energy inefficiencies by allowing the recirculation of pumped fluid, thereby lowering the effective pressure output of the pump (Yin et al., 2020). The dynamics of back leakage can be attributed to both partition length and localized resistances within the narrow radial gaps that exist between plunger and cylinder surfaces, where the liquid and gas velocities play a critical role (Wang et al., 2019). These hydraulic losses, which are proportional to the square of the flow velocity, contribute to inefficiencies that must be addressed to maintain pump performance (Wang et al., 2019).

The factors influencing hydraulic losses are diverse, including both resistance coefficients and the Reynolds number, which provides insight into the flow regimes and viscosity characteristics of fluids in the pumping process. The Reynolds number, as a key indicator, has been extensively studied as a measure of flow pattern and transition between laminar and turbulent states, with distinct impacts on energy loss rates (Reynolds, 1988). In laminar flow, losses remain lower and more predictable, as the flow regime is smooth and continuous; however, in turbulent flow, frictional losses increase substantially due to complex, chaotic flow dynamics that necessitate additional energy input (Reynolds, 1988).

In the context of pump design, relative roughness, defined as the ratio of absolute roughness to pipe diameter, is equally critical, as it impacts the friction factor within the flow system, especially in the turbulent regime where surface irregularities exert greater resistance on fluid movement (Ceylan and Kelbaliyev, 2003).

Relative roughness affects the friction factor, as described by Darcy's formula, which expresses hydraulic loss in relation to partition length and diameter of flow channels (Ceylan and Kelbaliyev, 2003). Ceylan and Kelbaliyev (2003) established that for oil transport systems, relative roughness is a defining parameter, with rougher pipes creating higher friction and resistance. This roughness is amplified by factors such as material wear, surface degradation, and scaling in pipes used for long-term oil extraction (Mustafayev, 2010). For optimal oil transport, studies run by Ceylan and Kelbaliyev (2003) suggested that maintaining a balance between pipe diameter and flow velocity is crucial, and this balance can be quantified through empirical formulas for cost-effective flow diameters that optimize energy consumption in relation to operational costs (Farshad and Rieke, 2005).

Addressing back leakage specifically in sucker rod pumps has led to the exploration of various modifications and design enhancements that minimize inefficiencies. For example, surface modifications such as cuffed plungers, annular grooves, and strategic placement of grooves and screw holes on the plunger have been proposed to control leakage and enhance wear resistance (Mustafayev, 2010). Mustafayev (2010) emphasized that these structural changes improve lubrication and reduce the accumulation of debris that commonly exacerbates wear on the plunger's surface, leading to compromised sealing and leakage. By introducing grooves and holes in a checkerboard pattern, the pump's surface area can be optimized to resist back leakage and maintain efficient lubrication, further preventing the buildup of solids in the partition area (Langbauer et al. 2021).

Empirical data supports the efficacy of these modifications, as studies have shown that an optimally grooved plunger can mitigate wear significantly in high-friction environments (Ivanovskiy et al., 2016), thereby extending the life of the pump and reducing maintenance needs. Wear patterns in sucker rod pumps reveals that targeted grooves reduce surface contact and enhance fluid displacement, which is especially critical in high-viscosity applications (Langbauer et al., 2021). Experimental research in oilfield pump engineering by Langbauer et al. (2021) has shown that wear-resistant designs can enhance fluid flow rates and pump output by up to 12%, while significantly reducing frictional losses. Similar conclusions were also supported by the studies of Jalikop et al. (2020). The economic benefits of these modifications are substantial, with potential revenue gains from increased oil production efficiency, as each percentage increase in recovery translates into millions in added revenue (Wang et al., 2019).

Further refinement of plunger and cylinder designs to mitigate back leakage aligns with broader advances in pump engineering, where the focus has increasingly been on maximizing reliability, minimizing maintenance, and enhancing output in artificial lift systems (Hansen et al., 2018). This field has benefitted from the integration of computational fluid dynamics (CFD) modeling, which allows for precise simulation and analysis of fluid behaviors within pumps, predicting leakage patterns, pressure differentials, and wear zones under various operational conditions (Jalikop et al., 2020). CFD models suggested by Jalikop et al. (2020) show that optimal design parameters, including groove depth, spacing, and alignment, can be adjusted to achieve the best possible balance between leakage prevention and flow efficiency. Such models are essential for improving pump designs with evidence-based modifications tailored to specific field conditions.

The integration of CFD modeling, empirical research, and practical design improvements creates a multi-faceted approach to sucker rod pump efficiency. As pivotal components of artificial lift systems, advancements in the design of these pumps directly influence oil recovery rates and operational costs. The modifications proposed, especially with regard to grooved and perforated plunger surfaces, have shown promise not only in laboratory settings but also in field applications, where they contribute to a more efficient and profitable oil extraction process. The findings of this study underscore the potential of optimized sucker rod pump designs to improve energy efficiency, reduce wear, and ultimately provide a more sustainable approach to oilfield production.

Theoretical modeling of hydraulic losses in sucker rod pumps

In the study of hydraulic losses within sucker rod pumps, the movement of liquid and gas through narrow radial partitions can be accurately modeled using fluid dynamics principles. The thin partition between the plunger and cylinder in these pumps can be simplified as a channel between parallel planes, where losses arise primarily due to frictional and localized resistances. These losses are proportional to the square of the fluid velocity, making velocity a critical factor in understanding energy dissipation within the pump system (Fakher et al., 2021).

The hydraulic loss (h) is initially defined by (Berrada and Loudiyi, 2019):

$$h = \alpha \frac{v^2}{2g} \tag{1}$$

where the α parameter is the resistance coefficient and depends on the structural parameters of the hydraulic devices. In the given partition of length (l) distance, the parameter α is calculated depending on the resistance coefficient (Berrada and Loudiyi, 2019):

$$\alpha = \lambda \frac{l}{d} \tag{2}$$

If substituted into equation (1), Darcy's formula is obtained (Berrada and Loudiyi, 2019):

$$h = \lambda \frac{l}{d} \cdot \frac{v^2}{2g} \tag{3}$$

where the friction factor (λ) depends on the flow's Reynolds number (Re) and the pipe's relative roughness.

Absolute roughness (Δ), defined as the average size of protrusions on the pipe's inner surface, influences flow primarily under turbulent conditions. Because absolute roughness remains constant regardless of pipe diameter, it has a more significant effect when scaled as a ratio to pipe diameter, forming what is known as relative roughness (Mustafayev, 2010):

$$\varepsilon_r = \lambda \frac{l}{d} \tag{4}$$

Relative roughness influences the friction factor (λ), a critical parameter in determining hydraulic losses. In laminar flow, λ depends only on the Reynolds number, under which smooth pipe conditions allow for the relationship (Mustafayev, 2010):

$$\lambda = \frac{64}{Re} \tag{5}$$

The friction factor in pipes consisting of grooved channels depends on the dimensions of those channels and is given by (Mustafayev, 2010):

$$\lambda = \frac{64}{Re \cdot B} \tag{6}$$

where the parameter B is a dimensionless quantity and depends on the groove geometry.

For pipes with grooved channels, the interaction of grooves with the fluid creates stable vortices within the grooves, reducing the friction factor by decreasing the volume of the potential flow. This phenomenon occurs as the aligned vortices streamline the flow, reducing frictional resistance. The friction factor in pipes with such channels is therefore dependent on both the Reynolds number and the groove dimensions.

In this context, λ is a central parameter that reflects both the Reynolds number (Re) and the relative roughness of the pipe's surface. The Reynolds number is especially important as it characterizes the transition from laminar to turbulent flow regimes, both of which have different implications for hydraulic efficiency (Fakher et al., 2021). In laminar flows, the fluid movement is orderly and frictional losses are minimal, allowing for more predictable and manageable energy dissipation. In turbulent flows, however, chaotic mixing of the fluid leads to higher resistance and greater energy loss. As such, maintaining laminar flow where possible can yield greater efficiency, though this often depends on the operational context of the pump.

The influence of pipe roughness becomes more pronounced in turbulent flow, where surface irregularities disrupt the boundary layer, increasing frictional resistance (Fakher et al., 2021). The absolute roughness (Δ), defined as the average height of protrusions on the inner pipe surface, plays a lesser role in laminar flow but becomes significant in turbulent regimes, where it contributes directly to energy losses. Relative roughness, defined as the ratio of absolute roughness to pipe diameter d, is a major determinant of the friction factor (λ) under these conditions, with its impact quantified by empirical relationships such as:

$$\lambda = 0.11 \left(\frac{68}{Re} + \frac{\Delta}{d} \right)^{0.25} \tag{7}$$

This formula accounts for the combined effects of the Reynolds number and surface roughness, allowing for a more nuanced calculation of frictional losses. As turbulent flow develops, the Reynolds number and relative roughness exert differing influences on the friction factor due to the formation of a laminar sublayer along the pipe's inner surface. This sublayer is sensitive to flow velocity and roughness, varying in thickness based on the Reynolds number and thereby altering the friction factor dynamically as conditions change. In industrial applications, managing these variables is key to minimizing energy losses.

Equations (1)–(7) establish the theoretical framework for evaluating hydraulic losses and wear depth distribution in sucker rod pumps. Specifically, equation (1) calculates hydraulic losses as a function of flow velocity and resistance, serving as a baseline for comparing pressure loss under modified and unmodified conditions. Equation (2) defines the resistance coefficient (α), which quantifies the impact of surface modifications (grooves and holes) on fluid flow. Equation (3), Darcy's formula, is applied to assess the friction factor, integrating parameters such as Reynolds number and relative roughness, which are critical in estimating wear rates. Equations (4) and (5) address relative roughness and its effect on the friction factor, correlating surface texture with fluid resistance. Equation (6) quantifies the friction factor for grooved surfaces, accounting for groove dimensions and alignment, directly supporting the wear analysis. Equation (7) combines these parameters to create a comprehensive model for predicting wear depth distribution. This aligns the theoretical basis with the empirical simulations conducted in this study.

Furthermore, to optimize the hydraulic performance of sucker rod pumps, finding the economically efficient diameter and flow velocity is essential. By selecting an optimal pipe diameter that minimizes energy losses, the system can operate more cost-effectively. This balance is achieved by identifying the diameter that corresponds to an economically efficient velocity, which is typically around 1 m/s for oil and petroleum products (Mustafayev, 2010). The relationship is captured by the equation (Mustafayev, 2010):

$$d = \sqrt{\frac{4Q}{\pi V_{ec}}} \tag{8}$$

where:
Q – liquid flow rate in the pipe,
d – efficient diameter,
V_{ec} – economical flow velocity.

This diameter provides an optimal cross-sectional area for efficient flow, ensuring that operational costs are kept low while maintaining acceptable pressure and flow rates.

Theoretical studies have shown that the amount of liquid during back leakage through the partitions in the plunger-cylinder pair is found by the following formula (Ahmedov, 2020):

$$q = \psi \pi D \frac{\Delta P \cdot \delta_0^3}{12 \mu \ell} \tag{9}$$

where:
q – volumetric flow rate of the leakage fluid [m^3/s],
ΔP – pressure differential across the plunger [Pa],
D – diameter of the plunger [m],
δ_0 – thickness of the leakage gap or clearance between the plunger and cylinder wall [m],
μ – dynamic viscosity of the flow [Pa·s],
ψ – coefficient representing plunger-cylinder misalignment,
l – length of the leakage path or effective sealing length [m].

Theoretical studies of back leakage further reveal the impact of eccentricity between the plunger and cylinder on hydraulic performance. When the plunger is offset within the cylinder, the partition thickness (δ) changes across the radial gap, which can significantly increase leakage. The partition thickness (δ) in an eccentric configuration is described as follows (Ahmedov, 2020):

$$\delta = \delta_0 \left(1 + \varepsilon \cos \phi\right) \tag{10}$$

where:
ε – eccentricity ratio indicating the degree of misalignment between the plunger and the cylinder,
ϕ – angular coordinate (central angle) in the radial direction [radians], measured between the line connecting the centers of the plunger and cylinder and the point of interest on the inner wall,
δ – local partition thickness between the plunger and cylinder wall at a given angle,
δ_0 – nominal (average) partition thickness under perfectly concentric conditions [m].

In concentric positions of the cylinder and plunger, $\varepsilon = 0$ and $\delta = \delta_0$ is taken. Experience has shown that the amount of back leakage through the annular partition is highly dependent on eccentricity. If $\varepsilon = 1$ during laminar flow, the amount of back leakage through the annular partition can increase 25-fold. $\varepsilon = 1$ indicates that the plunger and cylinder are perfectly concentric, implying no offset. This condition is typically associated with laminar flow, where the fluid flow remains stable and predictable.

For cases of misalignment, ε is calculated as follows (Mustafayev, 2010):

$$\varepsilon = \frac{\delta_{actual}}{\delta_0} \tag{11}$$

where:
δ_{actual} – actual radial gap between the plunger and cylinder,
δ_0 – nominal gap in a concentric configuration.

If $\varepsilon > 1$, the plunger is offset, leading to increased wear and potential flow disturbances. The degree of eccentricity directly influences wear distribution (Mustafayev, 2010).

If the plunger moves inside the cylinder, then the amount of back leakage through the annular partition is calculated by the following formula (Mustafayev, 2010):

$$q = \pi D \left(\psi \frac{\Delta P \cdot \delta_0^3}{12 \mu \ell} - \frac{U_0 \delta_0}{2} \right) \tag{12}$$

where:

D – plunger diameter [m],

ΔP – pressure differential across the plunger [Pa],

δ_0 – initial (uniform) thickness of the annular gap between the plunger and cylinder [m],

μ – dynamic viscosity of the fluid [Pa·s],

ψ – alignment coefficient representing deviation from concentricity between the plunger and cylinder,

q – volumetric back leakage rate [m³/s],

l – effective axial length of the sealing area (leakage path) [m],

U_0 – average velocity of the plunger relative to the fluid [m/s].

This model underscores the necessity of maintaining proper alignment in the plunger-cylinder pair to minimize leakage.

Overall, these theoretical models provide valuable tools for optimizing sucker rod pump designs by focusing on hydraulic parameters that influence energy losses. Through empirical and analytical approaches, insights into flow behavior, resistance, and optimal configurations can be applied to develop pump systems that operate with minimal hydraulic loss and enhanced efficiency.

It is known that the efficiency of the pump decreases as a result of back leakage of liquid from the annular partitions in the plunger cylinder pair of the sucker rod pump (Ismailov et al., 2018). Various methods exist to prevent back leakage in the pump. Common methods include the following (Fakher et al., 2021):

- using a plunger with a cuff;
- using a plunger with annular grooves;
- installing screw holes across the entire surface of the plunger;
- applying viscoplastic fluids to the plunger-cylinder surface.

Wear depth distribution on the plunger surface under variable friction and load

Long-term studies have revealed that during the operation of the plunger within the cylinder, wear predominantly occurs in three distinct regions on the plunger's surface, primarily at the top and bottom portions of the plunger, with comparatively minimal wear observed in the central section. To address back leakage and enhance the plunger's efficiency, several design modifications are recommended:

Lower Surface Modification: An 80 mm segment at the bottom of the plunger should be designated for targeted wear management. In this region, a metric groove should be machined at the area of highest wear to improve durability and fluid management. Additionally, on the opposing face of this groove, several small holes should be arranged in a checkerboard pattern and drilled at an upward 45° angle, strategically positioned to control fluid flow and facilitate lubrication, thereby reducing friction and minimizing wear.

Hole Placement for Optimal Fluid Dynamics: It is recommended to drill two additional holes beneath the groove, located at both the start and end of the grooved section along the plunger's surface. These supplementary holes will promote efficient fluid circulation around the plunger, further reducing wear by preventing the accumulation of debris and ensuring that lubricating fluids reach critical areas more effectively.

These targeted modifications aim to optimize the plunger's operational longevity by minimizing wear at high-friction points, enhancing fluid flow, and mitigating back leakage. This design approach ensures that the wear-prone sections of the plunger are adequately reinforced while improving overall hydraulic efficiency.

The implementation of this specially designed plunger in sucker rod pumps has proven to be highly effective due to the combined benefits provided by its grooves and checkerboard-patterned holes. The grooves help to control fluid flow along the plunger surface, while the strategically positioned holes further minimize back leakage. Together, these features help maintain a stable flow rate by minimizing fluid bypass, thereby improving overall pump efficiency. In addition to controlling

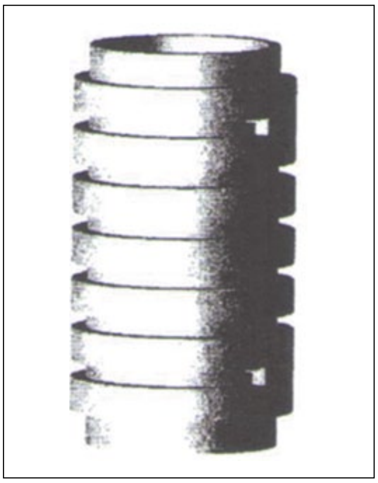

Figure 1. Front view of the groove on the plunger surface

Rysunek 1. Widok rowka na powierzchni tłoka, od przodu back leakage, the grooves and holes facilitate lubrication within the partition between the plunger and cylinder.

This lubrication is essential for reducing frictional wear on the plunger's surface, as it forms a lubricating film that prevents direct contact with abrasive particles. Furthermore, the grooves play a crucial role in preventing the buildup of solid debris, which could otherwise enter the partition and accelerate wear. By diverting debris away from the high-wear zones, these design modifications contribute to prolonged operational life and enhanced performance of the plunger.

The application of these design enhancements in artificial lift systems has demonstrated impressive results in terms of oil recovery rates. Studies indicate that these modifications can lead to a 3–12% increase in oil production, which translates into substantial financial gains for oil operations (Jamalbayov et al., 2024). For instance, even a modest 1% increase in oil output can generate millions in additional revenue annually (Jamalbayov et al., 2024). At the higher end of this improvement range, a 3–12% increase in oil production could generate an estimated $10 million or more in yearly income (Jamalbayov et al., 2024). Such gains underscore the significant economic impact that optimized plunger design can have on oil recovery efficiency, making it a worthwhile investment for enhancing artificial lift performance in oil and gas extraction.

In order to consider the parameters given for the unit, and to conduct a preliminary assessment, the objective of the simulation is to analyze the wear depth distribution along the surface of a plunger used in sucker rod pumps, taking into account variations in friction coefficients and applied load.

Here, wear depth distribution refers to the measurement of material loss across the plunger surface, typically expressed as a function of both axial and circumferential position. This distribution highlights zones of elevated frictional contact where material degradation is more pronounced, allowing for targeted design modifications to minimize wear and extend component lifespan. This approach helps to identify areas on the plunger that are more susceptible to wear and provides insight into optimizing the design to reduce wear rates in high-friction zones.

The friction coefficient varied along the length of the plunger from 0.2 to 0.5, simulating regions with different surface conditions or lubrication levels. Meanwhile, the applied load ranged from 500 N to 2000 N along the length of the plunger, representing varying pressure or load conditions in different sections of the pump. A constant sliding distance of 0.001 m was used for each wear calculation cycle. This distance represents the typical relative movement between the plunger and cylinder during operation.

Wear depth was calculated using the following equation (Mustafayev, 2010):

$$W = \frac{K \cdot F \cdot d \cdot \mu}{H} \tag{13}$$

where:
W – wear depth [mm],
d – sliding distance [mm],
μ – friction coefficient,
K – dimensionless wear coefficient (material-specific),
F – applied load [N],
H – hardness of the material [Pa].

The parameters used are shown in Table 1.

The plunger surface was divided into segments across the angular (circumferential) and axial (lengthwise) directions, creating a grid of 100×100 points to compute wear depth.

The simulation setup was based on several factors. The wear depth was calculated at each grid point along the plunger surface. Regions with higher friction coefficients and greater loads were expected to exhibit more wear, as indicated by Archard's model. The friction coefficient and applied load were adjusted along the length of the plunger to simulate realistic operational conditions, with more wear anticipated in regions with higher friction and load.

Results

A 3D cylindrical plot was generated to illustrate wear depth distribution across the plunger surface. The color intensity in the plot represents the wear depth, with brighter colors indicating areas of higher wear (Figure 2). The color scale ranges from dark purple (low wear) to bright yellow (high wear).

Table 1. Parameters used for simulation of the plunger
Tabela 1. Parametry użyte do symulacji tłoka

Cylinder geometry		Material properties		Variable friction and load		Distance
radius of plunger, r	length of plunger, l	wear coefficient, K	hardness of material, H	friction coefficient, μ	normal load, F	sliding distance, d
[m]	[m]		[MPa]		[n]	[m]
0.05	0.3	$1 \cdot 10^{-8}$	200	0.2–0.5	500–2000	0.001

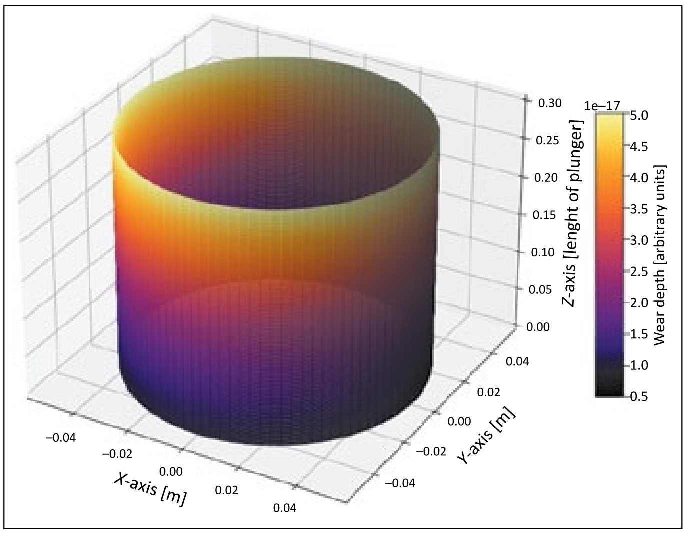

Figure 2. Distribution of wear depth on the plunger surface with variable friction and load

Rysunek 2. Rozkład głębokości zużycia na powierzchni tłoka przy zmiennym tarciu i obciążeniu

Table 2. Simulation setup details

Tabela 2. Szczegóły dotyczące konfiguracji symulacji

Software	Python 3.10 and Matplotlib library (version 3.7)
Simulation Type	Wear Depth Analysis (Archard's Wear Model)
Independent Variables	Friction coefficient (μ) and applied load (F)
Dependent Variable	Wear depth (W) calculated using equation (13)
Range of Friction Coefficients	0.2, 0.3, 0.4, 0.5
Range of Applied Loads	500 N, 1000 N, 1500 N, 2000 N
Sliding Distance	0.001 m

The wear distribution analysis revealed a concentration of increased wear depth in regions where the friction coefficient and applied load were higher, particularly at the top and bottom sections of the plunger. This pattern aligns with well-documented wear tendencies in sucker rod pumps, where the extremities of the plunger typically experience the most significant wear due to elevated frictional forces and pressures. Conversely, the central portion of the plunger exhibited comparatively less wear, attributable to lower friction and load in this area, resulting in reduced wear depth.

The simulation further demonstrated that wear depth increased proportionally with rising friction coefficients and applied loads. Specifically, areas with a friction coefficient of 0.5 and an applied load of 2000 N exhibited the highest wear rates, highlighting the impact of friction and load on plunger wear characteristics. In contrast, areas subjected to lower friction and load conditions experienced minimal wear, reinforcing the importance of controlling these factors to manage wear effectively.

Table 2 shows the details used to develop the testing and simulation methodology, as well as the parameters used to run the required visualizations.

A graphical representation of the relationship between friction coefficient, applied load, and wear depth is provided in Figure 3.

The graph demonstrates the direct correlation between increased friction coefficients (0.2–0.5), applied loads (500–2000 N), and resulting wear depth, highlighting the most wear-prone regions under varying operational conditions. The simulation results clearly show that higher friction coefficients and greater loads lead to an exponential increase in wear depth,

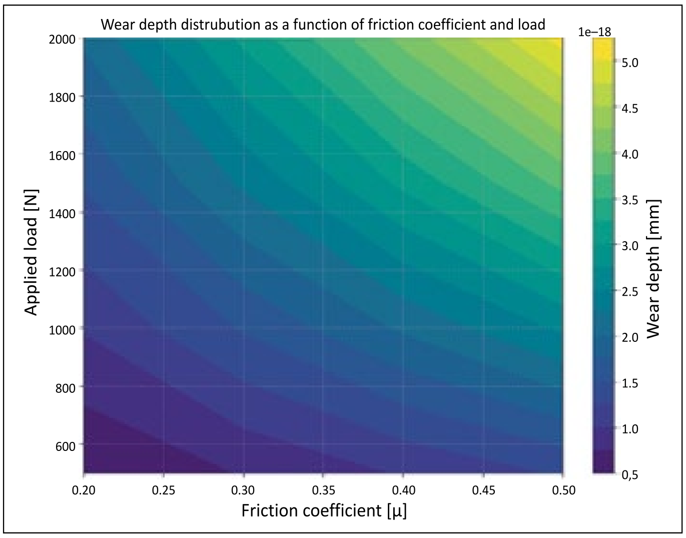

Figure 3. Relationship between friction coefficient, applied load, and wear depth

Rysunek 3. Zależność między współczynnikiem tarcia, przyłożonym obciążeniem i głębokością zużycia

particularly in the high-contact zones at the plunger ends. The color gradient represents wear depth, with lighter shades indicating higher wear values. As observed, wear depth increases proportionally with both friction coefficient and applied load. Regions subjected to high friction coefficients (0.4–0.5) and elevated loads (1500–2000 N) exhibited the most pronounced wear, as evidenced by the brighter yellow regions on the plot. This trend aligns with Archard's wear model, where wear depth is directly proportional to the product of applied load, sliding distance, and friction coefficient, and inversely proportional to the material's hardness. The observed pattern confirms that under elevated friction and load conditions, the material experiences more severe degradation, particularly in zones subjected to higher operational stress.

These findings offer valuable insights for optimizing plunger design. The concentration of wear at the top and bottom sections highlights the need for reinforcement in these areas.

Potential design improvements may include the incorporation of grooves to enhance lubrication or the application of wear-resistant coatings to protect high-stress zones from abrasion. Additionally, ensuring proper lubrication and optimized load distribution is essential for reducing wear rates, ultimately extending the operational lifespan of the plunger and improving performance.

In summary, the simulation effectively mapped the wear depth distribution across the plunger surface, demonstrating how variations in friction coefficient and applied load significantly impact wear rates. The model provides a practical tool for predicting wear patterns in plunger-based pump systems and offers valuable insights into regions that may require targeted reinforcement or operational modifications. By identifying zones of high wear susceptibility, this analysis supports informed decisions to reduce wear, enhance durability, and maximize efficiency of sucker rod pump components.

Advanced materials and coatings for enhanced durability and efficiency

A critical challenge in maintaining the efficiency of sucker rod pumps is managing wear and corrosion, which can compromise the integrity of the plunger-cylinder interface and increase back leakage over time. Advanced materials and specialized coatings offer promising solutions by enhancing surface durability and reducing friction, thereby extending the pump's operational life and improving its efficiency. The use of wear-resistant materials, particularly in high-contact regions of the plunger, significantly reduces degradation from continuous mechanical stresses. Materials such as tungsten carbide and ceramic composites have demonstrated remarkable resilience in high-friction environments, maintaining structural integrity where conventional steel-based materials tend to deteriorate (Wang and Liu, 2018). These advanced materials help preserve dimensional accuracy, thereby minimizing leakage, even after extended use.

Corrosion-resistant alloys, such as duplex stainless steel and nickel-based alloys, are particularly effective in applications involving corrosive fluids, preventing pitting and surface degradation. Since corrosion increases internal surface roughness – and therefore friction losses – the use of such alloys is essential for maintaining a low-friction environment within the pump. Coatings that reduce friction and enhance wear resistance play a crucial role in minimizing energy losses in the plunger-cylinder interface. Polytetrafluoroethylene (PTFE) and other self-lubricating, polymer-based coatings are commonly applied to plunger surfaces to reduce the friction factor. These coatings form a smooth, chemically inert layer that mitigates abrasive contact and reduces the likelihood of leakage-inducing wear over time (Farshad and Rieke, 2005).

Diamond-like carbon (DLC) coatings, known for their high hardness and low friction, have proven effective in reducing wear in dynamic applications (Aliev et al., 2009). Testing has shown that DLC-coated plungers experience significantly reduced back leakage due to their durability under high-stress conditions (Mustafayev, 2010). The high resistance to scratching and abrasive wear provided by DLC coatings helps preserve the surface smoothness of the plunger-cylinder, thereby sustaining efficient fluid flow and reducing energy losses typically associated with roughened surfaces.

Advanced fluid dynamics techniques in sucker rod pumps have led to improved control of fluid flow patterns, reducing back leakage and optimizing efficiency. These advances include flow-regulating components such as dynamic seals and adaptive clearances, which respond to pressure changes and fluid characteristics.

Dynamic seals, designed to adapt to internal pressure variations, offer an effective means of minimizing back leakage without compromising pump functionality. Unlike static seals, dynamic seals expand or contract based on internal pressures, forming a tighter seal during high-pressure changes. In sucker rod pumps, these seals help maintain optimal partition thickness, especially during high-pressure phases, thereby reducing the risk of backflow and enhancing sealing performance (Mustafayev, 2010).

For instance, seals made from shape-memory elastomers can adjust their configuration in response to thermal or pressure changes, maintaining effectiveness across a range of operating conditions (Yao and Zhou, 2018). This adaptability is key to minimizing back leakage in artificial lift systems, where internal pressures may fluctuate significantly.

Maintaining a stable clearance between the plunger and cylinder is also essential in reducing fluid bypass in sucker rod pumps. An adaptive clearance design approach, using materials that respond to temperature or pressure changes, helps maintain a consistent partition gap under variable conditions. This may involve materials with low thermal expansion or compensatory features built into the plunger design (Yao and Zhou, 2018).

One solution involves engineered metal-polymer composites in the plunger assembly. These materials combine the mechanical strength and durability of metals with the flexibility of polymers, enabling the clearance to adjust as needed. These materials slightly expand or contract in response to pressure changes. This helps preserve partition thickness, limits fluid bypass, and minimizes leakage rates.

Vortex generators, strategically placed within the plunger-cylinder assembly, can also reduce back leakage by regulating flow patterns and minimizing turbulence. These devices induce small, controlled vortices in the flow path, stabilizing the flow and minimizing the chaotic mixing that typically leads to energy losses. This approach improves both fluid flow stability and pump efficiency by reducing the energy needed to maintain the desired flow rate (Kelbaliyev and Rasulov, 2019).

Vortex generators maybe designed in various geometries, depending on the flow characteristics required, and are typically manufactured from wear-resistant materials. Studies indicate that integrating vortex control features reduces the internal pressure gradient, allowing more efficient operation with lower energy input, particularly beneficial in high-viscosity fluid applications where turbulent flow is common.

Conclusion

This study provides a comprehensive analysis of wear resistance enhancement in sucker rod pumps through the application of targeted surface modifications, specifically grooves and checkerboard-patterned holes. Simulation results identified critical wear zones along the plunger surface, particularly in high-contact regions at the top and bottom sections, where elevated friction coefficients and applied loads significantly influence wear depth. The proposed design modifications effectively mitigate wear by optimizing lubrication pathways, reducing debris accumulation, and controlling back leakage. These interventions are projected to yield a 3–12% increase in oil production. Even a modest 1% improvement in recovery can result in substantial economic benefits, reinforcing the strategic importance of optimizing pump components.

The advanced plunger design not only enhances operational durability but also reduces maintenance costs by limiting surface degradation under high-friction conditions. This research establishes a simulation-based framework for wear depth analysis, emphasizing the critical role of friction management, load distribution, and hydraulic efficiency. Future studies could extend these findings by incorporating additional variables such as temperature and pressure fluctuations, and fluid dynamics to further refine wear-resistant designs. Such efforts would support the development of more robust and efficient sucker rod pump components, aligning operational performance with industry demands for longevity and reliability.

Nomenclature

B – dimensionless parameter, dependent on groove dimensions,
d – diameter of the pipe or plunger [m],
D – diameter of the plunger [m],
δ – partition thickness in an eccentric configuration [m],
δ_o – initial thickness of the partition [m],
Δ – absolute roughness, average height of protrusions on inner pipe surface [m],
ΔP – differential pressure [Pa],
F – normal load or force [N],
g – gravitational acceleration [m/s^2],
h – hydraulic loss [m],
H – hardness of the material [Pa],
l – distance of the partition in the flow channel [m],
K – wear coefficient, material-specific,
q – back leakage flow rate through the partition [m^3/s],
Q – liquid flow rate in the pipe [m^3/s],
Re – Reynolds number, characterizes flow regime,
U_o – velocity of the plunger [m/s],
V_{ec} – economical flow velocity [m/s],
v – fluid velocity [m/s],
W – wear depth or volume [m],
α – resistance coefficient, dependent on hydraulic device parameters,
λ – friction factor, dependent on Reynolds number and roughness,
ε – relative eccentricity of the plunger inside the cylinder,
ε_r – relative roughness, ratio of absolute roughness to pipe diameter,
μ – dynamic viscosity of the fluid [Pa·s],
ψ – coefficient representing plunger-cylinder misalignment,
ϕ – central angle between the axes passing through cylinder and plunger centers [radians].

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