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ORIGINAL PAPER

Enhancing Efficiency in Screw Compressors Through Sustainable Polyglycol-Based Lubricants

A. Kumar[1,2]*, A. Kovacevic [1] and A. Chaudhari[2]
[1]Centre for Compressor Technology, City, University of London, London, UK
[2]Kirloskar Pneumatic Company Limited, Pune, India

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Abstract: This research examines the transformative impact of synthetic lubricants, particularly polyglycol-based oils, on the operational efficiency of screw compressors, emphasising the advancement of sustainable industrial practices. The synthetic oil, noted for its superior oxidation stability, prolongs oil change intervals and enhances the longevity of filters and separators. The integration of specialised inhibitors guarantees the preservation of internal compressor cleanliness, resulting in continued high efficiency. Experimental investigations comparing synthetic polyglycol oil to conventional mineral oil in screw compressors indicate substantial enhancements in overall efficiency. The synthetic oil offers extended maintenance intervals, achieving up to 8,000 operating hours in oil-injected screw-type compressors and 40,000 operating hours in turbocompressors, alongside prolonged filter and separator lifespans and diminished cleaning expenses due to its exceptional dirt-dissolving properties. Additionally, the synthetic oil aids in sustaining low oil vapour levels in compressed air, minimising oil use, and averting the gumming of pneumatic valves. The synthetic oil adheres to industrial requirements (DIN 51506-VDL and ISO 6743-3 L-DAJ) and demonstrates outstanding wear prevention for steel friction components. Possessing a kinematic viscosity of 55 mm^2/sec at 40 °C, it exceeds bearing life specifications, hence forming an efficient lubricating coating for anti-friction bearings. The study highlights the considerable potential of sustainable lubricants, especially polyglycol-based oils, in improving efficiency and reinforcing the environmental sustainability of screw compressors. This study offers significant insights into the practical applications of synthetic lubricants in industrial settings, highlighting polyglycol-based oils as a viable solution for enhancing screw compressor technology. The study elucidates a vital element of sustainable materials within the industrial sector, providing an in-depth comprehension of their influence on machinery efficacy.

Keywords: Compressor efficiency; Polyglycol-based lubricants; Screw compressors; Synthetic oil; Wear protection; Sustainable industrial practices

Introduction

Screw compressors, recognised for their efficiency and adaptability across various flow rates and discharge pressures, are essential in industrial applications. This rotary positive displacement apparatus, including a duo of helical rotors housed within a casing, provides a dependable and compact solution for various operational requirements. Screw compressors are classified into oil-flooded, oil-free, and water-injected types, with oil-flooded models prevailing in the market due to their benefits, including decreased mechanical complexity, increased efficiency, and the ability to achieve high pressure levels in a single stage [1, 2].

The incorporation of oil in screw compressors plays a crucial and diverse role in their operation. In addition to its traditional role as a lubricant for rotors and bearings, oil functions as a sealing medium, minimising internal leakage and enhancing operational stability. Moreover, it facilitates temperature regulation by collecting and dispersing heat produced during compression. The careful selection and optimisation of lubricants are essential to improve efficiency, reduce wear, and prolong the operating lives of vital components [3–5].

*Corresponding author, E-mail: abhishek.kumar.2@city.ac.uk

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Understanding the lifecycle cost of a compressor requires a thorough assessment of operational and maintenance expenditures during its entire lifespan. Although the initial capital investment is substantial, it is the aggregate impact of energy consumption, maintenance, and lubrication expenses that defines the actual economic footprint. In this scenario, reducing oil drag loss is a crucial factor due to its direct influence on the compressor's total power consumption [6].

The proportion of oil drag loss in the overall power consumption of a compressor is a significant statistic reflecting its operating efficiency. An astute analysis indicates that this ratio fluctuates among compressor types, with screw compressors frequently demonstrating a notable susceptibility to oil-related losses. Consequently, minimising oil drag loss is a primary objective in efforts to optimise energy efficiency and improve overall compressor performance [1, 7, 8].

The industrial sector offers a variety of biodegradable oils, each possessing unique characteristics and uses. Vegetable oils such as corn, soybean, and rapeseed, distinguished by triglyceride molecular structures, have excellent lubricating properties. Nonetheless, constraints in thermal, hydrolytic, and oxidative stability necessitate the investigation of synthetic alternatives. Polyalphaolefins (PAOs) perform exceptionally in low-temperature environments but can cause rubber seals to contract, whereas Diesters are recognised for their antioxidative qualities and ability to swell seals [9]. Polyalkylene Glycols (PAGs), also known as Polyglycols, are a diverse option, with water-soluble types suitable for fire-resistant lubricants. Nonetheless, PAGs can emulsify water, resulting in foaming and corrosion. Manufacturers frequently combine diesters with PAOs to improve biodegradability, solubility, and oxidation resistance.

The choice of a biodegradable fluid depends on the application. Vegetable oils are appropriate for "once through" lubrication in low to medium pressure hydraulic systems, whilst PAOs are utilised in cold environments and high-pressure hydraulic systems. Diesters are proficient in compressors and turbines but may adversely affect paint surfaces and sealing materials. PAGs, exhibiting diverse water solubility, necessitate comprehensive system flushing prior to the transition from mineral oil-based products [10].

In recent years, Polyethylene Glycol (PEG)-based oils have emerged as a significant synthetic alternative for industrial applications, including screw compressors. PEG-based lubricants, akin to PAGs, provide enhanced oxidation stability, prolonged maintenance intervals, and exceptional wear prevention. Their elevated temperature endurance, ecological friendliness, and reduced oil drag losses render them optimal options for enhancing the efficiency of screw compressors. Additionally, PEG-based oils are biodegradable, which corresponds with the increasing demand for sustainable practices in industrial lubrication [11]. This study examines the benefits of PEG-based oils relative to K-SMART oil, highlighting their capacity to enhance operational efficiency and promote environmental sustainability [12].

The quest for sustainable practices in industrial applications has driven research into alternative lubricants with diminished environmental impact. Sustainable lubricants can be classified into several categories: vegetable oils, synthetic ester-based oils, polyalkylene glycol-based oils, and polyalpha olefin oils. In the domain of screw compressors, the choice of an appropriate lubricant is of utmost importance. This study examines the influence of polyalkylene glycol-based oils, noted for their excellent oxidation stability and remarkable dirt-dissolving capabilities, on the efficiency of screw compressors [6].

The justification for selecting polyalkylene glycol oil in this study is based on its exceptional properties. These synthetic lubricants demonstrate prolonged maintenance intervals, less cleaning expenses, and superior wear prevention for steel friction components. The emphasis on polyalkylene glycol oil corresponds with the primary goal of improving efficiency while simultaneously addressing the necessity of sustainable industrial practices. This research examines the complex relationship between lubricants and screw compressor dynamics, highlighting the benefits of polyalkylene glycol-based oils in promoting operational efficiency and environmental sustainability.

Methodology

This study centres on the KAS-650 oil-flooded air screw compressor, a gear-driven device with an integrated volume ratio of 4.6. This screw compressor, produced by Kirloskar Pneumatic Company Limited in Pune, India, functions at a pressure ratio of 8.5 with a tip speed of 49 m/s. Owing to commercial considerations, particular details concerning the dimensions and specifications of the compressor are classified.

The investigative procedure commences with the precise modelling of the compressor in the Screw Compressor Rotor Grid Generation (SCORG) software created by PDM Analysis [13]. This constitutes the essential initial phase in understanding and modelling the dynamic behaviour of the examined screw compressor.

Before conducting the performance analysis, an essential aspect of the compressor's operation is examined - the lubrication state of the bearings. The lubrication state of the bearing is checked using SCORG, specifically examining one of the anti-friction bearings in the KAS-650 compressor block. A requirement set by the bearing manufacturer stipulates that for a certain lifespan of 40,000 h, the viscosity ratio 'k' must be between 1 and 4. This validation method guarantees the integrity of the bearing lubrication system, establishing a foundation for future performance assessments.

The synthetic polyglycol-based oil, selected as a sustainable alternative, is included into the SCORG tool by entering its pertinent parameters. A thorough comparison of the performance between the current semi-synthetic oil, 'K-SMART,' utilised in the KPCL screw compressor block, and the newly launched polyglycol-based oil is performed. This comparative analysis encompasses multiple operating factors, such as efficiency, oil vapour concentration, and wear prevention for steel friction components.

The experimental part of this investigation is presently underway. The data acquired from the experimental trials will validate and enhance the insights gained from the simulation research. The forthcoming work includes a thorough analysis of the experimental results, facilitating a complete knowledge of the performance differences between traditional mineral-based oil and the novel polyglycol-based lubricant. This research is grounded in the synthesis of modelling and experimental data, leading to a detailed examination of the transformative potential of sustainable lubricants in improving the efficiency and sustainability of screw compressors.

Physicochemical Characterization of Polyglycol-Based Lubricant

The lubricant utilised in this study was Klüber Summit Supra 32, a totally synthetic polyglycol-based oil specifically formulated for oil-injected screw compressors. Comprehensive physicochemical parameters were evaluated to assess the lubricant's performance and its effect on compressor efficiency. These qualities are essential in assessing the lubricant's capacity to minimise wear, improve sealing, and sustain performance for prolonged operational durations. Table 1 delineates the principal physicochemical properties of Klüber Summit Supra 32.

Viscosity The lubricant possesses a kinematic viscosity of 38 mm^2/s at 40 °C and 7.3 mm^2/s at 100 °C, rendering it appropriate for high-speed and high-temperature applications, including screw compressors. The elevated viscosity index ($\geq$ 145) guarantees that the lubricant sustains its efficacy over a wide temperature spectrum, providing reliable protection despite fluctuating operational conditions.

Oxidative Stability The polyglycol-based lubricant exhibits remarkable oxidation stability, facilitating extended maintenance intervals of up to 8000 working hours. This stability diminishes the accumulation of oxidation byproducts in the compressor, hence prolonging the lifespan of oil filters and separators.

Thermal Characteristics The flash point ($\geq$ 230 °C) and pour point ($\leq$ – 45 °C) indicate the lubricant's extensive working temperature range, rendering it useful in both hot and low-temperature conditions. The elevated flash point guarantees safety and efficacy in high-temperature applications, whilst the diminished pour point signifies superior fluidity at reduced temperatures.

Wear Protection and Additives The lubricant offers superior wear protection for steel friction components, markedly diminishing wear on essential parts including bearings and rotors. Specially developed additives and inhibitors maintain the compressor's cleanliness and efficiency by dissolving residues and preventing valve gumming.

The physicochemical qualities underscore the lubricant's appropriateness for screw compressor applications, leading to diminished maintenance expenses, enhanced efficiency, and prolonged service life. The comprehensive characterisation of these features underpins the improved performance noted in the experimental findings.

Bearing Lubrication Condition Analysis

This section conducts a thorough investigation of the lubrication state of the KAS-650 oil-flooded air screw compressor, highlighting the current lubricant and the prospective benefits of switching to polyglycol-based oil.

Existing Lubrication Medium in KPCL Compressor Block

The selection of lubricating oil is crucial for achieving optimal efficiency and longevity in KPCL screw compressors, as it prevents malfunctions and ensures prolonged performance. In response to this necessity, KPCL utilises the K-SMART grade of semi-synthetic lubricating oil, specifically designed for Electric Screw Compressors (see Fig. 1).

KPCL's K-SMART lubricant is a comprehensive solution, characterised by Systematic, Measurable, Accessible, Reliable, and Time-Bound qualities. This strategic formulation is designed to address the specific requirements of Electric Screw Compressors, promoting an optimal integration with complex components to improve overall efficiency and operational durability.

The details of K-SMART are confidential, in accordance with industry standards, highlighting the distinctive essence of a composition engineered for enhanced performance and extended durability of all moving components.

Table 1 Physicochemical properties of Polyglycol-based lubricant

Property	Value
Kinematic viscosity (40 °C)	38 mm^2/s
Kinematic viscosity (100 °C)	7.3 mm^2/s
Viscosity index	$\geq$ 145
Density (20 °C)	0.96 g/cm^3
Flash point (ISO 2592)	$\geq$ 230 °C
Pour point (ISO 3016)	$\leq$ – 45 °C
Foam test (ISO 6247, 24 °C)	$\leq$ 50/0 ml
Oxidation stability	High oxidation stability, enabling oil change intervals up to 8000 operating hours
Wear protection	Very good wear protection for steel friction bodies
Additives and inhibitors	Contains special inhibitors to prevent residue formation and enhance cleanliness in the oil cycle

Fig. 1 Rotary screw Kirloskar K-SMART oil

The strategic confidentially exemplifies the precise engineering that characterises this lubricating medium.

K-SMART ensures superior performance, guaranteeing dependability and accessibility in the maintenance of the compressor's moving components. The quantifiable effect of this lubricant is demonstrated by its capacity to endure the demands of screw compressor operation, highlighting a temporal strategy for lubrication maintenance.

The utilisation of K-SMART lubricant in KPCL screw compressors is strategic, intended to enhance efficiency and prevent problems. This lubricant, with its dependable, quantifiable, and customised attributes, significantly enhances the efficient operation and extended durability of Electric Screw Compressors.

Drawbacks and the imperative for exploration

Although K-SMART has demonstrated its efficacy in improving the performance of KPCL screw compressors, it is essential to investigate alternative lubricants for a more thorough comprehension. The limitations of proprietary formulations, including restricted environmental sustainability and possible efficiency thresholds, highlight the necessity for a more extensive investigation. This research seeks to overcome these restrictions by examining the advantages of polyglycol-based oils, with the objective of achieving a balance among performance, environmental effect, and sustainability in screw compressor technology.

Comparison Between K-SMART Oil and PEG-Based Oil

A comprehensive comparison was performed to emphasise the benefits of PEG-based oil relative to K-SMART oil, utilising several key performance measures. K-SMART oil is recognised for its superior performance in screw compressors; nevertheless, PEG-based oils provide numerous benefits, especially regarding sustainability and prolonged maintenance intervals. Table 2 presents a comprehensive comparison of the two oils.

This comparison underscores that although K-SMART oil is a high-performance compressor lubricant, PEG-based oil has further benefits, including enhanced oxidation stability, extended maintenance intervals, improved environmental sustainability, and superior reduction of oil vapour content. These considerations render PEG-based oils a persuasive alternative for improving operational efficiency and environmental sustainability in screw compressor applications.

Polyglycol-Based Oil: A Sustainable Alternative

Polyalkylene Glycol (PAG) oils exist in two principal categories: water-soluble and oil-soluble, both possessing unique characteristics that render them appropriate for particular industrial uses. The choice between these two categories is contingent upon the operational environment and the required performance attributes.

Table 2 Comparison between K-SMART oil and PEG-based oil

Parameter	K-SMART oil	PEG-based oil	Advantages of PEG-based oil
Oxidation stability	High oxidation stability; maintenance intervals of up to 6000 h under standard conditions	Extremely high oxidation stability, extending oil change intervals to up to 8000 h	Reduces oxidation breakdown, allowing for longer intervals between oil changes.
Operating temperature range	Suitable for temperatures up to 100 °C	Higher temperature tolerance (150 °C)	Better performance in higher temperature environments.
Maintenance intervals	Up to 6000 h (depends on conditions like intake air quality and ambient humidity)	Up to 8000 h in screw compressors	Extended maintenance intervals reduce downtime and overall costs.
Filter and separator durability	Reduces deposits in filters and separators, though deposits may form under extreme conditions	Minimizes deposit formation, prolonging filter and separator life	Less likely to form carbon deposits, ensuring better filter durability.
Oil vapor content reduction	Effective at reducing oil vapor with rapid air release and anti-foaming properties	Superior oil vapor content reduction	Significantly reduces oil vapor content, improving air quality in compressed air systems.
Wear protection	Advanced ashless anti-wear system, protecting internal metal surfaces	Excellent wear protection, especially for steel components	Superior wear protection, prolonging the life of internal components.
Environmental impact	Limited biodegradability	Biodegradable, eco-friendly lubricant	PEG-based oil is environmentally friendly, making it a better choice for sustainable practices.
Water separation properties	Effective water separation properties	Excellent water separation, especially in high-moisture environments	Superior water separation capabilities, especially in high-moisture conditions.

Water-Soluble Polyalkylene Glycol Oils Water-soluble PAG oils are commonly utilised in fire-resistant lubricating systems, where their superior heat dissipation characteristics are essential for preserving system stability. Their water solubility renders them suitable for applications necessitating clean-burning properties and efficient system flushing. These oils are exceptionally proficient in inhibiting the accumulation of deposits and residues, especially in elevated temperature settings, and are frequently utilised in sectors such as metallurgy, textiles, and plastics, where fire resistance is paramount [14, 15].

The water solubility further improves cooling efficiency in hydraulic systems and compressors, hence enhancing overall system performance. It is crucial to recognise that water-soluble PAG oils may emulsify upon contact with water, potentially resulting in foaming or corrosion in some systems. Consequently, their utilisation must be meticulously regulated in settings prone to water pollution [9].

Oil-Soluble Polyalkylene Glycol Oils Conversely, oil-soluble PAG oils are frequently utilised in screw compressors owing to their exceptional lubricating characteristics, elevated heat stability, and extended service lifespan. These oils create a protective lubricating layer that diminishes metal-to-metal contact, hence minimising wear and prolonging the operational lifespan of essential components such as bearings and rotors. Oil-soluble PAG oils possess low volatility and demonstrate superior oxidation resistance, facilitating prolonged maintenance intervals and diminished oil consumption [11].

Their elevated viscosity index guarantees uniform performance throughout an extensive temperature spectrum, rendering them appropriate for rigorous applications like high-speed rotary screw compressors. Furthermore, oil-soluble PAG oils exhibit compatibility with various elastomers and seals, hence reducing the likelihood of leakage or deterioration over time [16].

Table 3 delineates a comparison of the usual features and applications of these two categories of PAG oils, thereby elucidating their important performance indicators.

This comprehensive comparison elucidates the distinct characteristics and uses of water-soluble and oil-soluble PAG oils. Water-soluble PAG oils are excellent in fire-resistant and high-heat dissipation systems, but oil-soluble PAG lubricants are preferable for screw compressors due to their enhanced lubrication performance, extended service life, and compatibility with high-speed, high-temperature applications.

Polyalkylene glycol (PAG) lubricants are distinguished as an exceptional and sustainable alternative among synthetic lubricants. PAG oils' adaptability and performance characteristics establish them as a leader in numerous industrial applications, especially in screw compressors.

PAG oils, also known as polyglycols, possess a broad range of qualities that render them suitable for many applications. They can be designed to be either water-soluble or water-insoluble (oil-soluble). Water-soluble PAG fluids, characterised by moderate film strength, exhibit a high viscosity index (180 to 280), commendable

Table 3 Comparison of water-soluble and oil-soluble PAG oils

Property	Water-soluble PAG	Oil-soluble PAG
Primary application	Fire-resistant lubrication systems	Screw compressors
Heat dissipation	Excellent heat dissipation	High heat resistance
Clean burning	Clean-burning with minimal residue	Moderate residue formation
Solubility	Soluble in water, allowing for easy system flushing	Soluble in oil, forming a strong lubricating film
Oxidation resistance	Moderate, can emulsify with water	High, resistant to oxidation and thermal breakdown
Thermal stability	Suitable for high-temperature applications	Excellent for high-speed and high-temperature operations
Maintenance intervals	Moderate, may require frequent monitoring in moist environments	Long, suitable for extended intervals

performance at both low and high temperatures, and clean-burning features. Some variants are designated as food-grade and biodegradable, rendering them appropriate for environmentally sensitive uses.

The production of PAG oils entails customising the weight percentage of oxypropylene relative to oxyethylene units within the polymer chain. PAG oils containing 100 weight percent oxypropylene groups are insoluble in water, whereas those with 50 to 75 weight percent oxyethylene are soluble in water at ambient temperatures. The historical importance of PAG oils originates from their creation during World War II, as required by the U.S. Navy to combat hydraulic fluid fires on vessels. Throughout the years, PAG oils have developed and gained widespread application in textile lubrication, metal heat treatment, and industrial machinery.

PAG oils demonstrate remarkable lubricity, oxidative stability, a high viscosity index (ranging from 180 to 280), and low pour points, rendering them suitable for many industrial applications. Their solubility in water enables effortless cleanup, and they provide excellent shear stability. A notable characteristic is their low volatility in high-temperature applications, together with resistance to residue and deposit formation, making them suitable for ecologically sensitive applications.

PAG oils are favoured as the lubricating medium in screw compressors. They have exceptional heat and oxidative resilience, allowing for prolonged oil change intervals (up to 8000 h for screw compressors and up to 40,000 h for turbocompressors). These oils provide exceptional lubricity and anti-wear characteristics, assuring adherence to industry standards including DIN 51506-VDL and ISO 6743-3 L-DAJ. PAG oils, with its extensive operating temperature range of roughly 210–300 °C, save operating expenses by extending the lifespans of oil filters and oil separators.

The little environmental impact of PAG oils corresponds with the increasing focus on eco-friendly lubricants in industrial applications. The biodegradability and material compatibility of PAG oils render them a sustainable option for sectors pursuing high-performance synthetic lubricants with diminished ecological impacts.

PAG oils are essential in bearing lubrication conditions, a topic further examined in the next case study section.

Rationale for Selecting Polyglycol-Based Lubricants

Polyglycol-based lubricants were chosen for this investigation owing to their enhanced performance attributes relative to traditional options, including mineral oils, synthetic esters, and polyalphaolefins (PAOs). Multiple significant elements influenced this decision:

1. *Enhanced Oxidation Stability* Polyglycol-based oils demonstrate remarkable oxidation stability, markedly decreasing the accumulation of oxidation residues and deposits in the compressor. This improved stability extends oil longevity, decreasing the frequency of oil changes and enhancing overall system cleanliness. Conversely, mineral oils and PAOs exhibit a greater susceptibility to oxidation at elevated temperatures, resulting in increased maintenance requirements and possible performance deterioration [17].

2. *Enhanced Biodegradability* A primary rationale for using polyglycol-based oils is their superior biodegradability relative to mineral oils and synthetic esters. Polyglycol oils are recognised for their eco-friendly characteristics, exhibiting quick degradation and reduced toxicity, rendering them appropriate for applications where environmental effect is a significant consideration. This differs from mineral oils, which degrade more slowly and may possess a more detrimental environmental impact [18].

3. *Extended Maintenance Intervals and Reduced Oil Consumption* The elevated thermal stability and minimal volatility of polyglycol-based lubricants provide prolonged maintenance intervals and reduced overall oil use. This results in fewer oil changes and diminished waste, hence decreasing operating downtime and overall maintenance

expenses. In comparison to PAOs and synthetic esters, polyglycol oils often necessitate less frequent maintenance and have enhanced oil retention capabilities at elevated temperatures, hence enhancing their long-term cost-effectiveness [19].

These qualities render polyglycol-based lubricants an ideal selection for improving the efficiency and sustainability of screw compressors. The amalgamation of superior oxidation stability, biodegradability, and extended maintenance intervals highlights their benefits compared to other lubricant options.

Comparison Between PEG and PAG Oils

This study compares PEG-based oils with PAG (Polyalkylene Glycol) oils, as both are regarded as effective choices for improving the operational efficiency of screw compressors. Although they exhibit numerous commonalities, there are notable variances in their chemical and physical properties that can affect their efficacy in diverse applications.

Viscosity Attributes PEG and PAG oils demonstrate comparable viscosity characteristics, enabling them to provide sufficient lubrication at elevated temperature and pressure conditions in screw compressors. Both oils are engineered to create a robust lubricating coating, reducing metal-to-metal contact and wear. Nevertheless, PEG oils often have a marginally superior viscosity index, facilitating enhanced performance across an extended temperature spectrum [14].

Oxidation and Thermal Stability PEG and PAG oils provide significant resistance to oxidation and heat deterioration, essential for prolonging maintenance intervals in screw compressors. Their capacity to endure elevated temperatures (up to 150 °C) renders them appropriate for heavy-duty industrial applications. PEG oils may provide enhanced oxidation resistance under specific extreme operating circumstances owing to their molecular structure [16].

Compatibility with Various Materials (Seals) A primary factor in lubricant selection is its compatibility with seals and other components within the compressor system. PEG and PAG oils exhibit compatibility with various materials, including synthetic rubbers and metals. It is essential to recognise that PAG oils, especially water-soluble types, may exhibit distinct interactions with specific elastomers in comparison to PEG oils. This discrepancy may impact seal expansion or contraction, potentially affecting the durability of components inside the compressor system [20].

Solubility Solubility is a defining feature of PEG and PAG oils. PEG-based oils have greater solubility in water, rendering them beneficial in scenarios where water contamination poses a risk. PAG oils can be manufactured as either water-soluble or oil-soluble, offering enhanced flexibility according on the system's specific requirements. Water-soluble PAG oils are especially advantageous in fire-resistant applications, whereas oil-soluble variations are favoured in conventional lubrication contexts [10].

Interchangeability in Screw Compressors Notwithstanding the aforementioned distinctions, PEG and PAG oils are frequently utilised interchangeably in screw compressors. Both oils offer superior lubrication, diminish wear on internal components, and save total operational expenses by extending maintenance intervals. Moreover, their biodegradability and little toxicity render them ecologically sound options, consistent with the objectives of sustainable industrial practices. Their comparable lubricating efficacy guarantees that either oil can be employed effectively, contingent upon the unique demands of the compressor system [9].

This comparison highlights the adaptability of PEG and PAG oils and their capacity to enhance the efficiency and sustainability of screw compressors, rendering them advantageous substitutes for conventional mineral-based lubricants.

Examples Illustrating the Versatility of PAG Oils

Polyalkylene Glycol (PAG) oils are esteemed for their adaptability in several industrial domains. Their capacity for efficient performance across various applications arises from distinctive qualities such as low toxicity, great biodegradability, exceptional thermal stability, and compatibility with diverse materials. This document presents specific instances of the application of PAG oils across various industrial settings to underscore their adaptability and ecological advantages.

Applications for Food Grade Purposes PAG oils are frequently utilised in food-grade applications owing to their low toxicity and biodegradability, where safety and environmental factors are of utmost importance. PAG oils are sanctioned for incidental food contact and are frequently employed in machinery that processes food items, including mixers, conveyors, and packaging apparatus. Their clean-burning characteristics and low residue production minimise contamination hazards, rendering them an optimal selection for upholding food safety regulations [21].

2. High-Temperature Machinery PAG oils exhibit exceptional heat stability, rendering them appropriate for high-temperature applications, including metalworking and manufacturing machinery. Their capacity to retain lubricating characteristics at high temperatures safeguards essential components, such bearings and gears, against wear and heat deterioration. In sectors such as automobile production, where machinery functions at elevated temperatures, PAG oils offer enduring lubrication, hence minimising downtime and maintenance expenses [22].

3. Sustainable Hydraulic Systems With the tightening of environmental restrictions, numerous sectors are pursuing environmentally sustainable alternatives to conventional hydraulic fluids. PAG oils are progressively utilised in hydraulic systems owing to their biodegradability and minimal environmental impact. PAG oils provide exceptional lubrication in outdoor construction equipment and hydraulic systems functioning in environmentally sensitive regions, while minimising the potential for environmental pollution. Their capacity to deliver effective lubrication in both cold and hot environments further illustrates their adaptability to varied operational circumstances [23].

These examples underscore the adaptability of PAG oils across diverse industries, including food processing, heavy machinery, and environmentally sustainable hydraulic systems. Their low toxicity, biodegradability, and thermal stability collectively ensure that PAG oils fulfil the requirements of diverse industrial applications while promoting sustainability and operating efficiency.

Rationale for Selecting Cylindrical Roller Bearings

This study selected cylindrical roller bearings for examination due to their substantial benefits in managing radial stresses, commonly found in screw compressors. Screw compressors function under substantial stresses, and cylindrical roller bearings are ideally suited for this application owing to their elevated load-bearing capability. These bearings are engineered to withstand substantial radial stresses while ensuring optimal alignment and resistance to misalignment, which is crucial for the efficient functioning of rotary machinery.

The cylindrical configuration of the rollers ensures uniform load distribution over an extensive contact surface, hence reducing wear and prolonging the bearing's operational lifespan. This is especially advantageous for high-speed applications, such as screw compressors, where the efficacy of alternative bearing types, such as ball bearings, may be diminished. Ball bearings are generally employed to manage axial loads; nevertheless, they are less efficient than cylindrical roller bearings in accommodating radial stresses.

Cylindrical roller bearings and ball bearings depend on oil lubrication to minimise friction and wear. This study aims to enhance the lubrication conditions of cylindrical roller bearings to guarantee excellent performance under elevated radial stresses.

Cylindrical roller bearings were chosen for this investigation; however, tapered roller bearings may be applicable in alternative scenarios. Tapered roller bearings accommodate both radial and axial loads; however, they may not perform as effectively in high-speed applications compared to cylindrical roller bearings. The use of cylindrical roller bearings in this study is warranted by the operating demands of screw compressors, where elevated radial load capacity and optimal alignment at high velocities are essential [24].

Case Study: Anti-friction Bearing Lubrication Validation

To assess the lubrication condition of the anti-friction bearing in the KPCL KAS-650 compressor block, the specifications provided by the bearing manufacturer are considered. The lubrication condition (κ), defined as the viscosity ratio, plays a pivotal role in determining the bearing's expected rated life. This condition is expressed as [24]:

$$\kappa = \frac{v}{v_1} \tag{1}$$

Where:

κ is the lubrication condition of the bearing.

v is the actual operating viscosity of the oil or grease base oil $[\mathrm{mm}^2/\mathrm{s}]$.

v_1 is the rated viscosity,

a function of the mean bearing diameter and rotational speed$[\mathrm{mm}^2/\mathrm{s}]$.

The actual operating viscosity (v) is determined from the ISO viscosity grade of the oil or grease base oil and the operating temperature of the bearing.

The rated viscosity (v_1) is obtained from the bearing manufacturer handbook, utilizing the bearing mean diameter ($\mathrm{dm} = 0.5(d + D)$) and the rotational speed of the bearing (n [r/min]).

A higher κ value indicates better lubrication condition and expected rated life. Typically, bearing applications are designed for a lubrication condition ranging from $\kappa = 1$ to 4.

Here, $\kappa = 4$ signifies a regimen where the rolling contact load is carried by the lubricant film, indicating full film lubrication. Beyond $\kappa = 4$ does not increase bearing rating significantly but may be useful in certain conditions, such as frequent start-stop running.

A $\kappa < 0.1$ indicates a regimen where the rolling element load is carried by the contact of asperities, implying boundary lubrication. In such cases, bearing size selection may be based on static safety factors.

For lubrication conditions with $0.1 < \kappa < 1$, considerations include low speed or low viscosity, prompting adjustments in bearing size selection or the selection of a higher viscosity oil.

This comprehensive understanding of lubrication conditions sets the stage for the subsequent case study, where the bearing lubrication conditions for the KPCL KAS-650 compressor block will be validated, considering the specifics provided by the bearing manufacturer.

In this case study, the SKF NU 309 ECM cylindrical roller bearing was examined, an integral component within the KAS-650 compressor block. The investigation involves assessing the bearing's performance under specific conditions (refer Table 4), particularly at an oil-injection temperature of 60 °C. The resulting diluted viscosity, determined to be 19 cSt, is visually represented in the dilution graph (Fig. 2).

Upon comprehensive analysis of the input conditions, the calculated viscosity ratio stands at 1.9. This falls well within the recommended range of (1–4), showcasing a favorable lubrication condition for the bearing. In comparison, the existing K-SMART oil exhibits a viscosity ratio of 0.95.

The outcomes of this case study affirm the efficacy of the chosen polyglycol oil, demonstrating its suitability for optimal bearing performance. This finding holds significant implications for advancing the validation process of the screw compressor, emphasizing the promising role of the selected lubricant in enhancing overall system efficiency.

Performance Evaluation

A stringent statistical methodology was employed to guarantee the reliability and repeatability of the experimental outcomes. Upon finalising the experimental configuration, testing were performed under steady-state circumstances at designated operating points. The compressor was permitted to attain steady operating conditions prior to data recording.

Data was continually gathered for a minimum of 10 min under each steady-state condition. At each operational point, ten data samples were collected and averaged. The averaged readings were subsequently normalised to the specified pressure ratios and speeds in compliance with the ISO 1217 standard for displacement compressor testing.

Table 4 Table displaying key properties of the selected oil alongside details for the cylindrical roller bearing (SKF NU 309 ECM)

Parameters	Value
Speed (RPM)	(2000–3000)
Bore diameter (mm)	45
Outside diameter (mm)	100
Oil injection temperature (°C)	60
Diluted kinematic viscosity (cSt)	19

The standard deviation of the results was computed for each test point to account for variability and evaluate repeatability. Despite the absence of error bars in the figures, the computed standard deviations were low at all test sites, signifying minimal variability and affirming the reproducibility of the experimental outcomes. The minimal standard deviations further corroborate the trustworthiness of the observed trends, affirming the statistical robustness of the findings.

The experimental research yielded essential data regarding the performance of the KAS-650 compressor block. The experimental data was utilised to develop a digital model of the compressor block in SCORG software. This computerised model facilitated an in-depth analysis of the performance assessment of the two oils, permitting a thorough comparison under uniform operational settings.

The efficacy of the KAS-650 compressor block (see Fig. 3) was assessed utilising both K-SMART and polyglycol-based oil via experimental trials and SCORG analysis. The particular qualities of the oils cannot be disclosed due to confidentiality regulations. Nonetheless, a fair comparison was achieved by utilising the identical compressor block and operating conditions, as detailed in Table 5. The amalgamation of experimental and digital analysis yielded a comprehensive validation of the performance enhancements given by the polyglycol-based oil.

The performance metrics employed for screw compressor evaluation are:

- *Specific Power Consumption* (kW/m^3/min) Specific power represents the power required to deliver a unit quantity of gas mass and is calculated as the ratio of compressor power (P) to volume flow rate ($\dot{V}$).

$$\mathrm{SPC} = \frac{P}{\dot{V}} \quad [\mathrm{kW/m^3/min}] \tag{2}$$

- *Adiabatic Efficiency (%)* Adiabatic efficiency compares actual indicated power (P) to theoretical adiabatic power (P_{ad}) for compression.

$$\eta_{\mathrm{ad}} = \frac{P_{\mathrm{ad}}}{P} \times 100 \quad [\%] \tag{3}$$

- *Discharge Temperature* (°C) The temperature of the discharged air from the screw compressor, reflecting the thermal effects of compression.

From the SCORG analysis, it is evident that the polyglycol-based oil yields notable improvements over K-SMART oil:

- A 2.8% reduction in specific power consumption (kW/m^3/min).
- A 2.9% increase in adiabatic efficiency (%).

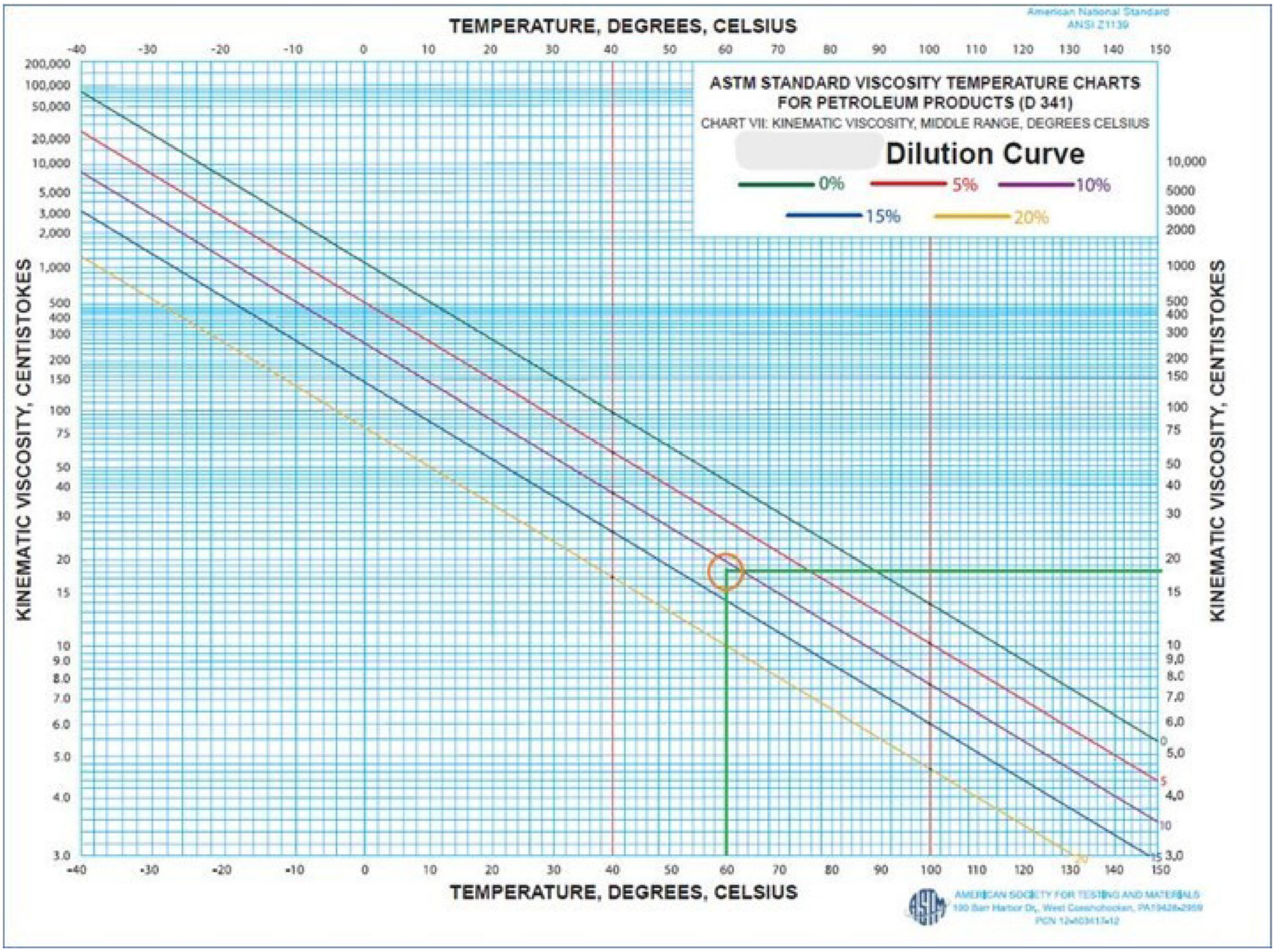

Fig. 2 Dilution curve for PAG oil

Table 5 KAS-650 compressor block working conditions

Parameters	Value
Pressure ratio	8.5
Speed (RPM)	4000
Volume index	4.6
Working fluid	Air
Suction temperature (°C)	20

- A reduction of approximately 9.1% in discharge temperature (°C) from the screw compressor perspective.

The experimental and digital examination of the KAS-650 compressor block shown notable enhancements in specific power consumption, adiabatic efficiency, and volumetric efficiency while employing polyglycol-based lubricants in contrast to K-SMART oil. The performance improvements are directly attributable to the physicochemical characteristics of the polyglycol-based lubricant, notably its exceptional oxidation stability, elevated viscosity index, and improved thermal resistance.

The decrease in specific power consumption directly results from the lubricant's capacity to reduce internal friction and oil drag within the compressor. Polyglycol-based lubricants provide diminished oil drag relative to traditional oils owing to their enhanced viscosity and low volatility, resulting in decreased friction between moving components, such as rotors and bearings. The decrease in internal resistance not only minimises power losses but also enhances the overall mechanical efficiency of the compressor. Conversely, less effective lubricants would elevate oil drag, resulting in increased frictional losses, which would subsequently diminish specific power consumption, hence escalating energy consumption over time.

The elevated oxidation stability of the polyglycol-based lubricant guarantees prolonged efficacy, ensuring constant performance under elevated temperature and pressure circumstances. The enhanced adiabatic efficiency noted in the data can be ascribed to the lubricant's capacity to maintain

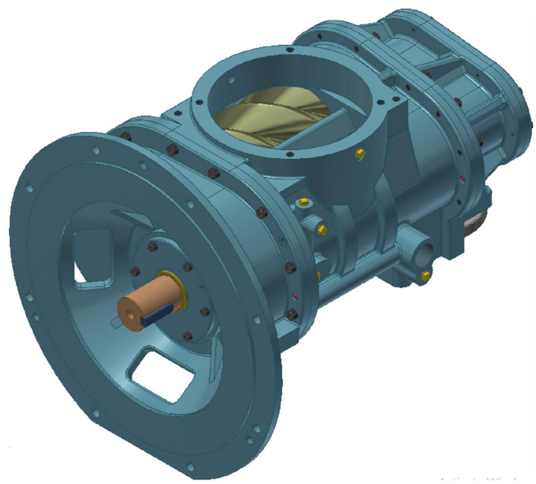

Fig. 3 KAS-650 screw compressor block

consistent thermal characteristics during operation, hence minimising heat-related losses during compression. This is additionally corroborated by the lubricant's exceptional thermal resistance, which inhibits overheating and guarantees that the compressor functions nearer to its optimal thermodynamic efficiency.

The volumetric efficiency improvements noted in the study can be attributed to the lubricant's superior sealing characteristics. Polyglycol-based oils enhance sealing between the rotors and the housing, minimising internal leakage and optimising the volume of air compressed in each cycle. The sealing effect, along with diminished friction and reduced drag, enhances volumetric efficiency, enabling the compressor to manage larger air volumes with increased precision and stability.

In practical applications, these enhancements result in substantial operational and financial advantages. Utilising polyglycol-based lubricants can result in decreased energy usage, diminished maintenance intervals, and prolonged compressor lifespan. This study highlights the necessity of choosing lubricants with suitable physicochemical characteristics to enhance compressor performance, increase efficiency, and minimise overall ownership costs.

Mechanisms for Performance Improvement

The performance enhancements noted using polyglycol-based lubricants in the screw compressor can be ascribed to many fundamental causes. A key feature is the lubricant's capacity to create a uniform and stable layer, which markedly decreases friction between the rotors and other moving parts in the compressor. The decrease in friction results in less specific power usage, enhancing the compressor's overall energy efficiency. Additionally, the polyglycol-based lubricant improves the sealing between the rotors and the casing, minimising internal leakage and enhancing volumetric efficiency. The sealing effect guarantees increased air compression every cycle, reducing losses and enhancing compressor efficiency.

The superior oxidation stability and temperature resistance of polyglycol-based lubricants are essential for prolonging maintenance intervals. The lubricant inhibits oxidation residue accumulation, hence maintaining the cleanliness of filters and separators for extended durations, minimising maintenance frequency and enhancing the compressor's longevity.

The SCORG software, utilising a chamber-based model to simulate thermodynamic processes within the compressor, was utilised to further examine the impact of the lubricant on compressor performance. The SCORG solution considers the interaction between the lubricant and the compressed gas, together with the lubricant's function in heat dissipation and friction mitigation. The model precisely forecasts the enhancement of specific power consumption, adiabatic efficiency, and volumetric efficiency by the polyglycol-based oil across diverse operating situations. Through the simulation of these interactions, SCORG offers an in-depth comprehension of the fundamental mechanisms that account for the noted enhancements in compressor performance, longevity, and maintenance schedules.

Conclusion

This study highlights the essential significance of oil in enhancing the performance and durability of screw compressors. Polyglycol oils, noted for their superior thermal and oxidative resilience, serve as significant enhancers of compressor performance. The specific bearing lubrication attained by a targeted viscosity ratio of 1.9 represents a substantial advancement in prolonging bearing lifespan. SCORG study further validates the benefits of polyglycol oils, demonstrating a notable 2.8% enhancement in Specific Power Consumption (SPC). This thorough study highlights the capability of polyglycol-based lubricants to enhance the efficiency and sustainability of screw compressors, representing a significant advancement in industrial lubrication.

No particular studies were performed in this work to evaluate the biodegradability of polyglycol-based lubricants; nonetheless, the environmental advantages of these oils are well-documented in the literature. Polyglycol-based lubricants exhibit superior biodegradability relative to traditional mineral oils, rendering them more environmentally friendly. Research indicates that these lubricants demonstrate accelerated breakdown rates and diminished toxicity, hence lessening their enduring environmental impact [?, ?]. Additionally, their enhanced oxidation stability and diminished volatility result in decreased oil consumption and fewer oil changes, hence further reducing waste production. The amalgamation of these characteristics underscores the environmentally beneficial attributes of polyglycol-based oils, endorsing their application as a sustainable alternative in industrial contexts.

Further Study

This research establishes a foundation for subsequent investigations focused on enhancing screw compressor technology. Experimental studies are scheduled to validate the SCORG analysis, offering actual evidence to support the results derived from the simulation. The forthcoming investigations will explore the practical ramifications of integrating polyglycol-based oils in industrial applications, providing a pathway for additional refining and optimisation. Moreover, subsequent study will concentrate on evaluating the biodegradability and ecological effects of polyglycol-based lubricants via specialised tests, thereby enhancing the understanding of their significance in sustainable industrial practices. The comprehensive investigation of sustainable lubricants and their effects on machinery performance is expected to provide significant insights into the advancement of screw compressor technology.

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Conflict of interest The authors declare no known conflict financial interest or personal relationships that might have influenced the work reported in this paper.

References

[1] N. Stosic, I. Smith and A. Kovacevic, Screw compressors: mathematical modelling and performance calculation. Springer Science & Business Media, Berlin (2005).

[2] A. Kumar, A. Kovacevic, S.A. Ponnusami, S. Patil, S. Abdan and N. Asati. On performance optimisation for oil-injected screw compressors using different evolutionary algorithms. In: IOP Conference Series: Materials Science and Engineering, vol. 1267, p. 012021. IOP Publishing, 2022.

[3] N. Basha. Numerical analysis of oil injection in twin-screw compressors. PhD thesis, City, University of London, 2021.

[4] A. Kumar, K. Patil, A. Kulkarni and S. Patil. Investigating alternative rotor materials to increase displacement and efficiency of screw compressor while considering cost and manufacturability. In: International Conference on Compressors and their Systems, pp. 115–125. Springer, 2023.

[5] A. Kumar, S. Patil, A. Kovacevic and S.A. Ponnusami, Performance prediction and Bayesian optimization of screw compressors using Gaussian process regression. Eng. Appl. Artif. Intell., *133* (2024) 108270.

[6] K. Venu Madhav. The commercial viability of water injected air screw compressor systems. PhD thesis, PhD Thesis, City University London, 2014.

[7] N. Stosic and K. Hanjalic. Development and optimization of screw machines with a simulation model—part i: profile generation. 1997.

[8] N. Stosic, I.K. Smith and A. Kovacevic, Optimisation of screw compressors. Appl. Therm. Eng., *23*(10) (2003) 1177–1195.

[9] W. Dresel and R.-P. Heckler. Lubricating greases. Lubr. Lubr. (2017) 781–842.

[10] L.O. Leugner, The practical handbook of machinery lubrication. Maintenance Technology International, Incorporated, 2005.

[11] M.R. Greaves, Polyalkylene glycols. In Synthetics, Mineral Oils, and Bio-Based Lubricants, pp. 119–146. CRC Press, 2020.

[12] Machinery Lubrication. Machinery lubrication. Website for lubrication technology and best practices, 2024. url: https://www.machinerylubrication.com/ (accessed August 2024).

[13] A. Kovacevic, S. Rane, and PDM Analysis. Scorg-screw compressor rotor grid generation. Software Package for Design and Analysis of Positive Displacement Machines, 2024. url: https://pdmanalysis.co.uk/scorg/ (accessed August 2024).

[14] P.L. Matlock, W.L. Brown, and N.A. Clinton, Polyalkylene glycols. Chem. Ind. New York-Marcel Dekker, (1999) 159–194.

[15] W.H. Millett, Polyalkylene glycol synthetic lubricants. Ind. Eng. Chem., *42*(12) (1950) 2436–2441.

[16] S. Lawford, Polyalkylene glycols. In: Synthetics, Mineral Oils, and Bio-Based Lubricants, pp. 137–156. CRC Press, 2005.

[17] F. Anwar, A.I. Hussain, S. Iqbal and M.I. Bhanger, Enhancement of the oxidative stability of some vegetable oils by blending with moringa oleifera oil. Food Chem., *103*(4) (2007) 1181–1191.

[18] B. Haq, J. Liu, K. Liu and D.A. Shehri, The role of biodegradable surfactant in microbial enhanced oil recovery. J. Petrol. Sci. Eng., *189* (2020) 106688.

[19] Vito Tič, Tadej Tašner and Darko Lovrec, Enhanced lubricant management to reduce costs and minimise environmental impact. Energy, *77* (2014) 108–116.

[20] A.S. Awale, A. Chaudhari, A. Kumar, M.Z.K. Yusufzai and M. Vashista, Synergistic impact of eco-friendly nano-lubricants on the grindability of AISI H13 tool steel: a study towards clean manufacturing. J. Clean. Prod., *364* (2022) 132686.

[21] D.A. Lauer, Industrial gear lubricants. In: Synthetics, Mineral Oils, and Bio-Based Lubricants, pp. 459–476. CRC Press, (2005).
[22] S.S. Sanukrishna, A.V. Raju, A. Krishnan, G.H. Harikrishnan, A. Amal, T.S. Krishna Kumar and M.J. Prakash. Enhancing the thermophysical properties of PAG lubricant using graphene nano-sheets. In: Journal of Physics: Conference Series, vol. 1355, p. 012041. IOP Publishing, 2019.
[23] R. Shah, M. Woydt and S. Zhang, The economic and environmental significance of sustainable lubricants. Lubricants, *9*(2) (2021) 21.
[24] SKF. Skf bearing maintenance handbook. SKF Bearing Maintenance Handbook, 2024. **url**: https://cdn.skfmediahub.skf.com/api/public/0901d1968013be94/pdf_preview_medium/0901d1968013be94_pdf_preview_medium.pdf (accessed August 2024).