Investigation of Thermal Properties of Lubricants Used in Refrigeration Systems

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ABSTRACT

The growing global need for cooling systems exacerbates sustainability challenges by increasing energy consumption and environmental impacts. In compressors, thermal properties of the preference lubricant play a critical role in reducing energy consumption and enhancing efficiency. The thermal stability of lubricant is a critical factor determining the performance and efficiency of compressors in refrigeration systems. High thermal stability means the ability of the lubricant to remain chemically intact under high temperature and pressure conditions, which increases durability during long-term use. Furthermore, thermally stable lubricants maintain their quality by strengthening resistance to oxidation and minimize wear and failures in the system. This improves energy efficiency, ensures low maintenance and supports the long life and reliable operation of cooling systems such as refrigerators. With increased thermal conductivity, the heat transfer capacity of the lubricant improves, enabling efficient heat dissipation within the system, resulting in consistent cooling performance. Therefore, the thermal properties of lubricant are an important parameter to consider in order to optimize the overall efficiency of refrigeration systems. This study aims to investigate the thermal properties of lubricants and their impact on compressor performance. The study investigated the thermal stability of lubricants through Thermogravimetric Analysis, oxidation resistance using Differential Scanning Calorimetry, heat transfer and cooling performance using Thermal Conductivity Meter and rheological behavior by creating viscosity-temperature curves. The contribution of the lubricant to energy efficiency was compared with compressor calorimeter tests at the end of the study. Thus, compressor efficiency has been improved by using a lubricant with stronger thermal stability.

Keywords: Lubricant, Refrigerator Compressor, Thermal Properties, Viscosity, TGA, DSC, Thermal Conductivity.

1. INTRODUCTION

The increasing global demand for cooling systems presents sustainability challenges due to increased energy consumption and environmental impacts. Compressors, key components in refrigeration systems, play a crucial role in compression and heat transfer, essential for maintaining optimal storage conditions. In today's era of energy conservation and sustainability, the importance of compressor energy efficiency is increasingly emphasized (Sanukrishna & Jose, 2022). Compressors contain various components such as pistons, rotors, and bearings, which generate friction during operation. To mitigate this friction and prevent wear, lubricants are used. Lubricants are essential for improving compressor energy efficiency, reliability, and sustainability by reducing frictional losses and extending the lifespan of the compressor and its internal components (Mangas et al., 2014). Moreover, it helps in maintaining the appropriate clearances between moving parts, ensuring efficient and leak-free compression. Compressors, rely on the thermal properties of lubricants to reduce energy usage and enhance efficiency. Thermal stability, a key attribute, ensures that lubricants maintain their integrity under high temperatures and pressures, enhancing durability, resisting oxidation, and minimizing wear and system failures. Additionally, increased thermal conductivity enables efficient heat dissipation, ensuring consistent cooling performance. Consequently, the thermal properties of lubricants are crucial in optimizing refrigeration system efficiency (Holz, 2019).

This study explores the thermal characteristics of three distinct lubricant types and their influence on compressor performance through an in-depth application of advanced thermal analysis techniques. Additionally, the study differentiates between fresh and used lubricants to discern the impact of high-speed and low-speed compressor operational on the lubricants' thermal behavior. By conducting these comprehensive evaluations, the study seeks to illuminate the dynamics of thermal stability in lubricants and identify the optimal lubricant for enhancing compressor efficiency.

2. MATERIALS AND CHARACTERIZATION

The objective of this study was to employ lubricants with different base oil types and low viscosity grades. Three distinct lubricants, each with a kinematic viscosity of 5 at 40°C, were chosen. These lubricants comprised synthetic and mineral base oils, representing a variety of chemical compositions. Specifically, one of the synthetic lubricants utilized Polyalphaolefin (PAO) as the base oil, while the other employed Alkylbenzene (AB) as the base oil. The mineral lubricant utilized a naphthenic base oil.

2.1 Measurement of Rheological Properties

In this study, the fluidity characteristics of oils were examined using kinematic viscosity and temperature curves. Measurements were conducted with a Cannon Ubbelohde Type I Viscometer, which has a range of 2-10 mm^2/s. Samples were placed in capillary tubes and submerged in a thermostat-controlled bath to maintain precise temperatures. The kinematic viscosities of the oils were recorded at 40°C and 85°C. These values were used to create kinematic viscosity-temperature curves based on the Walther Equation (Sánchez-Rubio et al., 2006). The performance of the lubricants was then evaluated through these curves. The Viscosity Index (VI) was determined in accordance with the ASTM D2270 standard, which is employed to characterize the viscosity behavior of lubricants. This calculation utilizes the kinematic viscosity measurements of the lubricants at two specific temperatures, 40°C and 100°C, to assess their performance under varying thermal conditions. As temperature rises, the lubricant's intermolecular bonds weaken, causing a reduction in viscosity and thus a thinner protective film. Conversely, if the lubricant thickens too much at low temperatures, it can cause blockages in bearings. Therefore, an ideal lubricant should maintain a balance, avoiding excessive thinning at high temperatures and excessive thickening at low temperatures. These analyses aim to predict how the oil's viscosity will behave during compressor operation, ensuring optimal fluidity within a sealed system (Kotzakoulakis & George, 2017).

2.2 Measurement of Thermal Characterization

Thermogravimetric analysis was employed to evaluate the thermal stability and volatility of lubricating oils in this study. Using the TA Discovery 550 TGA instrument, the analyses were performed in a nitrogen atmosphere to prevent oxidation. The oils were heated from 20°C to 500°C at a rate of 10°C/min within this inert atmosphere, allowing for a thorough investigation of characteristic thermal properties. The stability of the lubricants was assessed by analyzing the TG and DTG curves. TGA provides insights into how well the oil withstands high temperatures and indicates the specific temperatures at which the oil starts to break down (Smook et al., 2022). This method reveals the rate at which the oil deteriorates, helping to determine its longevity. Understanding the temperature resistance of materials through TGA is essential for effective product design, particularly for ensuring the efficiency and reliability of compressor oils by identifying how rapidly they decomposition under high temperature conditions (Santos et al., 2017).

2.3 Measurement of Oxidation Stability

Differential scanning calorimetry was used to evaluate the oxidation resistance and decompositions of oils in this study. The TA Discovery DSC250 instrument facilitated these analyses under a controlled dry air environment to ensure consistent experimental conditions. The oils were subjected to a heating process within a reactive atmosphere to initiate their decomposition reactions. Initially, the samples were heated from 40°C to 50°C at a rate of 8°C/min in a nitrogen atmosphere and held at this temperature for 1 minute under isothermal conditions. Following this, the atmosphere was switched to dry air, and the samples were maintained in an isothermal state for another minute. Subsequently, the samples were heated from 50°C to 360°C at a rate of 10°C/min. The decomposition of the lubricants was analyzed by observing the heat flow curves and identifying exothermic reactions as the temperature increased. Over time, lubricants can degrade and age due to exposure to high temperatures and oxygen (Abdelkhalik et al., 2018). This degradation can alter the lubricant's molecular structure, leading to reduced compressor efficiency. The objective of this study was to use DSC to investigate how oils break down and to determine which oil exhibits the greatest resistance to degradation. This method allows for monitoring the service life of lubricants and comparing their resistance to potential leaks and contamination (Gamlin et al., 2002).

2.4 Measurement of Thermal Conductivity

Thermal conductivity measurement was employed to determine the heat transfer performance of lubricating oils in this study. The Transient Hot Wire Liquid Thermal Conductivity Meter was utilized for the analyses. Heating of samples was conducted from 20°C to 100°C. The cooling performance of the lubricants was analyzed based on thermal conductivity. Thermal conductivity of lubricants is a crucial performance characteristic. Because there exists a robust correlation between the thermal conductivity of oils and compressor efficiency. This is because oils with higher thermal conductivity values will facilitate quicker cooling, leading to higher efficiency and minimizing frictional losses (Gyimah et al., 2016).

3. RESULTS AND DISCUSSIONS

The VG5 lubricants were subjected to rigorous testing within a refrigerator compressor under two operational conditions: high-speed conditions at 145°C and 30 bar, and low-speed conditions at 120°C and 20 bar, each for a duration of 72 hours. R600a (isobutane) was used as refrigerant in the tests. The compressors were kept in pre-conditioned cabinets, their temperature controlled by a fan and their pressure regulated by an expansion valve. The study employed advanced thermal analytical techniques to evaluate both fresh and used lubricants extracted in the compressor test. The first stage involved a comparative evaluation of the thermal properties of fresh lubricants to determine the most suitable oil for compressor operation. Subsequently, the thermal properties of the used lubricants were juxtaposed with their fresh condition to elucidate the variation of their thermal properties under high speed and low speed com- pressor conditions. This comparative analysis aimed to identify the lubricant that maintained the most stable thermal behaviour under various operational stresses. Compressor calorimetry tests were conducted adhering to the ASHRAE specifications, which set the evaporation temperature at -23.3°C and the condensation temperature at 54.4°C. These tests aimed to assess the energy efficiency and performance of various lubricants within compressors. Throughout the testing process, the Coefficient of Performance (COP) [W/W] was meticulously measured once the compressor, operating under automated calorimetric conditions, achieved a stable operational regime.

3.1 Rheological Modelling

Viscosity-temperature curves have been established utilizing the kinematic viscosity values of lubricants at 40°C and 85°C as utilized within the Walther Equation.

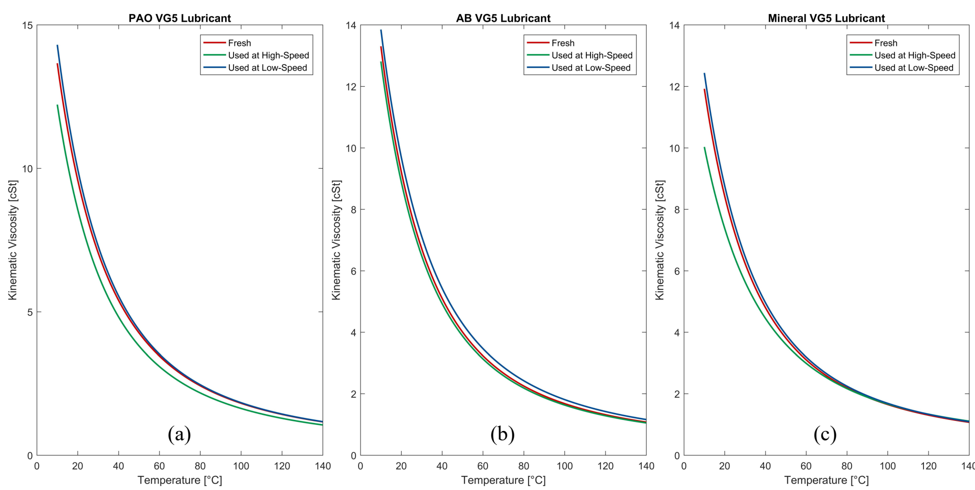

Figure 1: Viscosity-temperature curves of fresh, used at high-speed and used at low-speed: (a) PAO, (b) AB and (c) Mineral VG5 lubricants

The viscosity index for PAO, AB, and Mineral VG5 lubricants have been calculated as 110, 84, and 57, respectively. A comparative analysis of these lubricants reveals that the PAO VG5 lubricant demonstrates the most stable viscosity behavior, as indicated by its superior VI value. This stability underscores its advantageous performance characteristics relative to the other lubricants. The viscosity of PAO VG5 lubricant exhibits gradual decreases under escalating temperature conditions and modest increments under declining temperature regimes, as delineated in Table 1.

Consequently, the PAO VG5 lubricant, with its consistent flow characteristics, promises the establishment of a uniform oil film crucial for compressor functionality.

Table 1: Kinematic viscosity values of fresh and used lubricants

		Kinematic Viscosity [cSt]		
Oil Type	**Oil Usage**	**40°C**	**85°C**	**100°C**
PAO VG5	Fresh	5.4	2.24	1.81
	High-Speed	4.82	2.01	1.63
	Low-Speed	5.5	2.27	1.84
AB VG5	Fresh	5.1	2.08	1.68
	High-Speed	4.98	2.04	1.64
	Low-Speed	5.43	2.24	1.81
Mineral VG5	Fresh	4.89	2.0	1.62
	High-Speed	4.45	2.02	1.61
	Low-Speed	4.92	2.08	1.69

Observations reveal discrepancies in the viscosity of oils extracted from compressor tests when compared to fresh oils. Specifically, viscosity reductions are observed in PAO VG5 oil derived from high-speed tests in contrast to its fresh counterpart, while an opposing trend of viscosity augmentation is noted in PAO VG5 oil derived from low-speed tests. Similar observations are discerned in AB VG5 and Mineral VG5 oils. High-speed tests reveal a decrease in oil viscosity attributed to temperature-induced molecular breakdown. Conversely, low-speed tests unveil viscosity increases attributed to the formation of impurities within the lubricant. This phenomenon occurs due to the limited time available for the oil to form a protective film, a consequence of the sluggish movement of the lubricant.

3.2 Thermal Characterization

The temperature-mass loss curves of the lubricants were established by exposing them to high temperatures under an inert nitrogen atmosphere.

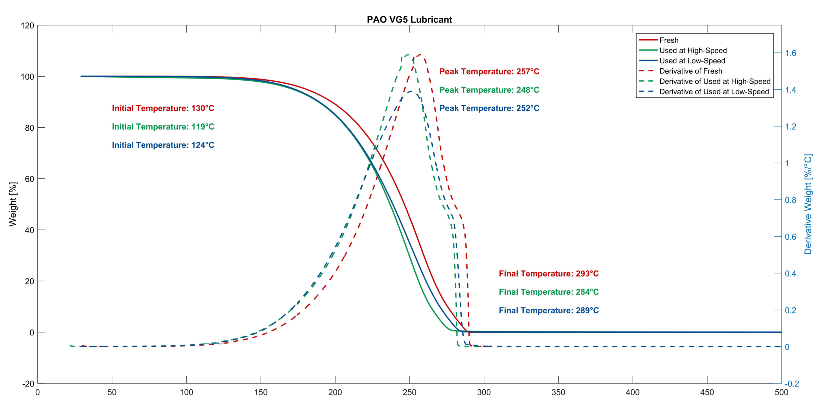

Figure 2: TG-DTG curves of fresh, used at high-speed and used at low-speed PAO VG5 lubricants

Upon analysis of the Thermogravimetric and Differential Thermogravimetric curves depicted in Figure 2, it became apparent that the thermal decomposition profile of fresh PAO VG5 oil manifests in a distinct manner. Notably, the onset of volatility was commenced at approximately 130°C, was delineated a two-step mass loss phenomenon. This stage of mass loss extends up to approximately 293°C, concurrently with the identification of the peak temperature of thermal degradation at 257°C. The observed disparities between fresh and used oils in compressor applications underscore the dynamic nature of oil thermal stability, influenced by factors such as temperature, pressure, and mechanical stresses. It was discerned that the onset of volatility for oils subjected to high-speed tests commenced 11°C earlier than that of fresh oil. Conversely, oils obtained from low-speed tests exhibited an onset of volatility 6°C earlier than fresh oil.

Moreover, a notable divergence was observed in the peak temperature of thermal degradation, with oils from high-speed tests registering a 4°C lower peak temperature compared to those from low-speed tests. This discrepancy delineates a crucial distinction in the thermal stability of PAO VG5 oil utilized in low-speed and high-speed tests. Consequently, it can be inferred that the oil degradation process is more pronounced during high-speed tests, underscoring the dynamic interplay between operational conditions and oil thermal stability.

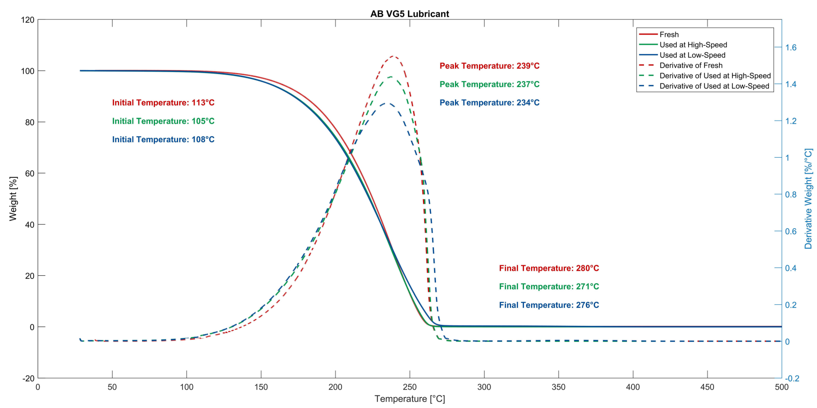

Figure 3: TG-DTG curves of fresh, used at high-speed and used at low-speed AB VG5 lubricants

The thermal decomposition of fresh AB VG5 oil was observed through the TG&DTG curves depicted in Figure 3, revealing a single-stage mass loss process initiating at approximately 113°C and persisting until around 280°C. Simultaneously, the peak temperature of thermal decomposition was determined to be 239°C. As evidenced by the thermo- gravimetric results depicted in Figure 3, it was observed that the volatility of the oil used high-speed test is 8°C lower than that of the fresh oil. Conversely, the AB VG5 oil used low-speed test initiated volatility 5°C earlier than the fresh oil.

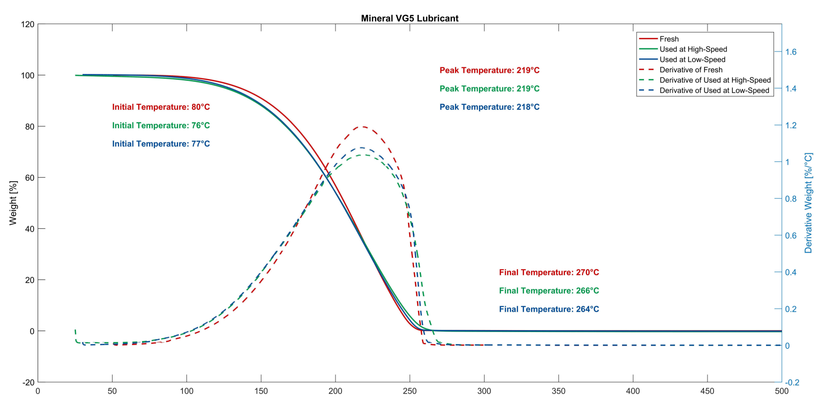

Figure 4: TG-DTG curves of fresh, used at high-speed and used at low-speed Mineral VG5 lubricants

The thermal decomposition characteristics of fresh Mineral VG5 oil were scrutinized through TGA, as illustrated in Figure 4. These analyses revealed a single-stage mass loss process commencing at approximately 80°C and persisting until around 270°C. Notably, the peak temperature of thermal decomposition was identified at 219°C. Upon subjecting the oil to high-speed test conditions, observed volatility patterns indicated a slight reduction in volatility compared to the fresh oil counterpart, with the onset of mass loss occurring approximately 4°C earlier and the completion of the mass loss process occurring 4°C sooner. Conversely, in the case of Mineral VG5 oil subjected to low-speed test conditions, volatilization commenced approximately 3°C earlier.

3.3 Oxidation Stability

Under exposure to oxygen atmosphere and high temperatures, alterations in their structures were monitored through heat flow-temperature curves. The exothermic peaks observed signify the onset of oxidation reactions.

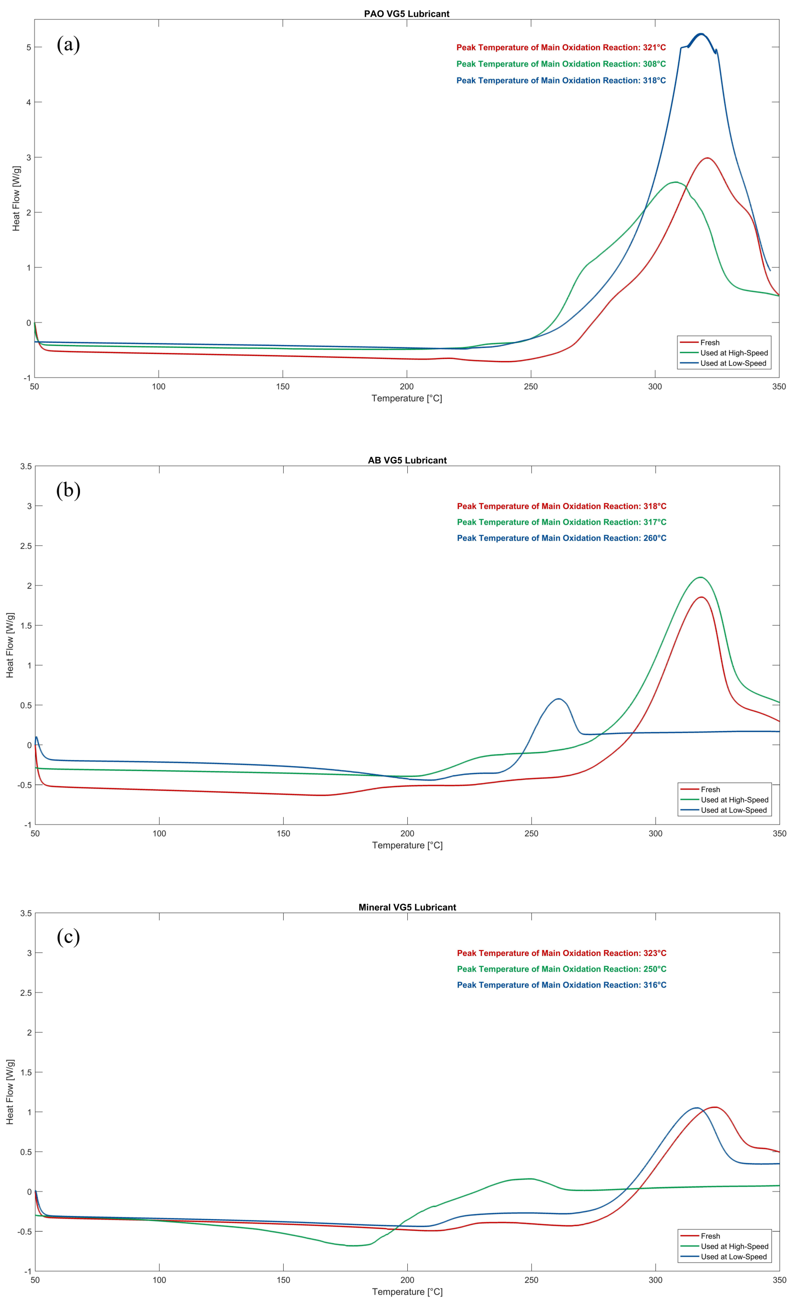

Figure 5: DSC curves of fresh, used at high-speed and used at low-speed: (a) PAO, (b) AB and (c) Mineral VG5 lubricants

Comparison of the oxidation/degradation reactions and resistances among three distinct types of fresh oils, as depicted in Figure 5, reveals notable similarities in the peak temperatures of their primary exothermic reactions. Specifically, the maximum temperatures recorded for oxidation reactions of PAO VG5, AB VG5, and Mineral VG5 lubricants are determined to be 321°C, 318°C, and 323°C, respectively. Deviations in heat flow curves for PAO and Mineral VG5 lubricants become evident beyond the threshold of 210°C. Upon scrutiny of oils used in compressor tests vis-à-vis fresh counterparts, substantial alterations in degradation reactions emerge.

Notably, peak temperatures of primary oxidation reactions in used oils exhibit a leftward shift, denoting initiation at lower temperatures. Specifically, for PAO VG5 lubricants, the oil subjected to high-speed tests attains its peak temperature 13°C earlier than its fresh counterpart, while the oil from low-speed tests precedes by 3°C. Similarly, for AB VG5 lubricants, the high-speed tested oil reaches its maximum 1°C earlier than fresh oil, whereas the low-speed counterpart precedes by 58°C, indicating heightened stress levels at lower speeds. Further analysis of oxidation reactions in Mineral VG5 lubricants unveils significant deviations, with the oil from high-speed tests peaking 73°C earlier than fresh oil, and the low-speed variant preceding by 7°C. These findings suggest distinct stress patterns, with AB VG5 lubricants exhibiting increased susceptibility to stress at low speeds, while Mineral VG5 lubricants demonstrate heightened stress levels under high-speed conditions.

3.4 Thermal Conductivity

Thermal conductivity coefficients of lubricants within the range of 20-100°C have been measured, and linear regressions have been established.

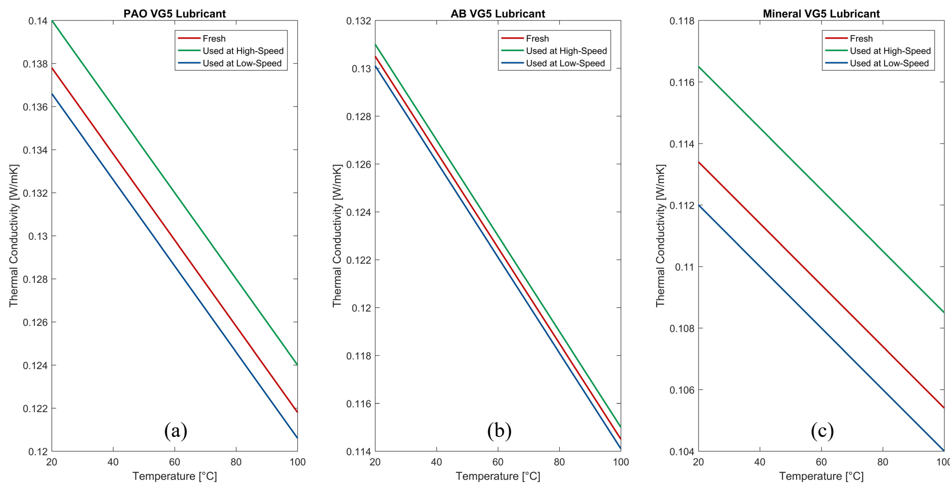

Figure 6: Thermal conductivity-temperature curves of fresh, used at high-speed and used at low-speed: (a) PAO, (b) AB and (c) Mineral VG5 lubricants

The thermal conductivity curves in Figure 6 show a clear decrease as temperature rises. Given the low thermal conductivity coefficients of the oils, which further declines with increasing temperatures, it was considered important to compare the thermal conductivity coefficients of the oils at different temperatures, as shown in Table 2. Fresh PAO VG5 oil has a thermal conductivity at 100°C similar to fresh AB VG5 oil at 64°C, indicating its superior thermal properties. Additionally, fresh AB VG5 oil at 100°C exceeds the thermal conductivity of fresh Mineral VG5 oil at 20°C, highlighting its distinct advantage. Thus, PAO VG5 oil, with the highest thermal conductivity, is the best for cooling compressors. For used oils, PAO VG5 shows increased thermal conductivity in high-speed tests compared to fresh oil, while it decreases in low-speed tests. This pattern is consistent in used AB VG5 and Mineral VG5 oils. This can be attributed to the decrease in the viscosity of the oils in high-speed tests, which increases the thermal conductivity. On the other hand, the decrease in thermal conductivity in low-speed tests is due to the increase in the viscosity of the oil in these tests.

3.5 Calorimeter Test Results

Compressor calorimetry tests were carried out under ASHRAE 2100 rpm conditions. Normalized COP values for the PAO, AB, and Mineral VG5 lubricants were shown respectively in Figure 7. These results are a crucial criterion for assessing the impact of lubricants on compressor performance.

The COP value of the Mineral VG5 lubricant was assumed to be 100, then then the COP values of PAO and AB VG5 lubricants were normalized respectively as 104 and 102. Thermal analysis reveals distinct differences in COP among the lubricants. The PAO VG5 lubricant exhibits the highest COP, attributed to its superior viscosity control, thermal stability, oxidation resistance, and thermal conductivity, thereby enhancing compressor efficiency.

Table 2: Thermal conductivity values of fresh and used lubricants

		Thermal Conductivity [W/mK]		
Oil Type	**Oil Usage**	**20°C**	**60°C**	**100°C**
PAO VG5	Fresh	0.1378	0.1298	0.1218
	High-Speed	0.1400	0.1320	0.1240
	Low-Speed	0.1366	0.1298	0.1206
AB VG5	Fresh	0.1305	0.1225	0.1145
	High-Speed	0.1310	0.1230	0.1150
	Low-Speed	0.1301	0.1221	0.1141
Mineral VG5	Fresh	0.1134	0.1094	0.1054
	High-Speed	0.1165	0.1125	0.1085
	Low-Speed	0.1120	0.1080	0.1040

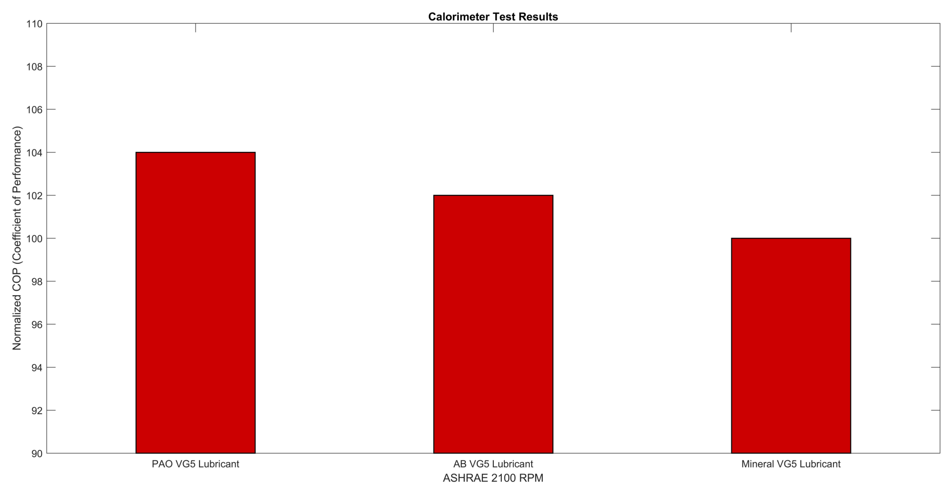

Figure 7: Normalized COP values of PAO, AB and Mineral VG5 lubricants

In contrast, the AB VG5 lubricant, ranking second, follows closely due to its substantial thermal conductivity, and thermal stability. Conversely, the Mineral VG5 lubricant records the lowest COP, reflecting its inferior viscosity control, thermal conductivity, and thermal stability, which contribute to less efficient compressor performance compared to the other lubricants.

4. CONCLUSION

The optimization of compressor energy efficiency depends on careful evaluation of lubricant properties, especially in the area of viscosity management. The PAO VG5 lubricant in particular exhibits a remarkable capacity to maintain consistent viscosity levels even during changing thermal dynamics. This is because high viscosity index of PAO VG5 lubricant make them adept at adapting fluctuating temperature conditions, thus ensuring sustainable and stable performance in a variety of operational environments. Their superior ability to form and maintain protective oil films, especially at elevated temperatures, outshines alternative lubricants in terms of compressor reliability and longevity.

Critical to the safe and efficient operation of compressors is the thermal stability of lubricants. PAO VG5 lubricant emerges as a frontrunner in this aspect, showcasing unparalleled resistance to thermal degradation owing to its elevated peak temperature of thermal decomposition. This high thermal stability translates to prolonged operational durations and enhanced reliability, accentuated by the oil's reduced volatility, which ensures its retention within the compressor at elevated temperatures, thus facilitating sustained lubrication efficacy.

Furthermore, oxidation resistance stands as a paramount consideration in lubricant selection, with PAO VG5 lubricant once again asserting their superiority over competing variants. Through comprehensive examination of oxidative reactions in fresh and used oils, PAO VG5 lubricant consistently exhibit greater stability, underscored by their ability to withstand oxidative breakdown under varying conditions, thereby ensuring sustained compressor performance and longevity.

Furthermore, the thermal conductivity of lubricants is emerging as an important determinant of cooling efficiency and friction loss reduction in compressors. PAO VG5 lubricant, characterized by its outstanding thermal conductivity, promises improved heat dissipation in compressor assemblies, promoting higher cooling efficiency. In varying test conditions, differences in the thermal conductivities of oils have been noted. The thermal conductivity of oil obtained from high-speed tests has shown an increase, whereas that from low-speed tests has exhibited a decrease. This observation can be explained by the reduced viscosity of oil from high-speed tests. Conversely, the decrease in thermal conductivity can be attributed to the higher viscosity of oil from low-speed tests.

In summary, calorimeter results revealed that the highest COP was achieved using the PAO VG5 lubricant due to its superior viscosity control, thermal stability, oxidation resistance, and high thermal conductivity. These findings underscore the importance of considering the thermal properties of lubricants to maximize the performance and efficiency of refrigeration systems. By embracing these lubricants, compressor systems stand to benefit from enhanced performance, prolonged operational lifespans, and heightened reliability across diverse operating conditions.

NOMENCLATURE

VG	Viscosity Grade	
PAO	PolyAlphaOlefin	
AB	AlkylBenzene	
TGA	Thermogravimetric Analysis	
DTG	Thermogravimetric Analysis	
DSC	Differential Scanning Calorimetry	
COP	Coefficient of Performance	
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers	
cst	Kinematic Viscosity	(mm2/s)

REFERENCES

Abdelkhalik, A., Elsayed, H., Hassan, M., Nour, M., Shehata, A., & Helmy, M. (2018). Using thermal analysis techniques for identifying the flash point temperatures of some lubricant and base oils. *Egyptian Journal of Petroleum*, *27*(1), 131-136. doi: https://doi.org/10.1016/j.ejpe.2017.02.006

Gamlin, C., Dutta, N. R., CHOUDHURY, N. R., Kehoe, D., & Matisons, J. (2002, sep). Evaluation of kinetic parameters of thermal and oxidative decomposition of base oils by conventional, isothermal and modulated tga, and pressure dsc. *Thermochimica Acta*, *392-393*, 357–369. doi: 10.1016/S0040-6031(02)00121-1

Gyimah, G. K., Guo, Z. N., Huang, P., Jiang, S., Barber, G. C., Liu, G., & Liu, J. (2016). Improvers of pressure-viscosity coefficients of two-phase liquid-solid lubricants. *DEStech Transactions on Engineering and Technology Research*.

J. C. O. Santos, I. M. G. S., & Souza, A. G. (2017). Thermal degradation of synthetic lubricating oils: Part iii – tg and dsc studies. *Petroleum Science and Technology*, *35*(6), 540–546. doi: 10.1080/10916466.2016.1269127

Kotzakoulakis, K., & George, S. C. (2017). A simple and flexible correlation for predicting the viscosity of crude oils. *Journal of Petroleum Science and Engineering*, *158*, 416-423. doi: https://doi.org/10.1016/j.petrol.2017.08.058

Mangas, I., Sogorb, M., & Vilanova, E. (2014). Lubricating oils. In P. Wexler (Ed.), *Encyclopedia of toxicology (third edition)* (Third Edition ed., p. 670-676). Oxford: Academic Press. doi: https://doi.org/10.1016/B978-0-12-386454-3.00525-X

Perez, R. X. (2019). The importance of lubrication. In *Operator's guide to process compressors* (p. 201-212). John Wiley Sons, Ltd. doi: https://doi.org/10.1002/9781119581383.ch17

Sanukrishna, S., & Jose, V. M. (2022). Evaluation of thermal and rheological characteristics of cnt-pag nanolubricant for the development of energy efficient refrigeration systems. *Materials Today: Proceedings*, *58*, 114–120.

Smook, L. A., K. R., S. C., & Lugt, P. M. (2022). Evaluating the oxidation properties of lubricants via non-isothermal thermogravimetric analysis: Estimating induction times and oxidation stability. *Tribology International*, *171*, 107569. doi: https://doi.org/10.1016/j.triboint.2022.107569

Sánchez-Rubio, M., Chinas-Castillo, F., Ruiz-Aquino, F., & Lara-Romero, J. (2006). A new focus on the walther equation for lubricant viscosity determination. *Lubrication Science*, *18*(2), 95-108. doi: https://doi.org/10.1002/ls.9

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