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Investigation of Thermal Conductivity and Wear Resistance in Bio-Inspired Pitted Pistons for Enhanced Performance in Drilling Mud Pumps

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ABSTRACT

In the demanding environment of drilling mud pumps, failures attributed to piston wear constitute approximately 80% of malfunctioning incidents. While enhanced structural designs and superior materials have been employed, enduring challenges remain. A potential solution identified in previous works is surface texturing, specifically the optimization of pit structures on piston rings, with promising outcomes in friction reduction. Yet, the vital role of thermal parameters in high-intensity environments like mud pumps has been largely overlooked. In this study, the dung beetle's irregular pit structure, known for friction reduction by minimizing soil contact, is utilized as a biological model. The impact of pit geometry, including diameter, angle, and depth, on thermal conductivity, heat transfer, cooling, and heat dissipation has been thoroughly investigated. Preliminary analyses were conducted to gauge the effects of pit diameter on thermal conductivity and piston lifespan. Subsequent analyses were focused on the influence of pit angle in determining thermal gradients across the piston, and its effect on durability. Further investigation was performed to assess the implications of pit depth on heat dissipation and piston longevity. Utilizing Ansys software, the thermal and wear resistance mechanisms of the pitted piston were examined, revealing an enhancement in lifespan by up to 40.60% in comparison to non-pitted counterparts. These findings contribute to the broader comprehension of the interplay between surface texture, thermal performance, and wear resistance, heralding new avenues for thermal management in diverse mechanical machinery. The presented study lays a foundational framework for further research and represents a significant advancement towards a new generation of thermally efficient, wear-resistant mechanical components inspired by nature's perfected mechanisms.

1. INTRODUCTION

In the critical realm of drilling fluid circulation systems, mud pumps are beset by considerable operational challenges. A conspicuous issue, piston wear, has been identified as accountable for approximately 80% of mud pump failures [1]. Efforts to mitigate this problem have historically involved the enhancement of structural design, shape optimization, and the employment of higher-grade materials to improve piston lifespan [2]. However, such strategies have been marked by limitations, precipitating the exploration of novel avenues to address these deficiencies [3].

The concept of surface texturing was introduced by Hamilton et al. [4], positing it as an efficacious method to diminish friction between interacting surfaces. Subsequent investigations have diversified to evaluate various surface textures with the goal of improving the frictional properties of reciprocating components [5-16]. Significant attention has been garnered by the work of Sun et al. [17, 18] and Cheng et al. [19, 20], revealing that the incorporation of an optimal pit structure on the surface could augment piston lifespan by an impressive 92.06%.

In light of these findings, the current study proposes an expansion of this research paradigm to encompass thermal considerations, a vital aspect in the high-intensity environment of mud pumps. It is hypothesized that surface texturing, particularly pit structures, could exert a notable influence on thermal performance, enhancing heat transfer and cooling through turbulence-inducing features [21]. Moreover, the geometric variables of these pits, including diameter, angle, and depth, are theorized to impact thermal conductivity and heat dissipation significantly, thus emerging as integral factors in the evaluation of thermal performance.

The potential implications of these insights extend beyond mud pumps, inviting the possibility of groundbreaking thermal management strategies across various mechanical systems. Through the application of biomimetic designs, informed by nature's refined mechanisms, an innovative generation of thermally efficient and wear-resistant mechanical parts may be realized.

The investigation is further inspired by the surface morphology of dung beetles, characterized by a distinctive irregular pit structure that minimizes frictional contact with soil [22]. These natural structures are also believed to confer thermal advantages, such as improved heat dissipation [23]. Accordingly, the current research endeavors to transpose these principles to mechanical engineering, examining the prospective dual benefits of enhanced thermal performance and reduced wear in mud pump pistons.

Emphasis will be placed on the underlying thermodynamics, concentrating on the modulation of heat transfer and dissipation by pit structures and the consequent effects on piston performance and longevity. This nuanced exploration may contribute to a comprehensive understanding of the interplay between surface texture, thermal characteristics, and wear resistance, thus laying the groundwork for future research and practical applications.

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2. EXPERIMENTAL PROCEDURE

2.1 Experimental setup

A comprehensive experimental test was performed, facilitated at the facilities of Daqing Drilling Company No. 4, located in Jilin Province. The F-1300 drilling mud pump, characterized by a piston diameter of 180 mm, was selected for this investigation due to its demonstrated operational flexibility across a variety of conditions. This particular pump allowed for an intricate comparison between the standard piston and the newly developed pitted counterpart. Both piston types were installed within the mud pump under identical conditions, and during the course of operation, temperature profiles and heat transfer rates were systematically monitored. The service life of the pistons was assessed through the measure of water absorption, an established indicator of piston failure.

2.2 Experimental model design

The F-1300 mud pump piston, as depicted, consists of a leather cup, a steel core, a press plate, and a loop spring. The leather cup, fitted with a polyurethane rubber lip and a nylon root, is illustrated in Figure 1(a). In the redesigned model, a pit structure was introduced to the piston leather cup's surface. This innovation not only sought to bolster wear resistance but also aimed to fine-tune the thermal attributes. The underlying assumption was that these pits might enhance both heat transfer and dissipation.

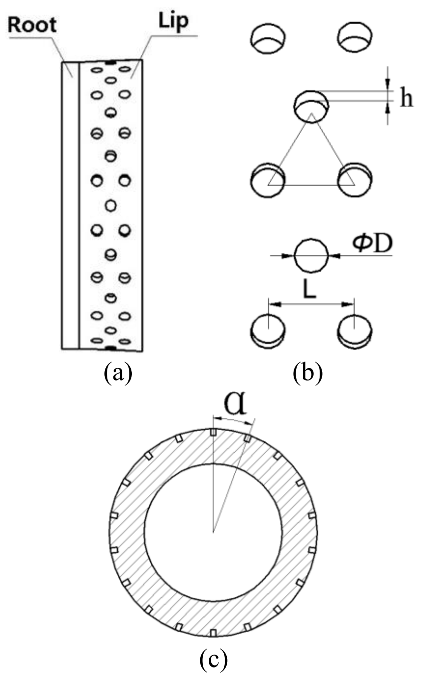


Figure 1. Pitted piston leather cup: (a) Piston leather cup; (b) Pit arrangement; (c) Cross section of leather cup

Three pivotal structural parameters were emphasized in the pit design: pit diameter (D), pit angle (α), and pit depth (h), as illustrated in Figure 1(b, c). An isosceles triangle pattern was adopted for pit arrangement, structured in three rows along the piston's axis. A uniform pit center spacing, L=17mm, was maintained, as evidenced in Figure 1(b). For pit fabrication on the piston surface, a CNC machining center was engaged, followed by a rigorous cleaning regimen to ensure the complete removal of any lingering debris within the pits.

Regarding thermal considerations, the geometric parameters (D, α, h) of the pits were systematically varied to discern their potential impact on heat transfer dynamics. Temperature sensors were embedded at strategic locations, capturing real-time data on localized temperatures within and proximate to the pits during operational phases. This approach was pivotal in ascertaining the heat dissipation rates and overarching thermal performance of the piston.

3. EXPERIMENTAL PLAN AND THERMAL ANALYSIS

3.1 Investigation of bionic pistons with varied pit diameters

In this segment of the study, the pit angle and depth were maintained constant, while the pit diameter served as the principal experimental variable. Table 1 encapsulates the examination plan and corresponding analysis concerning bionic pistons with diverse pit diameters. Simultaneously, thermal profiles corresponding to various pit diameters were systematically evaluated, with specific focus on temperature deviations, localized hot spots, and consequential implications on the thermal stress distribution within the material.

Table 1. Investigation and thermal examination of bionic pistons with varied pit diameters

No.	Factor			Piston Life (h)	Improved Life (%)
	Pit Diameter D (mm)	Pit Angle α (°)	Pit Depth h (mm)		
1	0	0	0	266	
2	1.5	15	5	374	40.60%
3	3.0	15	5	320	20.30%
4	4.5	15	5	342	28.57%

3.2 Exploration of bionic pistons with altered pit angles

Table 2. Exploration and thermal analysis of bionic pistons with different pit angles

No.	Factor			Piston Life (h)	Improved Life (%)
	Pit Diameter D (mm)	Pit Angle α (°)	Pit Depth h (mm)		
1	0	0	0	280	
2	3	5	5	341	21.79%
3	3	10	5	380	35.71%
4	3	15	5	374	33.57%

The alteration of pit angle constituted the primary variable in this phase of the experiment, whereas the diameter and depth of the pits were held constant. As delineated in Table 2, a detailed experimental plan was devised, complemented by a comprehensive evaluation of the resultant data involving bionic pistons with modified pit angles. Furthermore, the investigation extended to the examination of temperature distributions across differing pit angles and their consequential impact on heat transfer rates and patterns.

3.3 Thermodynamic inquiry into bionic pistons with alternating pit depths

The concentration of this portion of the examination was on the pit depth within the bionic piston, with both pit diameter and angle kept constant. Table 3 presents the ensuing experimental design and insights extracted from the evaluations involving bionic pistons with varying pit depths. A comprehensive study of the thermodynamic aspects was also conducted, focusing on fluctuating pit depths and their influence on thermal attributes.

Table 3. Experimental framework and thermodynamic interpretation of results for bionic pistons with different pit depths

	Factor				
No.	Pit Diameter D (mm)	Pit Angle α (°)	Pit Depth h (mm)	Piston Life (h)	Improved Life (%)
1	0	0	0	257	
2	3	15	3	318	23.74%
3	3	15	5	355	38.13%
4	3	15	7	325	26.46%

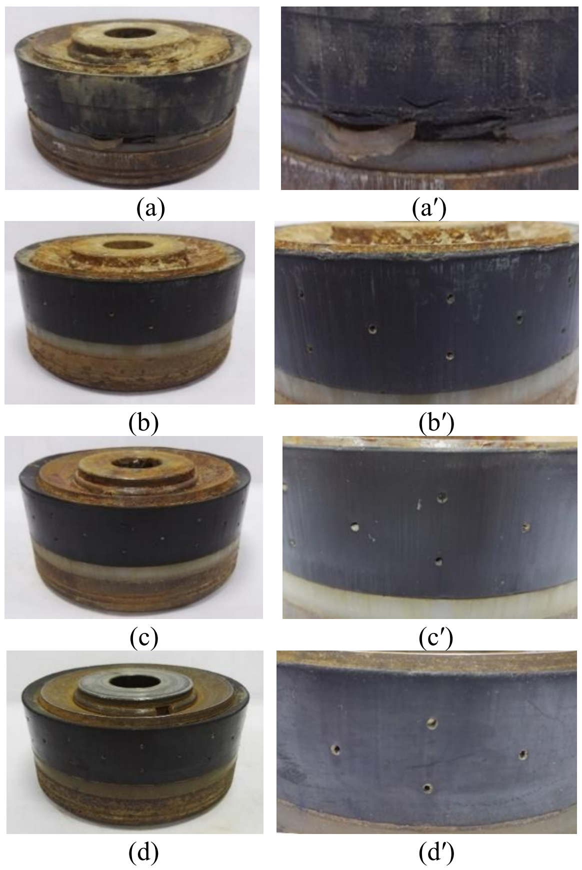


Figure 2. Comparative analysis of piston wear under thermodynamic scrutiny: (a) No.1 standard piston; (b) No.2 pitted piston; (c) No.3 pitted piston; (d) No.4 pitted piston. (a′, b′, c′, d′) are detailed enlargements of (a, b, c, d)

A discernible pattern was observed as the pit depth increased: the lifespan of the piston initially extended before subsequently diminishing, with peak lifespan enhancement recorded at 38.13%. This pattern implies that excessive pit depths might undermine the overall robustness of the piston surface, culminating in adverse thermal and mechanical stress states.

The thermodynamic behavior of the pistons, inclusive of variations in pit depth, is visually manifested in Figure 2. A stark contrast in wear patterns between standard and pitted pistons is evident. The failure of the No.1 standard piston was mainly correlated with elevated root stress, as shown in Figure 2(a). Conversely, pitted pistons exhibited unique wear characteristics. Figure 2(b-d) illustrates various force distributions and thermal stress concentrations in the pitted pistons, revealing the critical role of pit depth in the overall structural integrity and thermal stress distribution of the piston.

4. THERMODYNAMIC EVALUATION AND ASSESSMENT OF WEAR RESISTANCE IN MUD PUMP BIONIC PITTED PISTONS

The functional dynamics of mud pumps are dictated by the immediate engagement between the piston and the cylinder liner, responsible for propelling the mud. The lip of the piston leather cup, maintaining close contact with the inner wall of the cylinder liner, is essential in sealing and safeguarding the piston against wear. Conversely, stability and prevention of compressive damages are provided by the roots of the piston leather cup. An extensive investigation encompassing both mechanical and thermodynamic facets is necessitated by these complex interactions to elucidate the piston's performance attributes and the underlying mechanisms of its wear resistance.

During the mud discharge stroke, a phenomenon referred to as the "centripetal effect" is observed at the piston lip, inducing a spatial separation between the lip and the cylinder liner. With an increase in contact pressure, this gap is proportionally reduced. This reduction serves to mitigate the possibility of high-pressure mud infiltrating the contact interface, thereby diminishing wear. Moreover, the attenuation of equivalent stress on the piston root under intense pressure conditions reduces the risk of crushing. An intricate interplay between the contact pressure at the piston lip and the equivalent stress at the root emerges as instrumental in understanding the piston's wear resistance mechanism, especially when considered in conjunction with thermodynamics.

Comparative evaluations of lip contact pressure and root equivalent stress were conducted for a standard piston, a No.1 pitted piston (with optimal life enhancement, characterized by D=1.5mm, α=15°, h=5mm), and a No.2 pitted piston (exhibiting minimal life improvement, with parameters D=3.0mm, α=15°, h=5mm), using the Ansys Workbench software. Insights garnered from thermodynamics offer a more comprehensive understanding of the wear resistance mechanisms in these pistons, emphasizing the influence of thermal stress in wear processes.

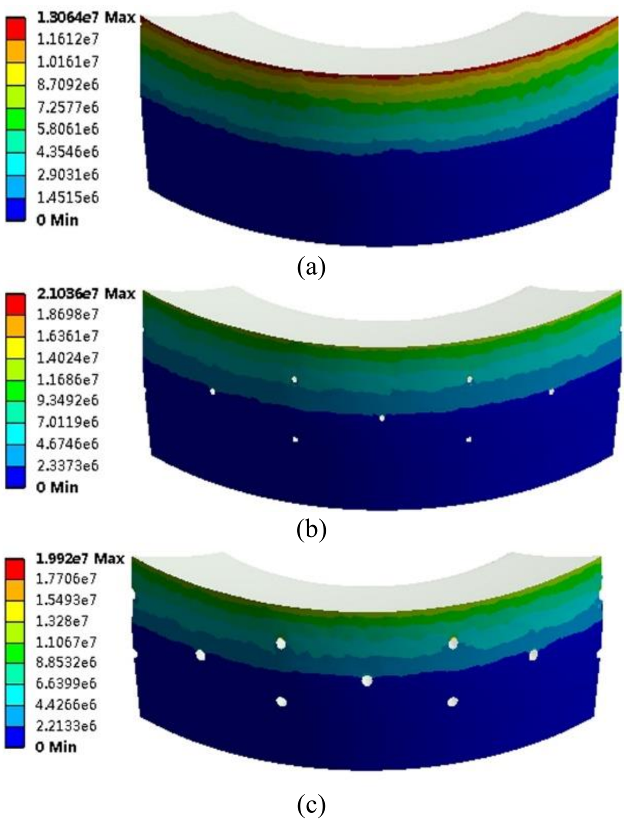
The collaboration between mechanical and thermodynamic attributes in governing the wear resistance of bionic pitted pistons is thus elucidated. The findings reveal a nuanced interplay between spatial separation, contact pressure, and equivalent stress, all influenced by underlying thermal stresses. These insights contribute to an enriched understanding of wear resistance mechanisms, laying the groundwork for future investigations into the optimization of mud pump pistons.

4.1 Thermodynamic evaluation and contact pressure analysis of bionic pitted pistons

An in-depth examination of the wear resistance mechanisms of mud pump pistons necessitates an intricate investigation of not only the contact pressure dynamics but also the thermodynamic conditions inherent within the system. A significant interrelation has been observed between the contact pressure experienced by both standard and pitted pistons and the system's thermodynamic behavior. The elucidated contact pressure for the evaluated pistons, as portrayed in Figure 3, emphasizes the profound influence exerted by temperature dynamics and heat transfer on piston functionality.

As revealed by Figure 3, a transformation in the state of the contact pressure distribution is induced by the pit structure on the piston surface, with thermodynamic variables performing a crucial role in this alteration. Contact pressures of 13.0440Mpa, 21.0160Mpa, and 19.9000Mpa were measured for the standard, No.1, and No.2 pistons, respectively.

Among the evaluated pistons, the No.1 pitted piston demonstrated a remarkable enhancement in contact pressure and a minimalized gap with the cylinder liner in comparison to the standard piston, thereby effectively mitigating the abrasion from particles and substantially augmenting the piston's lifespan. This enhanced performance is also attributable to the superior thermal management enabled by the pit structure. In contrast, the elevated contact pressure of the No.2 pitted piston was found to be less significant, and the corresponding extension in piston lifespan was marginal. Such observations imply that the thermodynamic conditions in this particular configuration may not be optimally conducive.



(a)

(b)

(c)

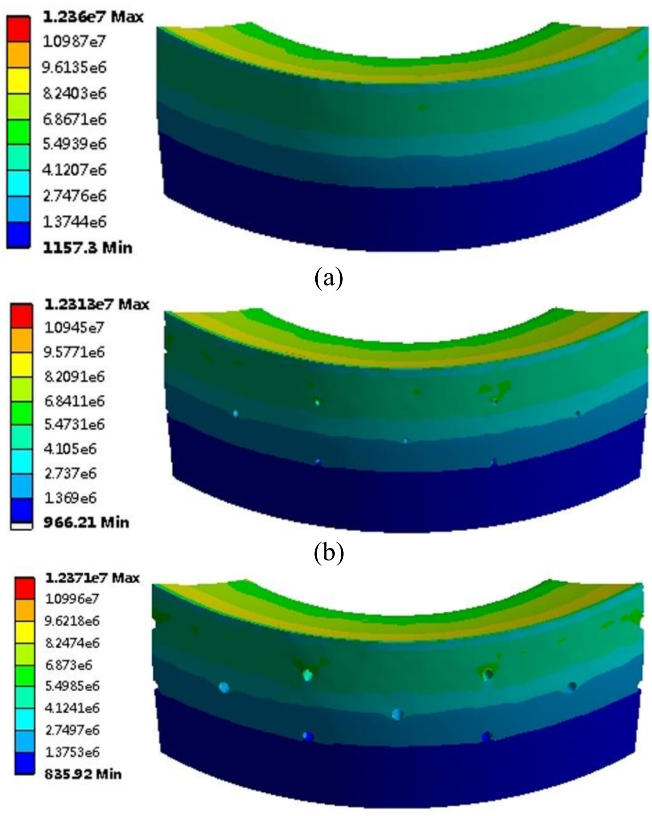
Figure 3. Piston contact pressure: (a) Standard piston; (b) No.1 pitted piston; (c) No.2 pitted piston

In synthesizing these findings, a distinct correlation between the thermodynamic parameters and the wear resistance mechanisms of mud pump pistons has been established. The integration of these variables furnishes a multifaceted framework for subsequent exploration and innovation in optimizing the design and operation of mud pump pistons. The study underscores the importance of nuanced thermodynamic management within piston structures and opens avenues for targeted improvements, capitalizing on the interplay between mechanical dynamics and thermodynamic principles.

4.2 Thermodynamic evaluation and analysis of equivalent stress in bionic pitted pistons

An exhaustive scrutiny of wear resistance mechanisms within mud pump pistons commands an evaluation of the equivalent stresses exerted at the roots of both standard and pitted pistons. Influenced by the thermodynamic conditions inherent to the system, these stresses critically determine the wear processes and lifespan of the pistons, as depicted in Figure 4.

As illustrated in Figure 4, substantial force at the root was observed in the standard piston, rendering it more susceptible to crushing. Such susceptibility may accelerate wear, thereby leading to a diminished lifespan of the piston. Conversely, the incorporation of pit structures was found to ameliorate the stress state on the piston surface, resulting in a decrease in equivalent stress at the piston root, and consequent extension of piston life. It was discerned that these alterations and ensuing enhancements were profoundly influenced by the thermal stresses inherent within the system.



(a)

(b)

(c)

Figure 4. Piston equivalent stress: (a) Standard piston; (b) No.1 pitted piston; (c) No.2 pitted piston

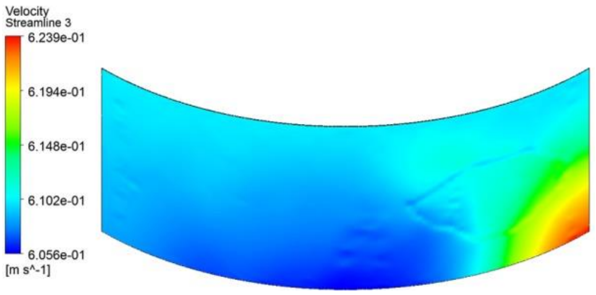
Specific measurements of equivalent stress were recorded as 0.1289Mpa for the standard piston, 0.1107Mpa for the No.1

piston, and 0.1208Mpa for the No.2 piston. It was revealed that the pit structure markedly reduced the equivalent stress at the root of the No.1 piston, hence diminishing the propensity for root crushing and wear. Such a reduction can be ascribed to the optimized thermal management facilitated by the pit structures. In contrast, the equivalent stress at the root of the No.2 pitted piston was found to be less significantly alleviated, and the correlated increase in piston lifespan was minimal, indicating less optimal thermodynamic conditions in this configuration.

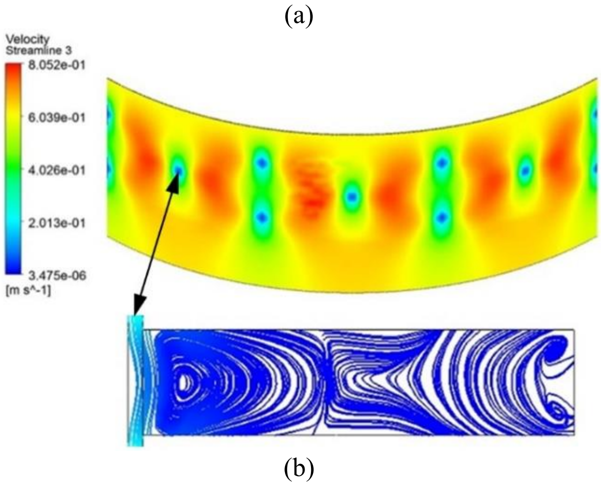
In summary, the analysis elucidates a vital interconnection between the equivalent stresses at the piston roots and the thermodynamic conditions of the system. The observed reductions in stress through the implementation of pit structures underscore the criticality of nuanced thermal management within the piston system. The results proffer valuable insights for future research, particularly in the design and development of bionic pitted pistons, steering towards a more efficient and resilient configuration. By extending the understanding of wear resistance mechanisms in conjunction with thermodynamic factors, this study lays a foundation for engineering advancements in mud pump piston technologies.

4.3 Thermodynamic assessment and surface streamline analysis of a bionic pitted piston

Lubricating oil, residing on the surface of the mud pump piston, has been identified as a fundamental element in preventing direct contact between the piston and the cylinder liner. Through this mechanism, significant reductions in friction and wear have been observed, thus leading to an extension in the piston's lifespan. In the context of the piston's reciprocating motion, the role of thermodynamics emerges as crucial, as displacement of the lubricating oil has been found to contribute to wear within the piston.



(a)



(b)

Figure 5. Piston surface streamline: (a) Standard piston; (b) Pitted piston and pit section view

The surface distribution of lubricating oil on the piston was investigated utilizing CFX, resulting in the depiction of oil flow lines as shown in Figure 5. Within the framework of this thermodynamic analysis, novel insights were gleaned into the manner in which variations in the system's heat and pressure might influence the behavior of the lubricating oil and, consequently, the wear processes.

This exploration has served to establish a complex interrelation between the thermodynamic conditions, the stress state of the piston, and the behavior of the lubricating oil within the system. A deeper understanding of this intricate connection provides a comprehensive foundation for further research and development, aimed at enhancing mud pump piston design and performance. The synergy between thermodynamic and mechanical factors reveals untapped potential in engineering advanced mud pump pistons. Such advancements could lead to improved wear resistance and extended lifespan, presenting significant implications for the broader field of mechanical engineering.

In particular, the quantification of thermodynamic effects on the lubrication process opens new avenues for specialized design considerations. By assessing the subtle interplay between surface streamlines, heat transfer, and pressure variations, further optimizations can be envisioned. The surface streamline analysis, as depicted, offers not merely a descriptive account but also a predictive model that could be leveraged for future design iterations.

In conclusion, this study forms an integral part of an ongoing discourse on the dynamic interactions within mud pump pistons, with a particular focus on the influence of thermodynamics. The insights garnered here contribute to a more nuanced understanding of wear mechanisms, positioning this research within a broader landscape of mechanical innovation and sustainability.

5. CONCLUSION

In the study conducted, an examination of the efficiency of an innovative pitted piston configuration within a mud pump was undertaken, characterized by the incorporation of a uniform pitting structure on the piston leather cup's surface. The findings were deduced through a comparative lifespan analysis between the pitted and standard pistons, with an integration of thermodynamic perspectives that elucidated the operational enhancement endowed by the pitted piston design. The following principal observations were derived:

(1) An enhancement in lifespan was discerned in the pitted piston in comparison to the standard variant, with increases observed to range from 20.30% to 40.60%. Such improvements were found to be partially attributable to an advanced heat distribution and dissipation process facilitated by the pitted structure, an effect that was noted to reduce thermal stresses and augment durability.

(2) In instances where pit angle and depth were maintained at constant values, a complex pattern in piston lifespan was observed, with initial decreases succeeded by increases as pit diameter augmented, reaching a peak improvement of 40.60%. Such behavior was identified to be correlated with the evolving thermodynamics within varying pit diameters, thereby influencing wear mechanisms and the corresponding piston lifespan.

(3) With fixed pit diameter and depth, a progression characterized by initial increase and subsequent decrease in

piston lifespan was documented as pit angle broadened, with the optimal improvement in lifespan recorded at 35.71%. This phenomenon was linked to the substantial influence of pit angle on the thermal and fluid dynamics within the pit, an effect that was observed to directly modulate the piston's lifespan.

(4) Similarly, variations in piston lifespan were recorded as pit depth escalated, with the apogee of lifespan enhancement documented at 38.13%. Such fluctuations were discerned to be associated with alterations in the piston's thermal behavior contingent upon pit depth, further impacting wear resistance and lifespan.

(5) The pitted structure was determined to amplify the stress condition on the piston surface, enhance wear resistance, alleviate root crushing, and expand oil storage space, thereby augmenting the lubrication conditions of the friction pair. These modifications were identified to be principal contributors to the enhancement of the mud pump piston's lifespan. The vital significance of thermal management via the pitted structure was underscored across all these benefits, highlighting the indispensability of thermodynamic considerations in the analysis and design of such systems.

In conclusion, these findings collectively suggest that a meticulously optimized pitted piston design, underpinned by a robust comprehension of its thermodynamic behavior, holds potential for significant advances in the wear resistance and lifespan of mud pump pistons. Moreover, the insights presented serve to spotlight the promising prospect of integrating thermodynamic principles into piston design to foster greater efficiency and longevity. These discoveries not only represent a meaningful advancement in the sphere of mud pump technology but may also provide a template for the exploration of similar innovations in related mechanical systems, underscoring the broader implications of this research.

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