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TRIBOLOGICAL CHALLENGES ASSOCIATED WITH HYDROGEN IN INTERNAL COMBUSTION ENGINE

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ABSTRACT

Hydrogen internal combustion engines (H_2ICEs) have attracted increasing attention as a low-carbon propulsion technology due to their high thermal efficiency, near-zero carbon emissions, and compatibility with existing engine architectures. However, the fundamentally different combustion characteristics and physicochemical properties of hydrogen introduce distinct tribological challenges that can adversely affect engine durability and reliability. This overview paper critically examines the major tribological issues associated with hydrogen-fueled internal combustion engines, including the absence of carbonaceous soot, the nature of hydrogen combustion by-products, elevated combustion temperatures, lubricant degradation, and hydrogen-induced material damage. The influence of these factors on lubrication regimes, tribofilm formation, wear mechanisms, and material integrity is discussed based on recent experimental and analytical studies. By consolidating current understanding of hydrogen-related tribological challenges, this paper provides a technical foundation for future research aimed at improving the long-term performance and reliability of hydrogen internal combustion engines.

KEYWORD

Hydrogen fuel, tribology, greenhouse gas (GHG), automotive tribology

INTRODUCTION

The utilization of hydrogen as a fuel for internal combustion engines (ICEs) is a well-established concept rather than a recent development. The goal is to reduce the greenhouse gas (GHG) emissions. Global agreed to achieve net zero emission by 2050 as illustrated in Figure 1. Historical records trace its earliest implementation to 1807, when François Isaac de Rivaz constructed one of the first internal combustion engines operating on a hydrogen–oxygen mixture (Verhelst & Wallner, 2009). Interest in hydrogen-fueled engines intensified during the 1970s oil crisis, which stimulated extensive research into hydrogen as a potential alternative to conventional petroleum-based fuels. Studies conducted during this period, including those by De Boer, highlighted the long-term potential of hydrogen-powered engines. Nevertheless, the widespread adoption of hydrogen ICEs was constrained by the technological limitations associated with hydrogen production, storage, and infrastructure. In recent decades, the rapid expansion of renewable energy sources, particularly solar and wind power, coupled with increasing global commitments to carbon emission reduction, has revitalized research efforts toward hydrogen-based propulsion systems (Dincer & Acar, 2015). More recently, major automotive and engine manufacturers, including Toyota, BMW, and Cummins, have initiated dedicated development programs on hydrogen internal combustion engines, underscoring their feasibility for near-term commercialization, particularly in heavy-duty and off-highway applications. Collectively, these developments indicate that hydrogen internal combustion engines represent a mature yet evolving technology, continuously refined in response to energy security concerns and long-term sustainability objectives.

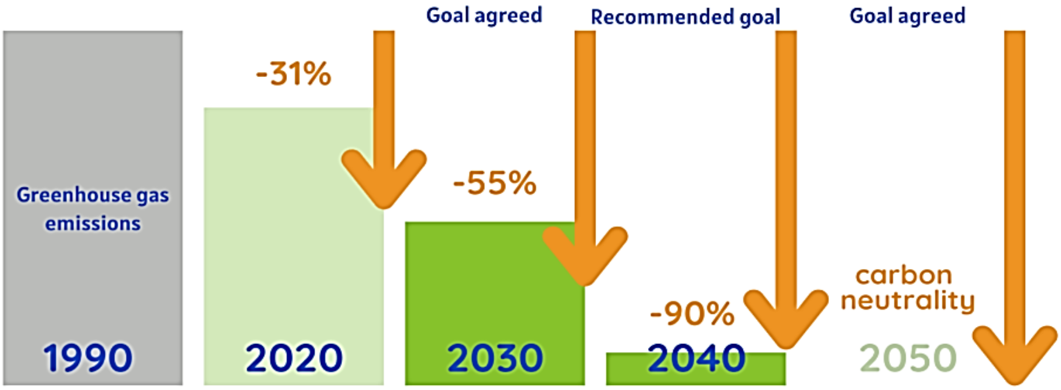

Figure 1: Target for GHG emission reduction (European Commission, 2025).

ADVANTAGES AND DISADVANTAGES OF HYDROGEN AS FUEL

Hydrogen offers several advantages as a fuel for internal combustion engines. Its wide flammability limits, high flame propagation speed, and low minimum ignition energy enable stable and efficient combustion across a broad range of operating conditions (Verhelst & Wallner, 2009). Hydrogen combustion produces water vapor as the primary exhaust product, resulting in near-zero carbon emissions. In addition, hydrogen exhibits a high gravimetric energy density (~120 MJ/kg), which can support high thermal efficiency when suitable combustion strategies are employed. A notable advantage of hydrogen internal combustion engines is their compatibility with existing engine architectures and manufacturing infrastructure, offering a cost-effective pathway compared to fuel-cell-based systems. Although modifications to fuel injection systems and air management are required, the performance and environmental benefits of hydrogen operation outweigh the associated increases in system complexity. Furthermore, hydrogen engines are well suited for applications demanding high robustness, such as heavy-duty, marine, and commercial vehicles, where battery-based solutions face limitations related to mass, durability, and refueling constraints

Despite all these advantages, hydrogen operation introduces distinct tribological challenges that directly affect engine durability and reliability. Rahmani reported that hydrogen combustion can adversely influence engine tribology due to its inherently low lubricity and the reduced presence of carbonaceous species in the exhaust, which limits the formation of protective boundary films on sliding surfaces (Pardo et al., 2018). A reduction in lubricant viscosity of up to 26% under hydrogen operation has been observed, increasing metal-to-metal contact and wear in critical components such as piston rings, cylinder liners, bearings, and valve trains.

Furthermore, Pardo reported a significant increase in metallic wear debris, including iron (17.7%), copper (29.3%), aluminium (21.95%), and chromium (27.4%), indicating enhanced wear and oxidative degradation. In addition, hydrogen diffusion into metallic materials may induce hydrogen embrittlement, thereby reduce mechanical strength, and accelerate fatigue failure, with degradation strongly dependent on operating pressure, temperature, and material composition. Elevated combustion temperatures in hydrogen engines further accelerate lubricant oxidation and additive depletion, highlighting the need for advanced lubricant formulations incorporating thermally stable base oils and tailored anti-wear additives. Collectively, these challenges underscore the importance of targeted research in materials selection, surface engineering, and bio-based lubricant development to ensure the long-term reliability of hydrogen internal combustion engines.

TRIBOLOGICAL CHALLENGES

The tribological challenges observed in hydrogen internal combustion engines primarily arise from the fundamental differences in combustion characteristics and fuel properties compared to conventional hydrocarbon fuels. Hydrogen's high flame speed, elevated combustion temperature, absence of carbon-based species, and low inherent lubricity significantly alter lubricant behavior, surface interactions, and tribofilm formation mechanisms. These differences lead to distinct wear, lubrication degradation, and material compatibility issues, necessitating tailored approaches in lubricant formulation, materials selection, and surface engineering.

SOOT FORMATION

Soot formation is a major tribological concern in conventional diesel engines, as soot particles generated during incomplete combustion can enter the lubricant through blow-by gases. Once suspended in the oil, soot acts as a hard abrasive contaminant, accelerating abrasive and three-body wear in critical engine components such as piston rings, cylinder liners, and bearings. High soot loading also increases lubricant viscosity, which disrupts hydrodynamic lubrication and promotes boundary or mixed lubrication regimes, thereby increasing friction and wear (Taylor & Coy, 2000; Green & Lewis, 2007). Although hydrogen-fueled internal combustion engines produce negligible soot due to the absence of carbon in the fuel, this reduction introduces a secondary tribological issue. The lack of carbonaceous soot limits the formation of protective tribofilms that typically arise from soot–additive interactions in conventional engines. As a result, anti-wear additives such as ZDDP may become the primary mechanism for surface protection, placing greater demand on lubricant formulation and additive stability. This shift highlights the need to redesign lubricants to compensate for the reduced surface passivation traditionally assisted by soot-derived films (Pardo et al., 2018; Newadkar et al., 2021).

COMBUSTION BY-PRODUCT

Combustion by-products significantly influence lubricant degradation and tribological performance. In hydrocarbon-fueled engines, by-products such as unburned fuel, sulfur oxides, nitrogen oxides, and partially oxidized hydrocarbons can contaminate the lubricant, leading to sludge formation, corrosive wear, and additive depletion. These contaminants alter lubricant chemistry, reduce alkalinity, and promote corrosive attack on bearing materials and ferrous components (Spikes, 2004; Mang & Dresel, 2017). In hydrogen internal combustion engines, water vapor is the dominant combustion by-product. While carbon-related contaminants are largely eliminated, water contamination poses a different tribological challenge. Dissolved or emulsified water in lubricants can reduce oil film strength, promote lubricant oxidation, and accelerate additive hydrolysis. Furthermore, water facilitates corrosion of metallic surfaces and may disrupt boundary film formation, particularly under low-temperature or intermittent operating conditions, thereby increasing wear risk (Pardo et al., 2018).

COMBUSTION TEMPERATURE

Combustion temperature plays a critical role in determining lubrication regime stability and lubricant durability. Hydrogen combustion is characterized by high flame speed and elevated peak combustion temperatures, which increase thermal loading on piston assemblies, cylinder liners, and valve train components. Elevated temperatures reduce lubricant viscosity, thinning the oil film and increasing the likelihood of asperity contact under high load conditions (Verhelst & Wallner, 2009; Heywood, 2018). Moreover, sustained high temperatures accelerate lubricant oxidation and thermal degradation, leading to viscosity increase, sludge formation, and depletion of anti-wear and antioxidant additives. Oxidized lubricants lose their ability to form stable tribofilms, resulting in increased friction and wear. These effects are particularly severe in hydrogen engines, where higher combustion temperatures combined with lean operation demand lubricants with superior thermal stability and oxidation resistance (Mang & Dresel, 2017; Dincer & Acar, 2015).

MATERIAL DEGRADATION

Material degradation is a critical tribological challenge in hydrogen-fueled engines due to hydrogen–metal interactions. Hydrogen atoms can diffuse into metallic components during combustion and high-pressure operation, leading to hydrogen embrittlement as shown in Figure

2. This phenomenon reduces ductility, tensile strength, and fatigue resistance, making components more susceptible to crack initiation and propagation under cyclic tribological loading (Gangloff & Somerday, 2012). The severity of hydrogen-induced material degradation depends on operating conditions such as temperature, pressure, stress state, and material microstructure. Ferrous alloys, high-strength steels, and certain bearing materials are particularly vulnerable. In tribological contacts, embrittlement combined with mechanical wear accelerates surface damage and reduces component lifespan. These risks necessitate careful material selection, surface engineering solutions such as coatings, and lubricant formulations capable of minimizing hydrogen ingress and surface reactivity.

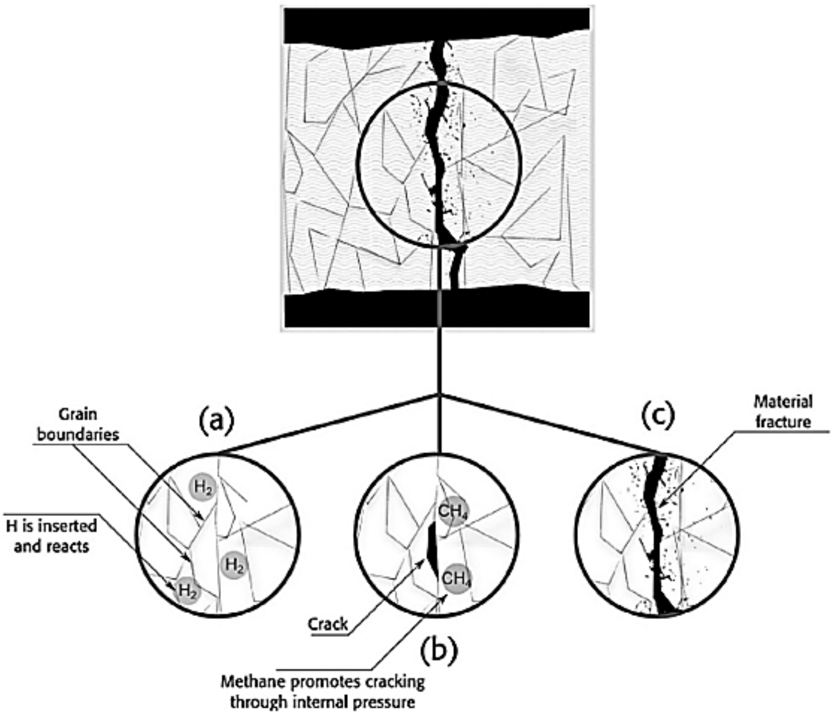

Figure 2: The mechanism of material degradation (Qayyum et al., 2024).

CONCLUSION

Hydrogen internal combustion engines represent a promising pathway toward low-carbon propulsion, offering advantages such as near-zero carbon emissions, high combustion efficiency, and compatibility with existing engine architectures. However, the distinct combustion characteristics and physicochemical properties of hydrogen introduce unique tribological challenges, including altered lubricant degradation pathways, reduced boundary film formation, increased thermal loading, and heightened risks of material degradation and hydrogen embrittlement. Addressing these challenges requires a multidisciplinary approach encompassing advanced lubricant formulation, optimized additive chemistry, improved materials selection, and surface engineering solutions tailored for hydrogen-rich environments. Continued research in these areas is essential to ensure reliable long-term operation and to enable the broader deployment of hydrogen internal combustion engines, particularly in heavy-duty and off-highway applications where durability and robustness are critical.

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