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A Review on Nanolubricant for Refrigeration Systems: Stability, Thermophysical Properties, and Performance Characteristics

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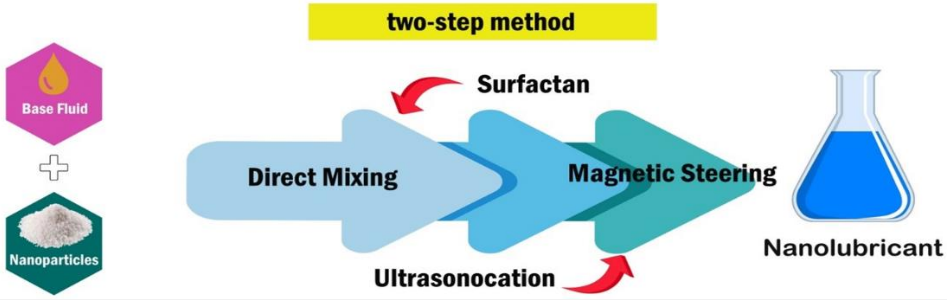

Highlights:

- This study provides a comprehensive overview of the methods used by researchers to synthesize nanolubricants and their stability.
- The review highlights how the incorporation of nanoparticles improves thermophysical properties such as thermal conductivity, density, and dynamic viscosity, which are critical for effective heat transfer.
- This review highlights the performance characteristics of the addition of nanoparticles to lubricants used in refrigeration systems.

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Abstract

Many researchers have introduced nanolubricants in the field of refrigeration systems to improve performance. Nevertheless, academic literature lacks comprehensive explanations of the impact of nanoparticles on the physical phenomena that influence the refrigeration system. Several factors such as stability, agglomeration, and distribution can significantly affect the sustainability of performance. Hence, this work provides an analysis of the methods using nanolubricants to improve the performance of refrigeration systems. This study provides a comprehensive analysis of the performance parameters of the refrigeration system, including compressor work and coefficient of performance (COP), when utilizing nanolubricants. The study findings suggest that including nanolubricants in the refrigeration system can enhance the heat transfer coefficient. Hence, nanolubricants are identified as the most promising contenders for enhancing the efficiency of the refrigeration system.

Keywords: Nanolubricant; Refrigeration system; Stability; Thermophysical properties, Performance

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1. Introduction

The refrigeration sector has been identified as the most energy-intensive among various thermal system sectors, consuming around 17.6% of global electricity consumption, as in **Figure 1**

[1]. Most refrigeration and HVAC (heating, ventilation, and air conditioning) applications use vapor compression refrigeration systems [2]-[5]. Extensive research has been carried out to enhance the performance and efficiency of thermal systems, mostly driven by the constraints enforced by limited energy resources. An approach to achieve this goal is to alter the composition of the working fluid [6]. Thermo-physical characteristics can be enhanced in nanofluids by incorporating suspended solid particles with enhanced thermal conductivity into conventional fluids [7]. The most common particles dispersed in liquids are materials in the form of particles measuring 1-100 nanometers, also called nanoparticles [8]. In comparison to conventional fluid, the stochastic motion of nanoparticles inside the nanofluid leads to heightened levels of fluid turbulence, diminished thermal resistance, and the attainment of superior thermal efficiency [9].

The utilization of nanoparticles has been extensively employed in refrigerants and lubricants to improve the operational effectiveness of cooling mechanisms [10],[11]. The inclusion of nanoparticles in the refrigerant has been found to enhance its thermal properties, as demonstrated by previous studies [12]-[14]. Consequently, there is an enhancement in the effectiveness of the heat transfer process of many essential systems due to an augmented heat transfer [15], [16]. Nanolubricants demonstrate significant potential in improving energy efficiency in diverse applications. It has been shown that using SiO_2/PAG nanolubricants in car air conditioning systems lowers the workload on the compressor by 16.5%, cuts power use by 4% and raises the coefficient of performance by 21% [17].

The integration of nanoparticles to the cooling system is facilitated by two distinct approaches. One approach involves the creation of a nanoparticle-lubricant composite through the introduction of nanoparticles into the lubricant fluid. The combination is commonly referred to as nanolubricant. Subsequently, the nanolubricant is introduced into the compressor to serve as a lubricating agent. The second approach involves the direct integration of conventional refrigerants and nanoparticles into the system. The term used to refer to these substances is nanorefrigerants. One of the important steps to improve the thermal performance of nanofluids to obtain nanofluids with good stability is the preparation of stable nanofluids [18]. When nanoparticles are not uniformly dispersed throughout the host fluids, the systems fail to fully exploit the advantageous features of the nanoparticles. Typically, nanofluids exhibit instability as they consist of two phases, mostly due to the presence of cohesion forces between particles on the nano scale and Van der Waals contact forces [7]. Heat transfer improvement in nanofluids depends on the dispersion stability of the nanoparticles in the fluid, which is determined by their thermophysical characteristics [19]. Furthermore, the utilization of nanolubricants has been found to enhance lubrication and decrease wear, hence offering notable benefits to compressors [20]. For instance, Bobbo et al. [21] investigated the effects of nanoparticle/POE (polyolester) mixtures on the friction and solubility characteristics of the refrigerant R134a. The study demonstrated that TiO_2/SW32 oil mixtures exhibited the best tribological performance compared to other mixes. Similarly, the application of SiO2/PAG (polyalkylene glycol) nanolubricant in compressors was found to significantly improve performance, with increases in heat absorption capacity and COP of up to 24% [22]. These findings highlight the critical role of nanolubricants in enhancing both thermal and tribological properties, underscoring their potential to optimize refrigeration system performance.

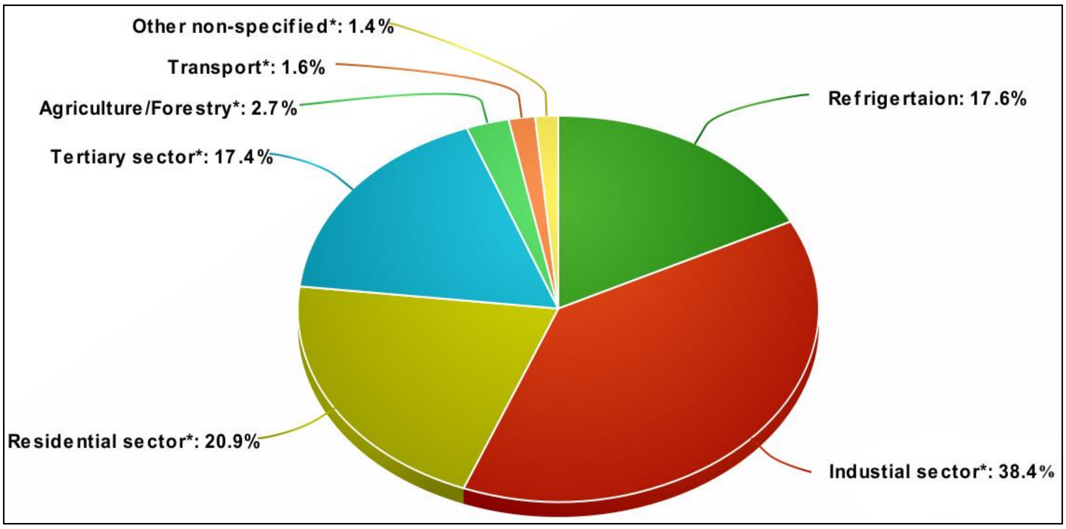

Figure 1. Global refrigeration sector's electricity consumption [1]

Many articles have written in-depth about how nanolubricants can be used in cooling systems, and many scientific articles have talked about how nanolubricants could greatly improve the performance of many different systems [23]. However, most of these reviews only talk about single aspects, like thermal conductivity or stability, without looking at how they affect system performance. This article offers a comprehensive analysis of the relationship among stability, thermophysical parameters, and performance characteristics in refrigeration systems. This research distinctly emphasizes the practical ramifications of nanolubricants in real-world working settings, encompassing their long-term stability, environmental sustainability, and compatibility with upcoming technologies such as renewable energy-powered HVAC systems. This study identifies existing constraints and suggests specific future research options, so addressing significant gaps in the literature and offering practical insights to enhance both academic research and industrial applications.

2. Preparation of Nanolubricant

One of the most essential steps in each experimental research is the development of the nanolubricant. The process for developing nanolubricant involves more than simply mixing nanoparticles with liquids. The preparation of nanolubricant involves a series of physical and chemical steps to provide a mostly uniform composition, therefore mitigating the occurrence of agglomeration. The synthesis of nanofluids is a critical phase, significantly influencing both their thermophysical characteristics and stability [24]. The key requirement for the proper application of nanofluid is that of a successful dispersion. Therefore, surfactants are occasionally employed to improve the stability of nanolubricant [25]. There are two ways to prepare nanolubricant: two-step and single-step methods.

2.1. Two-step Method

This method is the most popular approach to producing nanolubricants. This method is considered the most economical and efficient method to produce nanolubricants on a large scale [25]. However, producing nanolubricant using this two-step approach can result in a high increase in agglomeration levels, thereby reducing its stability compared to the one-step method [26]. The synthesis of the nanomaterials (nanoparticles, nanocomposites, nanotubes, and nanofibers) that will be utilized is the initial stage in this process. The following stage involves dispersing the particles uniformly throughout the fluid using a variety of techniques, including high shear mixing [27], homogenization [28] ultrasonication [29], magnetic stirring, and simple mixing. Maintaining the homogeneous distribution of the nanoparticles in the base fluid over an extended duration is the aim of this technique [30]. Notwithstanding, the proclivity of nanoparticles to form aggregates because of their elevated surface activity and surface area necessitates the process of dispersion [31]. Consequently, the sonication technique employing high-power pulses can enhance particle dispersion in nanolubricant manufacturing. The sonication process is seen in **Figure 2**. In addition, surfactants have been employed to augment the stability of nanoparticles in fluids under such circumstances [32]. **Error! Reference source not found.** illustrates the nanolubricant synthesis process using a two-step preparation method.

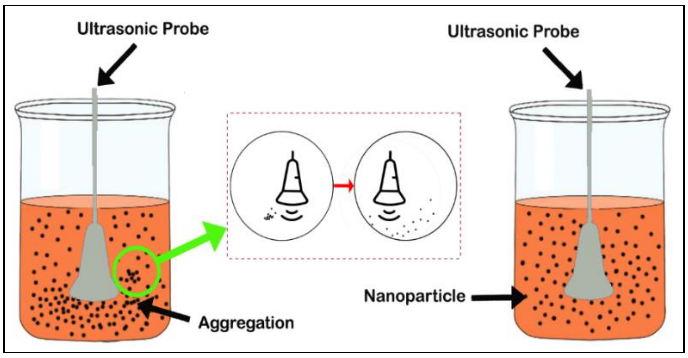

Figure 2. Ultrasonication mechanism process on nanolubricant

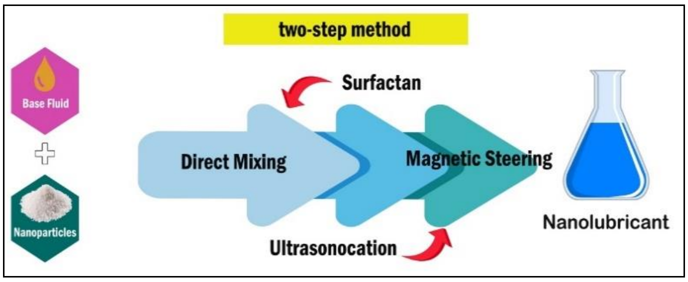

Figure 3. Two-step preparation of nanolubricant

2.2. One-Step methods

This one/single step nanolubricant manufacturing approach integrates the nanoparticle preparation and nanolubricant synthesis processes into one streamlined method [33]. The process of making these nanoparticles is directly done using liquid chemical methods [34] or physical vapour deposition (PVD) techniques. The advantages of this approach include excellent fluid stability and less nanoparticle aggregation, thereby enhancing its productivity. This is because in the process of nanoparticle dispersion, drying, storage, and transportation can be avoided. However, the weakness of this method is that it has limitations, namely that only compatible low-vapour-pressure liquids can be processed. According to Chakraborty and Panigrahi [35], in a single step, particles of a particular size are produced and dispersed simultaneously into base fluids, usually leading to less agglomeration. The dispersion stability of the single-step method was found to be improved in comparison to the two-step method [36]. However, nanolubricant preparation using a one-step method has risks for automotive applications. This is due to the potential disruption of the system's operation within the automobile, even with the presence of a minimal amount of contaminants. The potential consequences include a reduction in system efficiency and a decrease in system lifespan [37]. Furthermore, the exorbitant expense of large-scale manufacturing hinders the execution of the process [38]. **Figure 4** shows the preparation of nanolubricant using the single step nanolubricant preparation method.

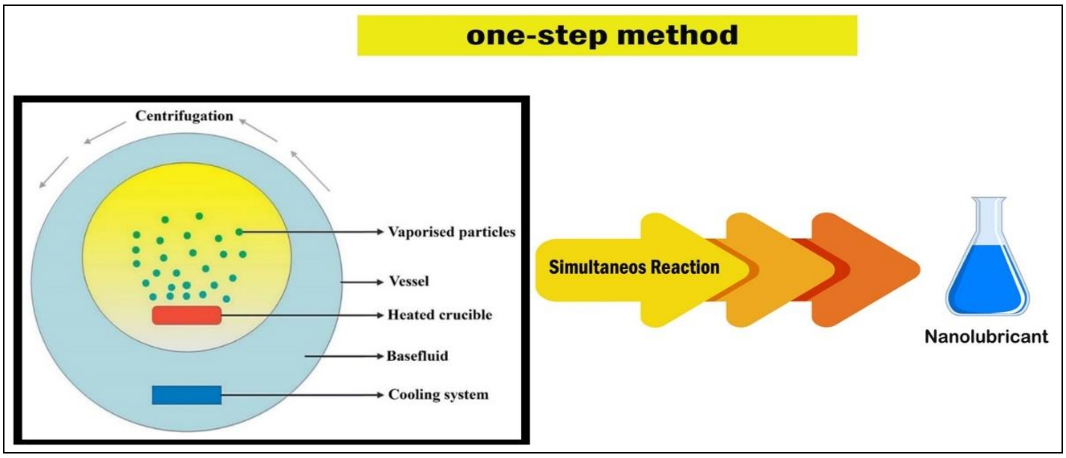

Figure 4. One-step preparation of nanolubricant

2.3. Two-Step Versus One-Step Methods

The two-step process is esteemed for its practicality and cost-effectiveness, particularly in the production of large-scale nanolubricants. This method enables meticulous regulation of nanoparticle characteristics during synthesis and employs techniques like ultrasonication and surfactant incorporation to improve dispersion stability. Nonetheless, it is susceptible to nanoparticle agglomeration throughout the drying, storage, and re-dispersion processes, thereby undermining the stability of the final nanolubricant product. The single-step process combines nanoparticle synthesis and dispersion into one operation, thereby minimizing the danger of agglomeration and enhancing stability. This is especially beneficial in applications necessitating high-performance nanolubricants with little nanoparticle aggregation. Research by Chakraborty and Panigrahi indicates that single-step approaches attain enhanced dispersion stability relative to the two-step method, owing to the concurrent synthesis and dispersion processes.

From a cost perspective, the two-step process is more cost-effective at big volumes, as it employs readily accessible equipment and techniques. Nonetheless, the single-step process, despite its enhanced performance attributes, entails elevated costs owing to the sophisticated procedures and apparatus necessary, such chemical vapor deposition or liquid-phase synthesis. The expenses increase significantly when scaling up for industrial manufacturing, as maintaining exact synthesis conditions becomes difficult.

The two-step approach exhibits superior scalability for mass production, although the extra dispersion phases are involved. The single-step approach, while more efficient, encounters constraints in high-volume production, especially due to the requirement for compatible low-vapor-pressure liquids and the intricacies involved in scaling advanced synthesis methods. Furthermore, the sensitivity of the single-step approach to pollutants presents further obstacles for its implementation in automotive and industrial sectors. In summary, the two-step method is more appropriate for economical large-scale production, but the single-step method is superior in applications demanding high stability and performance, despite its elevated costs and scalability issues. A hybrid technique that utilizes the advantages of both methods may offer an optimal solution for industrial needs.

3. Stability of Nanolubricant

The phenomenon characterized by the absence of substantial particle aggregation is referred to as stability [39]. A significant presence of nanoparticles leads to a reduction in the thermal conductivity of the nanolubricant and an increase in its viscosity [40]. The nonuniform diffusion and agglomeration of nanoparticles within the fluid medium also can result in a subsequent decline in the performance of heat transmission and flow obstruction in nanolubricants [41]. The assessment of nanolubricant stability commonly relies on the phenomenon of nanoparticle aggregation, which is influenced by both the thermodynamic properties and the overall interparticle interactions [42]. The phenomenon of Brownian motion gives rise to the collision of nanoparticles, resulting in the formation of secondary particles. The interaction between these secondary particles results in the formation of substantial conglomerates. Once the aggregation of particles reaches a specific threshold, sedimentation takes place, leading to the destabilization of the suspension of nanolubricant [43]. Various preparation techniques provide nanolubricant exhibiting distinct stabilities, as depicted in **Figure 5**. The presence of nanoparticles in nanolubricants reduces their stability; this is due to aggregation caused by contact and their high surface activity.

In general, the stability of nanofluid dispersions tends to be compromised by larger particle sizes and higher particle densities. A number of factors affect the stability of nanofluids, including: material type [44], nanoparticle size [45], shape [46], nanofluid temperature [45], and concentration of nanoparticles [47]. Collisions between nanoparticles and the volume fraction of the nanolubricant result in significant agglomeration and reduce the stability of the nanolubricant [47]. There are several approaches to enhance the stability of nanolubricant, including chemical and physical methods [48]. The reduction of nanoparticle size in physical approaches primarily involves the utilization of ultrasonic oscillations and nanofluid agitation [49]. The chemical approach method requires the use of surfactants and manipulation of different pH levels in the liquid to modify the surface characteristics of the nanoparticles [50].

Table 1 presents an overview of the stability methods employed for various nanolubricant in refrigeration system, together with the corresponding accomplishments in terms of stability. According to Salem [51], the carbon-based nanoparticles, including graphene, diamond, and MWCNT, have a maximum stability duration of 60 days, as per the available knowledge. In this study, the researcher employed multi-walled carbon nanotube (MWCNT) nanoparticles in conjunction with POE as the fundamental lubricating fluid. The experimental procedure involved a two-step approach, which was subjected to ultrasonic vibration for a duration of six hours. Nanolubricants with multi-walled particles have a longer stability duration than nanolubricants with spherical nanoparticles, especially oxide materials such as Al_2O_3, TiO_2, SiO_2, and CuO. The diameter of the lubricant nanoparticles has an influence on their initial stability, and nanolubricants with large particle diameters show poorer stability. Compared with other research, Joshi et al. [52] using Al_2O_3 particles with an average particle diameter of 35 mm resulted in a nanolubricant stability duration of only 2 days. Research by Feng et al. [53] indicated that hybrid nanorefrigerants, such as Al_2O_3/TiO_2-R123 and ZnO/TiO_2-R123, had enhanced stability relative to mono nanorefrigerants, with no absorbance reduction over a 24-hour period. Moreover, it was disclosed that pH levels influenced stability and viscosity.

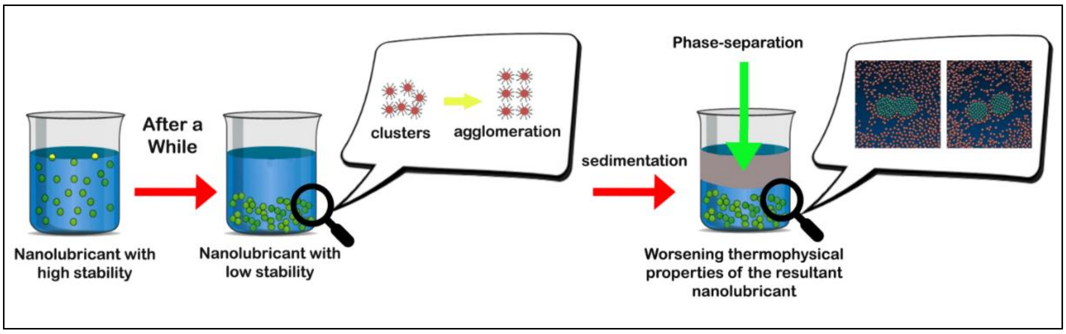

Figure 5. Schematic diagram of aggregation mechanism of nanoparticles

Table 1. Research on stabilization methods in nanolubricant

Refs.	Nanoparticles	Dimension	Base fluid	Method	Stability Duration (days)
[52]	Al_2O_3 (0.02 - 0.1 wt%)	diameter 35 nm	POE, MO	two-step methods: vibrated using probe ultra sonicator	2
[51]	MWCNT (0 ≤ ϕ ≤ 0.5 wt%)	outer Ø: 50-80 nm inner Ø: 5-10 nm length: 10-20 µm	POE	two-step methods: vibrated ultrasonically for 6 h, 36 hours in 4 consecutive days at 85°C	60
[53]	Al_2O_3/TiO_2 (0.1, 0.08, 0.06, 0.04, and 0.02 wt%.)	diameter 15 nm/ 23 nm	-	the two-step method with magnetic stirring and ultrasonic vibration is applied in this study.	1
[54]	Al_2O_3 (0.05 - 1.0 wt%)	diameter 13 nm	PAG	two-step methods: 2h magnetic stirrer, ultrasonic homogenization 1h	30
[55]	Al_2O_3-SiO_2 (0.02 - 0.1 wt%)	diameter 13 nm and 30 nm	PAG	two-step methods: ultrasonic bath, sonication time (0-2h)	30
[56]	TiO_2 (0.1 to 0.3 vol%)	diameter 15 nm	POE	two-step methods: ultrasonic homogenization and magnetic stirrer for 2 h	30
[57]	SiO_2 (0.01 - 0.20 wt%)	diameter 5-20 nm	POE	two-step methods: magnetic stirring for 1 hour and sonication for 12 hours	22
[58]	FAl_2O_3 (0 to 0.2 vol%)	diameter 43.11 nm	POE	two-step methods: The sample was subjected to magnetic stirring for a duration of 30 minutes, followed by an ultrasonication treatment for a period of 100 minutes.	30
[59]	Diamond (0.1wt% and 0.5 wt%)	diameter 10 nm	POE	two-step methods: The ultrasonic vibrator was operated at a power level of 650 Watts for a duration of 30 minutes.	7
[60]	Graphene (0.07 - 0.6 vol%)	plate thickness: 1-3 nm	PAG	two-step methods: magnetic stirrer for 1 h, ultrasonically 6 h	5
[61]	TiO_2 (0.07 - 0.8 vol%)	diameter 21 nm	PAG	two-step methods: The solution was subjected to magnetic stirring for a duration of one hour, followed by agitation using an ultrasonic agitator for a period of twelve hours.	5
[62]	TiO_2 (0, 0.2, 0.4 and 0. 6 g/L)	diameter 5–15 nm	MO	two-step methods: magnetic stirrer for 2 h, ultrasonic homogenization	30
[62]	CuO	diameter 20–30 nm	MO	two-step methods: ultrasonication 70 min	3

Several factors, such as the duration of sonication, the inherent characteristics of the base fluid, and the specific type of surfactant used can affect the stability of nanolubricants. The impact of ultrasonic oscillation durations on the stability of nanolubricant exhibits variability, and it is crucial to acknowledge that an extended duration of ultrasonic oscillation does not necessarily imply enhanced stability of the nanolubricant [47]. The two-step approach has various advantages over the one-step technique, such as its simplicity, cost-effectiveness, ability to be applied to oxide nanoparticles, and appropriateness for large-scale production. The utilization of the two-step strategy is linked to certain limitations, such as insufficient stability, vulnerability to aggregation, and sedimentation. The conclusion that can be inferred is that in order to produce nanolubricant using two-step procedures, it is necessary to include surfactants or implement surface modification techniques.

Furthermore, the long-term stability and endurance of nanolubricants are mostly unexamined in the majority of research. Although several studies, such Sharif et al. [22], emphasize immediate advantages such as less compressor workload, there is scant discourse on the sustainability of these effects over prolonged durations under diverse operational situations. Long-term stability assessments, including sedimentation analysis over extended periods, are hardly performed, resulting in a deficiency in our comprehension of the actual application of nanolubricants in industrial environments.

4. Thermophysical Properties of Nanolubricant

A deep knowledge of the thermophysical characteristics of nanolubricants is crucial for obtaining a thorough grasp of their heat transfer behavior. The incorporation of nanoparticles into a host liquid medium allows for a substantial enhancement in thermal conductivity, viscosity, specific heat, and density, all of which have a direct effect on convective heat transfer [63]. To evaluate the thermal efficiency of a system, it is crucial to determine essential thermophysical properties such as thermal conductivity, density, and viscosity. These characteristics are of paramount importance in ascertaining the extent of heat transfer. The passive strategy of enhancing heat transfer efficiency by incorporating nanoparticles into a base liquid has been described by Patil et al. [64]. This section provides a thorough and current examination of the thermophysical properties and factors that affect different base fluids and nanoparticles. The critical parameters affecting the thermophysical characteristics of nanolubricants are illustrated in **Figure 6**.

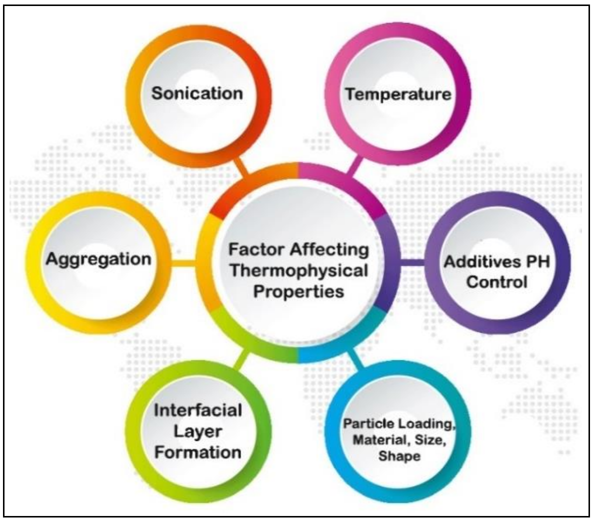

Figure 6. The factors affecting thermophysical properties

4.1. Thermal conductivity

Considerable theoretical and empirical investigations have been undertaken to examine the variability in thermal conductivity of nanolubricant. The thermal conductivity of materials in a fluid greatly influences the value of the heat transfer rate [65], [66]. The phenomenon of Brownian motion has been found to lead to an augmentation in the thermal conductivity of nanolubricant [67]. Brownian motion can trigger the random motion of nanoparticles, which causes the heat to be indirectly dispersed throughout the nanolubricant body [37]. Additionally, it has been observed that an augmentation in the proportion of nanoparticles in the operative medium leads to an elevation in the thermal conductivity of nanolubricant. The expansion of the surface area of nanoparticles also influences the increase in thermal conductivity in nanolubricants. For instance, when nanoparticles exhibiting diverse dimensions are dispersed individually in a liquid with the same mass fraction, it is observed that nanoparticles with smaller grain sizes possess a larger total surface area compared to those when the grain sizes are greater. As a result, the increased contact area between the surface of the nanoparticle and the base fluid results in enhanced thermal conductivity and heat transfer rates in nanoparticles of smaller dimensions. To address this issue, Asadi et al. [68] employed sonication techniques including high-powered pulses to enhance the dispersion of particles during the production of nanolubricants. The findings of their study demonstrated a notable enhancement in thermal conductivity after the sonication process. The authors, Nugroho et al. [69], provided a description of the effect of sonication duration on the stability of Al_2O_3-POE nanolubricants. A two-step procedure was employed in the synthesis of the nanolubricant. Based on the study findings, the researcher concluded that the optimal length of sonication was 80 minutes.

The method performed for the manufacture of nanolubricant is a significant factor that can impact the thermal conductivity measurement of these fluids. The utilization of a preparation procedure that guarantees prolonged stability and uniformity results in nanolubricant that exhibit a propensity to sustain their elevated thermal conductivity levels over extended periods of time. If these issues are not addressed, several challenges may arise, including the presence of inhomogeneity, instability, and sedimentation in the nanolubricant. Consequently, these factors might lead to a decline in the thermal conductivity value.

Numerous study investigations were undertaken to examine the diverse thermal conductivity characteristics exhibited by nanolubricants within the framework of refrigeration systems. Said et al. performed an experiment to systematically examine the thermal characteristics of the MWCNT-R152a nanolubricant. The thermal conductivity of MWCNTs-R134a and CuO-R134a nanolubricants exhibited an increase of 57.06% and 56.52%, respectively. The nanolubricant was acquired in volumetric fractions of 0.5%, 1%, and 2% [70]. The approaches utilized in research on nanolubricants are essential for confirming their effectiveness; yet they sometimes exhibit considerable variability, leading to concerns regarding reproducibility. For instance, Sanukrishna et al., [71] the thermal conductivity of the TiO_2/PAG nanolubricant increased 1.38 times when compared to the thermal conductivity of pure lubricant at volume concentrations between 0.07% and 0.8%. However, their study relied on a two-step synthesis process involving ultrasonic dispersion, which, while effective, introduces variability in nanoparticle distribution due to differences in sonication duration and energy input. Such details are often inconsistently reported across studies, making it challenging to replicate results under identical conditions.

Similarly, Aljuwayhel et al. [72] examined the thermal conductivity of ND/POE nanolubricants, utilizing photo imaging and ultraviolet-visible spectroscopy (UV-Vis) analysis to assess their stability. Photo imaging provided visual evidence of nanoparticle dispersion and sedimentation over time, while UV-Vis spectroscopy quantified absorbance levels to evaluate the degree of aggregation at the nanoscale. These techniques revealed excellent stability of the nanolubricant. The study further highlighted that using 0.1 vol% ND/POE nanolubricant enhances thermal conductivity, contributing to increased lifespan of the AC compressor due to improved heat dissipation. While these techniques are robust for assessing nanoparticle stability, the reproducibility of these findings may be affected by variations in experimental conditions, such as the concentration of nanoparticles and preparation methods. For instance, UV-Vis spectroscopy is highly sensitive to the path length of the cuvette and nanoparticle size, parameters that must be strictly controlled but are sometimes underreported in the literature.

Madyira et al. [73] employed graphene nanoparticles as an addition in POE lubricants to enhance their cooling capability. The outcome is a rise in the thermal conductivity of the nano lubricant, leading to an enhancement in cooling efficiency ranging from 5.2% to 14.2%. The reason for this is that the surface area of graphene nanoparticles is significantly more than that of the basic lubricant. The research examined the cooling properties of the nanolubricants but failed to disclose details of their experimental configuration, including the temperature range and system pressure, which are essential for evaluating the practical relevance of their results. The absence of a standardized technique for such testing complicates cross-comparison among research, as minor discrepancies in experimental configuration might result in significant changes in observed performance.

Research using nanolubricant Al_2O_3/MO with a concentration of 0.1 wt% was carried out by Joshi et al. [74] resulting in an increase in thermal conductivity of 57%. In another study, Joshi et al. [75] investigated to determine the maximum thermal conductivity that could be achieved, namely 51.8%. Experiments were carried out using graphene particle concentrations of 0.09 percent by weight (wt%) in GNP-POE nanolubricant and 40.7% in GNP-MO nanolubricant. The research conducted by Jatinder et al. [76] shown that the inclusion of TiO_2 nanoparticles in nanolubricants had a beneficial effect on thermal conductivity. Specifically, when the concentration of TiO2 nanoparticles was increased from 0.1 to 0.6g/L, there was a significant 23.49% increase in thermal conductivity. **Figure 2** provides a comprehensive summary of the studies conducted on the thermal conductivity of nanorefrigerants and nanolubricants.

The general viewpoint among investigated studies highlights that there is a positive correlation between thermal conductivity and nanoparticle fraction ratio. The viscosity and thermal conductivity of nanolubricants exhibit a positive correlation with the volume fraction, meaning that as the volume fraction increases, both the viscosity and thermal conductivity rise. Moreover, they exhibit an inverse relationship with temperature, suggesting that as the temperature rises, both thermal conductivity and viscosity decline. The investigation undertaken by Sanukrishna and colleagues [71] demonstrated that the enhancement in thermal conductivity of the TiO_2/PAG nanolubricant was found exhibited an increase of 1.38 times when compared to the thermal conductivity of pure lubricant at volume concentrations between 0.07% and 0.8%. The thermal conductivity of TiO_2-PAG nanolubricant at different concentration ratios is depicted in

Figure 7. Nevertheless, regrettably, the act of increasing the concentration ratio will result in an elevated likelihood of blockage occurring within the microchannels, as well as an increase in viscosity. Undesirable conditions are commonly observed in various fluid systems, including expansion valves and capillary tube, among others. Consequently, it is of utmost significance to determine the ideal concentration ratio of nanoparticles in order to optimize both heat conductivity and viscosity. Conversely, existing literature indicates that a positive link has been seen between temperature and thermal conductivity. This relationship can be attributed to the heightened particle velocity resulting from Brownian motion.

Table 2. Summary of increases in thermal conductivity related to nanolubricants

Ref.	Nanolubricants	Fraction	Nanoparticle size (mm)	Remarks
[70]	MWCNT, CuO/R134a, R152a/POE	0.5, 1, and 2% (% vol.)	MWCNT: 50 CuO: 15	The thermal conductivity of MWCNTs-R134a and CuO-R134a nanolubricants with a concentration of 2 vol% was observed to be 57.06% and 56.52% higher, respectively, than R134a. The highest growth rates were observed for R152a-MWCNTs and R152a-CuO nanolubricants at 57.12% and 56.47%, respectively.
[61]	TiO_2-PAG-HFCs	0.07 to 0.8% (% vol.)	21	The thermal conductivity of nanolubricant with volume fraction of 0.8% and 0.6% respectively showed an increase of 1.38 times when compared to the thermal conductivity of pure lubricant.
[72]	ND/POE	0.05 to 0.5% vol.	10-20	With higher concentration of ND particles, the thermal conductivity increased by an average deviation of 7%. Conversely, it decreased as the preparation temperature increased.
[73]	Graphene/R600a/ POE	0.2-0.6 (g/L)	Thickness: 6–10	The outcome entails a rise in thermal conductivity, leading to an augmentation in cooling capacity ranging from 5.2% to 14.2%.
[74]	Al_2O_3/R600a/ POE, MO	0.02, 0.04, 0.07 wt%	30–50	The addition of Al_2O_3 nanoparticles at a concentration of 0.1 wt% into mineral oil resulted in a significant increase in thermal conductivity, with an observed increase of about 57%. This increase in thermal conductivity was accompanied by a slight increase in viscosity.
[75]	Graphene/POE, MO	0.03, 0.06, and 0.09 wt%	-	The highest thermal conductivity was achieved at 51.8% at 0.09% specific gravity of GNP-POE nano lubricant and 40.7% for GNP-MO nano lubricant.
[76]	TiO_2/R600, LPG/MO	0, 0.2, 0.4 and 0.6 g/L	5–15	The addition of TiO_2 nanoparticles in nano-lubricants was shown to have an impact on thermal conductivity, which can result in an increase of about 23.49% when the concentration is increased from 0.1-0.6 g/L.
[77]	Al_2O_3/R141b	1-4 (vol. %)	10-35	The 4% fraction had a 28.88% rise in thermal conductivity.

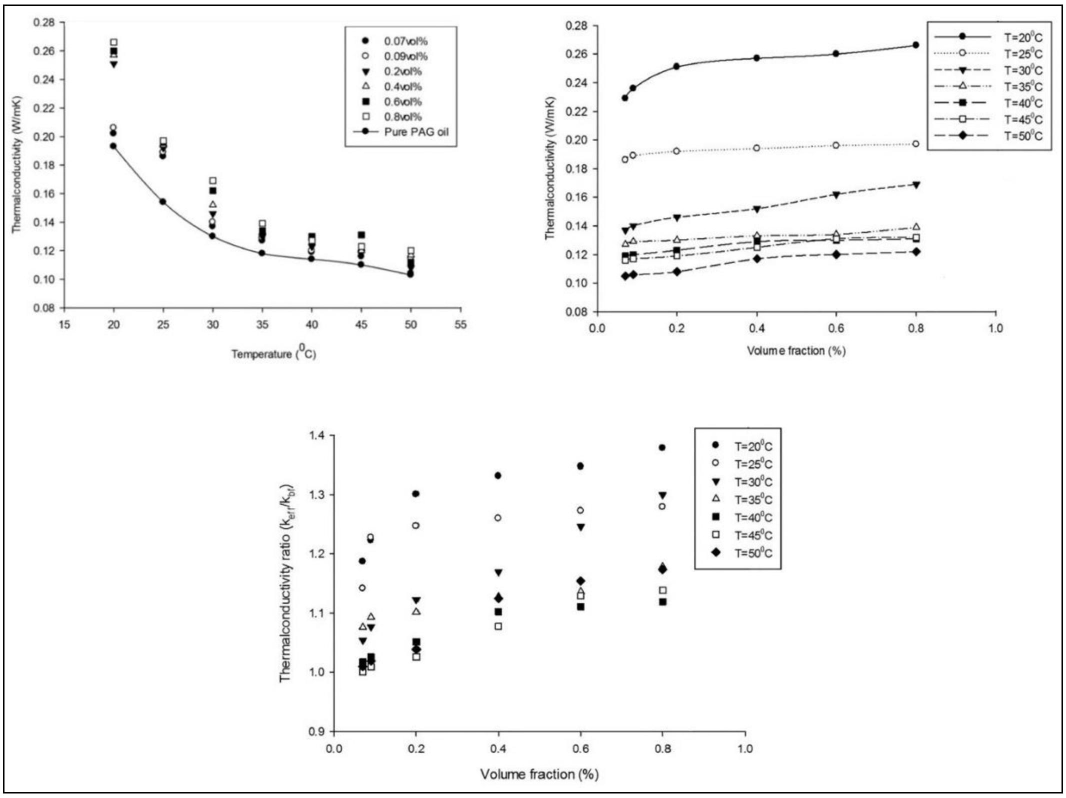

Figure 7. Thermal conductivity of nanolubricant at various volume fractions and temperature [71]

Prior to commencing an experiment, researchers must conscientiously consider the determination of the concentration ratio to be employed. Several studies in the literature employ mass fractions despite the variation in nanoparticles doped included within the foundational liquid. From the literature that has been listed, many papers use mass fractions even though they dope different nanoparticles into the base fluid [78]. Evaluating the effect of the existence of various categories of nanoparticles on thermal conductivity only based on mass fraction is not considered relevant in this context. This phenomenon arises due to the inherent variation in density across distinct nanoparticles. Nanoparticles that have low density tend to be distributed in large quantities, while nanoparticles that have high density tend to have the same mass fraction. Hence, although possessing an equivalent mass fraction, low-density nanoparticles exhibit a significantly greater surface area coverage. Given the significance attributed to the surface area of nanoparticles; to obtain maximum research results, it is recommended to use volumetric fractions.

4.2. Dynamic Viscosity

The concept of viscosity could be defined as the proportionality between the resistance to deformation caused by shear and lateral stresses inside nanofluids [79]. Meanwhile, dynamic viscosity is an expression of the fluid's ability to resist shear flow [80]. Dynamic viscosity is related to the flow properties of fluids, so it is very important in nanolubricant synthesis and is influenced by parameters such as pumping force, pressure reduction, and convective heat transmission. Typically, the dynamic viscosity of nanolubricant has a significantly greater magnitude compared to that of conventional working fluids, especially when the mass-to-volume ratio of nanoparticles is raised [81]. The suggested study sharing does not provide a guarantee on the dynamic viscosity of nanolubricant due to its reliance on empirical data, which may not yield the required results for alternative nanolubricant [82]. The researchers observed variable dynamic viscosity outcomes even while working with the same nanolubricant. These differences are due to nanoparticle concentration, use of different measurement equipment or geometries, methods, shear ranges, agglomeration, extent of clustering, and materials used for nanolubricant synthesis. According to several researchers, several elements that influence the dynamic viscosity of nanolubricant include the type of base fluid, size, shape, volume, distribution method, working temperature, and type of surfactant [45], [83]. Researchers employ a highly efficient and economically advantageous approach in which solid microparticles or materials with superior thermal conductivity are included in the base fluid. This method aims to enhance the efficacy of heat transfer techniques. Nevertheless, it is imperative to impose restrictions on this practice, as the introduction of nanoparticles in excessive quantities leads to an elevation in the dynamic viscosity of the nanolubricant. The concentration of nanoparticles influences the flowability of nanolubricants. An increased concentration of nanoparticles in base lubricants may lead to sedimentation and potential system blockage [84]. This phenomenon can lead to a reduction in pressure, convective heat transfer, and pumping efficiency within the cooling system.

Several studies related to the dynamic viscosity of refrigeration systems have been conducted. The performance coefficient of VCRS can be increased using graphene nanoparticles, for example, in experiments carried out by Raghavulu and Rasu. The dynamic viscosity value increases as the nanoparticle suspension increases, while the viscosity value gradually decreases as the temperature increases [85]. The viscosity values of TiO_2-PVE nanolubricant were studied by Ismail et al. across various fractions. The experiments were conducted within a temperature range of 40°C to 80°C. The observed temperatures showed a drop of up to 11% in the dynamic viscosity of the 0.01% TiO_2/PVE nanolubricant [86]. The viscosity values of the BN-POE nanolubricant were examined by Harichandran et al. The experiments were conducted within a temperature range of 34°C-70°C. The viscosity of a solution with a volume percent of 0.4 experienced a 14% increase [87]. Zawawi et al. conducted a work wherein they created a nanolubricant by amalgamating Al_2O_3 and SiO2 nanoparticles with PAG oil. The researchers then proceeded to examine the viscosity measurements at various fraction levels. The experiments were conducted within a temperature range of 30°C to 80°C. The viscosity value exhibited a 9.71% rise when subjected to a 0.1% fraction at a temperature of 60°C [88]. **Table 3** presents a concise overview of the research conducted on the alterations in viscosity observed in nanofluids.

The outcomes of the conducted searches are presented in **Table 3**. An increase in nanolubricant viscosity occurs when the nanoparticle doping level increases. The observed rise in viscosity of nanoparticles can be ascribed to the significant disparity between the surface area of nanoparticles and the quantity of the nanolubricant. The heightened viscosity and friction can be ascribed to the expanded surface area of the nanoparticles. According to basic reasoning, the viscosity of nanolubricant exhibits a positive correlation with the fraction ratio of nanoparticles. Furthermore, it is evident that an increase in temperature is accompanied by a concomitant decrease in entropy. This phenomenon can be ascribed to the acquisition of a higher quantity of thermal energy by the particles present in the fluid. It is widely recognized that high viscosity is unfavorable in numerous systems. It is crucial to consider the augmentation of nanoparticle viscosity will result in a reduction and convergence towards the viscosity of the base fluid as the temperature increases. Therefore, the negligible increase in viscosity caused by the inclusion of nanoparticles has minimal impact on these specific systems.

Table 3. Summary of increases in thermal conductivity related to nanolubricants

Ref.	Nanolubricant	Nanoparticle size	Fraction	Temp.	Remarks
[85]	Graphene-POE	Thickness (nm): 5-10 Length (Micron): 5-10	0.025–0.15 wt%	40°C To 80°C	The viscosity value increases with the nanoparticle suspension, while the viscosity value gradually decreases with increasing temperature.
[86]	TiO_2-PVE	diameter 46.66 nm	0.01, 0.05, 0.1 wt%	40°C, 60°C, and 80°C	Up to 11% reduction in dynamic viscosity was seen for all measured temperatures in the 0.01% TiO_2/PVE nanolubricant. The most significant decrease was in nanolubricant with a concentration of 0.01% at 40°C.
[87]	BN-POE	diameter 70 nm	0.1 to 0.4 wt%	34°C-70°C	Analysis of the kinematic viscosity of a nanolubricant oil with a volume percentage of 0.4 is found to be around 14 percent higher compared to that of a standard polyolester (POE) oil.
[89]	MWCNTs-Compressor Oil	diameter 10-30 nm	0.01, 0.02, 0.04, 0.06, 0.08, and 0.1 wt%	15°C - 50°C, with increments of 5°C.	There is an increase in viscosity ranging from 40% to 90% when the temperature is increased to 50°C and the mass concentration is at 0.1%.

Ref.	Nanolubricant	Nanoparticle size	Fraction	Temp.	Remarks
[90]	ND-POE32	diameter 10-20 nm	0.05, 0.10, 0.25, and 0.50 % (vol.%)	10°C-100°C	At a concentration of 0.5 volume percent a significant increase in viscosity was detected. Specifically, the maximum increase was found to be 498% at 100°C for viscosity.
[91]	Carbon Nano Tube (CNT)-PAG	-	0.03–0.2 vol.%	20 °C-90 °C	Nanolubricants show sufficient relative viscosity at high temperatures, and as the shear rate increases, there is a decrease in the relative viscosity.
[92]	Al_2O_3-SiO_2/DEC PAG	average diameter Al_2O_3 ±13 nm and SiO_2 ±30 nm	0.01 vol.% and 0.05 vol.%	0 °C - 100 °C	The dynamic viscosity value of SiO_2/DEC PAG nanolubricant showed the smallest increase, with a value of 1.88%. Meanwhile, the hybrid nanolubricant Al_2O_3-SiO_2/DEC PAG and Al_2O_3/DEC PAG increased by 2.74% and 3.56%, respectively.
[93]	Al_2O_3-SiO_2/PAG	average diameter Al_2O_3 ±13 nm and SiO_2 ±30 nm	0.02 to 0.1 vol%	303°K to 353°K	A maximum increase in dynamic viscosity of 9.71% is achieved when the volume concentration is 0.1% and the temperature is 333°K.

4.3. Density

Density is a fundamental characteristic that exerts influence on pumping power, Reynolds number, stability, frictional forces, and various other aspects. The heat transfer performance of the refrigeration system is significantly affected by the density of nanolubricant [6]. The density of nanofluids is determined by the combined densities of the nanoparticles and the base fluid. These densities can be determined using various density meters that are now available [94]. In a broad context, the incorporation of nanoparticles into the underlying liquid results in a drop in specific heat and an increase in density. Numerous research investigations are currently centered on examining the density fluctuations shown by nanolubricants and nanorefrigerants. The following are several studies on the density of nanofluids that have added nanoparticles. For example, the study conducted by Ho et al. examined variations in the density measurements of the TiO_2-POE nanolubricant across various fractions. The experiment yielded a result, the volume of the mixture exhibits a rise, but the density demonstrates a linear drop as the temperature is increased [94]. The study conducted by Rio et al. yielded findings indicating that, when subjected to consistent concentration levels, the substance's density exhibited a drop as temperature increased, with an estimated reduction of 6.7%. Additionally, it was noted that the dispersion density demonstrated a proportional increase of 0.29% with increasing nanoparticle concentration, especially at the 0.50% concentration level [95]. Nasser et al. investigated h-BN/Ils/PAO32 nanolubricant regarding variations in density values within the 1% weight fraction. The density value exhibited a 7% increase in comparison to that of pure PAO32 [96]. In their study, Walvekar et al. successfully synthesized a nanolubricant by incorporating multi-walled carbon nanotube (MWCNT) nanoparticles into polyethylene glycol (PEG) oil. The researchers then proceeded to investigate the alterations in the density of the resulting nanolubricant. The inclusion of MWCNT led to an increase in the resulting dynamic viscosity of the nanolubricant, although the density showed negligible alterations [97]. In their research, Alawi et al. [98] investigated the variations in density of Al_2O_3-141b nanorefrigerant across various temperature conditions. The density experienced an increase of 11.54% within a 4% fraction at a temperature of 35°C. **Table 4** provides a concise overview of the research conducted regarding the topic of nanolubricants. This discussion will focus on their density.

Table 4. Density studies on nanolubricant

Ref.	Nanolubricants	Nanoparticle size (mm)	Fraction	Remarks
[94]	POE/TiO_2-R134a	diameter 15 nm	0.1, 0.2 and 0.3 vol%	The volume of the mixture exhibits a rise, but the density demonstrates a linear drop as the temperature is increased. The R134a and nanolubricant (POE/TiO_2) mixture exhibits its highest density when the TiO_2 concentration is 0.3%. Specifically, the density values on the suction and discharge sides are measured to be 1660 kg m^3 and 1370 kg m^3, respectively.
[95]	GnP-TMPTO	diameter:15 µm thickness:1–15 nm	0.05, 0.10, 0.25 and 0.50 wt%	Density increased with the addition of GnP. Under conditions of constant concentration, it is observed that the density of a substance exhibits a reduction of around 6.7% with a rise in temperature. Furthermore, it has been shown that the density of the dispersion exhibits a proportional rise of 0.29% as the concentration of nanoparticles within the dispersion reaches 0.50%.
[96]	h-BN/Ils/PAO32	diameter 70 nm	1 wt%	The increase in base oil viscosity reached a peak value of 7.0% due to the addition of hexagonal boron nitride nanoparticles (h-BN) and/or ionic liquids (IL). The combination of nanodispersion PAO32, IL2, and h-BN results in significant enhancements in both properties.
[97]	MWCNT-PEG	diameter 10-20 nm	0.01, 0.05 and 0.10 wt%	The incorporation of FMWCNT resulted in a notable augmentation of the dynamic viscosity of the nanolubricant, while the density exhibited minimal changes.
[87]	h-BN/R134a/POE	diameter 70 nm	0.1 to 0.4 vol%.	The density demonstrates a progressive increase as the volume fraction of nanoparticles increases.
[98]	Al_2O_3-R141b	diameter 15 nm	1-4 (vol. %)	The density of a fraction with a concentration of 4% had an increase of 11.54% when exposed to a temperature of 35°C.

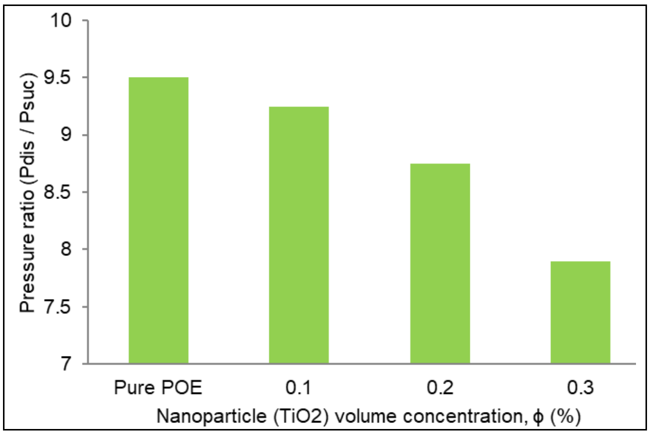

Figure 8. Pressure ratio in compressors with various concentrations [56]

Most existing studies show that the incorporation of nanoparticles into nanolubricants leads to an increase in density. However, it is observed that this enhancement decreases with rising temperatures. There exists a strong correlation between pressure drop and coolant pumping power. Several factors can affect the pressure drop of a coolant, including density and viscosity. The use of nanoparticles in lubricants at the nanoscale level has the potential to decrease the pumping force exerted by compressors in refrigeration systems. However, it should be noted that there exists an inverse relationship between density and thermal conductivity, as stated in reference [99]. Hence, the incorporation of nanoparticles into the base fluid results in a decrease in pressure on both the suction side and the discharge side. The data depicted in **Figure 8** illustrates the impact of varying concentrations of TiO_2 nanoparticles in the lubricant on the pressure ratio (Pdis/Psuc).

5. Performance Characteristics of Nanolubricant in Refrigeration System

The utilization of nanolubricants has been acknowledged as a promising strategy for enhancing the efficiency of cooling systems. This phenomenon can be attributed to its capacity to enhance the thermal conductivity and overall efficiency of the cooling mechanism. The incorporation of nanolubricant as a viable substitute for traditional lubricant in cooling systems holds the potential to offer a multitude of benefits. The possibility for enhanced thermal conductivity and increased heat transfer qualities holds considerable implications for the overall performance of a system [100]. Furthermore, the application of nanolubricants demonstrates improved tribological characteristics, hence providing additional benefits to the compressor. Within the context of the vapor compression system, a substantial proportion of the lubricant is predominantly situated within the compressor, whereas a little fraction is mixed with the refrigerant to produce the refrigerant-lubricant mixture. According to the claims put forth by the maker of HVAC products, it is suggested that around 50% of the lubricant is assigned to the compressor, while the remaining proportions are divided among the evaporator (20%), drier (10%), hoses (10%), and condenser (10%) [101]. The performance and efficiency of a vapor compression system are determined by key thermodynamic factors, namely compressor work, COP, and cooling capacity. This discussion explains the several aspects that lead to the augmentation of the overall efficacy of VCRS by employing nanolubricants.

Several investigations have demonstrated that the addition of nanoparticles to lubricant or lubricant-refrigerant mixtures can enhance the performance of refrigeration systems [8],[65],[102]. Extensive investigations have been conducted on the fundamental aspects of vapor compression systems employing nanolubricants [103]. The usefulness of SiO_2/PAG nanolubricants in VCRS was conducted by Sharif et al. [22] through experimental research. The findings of their study demonstrated that nanolubricants exhibit superior COP when compared to base lubricants. The COP of the system exhibited a 10.5% increase, as observed at a fraction of 0.05% SiO_2/PAG nanolubricant volume fraction. Furthermore, the study conducted by Pico et al. [104] investigated the impacts of utilizing POE-diamond nanolubricant on VCRS. The researchers noticed a notable enhancement in the COP when employing the nanolubricant. The POE-diamond nanolubricant demonstrated a peak enhancement in cooling capacity of around 7% when utilized at a concentration of 0.5 mass%. Furthermore, the performance coefficient exhibits a notable augmentation of around 8% when the diamond mass concentration reaches 0.5%. However, the utilization of diamond nanolubricant does not yield a substantial impact on the power consumption of the compressor. The energy-saving properties of nanolubricants are thoroughly established. Al_2O_3/PAG nanolubricants can decrease car air conditioning power usage by as much as 23.89% when utilized at appropriate concentrations [105]. This decrease is ascribed to the improved thermal and tribological characteristics of the nanolubricant. In a research investigation carried out by Zawawi et al. [106], an examination was carried out using an Al_2O_3/SiO_2-PAG nano hybrid lubricant. The findings indicated that the coefficient of performance (COP) saw a significant rise of 28.10% when the volume concentration of the lubricant was set at 0.015%. A decrease in compressor work and power consumption is seen, with reductions of 25.26% and 19.70% respectively.

In addition to their application in vehicle air conditioning systems, nanolubricants have also found utility in the realm of AC home. The examination of several study findings indicates that the incorporation of nanoparticles into the cooling working fluid leads to a notable enhancement in both COP and cooling capacity. The research investigation undertaken by Nugroho et al. [58] involved experimental investigations aimed at enhancing the performance and minimizing energy consumption in RAC systems through the utilization of nanolubricants. A volume concentration of 0.2% FAl_2O_3-POE nanolubricant was employed in the RAC system, resulting in the observation of a COP optimization of 32.26%. Additionally, the highest reduction in energy consumption amounted to 19.35%.

The utilization of nanotechnology holds promise for enhancing the performance of domestic AC systems. In their study, Ohunakin et al. [107] employed titanium dioxide (TiO_2), silicon dioxide (SiO_2), and aluminum oxide (Al_2O_3) nanoparticles within a refrigeration system that incorporated mineral oil lubricant and Liquefied Petroleum Gas (LPG) as the refrigerant. The objective of this research is to examine the effect of nanoparticles on system performance and energy conservation, while also conducting a comparative analysis across three distinct types of nanoparticles. Empirical findings show that the utilization of TiO_2 and SiO_2 nanolubricants results in a reduction in power consumption of 13% and 12%, respectively, compared to pure mineral oil lubricants. In contrast, the use of Al_2O_3 nanolubricants in the cooling system results in higher power consumption compared to pure mineral oil-based lubricants. **Table 5** provides a concise overview of the prior research conducted on the increase in performance of VCRS using nanolubricants.

Table 5. Performance study of nanolubricants with various nanoparticles in cooling systems

Refs.	Nanoparticle/ nanorefrigerant	Nanoparticle size	Fraction	Remark
[107]	TiO_2, SiO_2 and Al_2O_3-LPG-MO	SiO_2 (5–15 nm), Al_2O_3 (13 nm), and TiO_2 (15 nm)	0.2 g/L	There was a reduction in power consumption of 12% and 13%, respectively, when SiO_2 and TiO_2 nanoparticles were added to the LPG refrigerant compared to the base refrigerant. However, the application of Al_2O_3 lubricant in the cooling system causes increased consumption.
[22]	SiO_2-R134a-PAG	30 nm	0-0.7 vol%	The results showed that SiO_2/PAG nanolubricant showed a maximum COP value increase of 24% and an average increase of 10.5%. While the COP showed its largest value when the volume concentration was set at 0.05%.
[104]	diamond-R410a-POE	10 nm	0.1 and 0.5 wt%	The highest possible enhancement in cooling capacity is around 7% when the concentration is 0.5% by mass. The use of diamond nanolubricant does not have a significant impact on compressor input power consumption. The COP only increases by about 8% for a diamond mass concentration of 0.5%.
[105]	Al_2O_3-PAG	13 nm	0.006, 0.01, 0.014, 0.1, and 0.2 wt%	The maximum power savings of 23.89% is attained when the AAC system utilizes a 0.010% Al2O3/PAG nanolubricant. Moreover, it has been demonstrated that the condenser pressure and evaporator pressure are associated with the increase in power consumption, exhibiting average deviations of 3.129% and 2.919%, respectively.
[76]	TiO_2-LPG, R600-MO	5–15 nm	0, 0.2, 0.4 and 0.6 g/L	The findings indicate that the power consumption of compressors is approximately 33.33% lower in comparison to refrigerators that rely on LPG. The cooling capacity and COP of refrigerators using R600 as refrigerant exceed the capacity of refrigerators using LPG, with an increase of 17.39% and 62.54%, respectively.
[108]	TiO_2-R600a-MO	15 nm	0, 0.2 and 0.4 g/L	System energy consumption decreases in the range of 0.13%-14.09% when using TiO_2 nanolubricant with concentrations of 0.2 g/L and 0.4 g/L. The coefficient of performance shown an increase within the range of 0.05 to 16.32%.

Refs.	Nanoparticle/ nanorefrigerant	Nanoparticle size	Fraction	Remark
[106]	Al_2O_3/SiO_2-R134a-PAG	Al_2O_3: 13 nm SiO_2: 30 nm	0.005-0.06 vol%	The maximum Coefficient of Performance (COP) improvement of 28.10% was observed at a volume concentration of 0.015%. The reduction in power consumption was 19.70% while compressor work was 25.26%.
[109]	diamond-R410a-POE	10-20 nm	0.10%	The AC system saw its COP increase by a maximum of 8%, while cooling capacity increased by up to 6% and there was a reduction in power consumption by up to 3%.
[70]	MWCNTs and CuO-R152a and R134-POE	MWCNTs: 50 nm CuO: 15 nm	0.5, 1, and 2%	Nanolubricant-refrigerants based on R152a have higher coefficients of performance (COP) compared to those based on R134a. The nanorefrigerant composed of R152a-MWCNTs exhibited a notable enhancement in its coefficient of performance (COP), with a maximum increase of 27.63% compared to the conventional refrigerant R152a.
[58]	FAl_2O_3-R32-POE	43.11 nm	0.02-0.2 vol%	The utilisation of the recently developed FAl_2O_3-POE nanolubricant in conjunction with R32 has been found to result in a reduction in electrical power consumption ranging from 13.79% to 19.35%. COP showed an increasing trend in the range of 3.12%–32.26%.
[110]	$MWCNT/TiO_2$-R600a-MO	5 to 25 nm	0.4 g/L	Predicted an increase in COP of 3.7 with an increase of 32% using the ANFIS prediction model. The ANFIS prediction value provides more accurate results, is the right approach to predict COP parameters, and consumes 35 % less energy.

Based on the findings of the literature review, it can be inferred that the introduction of nanoparticles into base-lubricant yields superior system performance compared to the utilisation of pure lubricants. The data shown in **Table 5** clearly demonstrates that the utilisation of nanolubricant resulted in a significant enhancement in cooling capacity, Coefficient of Performance (COP), and reduction in energy consumption. Carbon nanotubes (CNTs) have shown potential as effective additives for increasing passive heat transfer, particularly when compared to spherical nanoparticles such as aluminium (Al), silicon (Si), titanium (Ti), copper (Cu), diamond, and their respective oxide counterparts. Moreover, it is widely believed that the reduction of friction within the compressor of the refrigeration system has a beneficial impact on the longevity of the compressor.

6. Challenges of Nanilubricant Usages

Nanolubricants have been shown to work better than base lubricant and can be used instead of them in vapor compression systems to make them work better. The utilization of nanolubricants has demonstrated their capability to enhance the cooling efficiency, coefficient of performance (COP), solubility, energy conservation, and heat transfer within vapor compression refrigeration systems (VCRS). Nevertheless, the issue of maintaining dispersion stability of nanoparticles during the production of nanoparticle additives for VCRS working fluid necessitates significant consideration. Currently, many efforts have been made by researchers to improve the quality of nanolubricant by increasing their stability. However, the majority of the study conducted thus far has focused on stationary systems rather than encompassing the entire system. In addition, system condensation and temperature in the evaporation process are important factors that greatly influence the decrease in nanolubricant stability [111]. Moreover, the phenomenon of particle aggregation arises in the context of temperature variations, particularly in mixes of refrigerants and lubricants [112]. Several methods have been introduced by researchers to increase the quality and stability of nanolubricants. In their study, Sharif et al. [113] introduced a novel approach that utilizes UV-visual spectral absorption analysis to enhance the stability of nanolubricants. While the efficacy of this approach in practical systems remains untested, the durability of nanolubricants has been significantly improved.

The findings of the researchers' investigation showed that, compared to base fluids, nanorefrigerants and nanolubricants showed higher thermal conductivity qualities. The viscosity of a substance exhibits an upward trend as the volume fraction of the substance increases, whereas it demonstrates a downward trend when the temperature of the substance improvement. The undesirability of rising viscosity in a refrigeration system stems from its propensity to induce a fall in system pressure, hence diminishing overall system performance. Hence, it is imperative to give due consideration to the utilization of appropriate concentrations of nanolubricants and nanorefrigerants. Enhancing system performance relies on the utilization of nanolubricants and nanorefrigerants characterized by elevated thermal conductivity values and reduced viscosity, hence facilitating minimized pressure drops. Nevertheless, specific categories of metal oxide nanoparticles exhibit significant restrictions. As an example, it can be demonstrated that SiO_2 nanoparticles demonstrate a reduced influence on the increase in viscosity and possess a lower effective heat conductivity when compared to other nanoparticles such as TiO_2 and Al_2O_3 nanoparticles. It is suggested that you investigate and possibly add hybrid or composite materials that contain nanorefrigerants and nanolubricants, which have different mixes of nanoparticles, to variable compression ratio systems (VCRS).

7. Environmental Impact Analysis of Nanolubricants: Risks and Mitigation Strategies

The utilization of nanolubricants presents significant gains in enhancing energy efficiency and diminishing frictional losses across diverse industrial and automotive applications. The manufacturing, utilization, and disposal of nanolubricants present significant environmental issues that must be resolved to guarantee sustainable technological advancement. Nanolubricants containing nanoparticles such as TiO_2, ZnO, or carbon-based compounds may provide toxicity threats to both aquatic and terrestrial ecosystems. When these particles are released into the environment during production, use, or disposal, they may interact with natural ecosystems, changing microbial communities and building up in higher animals. Research indicates that engineered nanoparticles (ENPs) may demonstrate prolonged bioaccumulation and toxicity, posing challenges to environmental health and safety standards [114]. Nanoparticles may agglomerate under environmental conditions, altering their physicochemical properties and complicating their management. Their persistence in ecosystems raises apprehensions regarding long-term environmental repercussions and unanticipated outcomes, including soil and water contamination [115]. The production of nanoparticles, especially via advanced techniques such as chemical vapor deposition or hydrothermal procedures, can be energy-intensive, resulting in considerable carbon emissions. In the absence of optimal methods, the environmental impact of nanolubricant production may negate its operational advantages [116].

The implementation of green nanotechnology in nanoparticle synthesis can reduce environmental hazards. Methods such as renewable solvents, microwave-assisted synthesis, and supercritical CO2 have been suggested to minimize detrimental byproducts and energy usage in manufacture. Utilizing Life Cycle Assessment (LCA) frameworks facilitates the evaluation of the environmental implications of nanolubricants over their entire lifecycle—from manufacture to disposal. This guarantees the optimization of energy and material inputs while minimizing waste outputs. Augmented databases for engineered nanomaterials (ENMs) can enhance life cycle assessment (LCA) precision and facilitate superior decision-making [115]. A safe-by-design methodology can reduce hazards by guaranteeing that nanoparticles are produced with regulated dimensions, morphology, and surface alterations to decrease toxicity. Encapsulation procedures or coatings can diminish the reactivity and mobility of nanoparticles in the environment, hence enhancing their safety for utilization [117]. Robust regulatory frameworks are crucial to mitigate environmental exposure to nanomaterials. Monitoring procedures for identifying nanoparticle emissions during production and disposal can mitigate their environmental impact.

Integrating the operational advantages of nanolubricant technology with environmental considerations is essential for their sustainability. Their capacity to diminish energy usage and improve mechanical efficiency must be considered alongside the possible hazards of nanoparticle discharge and industrial pollutants. The principles of green nanotechnology, lifecycle optimization, and regulatory compliance will be essential for ensuring that nanolubricants become a sustainable option for future technological progress.

8. Conclusion

In recent years, there has been an increasing scholarly focus on the advancement and exploration of nanofluids, specifically nano lubricants and nano refrigerants, due to their exceptional qualities that surpass those of conventional nanofluids in cooling applications. This paper presents a succinct summary of the application of nanolubricants and nanorefrigerants within the realm of refrigeration systems. This publication presents a comprehensive review of the methodology involved in the creation of nanolubricant, examines the factors influencing the stability of nanolubricant, investigates the thermophysical properties of nanolubricant, evaluates the performance characteristics of nanolubricant in refrigeration systems, and discusses the issues associated with the use of nanolubricant. Depending on the comprehensive analysis of existing scholarly works, it is evident that the following conclusions can be derived:

- The development of nanolubricant by a two-step technique has several benefits, including cost-effectiveness, simplicity, ease of application to oxide nanoparticles, and appropriateness for large-scale manufacturing. To achieve stability of nanolubricant requires the incorporation of surfactants or surface modification.
- Thermal conductivity can be increased by inserting materials in the form of nanoparticles into lubricants, hence enhancing their dispersion.
- The dynamic viscosity of nanolubricants exhibits a drop when temperature rises, while it demonstrates an increase with respect to their fraction. Hence, it is imperative to ascertain the ideal proportion of nanoparticles in order to effectively manage the equilibrium between fluctuations in thermal conductivity and dynamic viscosity.
- The addition of nanoparticles into the base liquid at specific concentrations has the potential to enhance the density measurement.
- The application of nanolubricants has led to a substantial enhancement in the COP values inside cooling systems.

This review uniquely synthesizes multiple facets of nanolubricants, encompassing synthesis processes and environmental impact, within the framework of cooling systems. This research consolidates knowledge about thermophysical properties while also addressing scalability obstacles, safety concerns, and compatibility with global sustainability objectives, distinguishing it from prior works. A significant contribution is the provision of a forward-looking roadmap that amalgamates technological advancements with environmental factors, guaranteeing a comprehensive strategy for the development of next generation nanolubricants.

9. Recommendation for Future Research

Recent years have seen a growing emphasis on the development of nanolubricants for cooling systems, attributed to their exceptional thermophysical qualities and capacity to improve performance. This review examines the synthesis processes, stability, thermophysical properties, and overall efficacy of nanolubricants, underscoring their potential to transform cooling systems by enhancing energy efficiency and prolonging system longevity. Notwithstanding these encouraging developments, significant deficiencies and obstacles must be tackled by forthcoming research to completely harness the potential of nanolubricants. Future study should focus on the following areas:

- **Long-Term Stability and Operational Durability** - Research into the long-term stability of nanolubricants under diverse operational settings is crucial. This encompasses the examination of sedimentation and aggregation throughout prolonged durations, along with their effects on system efficacy and upkeep.
- **Advanced Nanoparticle Functionalization** - Research into sophisticated surface functionalization strategies for nanoparticles is essential to boost compatibility with base lubricants and improve dispersion stability. This may entail investigating hybrid nanoparticles or composite materials.

- **Environmental and Safety Considerations** - Additional research is necessary to assess the environmental effects and biodegradability of nanolubricants. This encompasses evaluating their toxicity, potential ecological hazards, and the formulation of sustainable synthesis techniques.
- **Scalability and Cost-Effectiveness** - It is essential to tackle the issues associated with large-scale production, especially for single-step synthesis processes. Research should concentrate on enhancing procedures to save expenses while preserving the superior performance of nanolubricants.
- **Standardized Testing Protocols** - Implementing standardized techniques for assessing the thermophysical and tribological characteristics of nanolubricants will improve comparability across experiments and bolster reproducibility.
- **Integration with Emerging Technologies** - Investigating the use of nanolubricants alongside advanced technologies, such as intelligent HVAC systems and renewable energy-driven refrigeration, may enhance their applicability and support global sustainability objectives.

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Author’s Declaration

Authors’ contributions and responsibilities - The authors made substantial contributions to the concept and design of this study, details of which are as follows:

Galang Sandy Prayogo	: Main author and Writing - Original Draft
Agus Nugroho	: Research executor and data analysis
Jackly Muriban	: Writing - Review & Editing
Muhammad Kozin	: Visualization
Mohd Fairusham Ghazali	: Funding acquisition Data analysis and article review
Rizalman Bin Mamat	: Data analysis, Validation, and Supervision

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Nomenclature

AC	:	Air conditioning
Al_2O_3	:	Aluminium oxide
BN	:	Boron nitride
CNT	:	Carbon nanotube
CNT	:	Carbon nano tube
COF	:	Coefficient of friction
COP	:	Coefficient of performance
CuO	:	Copper oxide
DEC-PAG	:	Double-end-capped polyalkylene glycol
GNP	:	Graphene nanoparticles
HVAC	:	Heating, ventilation, and air conditioning
LPG	:	Liquified petroleum gas
MO	:	Mineral oil
MWCNT	:	Multi-walled carbon nanotube

ND	:	Nano diamond
PAG	:	Polyalkylene glycol
PEG	:	Polyethylene glycol
POE	:	Polyolester
PVD	:	Physical vapour deposition
PVE	:	Poly vinyl ether
SiO_2	:	Silicon dioxide
TiO_2	:	Titanium dioxide
TMPTO	:	Trimethylolpropane trioleate oil
UV-vis	:	Ultraviolet-visible spectroscopy
VCRS	:	Vapor compression refrigeration sysem

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