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Tribological Analysis of Lubrication Technologies and Their Impact on Machinery Lifespan

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This paper offers perspective on the special feature issue of Lubricants, a journal celebrating its tenth anniversary, with the theme "Current and Future Trends in Tribological Research: Fundamentals and Applications"[31]. With the application of numerous innovative techniques in industries, India has achieved remarkable progress in Science and Technology. To increase output at a reasonable cost, there is a pressing need for the purchase and upkeep of machinery and equipment. in order for tribology to be crucial for improved output, this study's data and analysis demonstrate how Indian industries are implementing new lubrication techniques. Since industrial tribology is still in its infancy, the government and private sectors of the Indian economy are focusing on research and development. This will lead to significant advancements in the field's future as tribology's subfields—such as Green, Nano, and Space tribology—as well as advancements in computation and dependable tools.

Keywords: Industrial Tribology, Green Lubricants, Automobile, Manufacturing.

1. Introduction

Global interest in the transport network and industrial activity has been sparked by energy and environmental sustainability. About one-fifth of the energy used in industrial systems is consumed by friction. Only one-third of all energy is used to get past obstacles [1]. The study of lubrication, wear, and friction—known as tribology—deals with preventing wear and tear on surfaces that move in relation to one another when under pressure. Jost first used the term "tribology" in 1966. The word "to rub" or "the science dealing with the rubbing of surfaces" is derived from the Greek word tribos[2]. Thus, wear and friction can also be referred to as lubrication science [33]. Approximately 23 percent of the energy used worldwide is used in tribological interactions. About 20% is used to reduce grinding, while 3% is used to replace worn-out components and excess hardware that has failed due to wear-related problems. Creative surfaces, materials, and lubrication techniques can reduce energy losses due to contact and wear by 18% in the short term and by 40% in the long term (15 years). Globally, cars, machines, and other equipment can have longer lifespans when there is less wear and friction. Over time, these savings would amount to 1.4% of the world's GDP and almost 8.7% of all energy used globally. As a result, while many creative technological solutions for lowering wear and friction have been suggested, they have not been extensively implemented [3]. Growing energy demands, precision manufacturing, miniaturisation, nuclear regulations, and essential economies all call for the use of efficient coolants and lubricants.

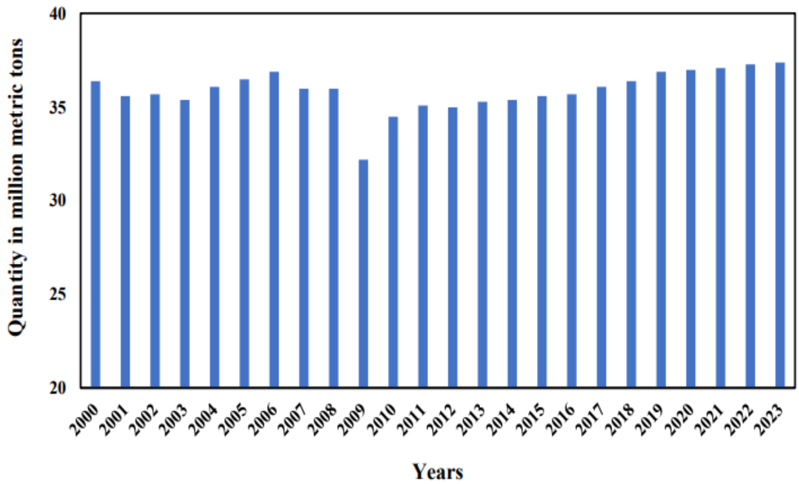

Figure 1: Global Demands of Lubricants from 2000 to 2023

Tribology is the study of two things: (1) the properties of the films of material that operate as an intermediary between contacting bodies; and (2) the effects of either film failure or lack thereof, which are typically indicated by extreme wear and friction. Reducing wear and friction—the two primary drawbacks of solid-to-solid contact—is the practical goal of tribology. But things aren't always like this. It is advantageous in some circumstances to maximise wear and maximise friction, minimise wear and maximise friction, or maximise both wear and friction. For instance, it is preferable to have less wear but not friction in brakes and lubricated clutches, less wear but not friction in pencils, and more wear and friction combined in erasers.

Numerous industrial applications needing relative motion, such as trains, cars, aircraft, and the production of machine parts, have made use of tribology. Tribology has an impact on our daily lives in addition to being significant for heavy industry. The principles of Tribology are being applied as two surfaces interact. It is impossible to walk, ride a bike, operate a car, or even write with a pen and pencil without friction [4]. These are some instances where friction is either required or advantageous.

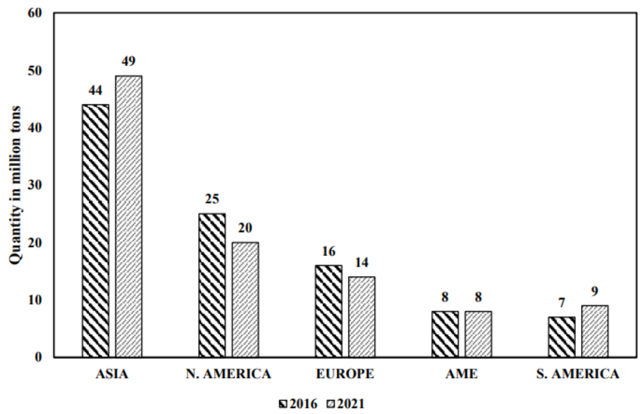

Figure 2: Global Demands of Lubricants of nations

The practice of applying grease—a material that reduces wear and rubbing—between two surfaces that are close to one another is referred to as oiling. Grease can be defined as a strong (such as molybdenum disulfide, or MoS2), strong/fluid scattering, fluid (such as water or oil), fluid scattering, oil, or gas. When using fluid lubricants, the applied load is either carried by the liquid being pumped under pressure between the surfaces or by the pressure created within the liquid as a result of the lubricating fluid's frictional viscous resistance to motion between the surfaces. It is a reality that tribology—the scientific study of wear and friction—has been recognised on its own. In essence, tribology is the study of wear, lubrication, and friction. It should come as no surprise that the human body uses blood as lubricant. Tribological applications entered the field of biomedical applications generally and heart-related operations specifically with the development of nano technology.

Given the detrimental effects of wear and friction, lubricants are essential in mitigating these effects on tribological processes. In addition to improving system performance, lubricants lower system temperatures in tribomechanical systems. Lubrication is an essential part of every maintenance type, working together to make the process work. Consistent performance and energy savings are the two main requirements for an environmentally friendly lubricant in mechanical systems[21]. Lubrication in the system is caused by the physio-chemical interactions between the lubricant molecules, material surfaces, and the environment [30].

2. Literature Review

Several research papers relevant to the nanoadditives, nanolubricants, development of nanolubricants, properties of lubricants and performance of journal bearings have been critically reviewed.

The production and processing of nanomaterials—materials with an average crystallite size of fewer than 100 nanometers—have become a new area of study made possible by nanotechnology [22]. Many studies on the use of nanoparticles as lubricant additives have been conducted within the past 20 years. Materials categorised as "nanomaterials" include carbon nanotubes, quantum dots, nanocrystalline materials, and nanocomposites. The four primary categories of nanomaterials are composites, metal-based, carbon-based, and nanosized polymers. The goal of mixing nanoparticles into regular engine oil is to increase heat conductivity and viscosity. Particles that are nanoscale in size actually solve problems that occur at high temperatures, improving the machinability, robustness, and lifespan of machine parts. [7]

Under boundary friction circumstances, [23] investigated the tribochemical mechanisms in the formation of lubricating layers in oils containing coordination compounds of transition metals. It has been shown that the synthesis of a tribopolymer nanocomposite from a complex molecule involves nickel nanoparticles. The experimental observations have been explained by a hypothesised mechanism. The study conducted by [9] examined the significance of lubricating fluids during cutting operations and the applicability of machining in manufacturing[6]. The explanation of diverse machining processes and a discourse on nanolubricants ensued. Further investigations focused on cutting boundaries such as cutting power, surface roughness, machining temperature, and environmental effects. The results demonstrate that, because of the characteristics of nanolubricants, they may be effectively used for cooling and lubricating in a range of machining processes.

The existence of a nano systemsize dependency on the potential energy of neighbouring atoms was explained physically in [10], and thermodynamic validation of this relationship is provided. Molecular-statics technique is utilised to simulate solid nanofilms of monoatomic metallic systems with an FCC structure utilising the Morse and Sutton-Chen potentials. A concept of the equivalent layer that forms mechanically integrated inclusions with nanoparticles in a fluid on their superficial surface was proposed in [24]. This can be interpreted as a significant rise in the volume concentration of primary particles, enabling the results of studies of nanolubricant viscosity to be explained by the current Bachelor formula. It has been discovered that the degree of agglomeration and the size of the primary nanoparticles affect the effective volume concentration. Moreover, published data indicates that the associated-layer thickness for particles less than 20 mm depends on the size of the nanoparticle.

An investigation of the wear and friction properties of Cu nanoparticles with surface alteration applied to 50CC oil was conducted in [12]. A four-ball analyzer was used to investigate the relationship between temperature and the tribological properties of Cu nanoparticles. SEM, EDS, and XPS were used to determine the morphologies, regular component transportation, and synthetic conditions of the ragged surfaces. Using a nano-space analyzer, the small mechanical characteristics of the jagged surface were examined in order to investigate the tribological interaction of Cu nanoparticles. The results indicate that the tribological capabilities of Cu nanoparticles improve with increasing applied oil temperature. Strong tribological performance is exhibited by Cu nanoparticles, particularly at elevated temperatures. The tribological properties of two cast iron pieces were investigated in [27]. Base oil and titanium oxide spherical nanoparticles added as additions were assessed through the use of a reciprocating slide tester in the friction and wear investigations. Using a homemade titanium nanolubricant, the friction between two pieces of cast iron was measured at 30–130°C on a friction test bench. Rolling qualities were given by spherical titanium nanoparticles that were submerged in oil for the two-iron friction test. The findings show that, even at higher temperatures, the friction coefficient attained with nanolubricant is consistently less than that attained with no nanoparticle oil. The nanoparticles' rolling action, increased viscosity, and surface healing capabilities make them an excellent lubricant. Titanium nanoparticles in spherical form provide benefits in tribology and other fields.

On the basis of comprehensive review of available studies, following gaps have been identified:

- There is a scope for study of improving tribological industrial revolutions properties.
- No research work has been done on the study of Impact of Tribology on the Industry[8]
- Limited research work has been carried out in order to determine the The effects of wear reduction and friction and tribology[13].
- Further, no study is conducted to investigate the static characteristics of Potential savings by tribological advances

Tribology's sustainability and newly developed eco-friendly lubricants have drawn a lot of interest. reports on the importance of lowering health and water problems while improving environmental compatibility. These days, new lubricating additives that are good for the environment are also being produced. Numerous aspects of green tribology are covered by Universitas & Minh (2020). Tribological problems can arise from other energy sources. An important example is the problems with wind turbine maintenance. Novel methods of lubricating wind turbines, as well as surface treatments including dark oxidation and guidance, are being developed specifically for them [8]. Reducing operational and maintenance costs is made possible by keeping an eye on wind turbine conditions.

Here the paper includes section 1 reviews the introduction following the section 2 analyses the related work. Section 3 explains the proposed tribological applications and section 4 demonstrated the discussion of the machinery life span in tribological works, finally section 5 concludes the work.

3. The Industrial Revolutions of Tribology

The first industrialization, sometimes referred to as the "industrial revolution" or the "age of steam," was marked by the use of the steam engine. It has to do with motorization and the transition from an agrarian to a modern culture. It began in the early years of the seventeenth century. Steam power, textile production, and mechanical engineering comprised the majority of the water and steam-powered industrial machinery. [14]. The second industrial revolution is referred to as the "electrical age". Between the end of the nineteenth and the start of the twentieth century (1840–1901), there was a significant increase in large-scale production, which was linked to the misuse of electrical energy. Its defining characteristics included the widespread use of oil and power, the severe division of labour, the growth of the rail network, and the increase in the production of steel.

The computer age, sometimes known as the "data period," is largely responsible for the third modern revolution. Currently, industry is using original data and correspondence innovation (ICT). The 1960s marked the beginning of Industry 3.0 in the 20th century. While some researchers argue that it came to an end in the 1990s or around the year 2000, others maintain that it is still a stronghold and has been perfectly absorbed into the upcoming contemporary period, also known as the fourth innovation revolution. Its distinction is in the way that industry uses electronics and information technology, or the "digital revolution.[11]" The first programmable logic controller (PLC), MODICON 084, went into manufacturing for sale in 1969. Every now and then, people refer to this day as the significant date. [15].

3.1 Tribology industrial 4th revolution

The organization-based association of real actual objects and people with virtual ones characterises Industry 4.0, sometimes referred to as the "period of cyber physical systems" or even the advanced unrest. The interconnectivity of creation frameworks is greatly impacted by the linking of machines, the Internet of Things (IOT), and the ict into proposed "cyber-physical systems" (CPS). Many people consider it to be the beginning of the twenty-first century. The year 2011 is noteworthy because it was then that the term "industry 4.0" was introduced as a high-tech strategy by the German industry at the Hannover Messe industrial trade exhibition [28]. The industry 4.0 environment was later defined in the final report of the German industry 4.0 working group, which was later formed. Following that, during its 2015 World Economic Annual Conference, industry 4.0 concepts were fully accepted. The third modern transition is quickly being surpassed by the fourth. A few academics argue that the term "advancement" is a better way to describe the developments than "revolution" because most of the essential components are already in place and only a few more need to be made. The primary change in any case is digitization.

3.2 Impact of Tribology on the Industry

- Tribology of polymers

The study of the bond, weariness, and scraped spot of polymer materials in a frictional environment is the foundation of polymer tribology[16]. Essential polymers can be applied in a variety of tribological contexts due to their fundamental properties; they are most frequently used as lattice and fillers in composite materials. Several components of tribology systems have recently been made using polymer nanocomposites. These rely on the significant findings of research on polymer erosion and wear, which consider the impact of load and temperature on the contact despite the viscoelasticity of the polymer and the determination of the actual area of contact. As ceramics cannot be used in the same way as metals to prevent wear, as is well known, e.g., by applying external lubricants. Our understanding of the mechanics underlying tribological phenomena cannot be applied to polymers. Polymer mechanical characteristics are directly affected by polymer chain entanglement. In light of polymers, it follows that certain compound designs often affect the tribological characteristics of materials [25]. Polymer tribology considers the wear and grinding consistency of polymers and polymer-based composites. Despite the complex relationships between adhesion and disfigurement, the standards of polymer tribology suggest that these two phenomena are what cause grating. Surface powers cause the grip portion, which results from interfacial bonds forming at the contact locations. The distortion component is caused by the polymer's resistance to deformation, which is greatly impacted by the properties of the material. Under these circumstances, erosion boundaries, mechanical characteristics, and polymer modification all have a significant impact on polymer wear. Tribological applications are numerous because of the polymer's versatility in mixing and combining with different fillers. Nanocomposites based on polymers show potential for a greater variety of uses. In the study of friction, adhesion and deformation are essential[28]. All materials, including polymers, can be processed using this procedure. The formation and breaking of connections between the actual points of contact on the surfaces does not permanently establish the grip portion. Hydrogen holding and Van der Waals dispersive interactions are typical characteristics of most polymers[19]. When asperities are sheared away and partner surfaces are shifted, interfacial connections are broken. Consider a completely level, temper-free surface as your perspective source. There will always be asperities or "bumps" on a rough surface. Above all, bumps indicate that the two interacting surfaces have a smaller effective contact area than the nominal size of perfectly flat surfaces. As a result, the friction drastically reduces. The prior explanation for this phenomena was described by the bump model.

- Tribology in hot metal forming

Hot rolling, hot manufacturing, and hot expulsion are some examples of hot framing techniques that use intensity to manufacture metal under stress. "Hot rolling" is the most popular method of reducing a bar's or chunk's size by passing heated metal pieces through rollers. Through this interaction, a short, thick thing becomes longer and thinner. This process, which is completed at a hot moving factory, is only applied to products that frequently don't require exact resiliences. "Hot manufacturing," or simply "producing," is the process of using any type of press or sledge to mould metal at high temperatures. Both small, accurate pieces and a broad variety of lengthy product shapes can be produced with hot forging. When a hot steel clear or workpiece is confined through a bite the dust with the appropriate cross-segment for hot expulsion, the cross-segment of the ejected component is reduced. The portion that is expelled will have a uniform cross-segment or structure throughout and a drawn-out grain structure [13]. Numerous devices, components, and processes operate at elevated temperatures. Examples of components are those utilised in the metal forming, aircraft, and power generation industries. Although metal forming has been practiced for millennia, there are numerous distinct processes involved in the process as well as numerous unexplained phenomena, particularly with relation to the tribology of the various processes. The majority of hot metal framing techniques excite uncomfortable. It prevents metal from flowing between equipment bites into the dust during open-pass manufacture, and it provides immediate back strain during closed-door bucket production to ensure that the pass-through cavity is filled. For example, it allows the metal to be drawn into the space between the rolls during rolling. In certain other frame applications, such as expulsion, a low degree of grating could be preferred in order to maintain a low shaping tension. These illustrations clearly demonstrate the significance of high and low rubbing for metal layout. The frame conditions and the heap (energy) should be adjusted to the optimal grinding level [14]. Wear and friction during metalworking are significantly influenced by the creation of different tribolayers. More studies have been conducted recently on the effects of high-temperature tribolayers. Jiang et al. put up a model to show how tribolayers arise. They proposed that wear debris may, in turn, be removed from the tribosystem or get trapped inside the wear-induced notches. The trapped debris will then modify the tribological response. If the debris is firm, it may act as free-moving particles and cause abrasion. As they glide, the particles may compress to form layers that prevent wear. The chemical sintering process that occurs between the particles in an oxidational environment also aids in the consolidation of these layers [29].

- Tribology Associated with Oil

The house's sliding surfaces are regularly oiled to stop squeaking or to prolong their lifespan. The lubing machine prevents seizures and prolongs their life. While friction reduction has not received as much attention as seizure or wear in the 20th century, it was vital in the 18th and 19th centuries during the construction of railroads and the widespread use of animal power. With the rise in petrol prices, which began in the early 1970s, it has become increasingly significant once again. Common definitions of a bearing's needs include stiffness, dynamic behaviour, and load carrying capacity. Excellent design considers various nonmathematical elements, like how to account for misalignment, handle starting and stopping a bearing, and how lubrication is delivered, even though many of these properties may be precisely described [23].

3.3 Friction and wear's effects on energy use, financial losses, and emissions

We used reference data from previous contextual assessments in our computations to provide explicit data on the impact of grinding, since street cars account for 75% of the energy used in the transportation industry[18]. Regarding the contemporary area, relevant data can be obtained from two studies: one examines the effects of grating on a highly automated, state-of-the-art fabrication industry, such as paper production; and the other examines the effects of wear and erosion on a deeply established, significant, but low-tech industry, mining (see reference Fig. 3. Regarding wear, the primary industry that we have thoroughly examined is the mining sector; wear in this area is substantially more important than in other contemporary fields that do not experience comparable levels of wear[33]. According to the mining study, of the overall maintenance costs associated with mining, half may be deduced from the production of discarded new components, and the remaining half are caused by labour costs, support costs, and margin time [33]. Utilising data on various areas' support costs (refer to Fig. 4), we estimate the costs associated with wear in these budgetary scenarios. Our analyses are predicated on the knowledge that maintenance expenses are directly related to the cost of worn components. The next sections will evaluate the energy miseries resulting from rubbing and wear in the four major energy-consuming endeavours: transportation, industry, energy industry, and private. The business section deals with assembly and creation areas, and the energy area deals with power plants used for power generation and warming.

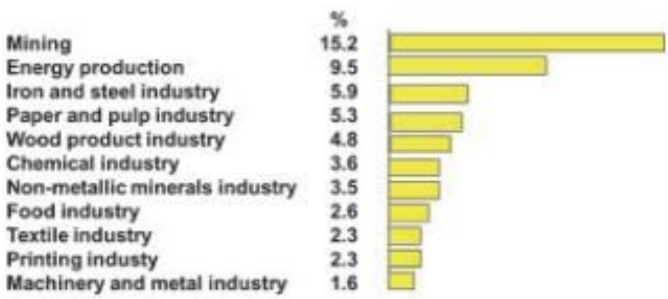

Fig. 3 Maintenance costs in Finland's contemporary areas in 1997.

3.4 Impact of tribology and friction and wear reduction

Over the past few decades, there has been a significant advancement in the discovery of novel tribological methods to lower wear and friction. Fig. 4 illustrates this progress by displaying the average grinding coefficients in tribological contacts found in trucks and transports today, along with the lowest values currently estimated in research labs and the characteristics anticipated for vehicles operating in 2025, considering contact and grease systems. The mechanical devices employed in the four economic domains, the extent of recently implemented innovation agreements, and functioning conditions are taken into consideration. Thus, the lowest levels predicted in research labs currently, levels predicted to be achievable later on up to 2030, and the average wear and grating levels of the current devices are identified and compared with the overall rubbing and don decrease in the current new advertisement gadgets. The following are the names of these levels: "Laboratory 2017," "Average 2017," "New 2017," and "Future 2030".

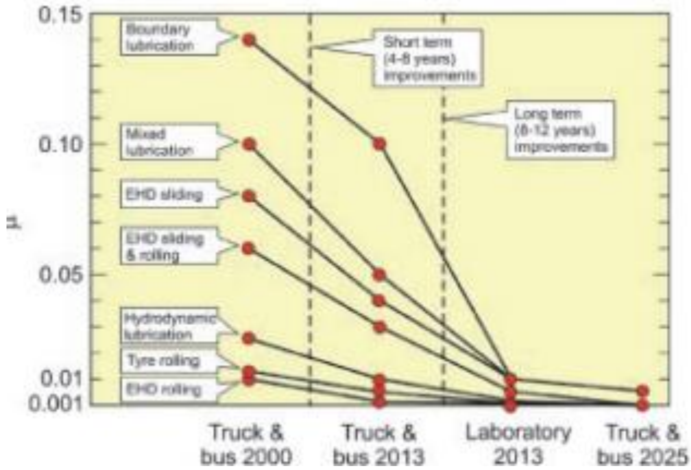

Fig. 4 Patterns in the decline of the coefficient of contact for different grease components and moving grinding in trucks and transports.

3.5 Tribological impact today and in the future

According to the estimations, 103 EJ of energy are currently needed globally to combat friction, and wear also results in a 16 EJ energy loss. Globally, friction and wear cost 250,000 million euros, and they produce 8,120 million tonnes of CO2 emissions overall. To our knowledge, this is the first time that the effects of wear and friction have been precisely calculated at this level. A comparison of the effects of wear and friction at the global level is presented in Figure 5. Friction has an impact that is six times more than wear's in terms of energy losses and CO2 emissions, and it has an impact that is three times greater in terms of the economy.

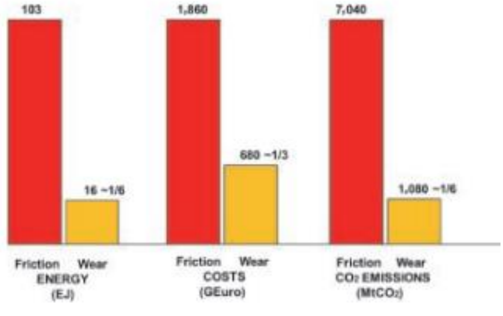

Fig. 5 Energy consumption, costs and CO2 emissions due to friction and wear globally.

3.6 Potential savings by tribological advances

Since there are large fleets with few owners, truck and bus manufacturers are more technologically savvy and quick to incorporate new technology into their vehicles, hence the implementation period is regarded as being quite short. This isn't the situation in the mining sector, where a lot of owners have doubts or unfavourable opinions about the use of modern technologies. Although paper machines have a longer lifespan than other types of machines, implementing new technologies takes time because of the need to recover existing investment plans. The review determined that the normal execution time in all areas should be 8 years for the present and 15 years for the longest duration achievable based on the average item lifetime, the shared ability to incorporate new innovation into things, and the construction of the four areas. It was decided how much money would be saved in the short and long run by shipping new grating and wear arrangements.

The widespread use of new innovation has the potential to reduce energy consumption by 21.5 EJ, emissions of 1,460 million tonnes of CO2 emissions, and 455,000 million euros over the medium term. The reserve funds have the potential to release 3,140 million tonnes of CO2, 46 EJ of energy, and 973,000 million euros over time. After 15 years, the reserve funds would account for 8.7% of global energy consumption and 1.39% of the GNP.

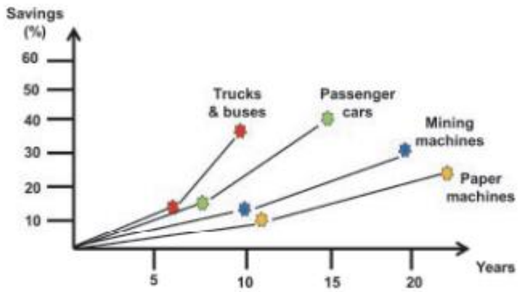

Fig. 6 Calculated potential savings over current state of the art by the introduction of advanced tribology solutions in four case studies and their time scale of implementation.

Figure 7 illustrates that the transportation and energy business sector have the largest potential savings over an 8-year period. In the industrial and residential sectors, the implementation takes longer, thus the short-term savings are not as great.

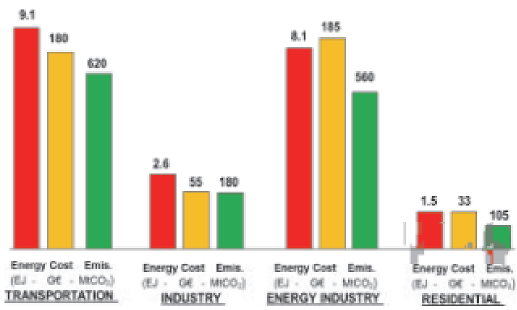

Fig. 7 Potential annual energy, cost and CO2 emission savings globally after 8 years of intensive advanced tribology implementation.

3.7 Tribology in Manufacturing Industry

One of the most important areas of tribological research is assembly area tribology. The decrease in liquids highlights the importance of investigating hot metal shape (contact and intensity transmission) [18]. The Base Amount Oil (MQL), a useful technique for applying cutting liquids by limiting their sum, is enormous in the current machining operations since it is cautious and naturally beneficial. Tribology may aid in the advancement of additive manufacturing by doing tribological investigations on freshly printed goods to learn more about their surface mechanical properties (friction, wear, lubricant contact). Direct integration of sensors and actuators into machine components is made possible by additive manufacturing. [20].

3.8 Tribology in Maintenance, Inspection, and Diagnostics

Most people understand that tribology plays a crucial role in support designing and It is essential to detect possible problems with a machine as soon as they appear when it is being operated in order to save margin time and associated expenses [7]. Headways in part-life expectations, such as moving orientation, research on depressing causes, demonstrative analysis, prognosis estimations, and maintenance of functional apparatus, are influenced by anthropology [4]. Moving orientation incorporates installed sensors that detect force, power, vibrations, and temperature. An additional choice is provided by a comprehensive condition monitoring system that combines sensors, power, diagnostics, and exchanges inside the course [4]. Expanded gear part life requires online ointment checking. Continuous estimations of wear garbage in the oil are conducted even though vibration examination is frequently used, either in conjunction with or independent of wear trash examination, to assess problems in machinery that incorporates moving heading and pinion wheels [4], [29]. Various approaches to verifying tribological conditions are explained. For space applications, maintenance-free mechanical congregations are anticipated, and research on tribological collaboration is essential for space applications with contemporary relevance. [7].

4. DISCUSSION

This paper provides a detailed discussion of the evolution of tribology within the framework of the research, showing how advances in engineering, materials science, and energy conservation have helped it advance over time[5]. It talked about how improved oil in machine parts reduces grating, which reduces energy consumption and reaps further financial rewards through obtaining a good deal on routine maintenance, part replacement, and ointment. In addition, it reduces personnel while increasing mechanical efficiency. In light of recent advances in tribology regarding energy utilisation, this analysis demonstrated how 33% of the energy wasted can be redirected and effectively used by the rate of contact decrease. The review examined the potential for reducing energy consumption in moving parts found in machinery, motors, and metalworking by advancing tribology through the use of liquid film heading. Additionally, this helps reduce the energy generated when machine parts come into contact with one another in situations such as internal ignition energy, where tribological advancements have lessened the release of harmful gases from the exhaust system of the various machines. This essay also covered the developments in the domains of materials, tribology, and erosive wear reduction in applications such as pipelines, in addition to the substitution of rubber-coated surfaces for conventional cast iron surfaces. It also revealed that applying a specific coating to surfaces such as those of tools and machine parts can reduce the rate of wear on those parts. Friction in its power and colloidal form is being reduced by the application of nanotechnology and tribological breakthroughs. When used in nanofluids, which are metal additions, metals' mechanical properties are enhanced.

5. CONCLUSIONS

The multidisciplinary nature of tribology and its wide range of applications in the physical sciences, engineering, and nature are discussed in the study. Tribology extends its reach and influence to merge with subjects like additive manufacturing, artificial intelligence, and biomimetics through its interactions with numerous other disciplines, including dynamics, vibration, thermodynamics, contact mechanics, surface engineering, rheology, and biology. With the application of numerous innovative techniques in industries, India has achieved remarkable progress in Science and Technology. To increase output at a reasonable cost, there is a pressing need for the purchase and upkeep of machinery and equipment. In order to ensure that tribology plays a significant role in improving production, this paper uses data and analysis to demonstrate how Indian industries are implementing new lubrication techniques. Since industrial tribology is still in its infancy, the government and private sectors of the Indian economy are focusing on research and development. This will lead to significant advancements in the future when tribology subfields like GreenTribology, Nanotribology, Spacetribology, Computation, and advancement reliable tools are added.

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