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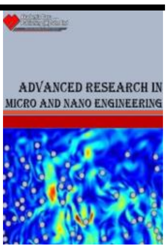

Enhancing Lubrication Efficiency and Wear Resistance in Mechanical Systems through the Application of Nanofluids: A Comprehensive Review

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ABSTRACT

Due to its potential to increase lubrication effectiveness and reduce wear, nanofluids have drawn substantial interest in the field of mechanical systems. Colloidal suspensions of nanoparticles dispersed across a base fluid to create nanofluids. This comprehensive study's goal is to examine recent developments, scientific discoveries, and possible applications of nanofluids in tribology. The scientific and technical characteristics of materials which move in relation to one another are the subject of the academic topic of tribology. The aim of this review paper includes a thorough investigation of phenomena like lubrication mechanism, wear and friction. Because of their unique features at the nanoscale, nanoparticles offer a special opportunity to mitigate enduring problems in tribological systems. This review critically evaluates the process utilized to create nanofluids, examines their tribological properties, and considers how they affect the effectiveness of how mechanical systems function. The higher lubrication effectiveness and wear resistance are the main points of attention. This study also investigates several methods for characterizing nanofluids to examine their behavior. The assessment also emphasizes important elements that affect the effectiveness of nanofluids, including the composition, concentration, size, and choice of nanoparticles, in addition to the choice of the base fluid. This study examines many problems and probable future endeavors within the industry, encompassing inquiries pertaining to long-term durability, and scalability. The primary objective of this review paper is to conduct a comprehensive analysis of the current state of nanofluid research within

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the domain of tribology. The objective is to foster further progress and encourage the extensive adoption of nanofluids as an innovative lubricating technology.

1. Introduction

Within the field of mechanical engineering, there has been a persistent endeavor to achieve optimal performance, longevity, and efficiency in machinery. The application of lubricants is of utmost importance in guaranteeing the efficient functioning and extended lifespan of mechanical systems [1]. The application of suitable lubricants is essential in various mechanical systems, ranging from the complex internal workings of automotive engines to the substantial gears found in industrial machinery. This crucial approach serves to minimize friction, disperse heat, and mitigate the effects of wear and deterioration [2]. As mechanical systems undergo further advancements, it becomes essential to come up with lubricants that can effectively safeguard and enhance their operational efficiency.

For several decades, the utilization of conventional oil as a lubricant has proven to be effective in achieving this objective. Nevertheless, the growing requirements imposed on contemporary machinery underscore the imperative to explore innovative methods for augmenting the efficiency of oil lubricants and mitigating the probability of mechanical deterioration. Mineral oils and synthetic fluids, comprising the predominant constituents of conventional lubricants presently employed, have demonstrated prolonged efficacy in fulfilling their designated functions [3]. However, when these conventional lubricants are put to work in extreme conditions, such as high temperatures, heavy loads, and challenging surroundings, they frequently run into issues that can cause them to be less efficient overall [4]. In light of these issues, the use of nanofluids has emerged as an intriguing possibility for enhancing lubrication and making things less prone to wear and tear [5].

Nanofluids are a new and remarkable technology that has attracted a significant amount of interest in recent years, and the domain of nanofluids is where the researchers intend to concentrate their attention and efforts [6,7]. A new category of fluid known as nanofluids can be created by dispersing solid particles with dimensions on the nanoscale (often having a diameter of less than 100 nanometers) throughout a lubricant as shown in Figure 1 [8]. Nanofluids have unique properties and advantages that could make mechanical systems work more efficiently and last longer once they are fully synthesized and included into lubricating oils [9]. Due to their ability to greatly enhance the performance of mechanical systems, nanofluids are very optimistic in the field of lubrication and have the potential to alter how processes are presently performed [10].

This comprehensive review goes into detail about the many different parts of nanofluid-based lubrication. It gives a thorough look at the many different aspects of this field. This paper looks at the science behind nanofluids, the different ways they are made, and the ways in which their unique properties make them an interesting choice for making lubrication work better. We also look at the many research projects that show how nanofluid lubrication can be useful in the real world. These benefits include lower friction ratios, better heat transfer, and better resistance to wear. Our goal is to help engineers, students, and industry experts who want to use nanofluid-based lubrication technology to its full potential by giving them important information about its current state.

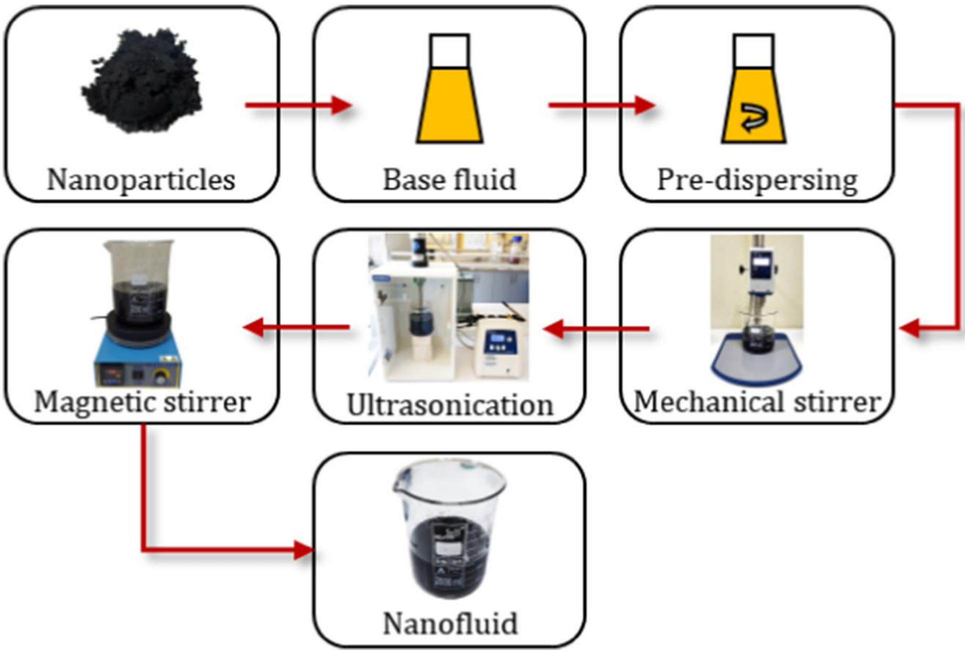

Fig. 1. Illustration of nanofluids' preparation procedure. Reproduced with permission from Şirin [8] Copyright 2023, Elsevier

2. Nanofluid Formulation and Properties

The process of creating nanofluids involves the incorporation of diverse nanoparticles into conventional heat transfer fluids. The correlation between the dispersion state of nanoparticles as additives and the development of superior physical properties in formulated nanofluids has been discovered [11]. Asadi *et al.,* [2] conducted a comprehensive review of the existing literature, highlighting the favorable performance of created nanofluids with regards to their physical properties. Asadi *et al.,* [2] further expounded upon the superior performance exhibited by created nanofluids in comparison to the base fluids. The determination of physical parameters associated with heat transfer nanofluids is heavily reliant on the stability of the dispersed nanoparticles. In addition, the loading concentration and stability of the created nanofluids are crucial factors that contribute to the enhancement of their physical properties.

Nanoparticles employed in nanofluids exhibit diverse forms, compositions, and morphologies, each possessing distinct properties and exerting a unique impact on lubrication [12-14]. The incorporation of nanoparticles into the base fluid can induce changes in its thermal, tribological, and rheological properties, hence resulting in improved operational efficiency across a range of machinery equipment and cutting instruments [15-18]. Metallic nanoparticles, including copper, silver, and gold, are commonly utilized in nanofluids. The nanomaterials are renowned for its exceptional thermal conductivity, a property that can greatly augment the process of heat transmission inside lubricating oils [9]. This characteristic facilitates the reduction of heat generated by friction, resulting in a decrease in the operational temperature of machinery, hence prolonging their longevity.

In the field of nanofluids, oxide nanoparticles such as alumina (Al_2O_3) and titanium oxide (TiO_2) have been used a lot due to the enhanced thermal conductivity [3]. Carbon nanotubes and graphene nanomaterials in the form of two-dimensional (2D) structures are commonly employed nanoparticles for enhancing the physical properties of nanofluid suspensions [19]. The peculiar structure and exceptional thermal, optical, and electrical capabilities of 2D nanomaterials have garnered significant attention in recent studies [20]. The MXene, a 2D nanomaterial, was first identified at Drexel

University in 2011 by Naguib *et al.,* [21]. The researchers have been motivated to conduct experimental investigations into the efficiency of this nanomaterial due to its superior qualities in comparison to other materials. The MXenes family of materials has demonstrated superior physical properties in relation to their potential uses [22]. All the nanoparticles aforementioned make lubricants more stable and also help keep surfaces from rusting. The greater surface area of nanoparticles can also make them better at reducing friction. Table 1 shows findings from tribological investigations using various type of nanoparticles.

Nanoparticles have been shown to have an effect on the parameters of lubrication, including a reduction in friction, an increase in wear resistance, an enhancement in thermal conductivity, and an increase in the stability of the lubricating fluid [23-26]. As a result of these enhancements, operating efficiency is increased, machine longevity is increased, energy consumption is decreased, and the intervals between maintenance are extended. To fulfill the unique requirements of the lubrication application, however, it is essential to carefully modify the composition of the nanofluid in order to ensure that it functions properly [27]. This is important because the specific impacts of the nanofluid can vary depending on parameters such as the kind, concentration, and quality of the nanoparticle dispersion that occurs inside the nanofluid. The persistent progress made in the area of nanotechnology has paved the way for the development of nanofluids that have nanoparticle compositions that are uniquely suited to a certain application [28]. There is significant potential for the commercialization of nanofluids to revolutionize conventional lubrication techniques across a wide range of industry sectors.

The significance of base fluids is of utmost importance in the context of nanofluids, which are characterized as colloidal suspensions of nanoparticles dispersed in a base fluid. The selection of the base fluid and its compatibility with nanoparticles are essential considerations in assessing the efficacy and durability of nanofluids. The selection of the base fluid should consider its compatibility with both the intended application and the nanoparticles employed. In certain instances, the interaction between the base fluid and nanoparticles during chemical reactions might result in instability or unfavorable consequences [29]. It is essential to evaluate the compatibility between the base fluid and nanoparticles within the precise temperature and pressure parameters relevant to the anticipated application. Certain combinations have the potential to exhibit instability or undergo phase transitions under severe circumstances. The choice of nanoparticles for nanofluids should consider their compatibility with the base fluid in terms of material properties [30,31]. For instance, water-based nanofluids commonly demonstrate compatibility with metallic nanoparticles such as copper or aluminum, whereas oils may be employed in conjunction with carbon-based nanoparticles. The enhancement of nanoparticles' compatibility with the base fluid frequently requires the implementation of surface modification techniques. The improvement of dispersion and stability can be achieved through the utilization of surfactants or the functionalization of the surface of the nanoparticle [30].

Table 1
Various type of nanoparticles' tribology investigation

Type of nanoparticle	Size (nm)	Type of Oil	Findings	Reference
Al_2O_3	78	Polyalphaolefin	Improved tribological performance is achieved at an optimum concentration of 0.1 wt.% Al_2O_3.	Luo *et al.,* [32]
Copper	2-6	Paraffin oil	Surface modified copper nanoparticles exhibits outstanding anti-wear properties.	Yang *et al.,* [33]
Silver	1-3, 3-6	Polyalphaolefin	Surface modified silver nanoparticles improve the frictional coefficient by 35% and wear by 85%.	Kumara *et al.,* [34]
Copper, TiO_2	<50 <20	SAE20W40	Nano additives improve the thermal efficiency of four-wheeler by 4–7%.	Sarma *et al.,* [35]
ZnO	<20	Polyalphaolefin 6	Minimum wear scar diameter is observed with PAO +0.3 wt.% ZnO.	Battez *et al.,* [36]
$CaCO_3$	<40	Lubricating oil	Excellent tribological performance under extreme conditions with 1 wt.% nanoparticle concentration.	Zhang *et al.,* [37]
MoS_2	<100 nm	Soybean oil	MoS_2 nanospheres show better dispersion stability as compared to other particles resulting in better friction and wear properties.	Xu *et al.,* [38]
Graphite	35, 80 nm	LB2000	At lower temperatures, bigger nanoparticles decrease C.O.F more, whereas minimum C.O.F is observed with smaller nanoparticles at higher concentration equal to 0.123.	Su *et al.,* [39]
CuO	20-150 nm	Coconut oil	Minimum C.O.F and wear is observed with 0.34% concentration.	Thottackkad *et al.,* [40]
CuO	50 nm	Castor Oil	Maximum improvement in WSD and C.O.F is equal to 28.3% and 34.6% at 0.1%.	Gupta and AP [41]
Cu	25 nm	Avocado oil	Improves the tribological properties with minimum C.O.F observed at 1 wt.%.	Shafi *et al.,* [42]
CeO_2, PTFE	90, 150 nm	Castor Oil	The reduction in WSD with CeO_2 and PTFE is equal to 37.4 and 35% respectively.	Gupta and Harsha [43]

2.1 Thermal and Rheological Properties of Nanofluids

The investigation of thermal characteristics holds significant importance in the discussion concerning nanofluids. The thermal conductivity of the base fluid can be greatly enhanced by nanoparticles, due to their high surface area-to-volume ratio [9]. This characteristic presents a wide range of possibilities for increasing the efficiency of lubricating systems. The integration of nanofluids into these systems offers the potential to improve heat dissipation capabilities and reduce operating temperatures, consequently extending the operational longevity of machinery and mitigating the likelihood of thermal degradation [6,31,44,45].

The thermal conductivities of different base fluids exhibit variations, and the choice of a certain base fluid can significantly impact the extent of enhancement that can be attained [46]. A wide range of base fluids can be suitably employed for various heat transfer applications. In instances where the evaporation of water-based nanofluids is a potential issue in high-temperature applications, there may be a preference for the utilization of oil-based nanofluids [47]. One of the foremost benefits associated with nanofluids is their increased thermal conductivity in comparison to the base fluid. The incorporation of nanoparticles has the potential to substantially enhance the thermal conductivity of the fluid [48]. In the context of lubrication applications, this particular characteristic has the potential to enhance the dissipation of heat, resulting in decreased operational temperatures within machinery. Reduced temperatures have the potential to extend the longevity of lubricants and minimize the occurrence of mechanical component degradation [49]. The enhanced thermal conductivity exhibited by nanofluids has the potential to enhance the overall heat transfer efficiency inside lubricated systems [50]. This property proves to be highly advantageous in situations characterized by elevated temperatures, as the effective dissipation of heat plays a critical role in mitigating the risk of overheating and the subsequent degradation of lubricants [50].

On the other hand, rheological characteristics related to the flow characteristics demonstrated by nanofluids [51]. The presence of nanoparticles has the potential to exert an influence on the viscosity, shear-thinning behavior, and stability of these fluids [51]. Comprehending these rheological alterations is crucial for the optimization of lubrication operations. Being able to precisely modify these characteristics has prospects for developing lubricants customized for particular purposes, ranging from automobiles to industrial machines. The rheological characteristics of nanofluids can be modified through the manipulation of nanoparticle type and concentration [51]. The selection of nanoparticles is crucial due to the thermal and rheological properties of nanofluids, which can be affected by nanoparticles that vary in types. As an instance, carbon-based nanoparticles such as graphene or carbon nanotubes exhibit elevated heat conductivity, but metallic nanoparticles like copper or silver could improve lubricity. Table 2 shows effect of nanoparticles on thermal conductivity and rheological properties of nanofluid.

The influence of nanofluids on lubrication reaches beyond just improvements in heat transfer and flow characteristics. Additionally, they have the ability to alleviate concerns like as friction and wear. Nanoparticles function as solid lubricants, effectively mitigating friction and wear within tribological systems by reducing contact between moving surfaces. The nanofluid innovation possesses the capacity to fundamentally transform the efficacy and longevity of mechanical constituents, hence resulting in energy conservation and diminished expenditures associated with maintenance.

Table 2
Thermal conductivity and rheological properties of nanofluid

Lubricant	Nanoparticles	Property findings	References
CNT	Gear oil, paraffinic oil	Thermal conductivity of for both oil increases to 0.6 w/m. k at 40 C and 2 wt.%	[52]
CuO	20W50	Thermal conductivity increases by 3%.	[53]
ZnO	Turbine oil	Viscosity of base oil increases from dyne/cm^2 at 0.1% to 31.4 dyne/cm^2 at 4%.	[54]
CuO	Gear oil	Viscosity of gear oil increases 3 times by the addition of CuO.	[55]
MWCNT	PAO	Thermal conductivity ratio increases from 1.1 at 0.04% to 3 at 0.36%.	[56]
Fe_3O_4	SAE20W50	Maximum thermal conductivity is observed at 0.4% equal to 0.163 w/mk.	[57]
Al_2O_3	Car engine coolant	The maximum increase in thermal conductivity ratio is observed at 0.035% equal to 10.41%.	[58]
CNT	Gear oil, paraffinic oil	Viscosity of gear oil increases from 75 cSt to 450 cSt at 2 wt.% and paraffinic oil 15 cSt to 102 cSt at 2 wt.%.	[52]

3. Lubrication Mechanisms

Lubrication is an essential component of mechanical systems, serving a critical function in facilitating their optimal and stable operation [59]. The process entails the utilization of a lubricant, commonly in the form of a fluid or solid substance, with the purpose of reducing friction and minimizing wear between moving components inside a machine or mechanical system. This method is essential in reducing excessive heat generation, reducing energy dissipation, and prolonging the operational lifespan of machinery [60]. Nanofluids have the potential to enhance lubrication by means of many underlying mechanisms, encompassing hydrodynamic lubrication, boundary lubrication, and mixed lubrication regimes as shown in Figure 2 [61].

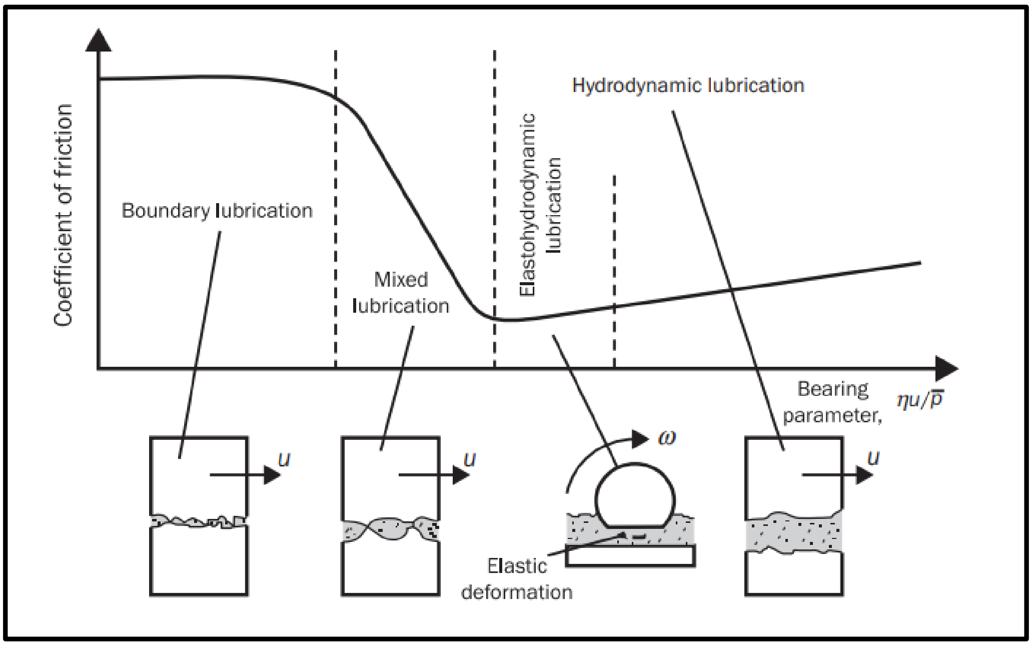

Fig. 2. Demonstration of lubrication regimes. Reproduced with permission from Burstein [61] Copyright 2023, Elsevier

3.1 Hydrodynamic Lubrication

When there is a bulk fluid phase between two solids that are submerged in a fluid, hydrodynamic lubrication happens [61]. There is a shear flow in the fluid when the objects are moving against each other. But the pressure of the fluid in the void might be high enough to make the solid forms stretch. When the fluid moves into the space between the surfaces, it makes a pressure difference [62]. At the spot where the surfaces are closest to each other, the pressure is at its highest. As you move away from this spot, the pressure goes down. The pressure of the fluid film works against the load or force from the outside that is acting on the surfaces. The process raises and separates the surfaces in a way that works well [62]. This makes a thin layer of lubricant that holds the force and keeps the surfaces from coming into direct touch. This process successfully reduces the effects of friction and wear significantly.

To make sure that hydrodynamic lubrication works, it is important to keep a steady flow of fluid to keep the fluid film in place [63]. Depending on the situation, this goal can be reached in a number of ways, such as by using oil pumps, splash lubrication, or oil rings. Hydrodynamic lubrication possesses numerous merits, encompassing its capacity to effectively manage substantial loads, mitigate frictional forces, and efficiently disperse the thermal energy created during operational processes [64]. Nonetheless, meticulous planning and supervision are necessary to guarantee the preservation of the lubricating coating and the efficient functioning of the system.

3.2 Elastohydrodynamic Lubrication

The transmission of power in machine parts or engine components, such as rolling bearings, gears, or cam/followers, typically involves concentrated rolling and rolling-sliding contacts [65]. In these contacts, the bodies experience local elastic deformation as a result of the contact forces at play. The Hertzian theory can be used to approximate the deformations, pressures, and stresses associated with dry contacts [65]. When an adequate amount of lubricant is present, it leads to the development of hydrodynamic pressure, resulting in the partial separation of the contacting surfaces by the formation of a thin fluid film. When the magnitudes of local elastic deformation and lubricant film thickness are comparable, this state is commonly known as elastohydrodynamic lubrication (EHL) [65].

Within the context of EHL, it is common to see the coexistence of zones characterized by both mixed and complete film lubrication. In the mixed lubrication regime, the contact surfaces undergo a combination of direct touch and lubricated contact. Conversely, in the full film regime, the lubricant film attains a thickness that effectively prevents any direct contact from occurring. The significance of EHL in the field of mechanical engineering lies in its ability to facilitate effective lubrication and minimize wear in applications characterized by high pressure and high speed [65]. This phenomenon is frequently observed in gears, rolling-element bearings, hydraulic components, and other devices that involve sliding or rolling contact.

3.3 Boundary Lubrication

Boundary lubrication is a lubrication mechanism that arises when two solid surfaces make contact and experience sliding motion under conditions of elevated pressure and limited or inadequate quantities of lubricating fluid [61]. Under such circumstances, the presence of a thin layer of lubricating film or lubricant is insufficient to completely separate the surfaces, resulting in direct contact between the metal surfaces. The aforementioned phenomenon may lead to heightened levels of friction, wear, and heat production, hence posing potential harm to the components involved in the interaction [66,67].

Boundary lubrication is a type of lubrication where the coating of lubrication is very thin or even missing in some areas due to high load and contact pressures. Asperities are tiny surface flaws that could come into contact with each other on the two surfaces that are touching. This could cause friction and wear [67]. In the worst cases, this situation could cause damage to the surface and could lead to the welding of metal asperities. Boundary lubrication is a common action that can be seen in practical applications like car engines, gearboxes, and equipment parts that slide against each other. Engineers and lubrication specialists have to do important things like build lubrication systems and choose the right lubricants. These experts try to reduce the bad effects of border lubrication and make sure that mechanical parts last long and work well.

3.4 Mixed Lubrication

Mix lubrication is a type of lubrication that happens when boundary lubrication and hydrodynamic lubrication both exist at the same time [61]. This is usually seen in mechanical systems with moving or rolling parts. In the case of mix lubrication, it is clear that a full-fluid-layer hydrodynamic lubrication is not enough to keep the sliding or rolling surfaces from coming into close contact. On the other hand, there is not enough metal-to-metal contact to fully count on boundary lubrication.

The transition from boundary lubrication to hydrodynamic lubrication is contingent upon various elements, including as speed, load, temperature, and the characteristics of the lubricant [68]. The equilibrium between the two lubrication processes plays a crucial role in ensuring the optimal performance of the mechanical components in mix lubrication. The appropriate choice and upkeep of lubricants are crucial factors in ensuring the optimal functioning of the system, while minimizing the occurrence of excessive wear [68].

The design of an effective lubrication mixture frequently entails the careful selection of an appropriate lubricant accompanied by the incorporation of acceptable additives. Additionally, it necessitates the choice of appropriate materials and surface treatments for the components involved, as well as the assurance that the operating circumstances fall within the prescribed limitations for the lubrication regime [69]. When executed with precision, the utilization of mix lubrication can offer a viable middle ground between the two extremes of boundary lubrication and full-fluid film hydrodynamic lubrication. This approach has the potential to extend the lifespan of mechanical systems while simultaneously mitigating friction and minimizing wear.

4. Heat Transfer Enhancement

Nanofluids have garnered considerable interest in recent times as a type of improved heat transfer fluids, mostly due to its capacity to augment the efficiency of heat transmission in mechanical systems [6]. Nanofluids are composed of a primary fluid, commonly water, oil, or ethylene glycol, that is combined with solid particles at the nanoscale scale, including metallic or non-metallic nanoparticles [44]. The incorporation of nanoparticles into the base fluid induces changes in its thermophysical characteristics, rendering it a potentially advantageous medium for enhancing heat transfer in diverse mechanical systems.

One of the most notable characteristics of nanofluids is their considerably enhanced thermal conductivity in comparison to that of pure base fluids [70]. Nanoparticles exhibit a superior thermal conductivity compared to the underlying fluid, hence enhancing the efficiency of heat transmission when they are scattered within the fluid. The heightened thermal conductivity facilitates enhanced heat dissipation and improved temperature distribution within mechanical systems, resulting in enhanced overall thermal performance [71].

Nanofluids demonstrate elevated heat transfer coefficients, leading to enhanced heat transfer efficiency between a solid surface and the encompassing fluid [72]. The aforementioned characteristic of this property proves advantageous in several applications, notably in heat exchangers, as it enhances heat transmission, resulting in enhanced energy efficiency and diminished equipment dimensions [72,73]. Nanofluids have the potential to enhance convective heat transfer, a process in which the fluid undergoes circulation as a result of temperature gradients. Nanofluids possess enhanced thermal conductivity and heat transfer coefficients, hence facilitating improved convective heat transfer. Consequently, nanofluids have gained significance in various applications such as cooling systems, HVAC systems, and automobile radiators [74,75].

Nanofluids have been observed to effectively decrease the energy consumption associated with pumping in various mechanical systems, particularly those employed in cooling processes [76]. This phenomenon can be attributed to the fact that nanofluids frequently have reduced viscosity in comparison to conventional heat transfer fluids. Reduced pumping power has the potential to result in energy conservation and enhanced overall efficiency of the system. The enhanced heat transfer characteristics of nanofluids present potential avenues for the downsizing of heat exchangers and other mechanical elements [77]. The utilization of smaller equipment in diverse applications offers notable benefits, especially in contexts with limited space availability.

Nanofluids can be made to fit the needs of different applications by carefully choosing the nanoparticles and base fluids that go into them. These devices are very flexible and can be used in many different fields, such as cooling electronics, automotive, aerospace, and green energy systems. Even though nanofluids have many benefits, it is important to recognize that they also have some problems, such as nanoparticle aggregation, worries about stability, and possible material compatibility problems with system parts [78]. Also, it is important to note that the costs of nanoparticles and the processes used to make them are usually higher than those of regular fluids.

In summary, it can be concluded that nanofluids exhibit significant promise in enhancing heat transfer efficiency inside mechanical systems. The significant properties of these materials lie in their capacity to enhance thermal conductivity, heat transfer coefficients, and convective heat transfer efficiency. This makes them highly advantageous for improving the performance and energy efficiency of diverse mechanical and thermal systems. However, it is important to acknowledge and tackle practical issues and obstacles that arise during the implementation of nanofluids in real-world applications. Ongoing research endeavors are currently concentrated on maximizing the properties of nanofluids and finding solutions to overcome these challenges.

5. Tribological Performance

The field of study concerned with the scientific principles governing friction, lubrication, and wear is known as tribology [79]. The application of the tribology technique is employed to reduce the effects of wear and friction. The occurrence of machine failure can be attributed to factors such as friction and wear [68]. Additionally, a significant amount of energy is wasted as a result of the friction experienced by machine components. Hence, employing a combination of many techniques to minimize friction in machine components and utilizing various types of lubricants. Subsequently, other researchers employed the tribology technique in order to mitigate energy losses in machinery [80-82]. Various strategies were employed to adjust the parameters of the lubricating fluid in order to enhance lubrication efficiency [83]. These techniques encompassed altering the fluid viscosity and incorporating nano-scale additives.

Tribology encompasses the examination of the various phenomena associated with friction, lubrication, and wear, including their underlying mechanical and chemical causes such as erosion and corrosion [79]. These strategies might be regarded as methods for implementing a low friction coating on a surface, enhancing the lubrication at the sliding contact, or mitigating wear by modifying the system architecture. The utilization of the nanocomposite lubricant additive results in a reduction in energy consumption and an extension of the operational lifespan of the engine, hence yielding significant cost savings [84]. Nanomaterials are employed as additives to lubricants in order to address tribological challenges.

The utilization of nanofluids has emerged as a potential approach in the quest for enhanced tribological performance. Nanofluids refer to synthetically produced mixtures consisting of solid particles with sizes in the nanoscale range, dispersed throughout a base fluid. These solid particles are carefully selected based on their desirable thermal and mechanical characteristics. The introduction of nanoparticles into standard lubricants or coolants has the potential to induce substantial modifications in the friction, wear, and heat transfer properties of the working fluids employed in mechanical systems. Table 3 summarized researches conduct on nano lubricant in tribological property.

Table 3
Nano lubricant reducing friction and wear

Lubricant	Nanoparticles	Tribology property findings	References
Phenol	Carbon nanotube	Friction, anti-wear and surface hardness	Igarashi *et al.,* [85]
Engine oil SAE10W	Hexagonal boron nitride	14.4% improvement in COF 6.5% improvement in wear	Çelik *et al.,* [86]
Liquid paraffin	CuO	Friction, anti-wear (COF = 0.185 and 0.123)	Asrul *et al.,* [87]
Water based lubricant	TiO_2	Reduction in friction	Gu *et al.,* [88]
Vegetable based oil	Graphite	Deposition film, friction and anti-wear	Su *et al.,* [39]
Mineral based oil	Multiwall-carbon nanotube	Lowest frictional force and high dispersion	Lijesh *et al.,* [89]
Lithium grease	Nanometer-Silicon dioxide	COF 26-39 % Wear 7%	He *et al.,* [90]

5.1 Bearings and Gears

Using nanofluids in bearing and gear lubrication has been found to be beneficial, as it significantly lessens friction and wear [91]. The nanoparticles' capacity to form a protective coating on the surface reduces the amount of wear caused by metals coming into direct contact with one another [92]. Nanofluids have the potential to demonstrate enhanced thermal conductivity, which aids in the dissipation of heat created during friction, hence minimizing the possibility of overheating and wear.

Nanofluids have shown that they can be used to reduce friction in bearings and gears. Nanoparticles can act as solid lubricants by filling in rough spots on surfaces. This reduces the amount of direct touch between metal surfaces, which reduces frictional losses [93]. Using nanofluids could increase the load-carrying capacity of lubricated parts. Industrial gears are a good example of an application where this is important because they have to handle heavy loads. When nanoparticles are added to nanofluids, they might slow down the wear that happens on bearing and gear surfaces. When nanoparticles are present, a protective layer forms on the surfaces. This stops the surfaces from coming into close contact, which reduces wear.

5.2 Engine Cooling

The utilization of nanofluids has been seen to result in the mitigation of friction between mobile components within engines, hence potentially enhancing fuel efficiency and diminishing mechanical deterioration [94]. The nanoparticles function as solid lubricants, thus creating a protective boundary layer on the surface of engine components. The incorporation of nanoparticles into nanofluids has been found to enhance the lubricating characteristics of the underlying fluid medium [95]. Surface asperities can be effectively filled by these substances, resulting in a more polished surface that facilitates the movement of components, hence minimizing friction and wear.

The major purpose of engine coolant is to facilitate the dissipation of thermal energy from the engine [96]. The heat transfer qualities of coolants can be improved by the incorporation of nanofluids, which is attributed to the enhanced thermal conductivity exhibited by nanoparticles. This occurrence has the potential to enhance cooling efficiency and optimize temperature regulation within the engine. The significance is in the assurance of stability and compatibility between nanofluids and engine materials and components [97]. The accumulation or precipitation of nanoparticles has the potential to cause obstruction or harm within the engine cooling system. Continued investigation and experimentation are necessary to comprehensively comprehend the enduring efficacy and resilience of nanofluids within the context of engine cooling system [97]. This crucial requirement arises from the need to ascertain their performance across diverse operational parameters and protracted timeframes.

In brief, nanofluids possess the potential to yield advantages in the realms of friction reduction, heat transfer enhancement, and wear resistance improvement inside engine cooling systems. Nonetheless, the effective integration of nanofluids in the cooling of engines necessitates meticulous examination of variables like particle dimensions, concentration levels, stability, and durability, alongside issues pertaining to environmental and health-related aspects. Comprehensive experimentation and scholarly inquiry are imperative in order to get a comprehensive comprehension and enhance the tribological efficacy of nanofluids within distinct engine implementations.

5.3 Metalworking and Machining

The investigation of nanofluids as lubricants and coolants in metalworking and machining processes is a significant field of study, focusing on the tribological performance of these fluids. Nanofluids possess the inherent capability to enhance lubrication efficacy within the context of metalworking operations. The incorporation of nanoparticles into a fundamental lubricant has the potential to diminish the level of friction experienced between a tool and workpiece, hence resulting in reduced wear and an extended lifespan of the tool [98]. This aspect holds special significance within the context of high-speed machining, as the presence of friction and subsequent heat generation can be considerably pronounced.

Nanofluids have the potential to enhance the cooling characteristics of metalworking fluids. Nanoparticles possess a notable capacity for enhancing heat dissipation inside the cutting zone, hence mitigating the risks of workpiece and cutting tool overheating as well as thermal damage [99]. The selection of nanoparticles has a pivotal role in shaping the tribological characteristics of nanofluids. Frequently employed nanoparticles encompass a variety of materials, such as graphene, carbon nanotubes, metal oxides (for instance, alumina and titanium dioxide), and nanodiamonds. The choice of selection is dependent upon various aspects such as cost, stability, and the unique requirements inherent to the metalworking process.

The role of nanoparticle concentration and stability in nanofluid is of considerable importance. Excessive concentration levels can result in the aggregation of nanoparticles, while insufficient concentration levels may fail to yield the intended tribological enhancements. The utilization of nanofluids in metalworking and machining presents certain obstacles, despite the potential advantages they offer. Several factors are of significance in the context of nanoparticles. These factors include the requirement for nanoparticle production that is both dependable and economically viable, apprehensions regarding the toxicity of nanoparticles, and the possibility of nanoparticle aggregation leading to obstruction in machining systems.

6. Conclusion

This comprehensive investigation explores the application of nanofluids in order to enhance the effectiveness of lubrication and improve the resistance to wear in mechanical systems. The review highlights the considerable potential of nanofluids as a pioneering solution in the field of tribology. Nanofluids, comprising of nanoparticles uniformly dispersed within base lubricants, have enhanced lubricating properties when compared to conventional lubricants. The increase in mechanical system efficiency can be ascribed to the decrease in friction and the augmentation of load-carrying capacity.

Nanofluids have demonstrated significant wear resistance properties, leading to enhanced longevity of components and decreased maintenance expenses. The improvement of wear resistance relies on two essential factors: the formation of protective nanoparticle coatings and the mitigation of material degradation. The utilization of nanofluids has exhibited significant effectiveness in the dissipation of heat produced during mechanical procedures, thereby making a valuable contribution to the maintenance of stable operational temperatures. The incorporation of temperature regulatory devices is essential in mitigating the risk of thermal damage to components and ensuring a sustained level of operational efficiency.

Despite multiple benefits, it is essential to meticulously address difficulties pertaining to stability, agglomeration, and the possibility for heightened viscosity during the integration of nanofluids into mechanical systems. Ongoing exploration and advancement in the realm of nanofluids present promising prospects for augmenting lubrication efficacy and bolstering resistance to wear. Exploration can be pursued through paths such as innovative designs of nanoparticles, enhanced procedures for dispersion, and utilization of new methodologies for tribological testing.

In conclusion, the use of nanofluids in mechanical systems offers a promising prospect for transforming lubrication technology and enhancing the durability and effectiveness of diverse engineering applications. Despite the presence of a few challenges, the potential advantages in this domain are considerable, rendering it a highly attractive field for continued research and practical application. With the continuous progress of technology and the increasing knowledge of nanofluids, it is foreseeable that substantial advancements will be made in the pursuit of improved lubrication efficiency and wear resistance in mechanical systems.

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