Friction

Review Article

Friction and corrosion properties of water–glycol fire-retardant hydraulic fluids (HFCs) and their modifications

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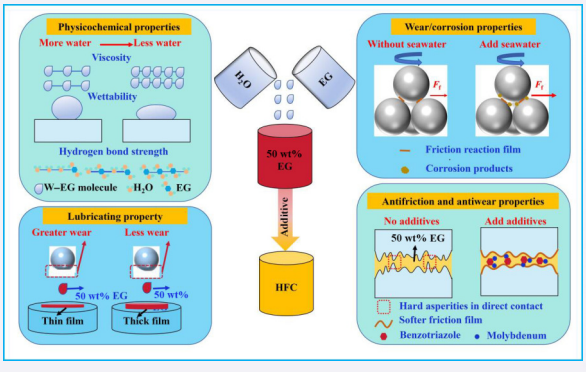
Cite this article: Wen XL, Gong P, Dong X, et al. *Friction* 2026, **14**: 9441199. https://doi.org/10.26599/FRICT.2025.9441199

ABSTRACT: The energy crisis and environmental pollution are worsening. Therefore, water-based hydraulic fluids, i.e., aqueous ethylene glycol-based, fire-retardant hydraulic fluid concentrates (HFCs), are becoming increasingly common. However, seawater intrusion inevitably occurs under marine conditions, generating hazards, such as corrosion and friction, within hydraulic system components, pipelines, and materials. Moreover, HFCs have several drawbacks, including low viscosity, inadequate lubrication, and high corrosivity. Therefore, the tribological characteristics and corrosivity of HFCs must be improved and reduced, respectively. This can be achieved using additives. Herein, we summarize the fundamental characteristics of HFCs and their modifications for use in the marine environment, focusing on the optimal water–ethylene glycol proportion and its influence on the physicochemical, lubricating, and tribological properties of this HFC under varying conditions. We discuss the latest progress on the effects of seawater on the tribological corrosion of HFCs and the reduction in corrosivity in the presence of different additives. Finally, we highlight challenges and propose future research to improve performance in the marine environment.



KEYWORDS: aqueous ethylene glycol flame-retardant hydraulic fluid; seawater environment; friction corrosion; compound additives; tribological characteristics

1 Introduction

Commonly used hydraulic oils include minerals, vegetables, and flame-retardant variants [1, 2]. These hydraulic fluids can be categorized based on their respective benefits, drawbacks, and future development (Table 1). In particular, the environmental impact of oil-based lubricants has drawn concern because of the energy crisis and increasing environmental pollution. The aromatic hydrocarbons in oil-based hydraulic fluids are primary pollutants characterized by high melting and boiling points, low solubilities, low vapor pressures, and high toxicity (including mutagenicity) [3]. Notably, the extensive use of petroleum oil since 1980 has caused severe marine pollution and reduced biodiversity [4, 5]. Furthermore, as industrial technology has advanced, hydraulic equipment is evolving toward the use of higher pressures, speeds, and temperatures, increasing the risk of hydraulic oil leaks from pipelines, pumps, and valves [6]. In addition, the use of high pressures and speeds with traditional oil-based lubricants increases service temperatures, potentially resulting in an explosion or fire, posing a safety risk to both humans and infrastructure [7].

Water-based hydraulic oils are eco-friendly alternatives, having excellent flame resistance and stability and making them an ideal hydraulic medium that addresses environmental concerns and the safety issues of oil-based hydraulic fluids. Water–ethylene glycol (EG) flame-retardant hydraulic fluid concentrates (HFCs) are the most important type of water-based hydraulic fluid and have advantages such as efficient heat transfer, compatibility with rubber, and shear and storage stability [8]. HFC comprises water, EG (or its derivatives), and additives [9]. Compared with traditional mineral oil-based hydraulic oil components, EG is biodegradable, has lower toxicity and a higher threshold, making it relatively environmentally friendly. However, the water content significantly affects the hydrogen-bonding structure and adsorption of EG on friction surfaces, impacting the break-in time and lubrication performance [10]. Characterized by

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Received: March 23, 2025; Revised: October 14, 2025; Accepted: November 26, 2025

Abbreviations

COF	Coefficient of friction	TEM	Transmission electron microscopy
EG	Ethylene glycol	WSD	Wear-spot diameter
HFC	Water–ethylene glycol flame-retardant hydraulic fluid	XPS	X-ray photoelectron spectroscopy
SEM	Scanning electron microscopy	δ	Wear rate

environmental sustainability, compatibility with multiple materials, and cost-effectiveness, HFCs have been widely applied in various fields. In aviation, they are used in starting hydraulic pumps, aircraft landing gear, and braking systems [11, 12]. Additionally, they are applied in mining equipment [13] and have potential uses in multiple industrial [14–16] and other applications [17].

Hydraulic systems are essential for the exploitation of marine resources (Fig. 1) because their high pressure, high power, and precise control characteristics make them a key component of the core equipment [24]. In offshore oil and gas exploration, hydraulic systems drive the lifting mechanisms of drilling platforms and subsea production valves to ensure stable platform positioning and reliable wellhead control, enabling the management of complex high-pressure conditions in the deep sea [25]. In deep-sea mining, hydraulic-driven mining machines and slurry conveying systems efficiently break down and collect minerals, significantly improving mining efficiency and enabling the long-distance transport of slurry via pipelines [26]. With respect to marine renewable energy, hydraulic systems convert wave oscillations into stable mechanical energy, providing continuous power output for tidal-energy converters [27]. These applications not only demonstrate the high reliability and adaptability of hydraulic systems in extreme environments but also highlight their potential for the sustainable development of marine resources.

To effectively manage the challenges arising from lifting hydraulic systems operating in high-salinity and high-humidity marine environments, the pressure resistance, sealing, wear resistance, and corrosion resistance of hydraulic components must be improved. Thus, the correct choice of hydraulic oil is crucial for improving operational efficiency, extending equipment service

Table 1 Classification of hydraulic fluids [18–23]

	Oil-based hydraulic fluid		Water-based hydraulic fluid			
Classification	Mineral-oil-based hydraulic fluid [18]	Plant-oil-based hydraulic fluid [19]	High-water-based hydraulic fluid [20]	Oil-in-water hydraulic fluid [21]	Water–EG hydraulic fluid [22]	Ester-type fire-resistant hydraulic fluid [23]
Advantage	High viscosity; excellent tribological properties	Good biodegradability, low ecological toxicity, excellent tribological performance	High safety, convenient storage and transportation, and no pollution	Excellent lubrication performance and good anticorrosion behavior	Good flame resistance, environmentally friendly, low cost, convenient storage and transportation, and high safety	High autoignition point, low volatility, and excellent fire resistance
Insufficient	High ecological toxicity, low biodegradability, high flammability and explosivity	Poor hydrolysis resistance, poor oxidation and corrosion resistance, poor low-temperature performance, and high cost	High cost, low boiling point, low viscosity, poor lubricity	Unstable and environmentally unfriendly	Poor lubrication performance	Poor hydrolysis stability, and the hydrolysis products are highly toxic
Development trend	Poor environmental performance; gradually being replaced	Environmentally friendly but costly; lacks economic benefits and universality	Domestic industries focus on cost-effectiveness, leading to low acceptance	Instability poses significant security risks; gradual loss in market share	Good safety and economy	It has been replaced by fatty acid ester type fire-resistant hydraulic oil

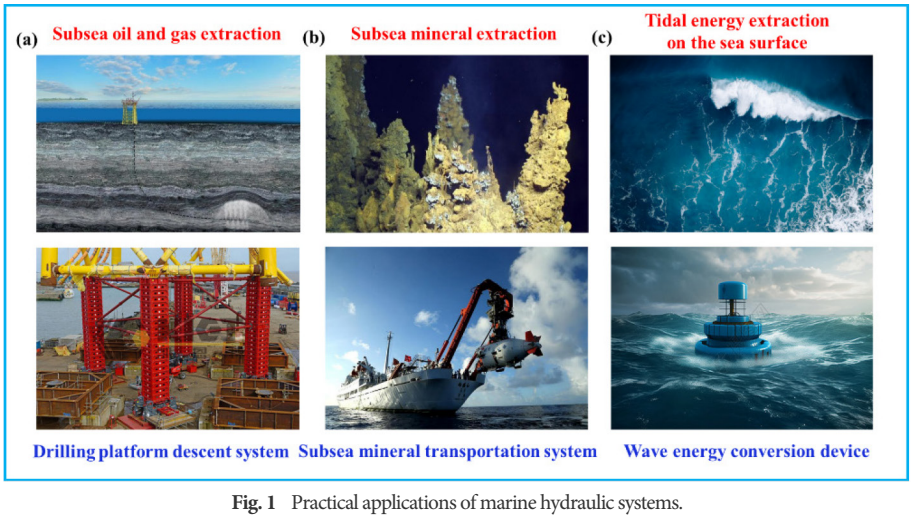

Fig. 1 Practical applications of marine hydraulic systems.

lifetime, enhancing environmental protection, and contributing to sustainable development [28, 29].

To understand HFCs and their performance optimization, we focused on mitigating friction and corrosion of HFCs and associated derivatives. In Section 1, we discuss the influence of the water content (the main HFC component) on the physical and chemical properties, break-in process, and tribological properties of EG-based HFCs. Next, the optimal water-to-EG ratio for aqueous EG is determined, followed by the mechanism through which its binding affects the tribological properties. Section 2 summarizes findings regarding the influence of seawater on HFC friction and corrosion, as well as the mechanism behind the loss of lubrication. These results were obtained by simulating seawater infiltration into an HFC prepared with the optimal water-to-EG ratio. Section 3 summarizes findings regarding existing additives and proposes solutions to address the degradation of the lubrication performance of HFCs in the marine environment to expand HFC applications further. All three sections of this review are related to the friction and anticorrosion properties of HFCs and their derivatives.

2 Effects of water content on EG performance as an HFC

Because HFCs are water-based hydraulic media, their performance depends directly on their composition, and the water-to-EG ratio plays a decisive role. Although high water contents significantly improve the fire resistance of an HFC, excessive water content reduces the viscosity and degrades the lubrication performance, thereby increasing the risk of increased friction with and corrosion of metal components. In contrast, increasing the EG content improves the lubrication and antifreeze performance of an HFC but reduces its fire resistance and increases costs. Because of this complex trade-off, the investigation of the optimal water-to-EG ratio is central to the development of high-performance HFC products. Therefore, the systematic investigation of the changes in the physicochemical properties, bonding interactions, and tribological behavior of aqueous EG-based HFCs with different water-to-EG ratios and the establishment of a quantitative component–performance relationship are crucial, both theoretically and practically.

In recent decades, the effect of water content on HFC performance has been extensively investigated, with a focus on its hydrophilicity. Both EG and water are polar compounds containing –OH bonds (Fig. 2(a)) [30]. Therefore, hydrogen bonds between electropositive hydrogen and electronegative oxygen form. Thus, EG has a strong affinity for water, and these two compounds are miscible in any proportion. Crucially, for use as HFCs, water–EG mixtures adsorb on friction surfaces as a result of the hydrogen-bonding network between EG and water, thus reducing friction and wear. Notably, the strengths of the hydrogen bonds between water and EG with different water-to-EG ratios vary significantly. For example, Wang et al. [31] examined hydrogen-bonding interactions in aqueous EG solutions with varying concentrations using Raman spectroscopy. They observed that, for water contents < 50 wt%, the primary hydrogen-bonding interactions were between EG and water. However, when the water content exceeded 0.5, intermolecular water–water hydrogen bonds began to dominate [31]. In addition, hydrogen bonds (EG–H_2O) are more common in mixtures than in a single medium (EG–EG) and (H_2O–H_2O), and in most cases, protons are transferred via the O atom in EG (Figs. 2(b)–2(d)) [32–34]. As the water content decreases, the hydrogen-bonded water clusters break down, forming more stable EG-H_2O interactions and increasing the viscosity [33]. Furthermore, when the concentration of EG is greater than 43 wt%, the rotation rate of the hydrogen-bonded EG–H_2O clusters decreases, leading to decreased proton transfer and a conductivity close to that of EG alone [34]. Zhang et al. [35] used theoretical calculations to show that the hydrogen-bonding ability of EG (via its –OH groups) mainly results from intra- and intermolecular interactions and its binding ability with H_2O increases with increasing EG content. These results indicate the substantial impact of the water content on hydrogen bond formation in this mixture. In addition, the water content significantly affects the physicochemical properties of EG solutions, such as the water activity [34, 36], thermal

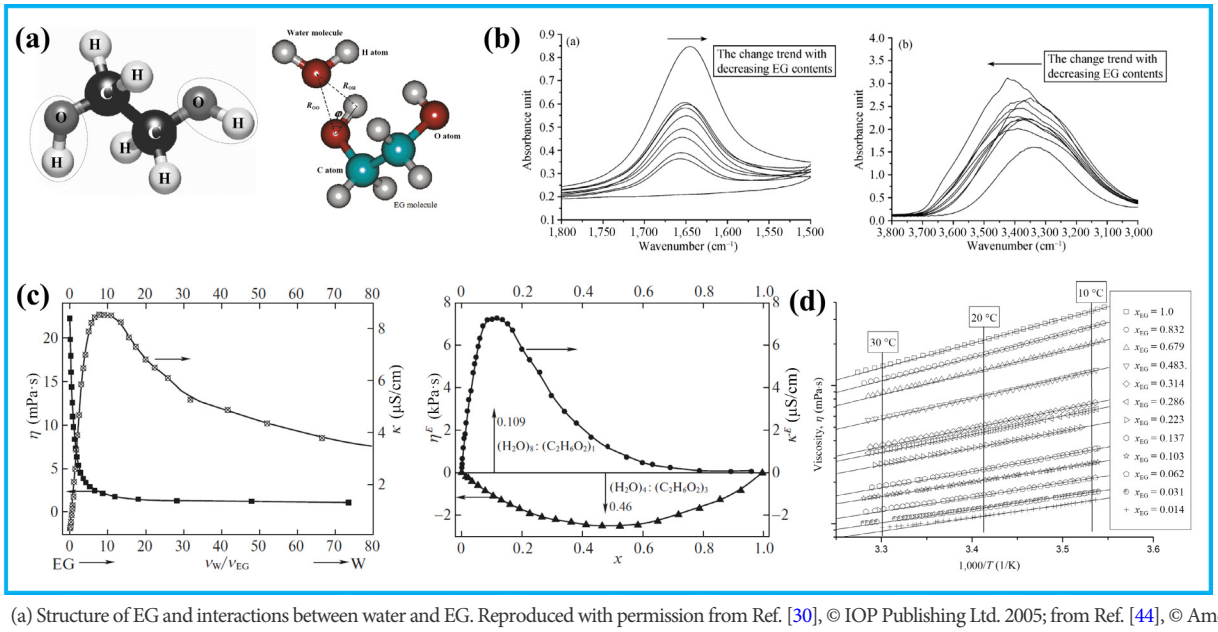

Fig. 2 (a) Structure of EG and interactions between water and EG. Reproduced with permission from Ref. [30], © IOP Publishing Ltd. 2005; from Ref. [44], © American Chemical Society 2011. (b) Fourier transform infrared spectra of aqueous EG solutions with different concentrations. Reproduced with permission from Ref. [32], © Science Press 2008. (c) Viscosity and specific resistivity. Reproduced with permission from Ref. [33], © Pleiades Publishing, Ltd. 2019. (d) Dynamic viscosity in the Arrhenius region. Reproduced with permission from Ref. [34], © Pleiades Publishing, Ltd. 2021.

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properties [37], viscosity–temperature characteristics [34], dielectric properties [38], and mechanical effects [39]. As the water content increases, the water activity and thermal properties of EG solutions degrade [34, 37]. In a previous work, we evaluated the impact of the water content on the viscosity and wetting of an EG solution using a rheometer and contact-angle-measuring instrument (Fig. 3) [40]. As the water content increased, the viscosity and adsorption of the mixture notably decreased, and the hydrogen-bonding strength of the mixed system changed markedly, which is consistent with the results of Ref. [31]. These changes could affect the properties of EG solutions used as solvents in catalytic reactions [41], hydrothermal synthesis [42], forced-convection heat transfer [43], and grinding processes for mechanical equipment components [44].

The water content not only affects the physical and chemical properties and hydrogen bonding mechanism of water–EG solutions but also has an impact on macroscopic friction, wear, and corrosion protection. Therefore, systematic studies on the lubrication and anti-wear properties of aqueous EG solutions on alloys, as well as the anticorrosion mechanism, have been carried out [45–49]. For example, a-CN_x coating containing sp^2 C=N/C=C and sp^3 C–N bonds was prepared by ion-beam-assisted deposition. The static contact angle of the EG solution on the surface decreased with increasing EG concentration, and the coefficient of friction (COF) was the lowest at 10% EG, only 0.019 (Fig. 4(a)) [45]. Furthermore, Li et al. [46] achieved an ultralow COF (0.004) for an EG solution with a water content < 50% via H^+ break-in in a Si_3N_4–SiO_2 system (Fig. 4(b)). Crucially, they identified the stable adsorption of H^+ on the friction surface. The formation of a hydration layer and elastohydrodynamic lubrication film from EG solution are two key factors for achieving macroscopic superlubricity. Recently, Kudo et al. [47] further elucidated the mechanism behind the improvement in the load-bearing capacity of Si_3N_4 in aqueous EG solutions using neural-network-based molecular dynamics (Fig. 4(c)). Theoretical calculations revealed that the chemical reaction between H_2O and Si_3N_4 under friction generates SiO_2 particles, whereas that between EG and Si_3N_4 generates C–N compounds with ring or chain structures composed of C and N atoms. At higher loads, with the failure of the SiO_2 lubricant, the C–N friction film effectively suppressed a sharp increase in COF, thereby improving the anti-wear performance of the Si_3N_4–Si_3N_4 system.

In addition, previous studies have shown that EG decomposes into acids, such as oxalic, glyoxylic, and glycolic acids, between 80 and 110 °C, which accelerates metal corrosion (Fig. 5(a)) [48]. In particular, increases in temperature, water content, and acid concentration lead to faster H_2 evolution and more severe corrosion at the alloy cathode. However, inorganic corrosion inhibitors adhere to metal surfaces by forming precipitates, reducing the contact between metals and the corrosive medium. In addition, organic small-molecule corrosion inhibitors have polar and nonpolar groups and form organic corrosion inhibition films on metal surfaces through chemical adsorption. In contrast, composite inorganic–organic small-molecule corrosion inhibitors can form denser and more stable corrosion inhibitor films, effectively inhibiting metal corrosion. For example, Liu et al. [48] prepared micro/nano hierarchical structures on smooth liquid-injected porous surfaces through plasma electrolytic oxidation and hydrothermal treatment, achieving good high-temperature resistance and oil film stability (Fig. 5(b)). After modification with low surface energy materials and the injection of silicone oil, the surface showed excellent lubrication performance, allowing the aqueous EG solution to slide off a surface tilted by 1.1° easily. In addition, the surface showed excellent corrosion resistance in aqueous EG, with a corrosion current rate four orders of magnitude lower than that of a smooth substrate.

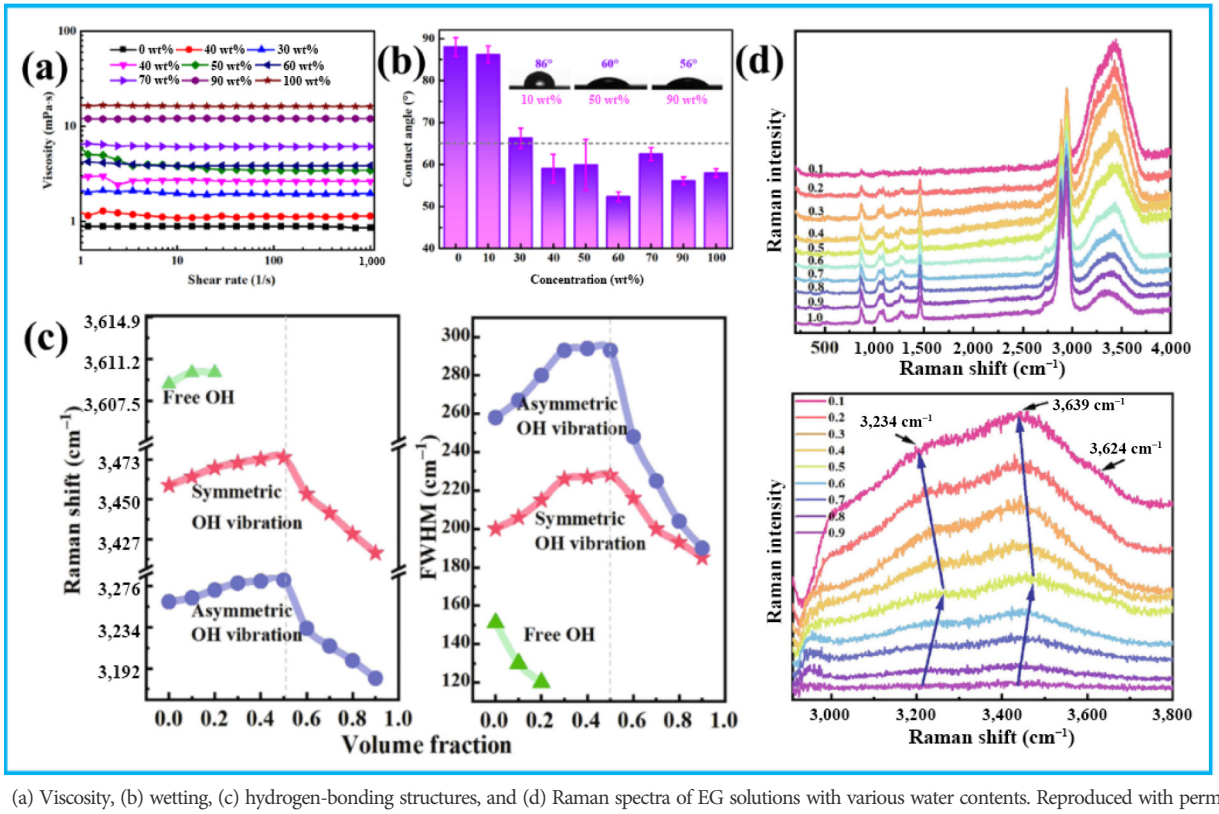

Fig. 3 (a) Viscosity, (b) wetting, (c) hydrogen-bonding structures, and (d) Raman spectra of EG solutions with various water contents. Reproduced with permission from Ref. [31] for (c, d), © Elsevier B.V. 2021; from Ref. [40] for (a, b), © the authors 2023.

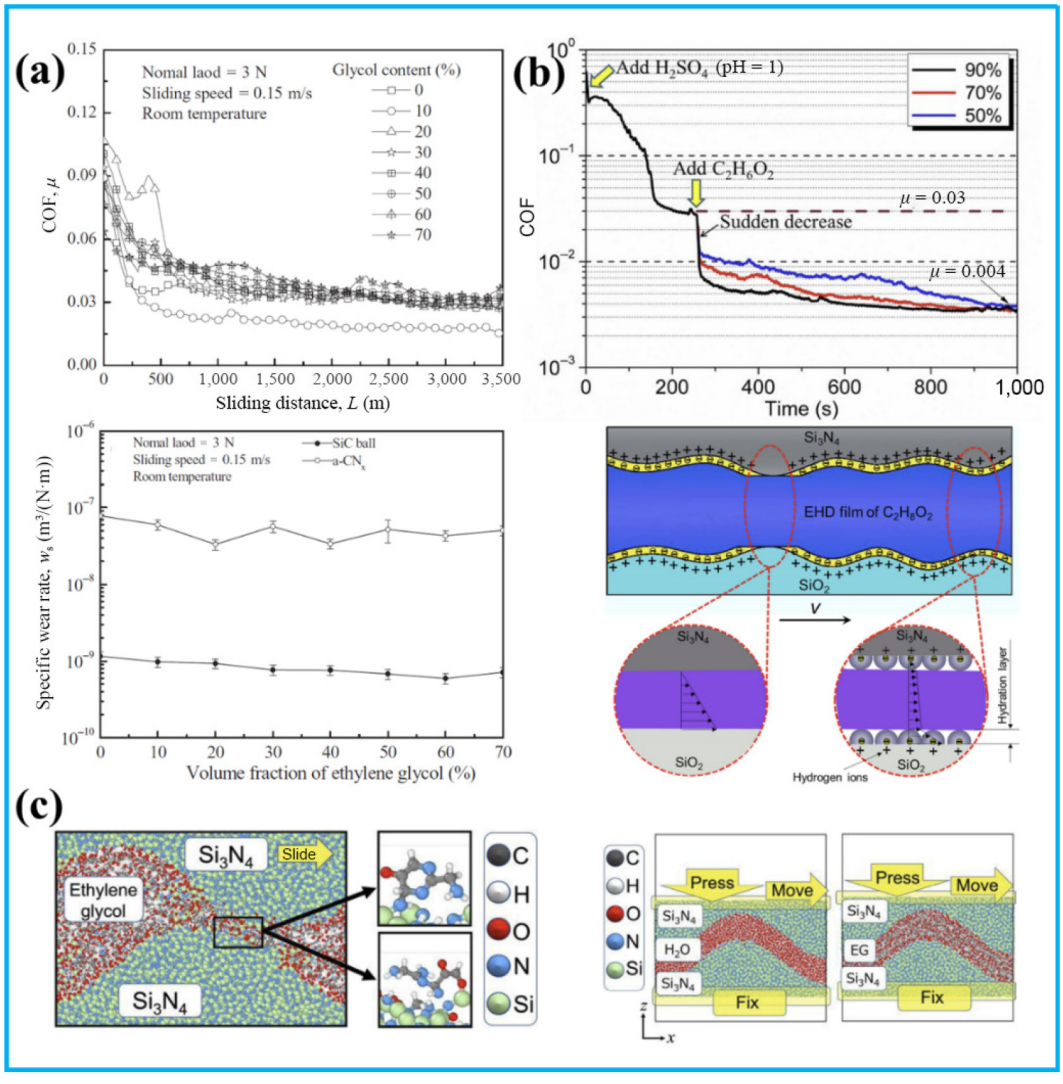

Fig. 4 (a) Lubrication and wear properties of EG solutions with different water contents in a SiC–a-CN_x system. Reproduced with permission from Ref. [45], © John Wiley & Sons, Ltd. 2010. (b) Lubrication properties and mechanism of action of EG solutions with different water contents after H^+ break-in in Si_3N_4–SiO_2 system. Reproduced with permission from Ref. [46], © The Author(s) 2014. (c) Kinetic analysis of chemical reactions of H_2O/EG solutions in Si_3N_4–Si_3N_4 system under friction. Reproduced with permission from Ref. [47], © The Author(s) 2024.

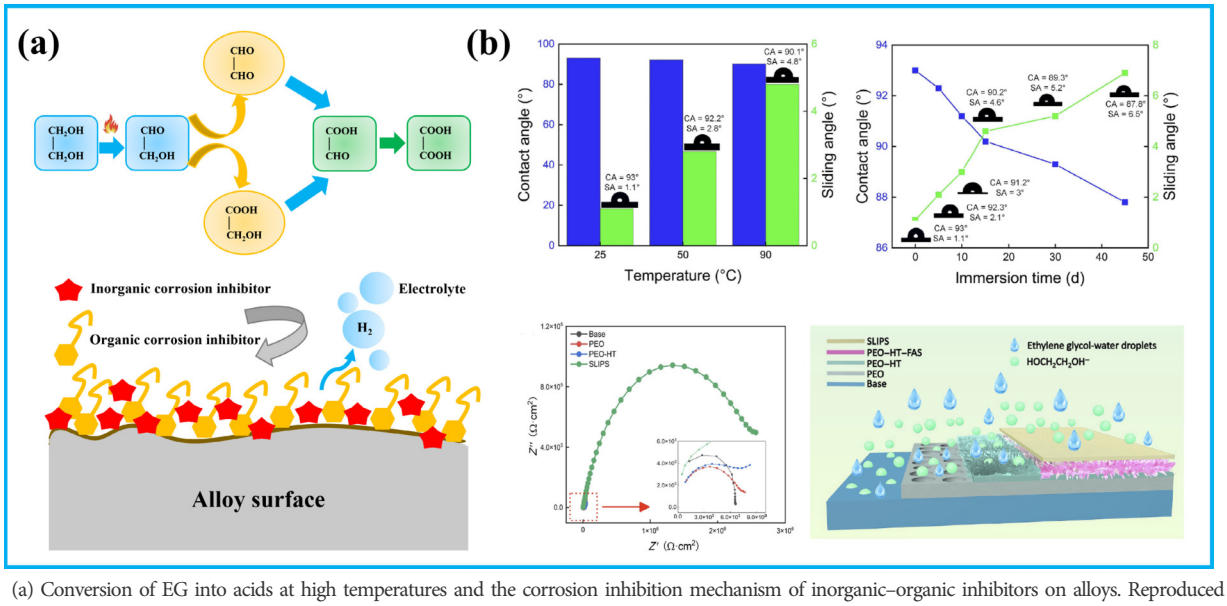

Fig. 5 (a) Conversion of EG into acids at high temperatures and the corrosion inhibition mechanism of inorganic–organic inhibitors on alloys. Reproduced with permission from Ref. [48], © Walter de Gruyter GmbH, Berlin/Boston 2023. (b) Wetting and electrochemical properties of EG solution on porous surfaces with lubricating properties and schematic of anti-corrosion mechanism on the surface of an alloy. Reproduced with permission from Ref. [49], © Elsevier B. V. 2024.

Recently, our research team utilized a universal microtribometer (UMT) multifunctional friction and wear tester to investigate the friction and wear behaviors of a Si_3N_4 ball–TiAlN disk system with water–EG solutions with varying concentrations. At a 50 wt% concentration, the water–EG solution showed stable superlubricity after 800 s of operation with minimal wear (Fig. 6) [40]. Furthermore, the strongest hydrogen-bonding interaction between water and EG was obtained at this water content. The results revealed a significant change in the hydrogen-bonding interactions between the water and EG with increasing water content [31]. This enhancement might arise from the ability of higher EG concentrations to disrupt hydrogen bonds between water molecules, thus forming a strong hydrogen-bond network between water and EG [50]. Under the same experimental conditions, the wear rate (δ) of Si_3N_4 balls decreased by 80.71%, and that of TiAlN disks decreased by 92.69% [40] in an aqueous EG solution containing 50 wt% water relative to that in pure EG; thus, long-lasting, efficient lubrication was achieved. Subsequent analysis of water–EG solutions with varying water contents using Raman spectroscopy revealed that the greatest hydrogen-bonding strength between water and EG occurred at an EG concentration of 50 wt%, which yielded a more stable $[H_2O]_m$–$[EG]_n$ binding structure [40]. This structure showed good resilience under specific loads and shear forces, enabling improved adhesion to the contact area of the friction pair, increasing the load-bearing capacity, preventing direct contact between rough regions, reducing the shear resistance, minimizing the running-in time, and enhancing the frictional performance of the water–EG solution.

Although extensive research has focused on water–EG solutions, limited research has been carried out using these solutions as HFCs. To investigate the friction, lubrication, wear, and corrosion characteristics of HFC for practical engineering applications, we examined the friction and wear performance of a commercial HFC under varying conditions using a four-ball friction and wear testing system [51]. With increasing load, the COF initially decreased and then increased. The lowest COF and δ of the HFC were recorded under a 392-N load (Fig. 7). With increasing rotational speed, the HFC viscosity, shear resistance, and COF decreased. The minimum COF was observed at a rotational speed of 1,200 r/min. A further increase in rotational speed reduced the oil film thickness and load-bearing capacity, resulting in a significant decrease in the anti-friction and anti-wear performance of the HFC. Furthermore, at temperatures below 55 °C, no significant changes in the HFC COF and δ were observed. This stability can be attributed to the thermal energy

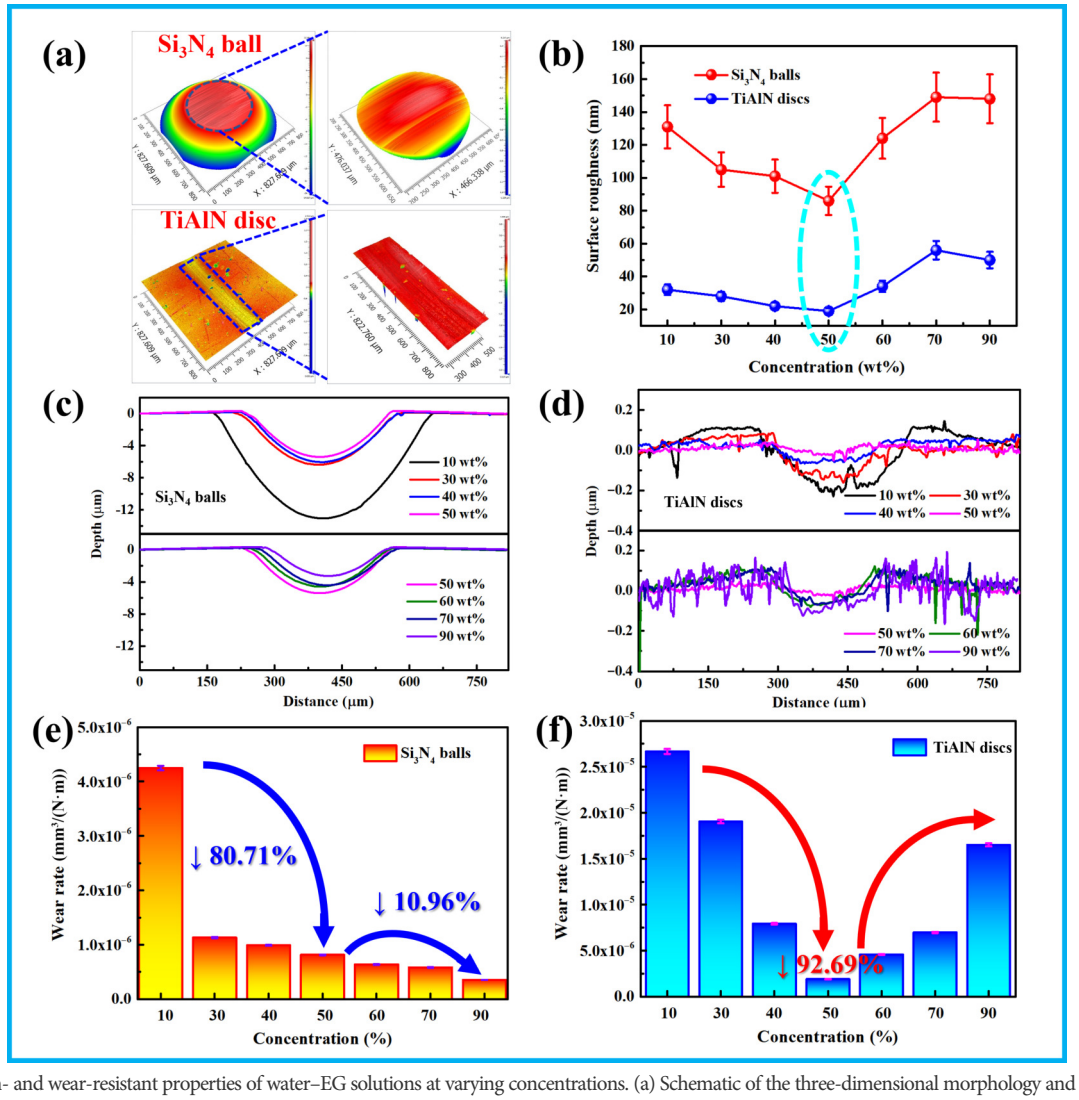

Fig. 6 Friction- and wear-resistant properties of water–EG solutions at varying concentrations. (a) Schematic of the three-dimensional morphology and comparison of (b) surface roughness, (c, d) wear depth, and (e, f) δ. Reproduced with permission from Ref. [40], © the authors 2023.

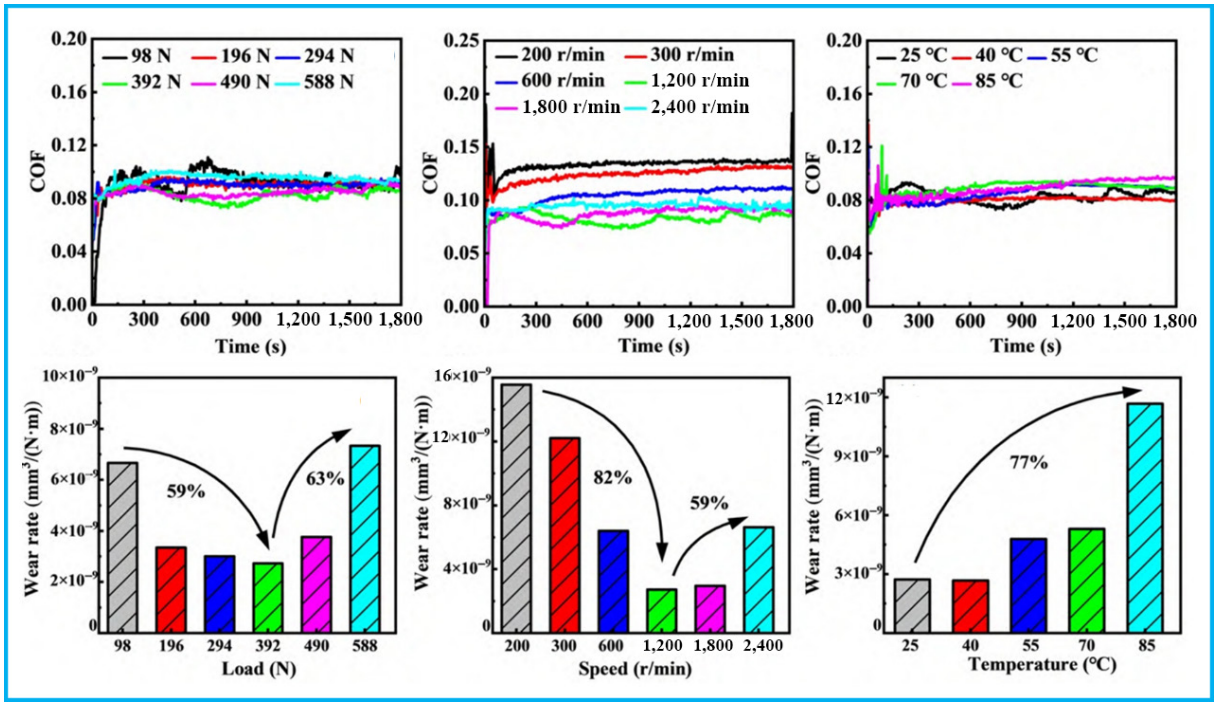

Fig. 7 Friction and wear performance of a commercial HFC under different operating conditions. Reproduced with permission from Ref. [51], © Editorial Office of the journal *Tribology* 2023.

generated by the sliding friction force upon contact of the friction pair, resulting in a localized increase in temperature at the steel-ball contact area. As the temperature increased, the HFC viscosity decreased; thus, the HFC lubrication performance decreased, whereas the COF and δ increased [51].

In summary, the water content influences the physicochemical properties of EG solutions. As the water content increases, the viscosity, adsorption performance, and surface tension of the EG solution decrease. The optimal ratio of a water–EG mixture is 1:1, which yields the most stable $[H_2O]_m$–$[EG]_n$ structure. This structure has the strongest hydrogen bonds, highest load-bearing capacity, and improved tribological properties, enabling stable superlubricity within a short run-in period and significantly reducing friction-pair wear. Thus, HFCs comprising water–EG solutions prepared at the optimal ratio with additives exhibit excellent friction performance and are widely used. However, limitations have been identified, such as unsuitability for high-load conditions (> 490 N) and high-temperature operations (> 70 °C). The findings summarized in this section provide an experimental and theoretical foundation for optimizing operating conditions and enhancing the performance of commercial HFCs.

3 Effects of seawater on friction and corrosion

In this section, the friction and corrosion performance of HFCs with a water-to-EG ratio of 1:1 is evaluated considering practical engineering applications. As the maritime power strategy of China has developed, the demand for high-performance hydraulic oil for use in various types of marine equipment, including deep-sea probes, hydraulic systems for marine platforms, and naval ship machinery, has increased. Seawater is highly saline and corrosive, and the marine environment has high humidity. Therefore, hydraulic systems have particularly stringent requirements. In this section, we summarize research simulating ocean operating conditions to evaluate key HFC performance indicators in the marine environment, including physicochemical properties, lubrication properties, wear properties, and corrosion resistance, systematically. The reported results provide an experimental and technical basis for engineering applications of HFCs in marine equipment.

HFCs are widely utilized in marine equipment, such as ship propulsion, hydraulic lifting, and underwater detection systems [52–54]. During ship operations, leakage from marine equipment (such as pumps, hydraulic drive systems, and blades) is common. Thus, hydraulic oil mixes with seawater, increasing the COF of the hydraulic fluid and energy loss. This leads to accelerated wear and corrosion of friction pairs, ultimately reducing their service life. Seawater intrusion can also induce severe corrosion in hydraulic equipment [30–32]. Since 1978, a significant proportion of ship engine failures have been found to result from the corrosion of lubricating oil systems following seawater intrusion. Notably, seawater contamination of lubricants can induce pipeline corrosion, and the produced rust particles can migrate to the bearings and cause substantial wear on their surfaces [55]. Therefore, in recent decades, the impact of seawater on hydraulic oil has been studied extensively [56–58]. The primary components of seawater are NaCl, $MgCl_2$, and Na_2SO_4. Furthermore, water has unique properties, including a low viscosity and high vapor pressure. Thus, when hydraulic fluids are mixed with seawater, their physicochemical properties are significantly affected; for example, the viscosity of the hydraulic fluid is reduced. Moreover, in the marine environment, significant changes in pressure and temperature occur with increasing seawater depth (Figs. 8(a)–8(c)) [15, 59]. For example, at a depth of 2,000 m, the temperature drops to 275 K. Furthermore, the pressure increases proportionally with depth. When the viscosity of hydraulic oil within a hydraulic system increases, more energy is required to counteract the shear force of the hydraulic oil during operation; thus, energy consumption increases. Crucially, the viscosity of hydraulic fluid increases with decreasing temperature and increasing pressure [15]. Consequently, in deep-sea

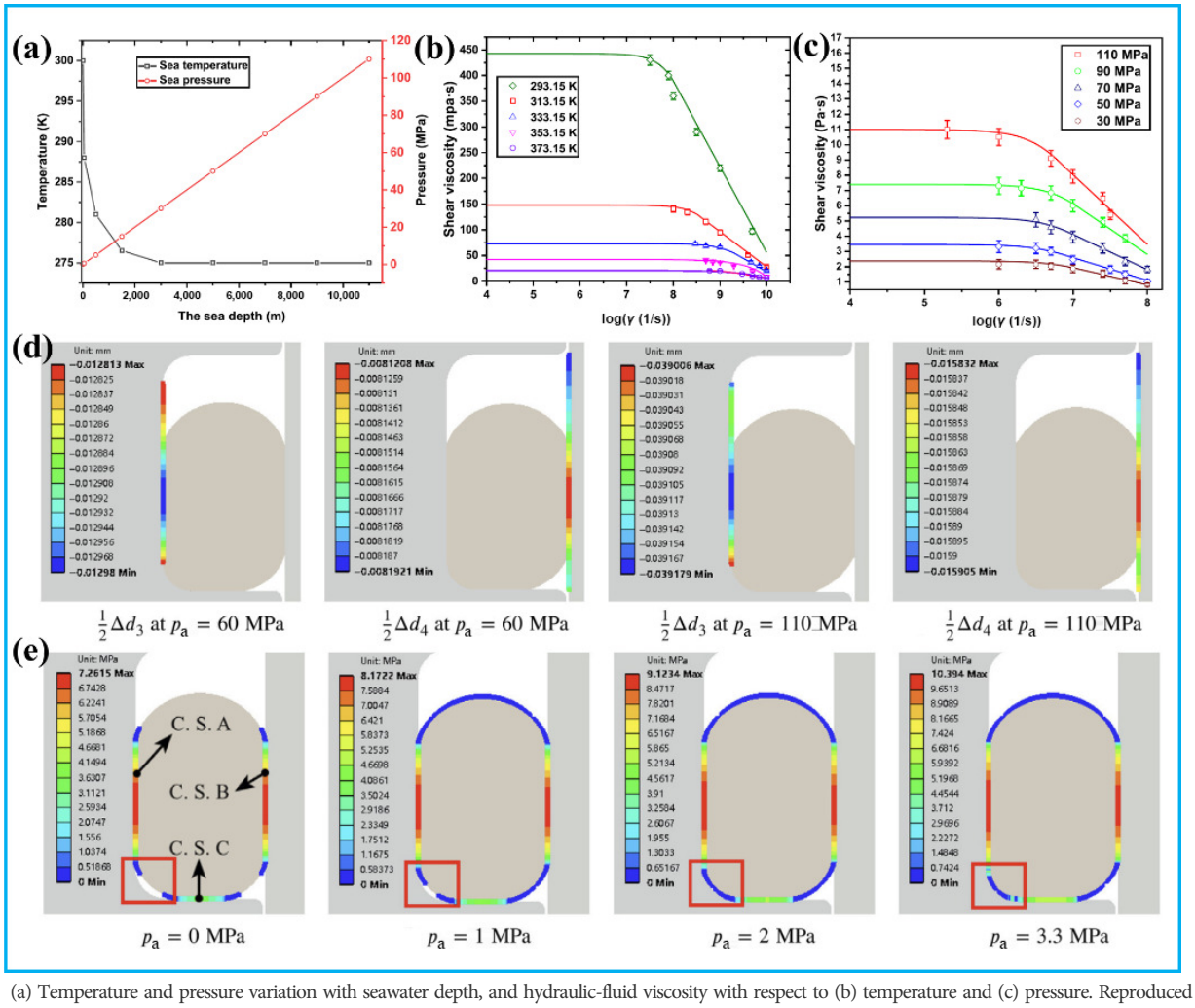

Fig. 8 (a) Temperature and pressure variation with seawater depth, and hydraulic-fluid viscosity with respect to (b) temperature and (c) pressure. Reproduced with permission from Ref. [15], © American Chemical Society 2023; from Ref. [59], © Elsevier B.V. 2023. (d) Radial deformation of shell size under different environmental pressures, and (e) O-ring contact pressure distribution. Reproduced with permission from Ref. [60], © Elsevier Ltd. 2022.

exploration, HFC viscosity increases exponentially with pressure, substantially affecting O-ring compression and structure. These changes further impact the lubrication and wear characteristics of hydraulic systems (Figs. 8(d) and 8(e)) [60]. Schatzberg and Felsen [61] reported that seawater infiltration exacerbated hydrogen embrittlement in equipment, manifesting as microcracks in the working area of the bearing, causing crack propagation to critical dimensions, and ultimately resulting in equipment failure.

The impact of seawater on the anti-friction and anti-corrosion performance of EG has also been investigated. For example, a decrease in lubrication by EG solutions after seawater exposure has been reported [62], as well as a reduction in corrosion resistance [63]. When seawater infiltrates a hydraulic system in large quantities, the increased water content thins the hydraulic oil film in the sliding bearing. This change significantly decreases the bearing capacity and lubrication performance of hydraulic oil, increasing energy consumption and decreasing service lifetime [64–66]. In addition to the viscosity, the thermal properties of hydraulic oil are affected by seawater ingress, altering the lubricating film and impacting the friction and wear performance. Notably, the reduced viscosity of hydraulic oil complicates the formation of an effective liquid adsorption film between friction pairs, reducing lubrication and increasing friction [11, 40, 67]. Zhuo et al. [68] investigated the effect of seawater mixed with water-based hydraulic oil on lubrication performance using a high-frequency reciprocating friction-testing machine. A significant increase in the COF and δ of the system was observed following mixing with seawater [68]. Additionally, the research on the wear behavior of bearings in artificial seawater has demonstrated that seawater can induce the wear and corrosion of friction pairs (Fig. 9) [68]. Xiao et al. [69] also examined the effect of seawater on hydraulic systems through ring–block experiments using rubber alloy bushings and copper bearings as friction pairs. They observed corrosion on the friction-pair surface, accompanied by adhesive wear [69]. Thus, when seawater infiltrates an HFC, it triggers corrosion and adhesion wear on the associated friction pairs, causing increased wear-and-tear of the overall hydraulic equipment and a significant reduction in service lifetime, directly affecting costs [70].

Research into the corrosion behavior of these three materials following the combination of EG with seawater has been carried out. Generally, the addition of seawater strongly affects the corrosion resistance of 316L stainless steel and cobalt tungsten carbide; specifically, both materials show signs of severe electrochemical corrosion [72]. Seawater can also induce corrosion in friction pairs via cavitation [71, 73–75]. For example, blending a 50% EG solution with seawater was found to increase the corrosion of 316L stainless steel [76]. Furthermore, the severity of corrosion increased with increasing temperature, which was related to the increased Cl^- concentration. A previous examination

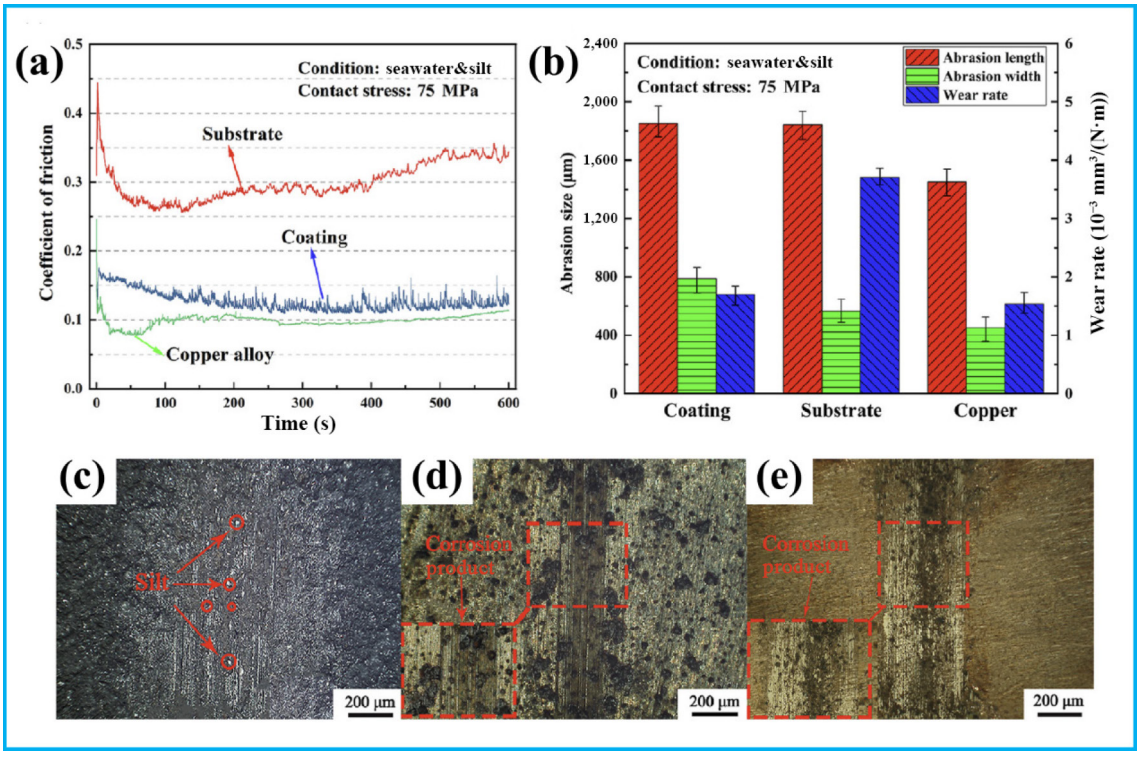

Fig. 9 (a) COF, (b) δ, and (c, d) wear morphologies of coating, substrate, and copper alloy under complex working conditions involving seawater and silt. Reproduced with permission from Ref. [68], © Elsevier B.V. 2023.

of the corrosion surface morphologies of pieces after the use of an HFC at 20, 50, and 70 °C revealed relatively smooth surfaces with minimal corrosion pits [76]. However, after the introduction of 50% seawater to the HFC (Fig. 10), substantial corrosion pits were evident at all temperatures and became increasingly severe at higher temperatures. This observation highlights the detrimental impact of seawater on the corrosion behavior of hydraulic fluids [76].

We have also studied the effect of seawater content on the frictional properties of a commercial HFC. We observed that with increasing seawater content, the frictional and wear properties of the HFC gradually decreased [77]. At 40 wt% seawater, more severe electrochemical corrosion occurred on the friction-pair surface. Overall, a higher COF and δ were observed with increasing seawater concentration. Figure 11 shows the microstructures and elemental analysis results obtained for the friction-pair surface following the friction experiment involving a mixture of HFC and 50 wt% seawater [78]. The analysis revealed the generation of numerous corrosion products outside the wear area. Furthermore, energy-spectrum analysis identified elements such as Mg and Cl in the corrosion products from seawater, as well as significant increases in the C and O contents. This indicates that severe oxidative corrosion reactions occurred on the friction-pair surface.

Thus, seawater can decrease the viscosity of hydraulic fluids and cause significant corrosion of friction surfaces. However, under specific conditions, seawater can also enhance the lubrication effectiveness of hydraulic fluids. For a friction pair of tetrafluoroethylene and GCr15 steel, a more stable COF was observed in the presence of seawater, and the surface roughness of the friction pair was greater after the friction experiments. This phenomenon is attributed to the formation of a mixed corrosion/friction product of MgOH and $CaCO_3$ on the friction-pair surface resulting from Mg^{2+} and Ca^{2+} ions present in seawater. This product effectively prevents direct contact between friction pairs [79]. Similarly, in a study investigating the impact of seawater concentration on the tribological properties of HFCs, we discovered that an HFC solution containing 50 wt% seawater formed a friction reaction film in the wear region of the GCr15 steel. This film prevented direct contact between the rough peaks of the friction pair, resulting in anti-friction and anti-wear effects (Fig. 12). Initially, the samples were tested in a 50 wt% seawater–HFC solution and a pure HFC solution. The samples were subsequently tested under identical conditions. The findings revealed notable anti-wear performance following exposure to an HFC solution containing 50 wt% seawater. The seawater may promote the formation of a friction reaction film on the friction-pair surface, thereby enhancing the frictional performance of the system. However, the specific compositions and structures of these reaction films remain unclear.

Inspired by earlier research, we used a four-ball friction and wear testing machine to evaluate the effect of seawater on a commercial HFC, THIF707 (Yantai Hengxin Chemical Technology Co., Ltd.). With increasing seawater concentration, the COF and wear-spot diameter of the HFC initially decreased and then increased. For a 35–45 wt% seawater concentration, the smallest COF and wear-spot diameter were obtained, as shown in Fig. 13. Subsequent comprehensive investigations revealed that the seawater produced a Mg-containing friction reaction film within the friction-pair wear region. This film effectively reduced the shear resistance, thereby enhancing the anti-friction and anti-wear properties of the HFC. Consequently, seawater does not entirely compromise the frictional properties of hydraulic fluids, and the inorganic salts present in seawater may precipitate on the friction-pair surface, forming a friction reaction film that further boosts the anti-friction and anti-wear attributes of the hydraulic fluid.

Therefore, the mixing of seawater with HFCs yields a mixture with lower viscosity, resulting in a thinner lubricating film and reduced load-bearing capacity, which degrades the lubrication performance. Seawater can also reduce HFC corrosion resistance,

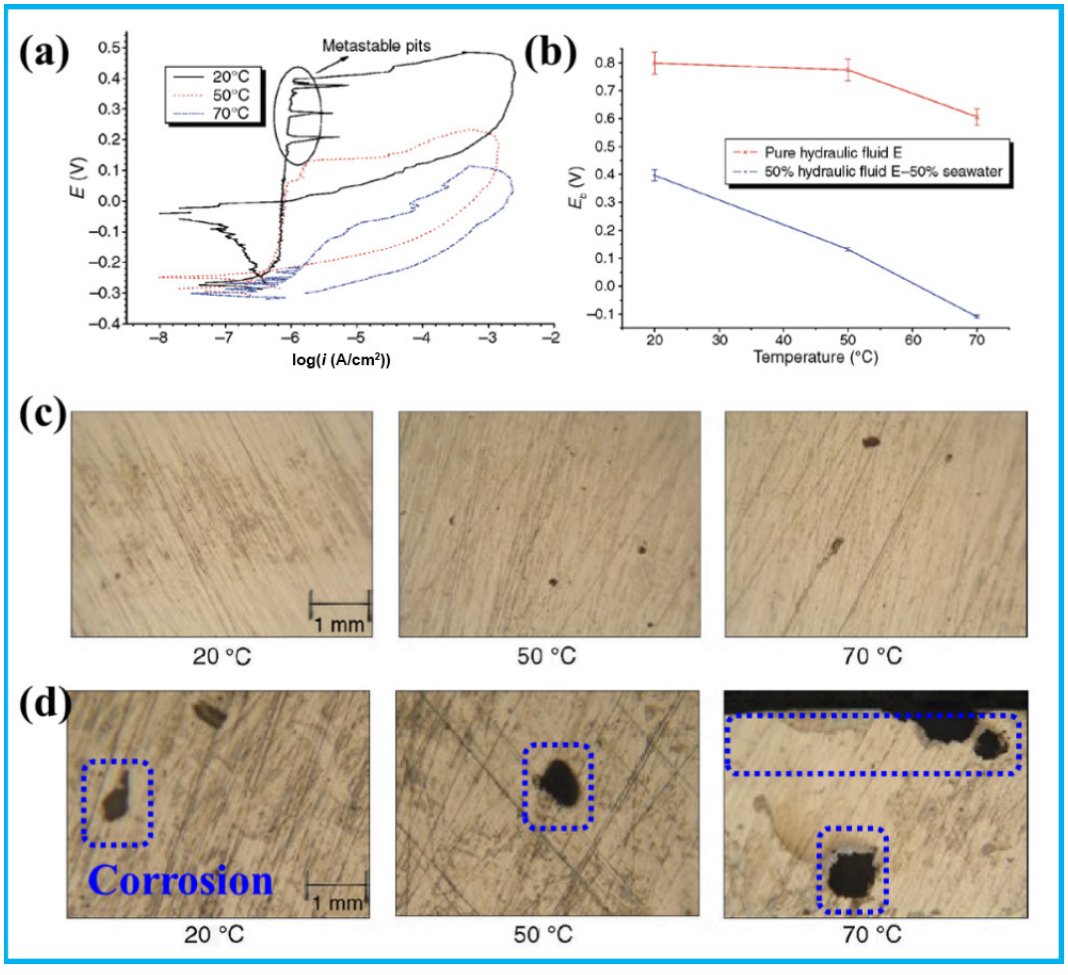

Fig. 10 (a) Cyclic potentiodynamic polarization curves and (b) breakdown potential. Corrosion-area morphologies of friction pairs at different temperatures: (c) HFC and (d) hydraulic oil mixed with 50% seawater. Reproduced with permission from Ref. [76], © NACE International 2009.

promoting the oxidative corrosion of friction pairs and exacerbating wear in hydraulic equipment, significantly reducing service lifetime. As mentioned, under specific conditions, inorganic salts in seawater can generate a corrosion product film containing Mg on the friction pair surface. This film prevents direct contact between the friction pair, thereby enhancing the anti-friction and anti-wear performance of the HFC. However, the microscopic formation and transformation mechanisms of the friction corrosion product films, along with their macroscopic mode of action, remain unclear.

4 Enhanced resistance to damage and corrosion using HFC additives

Compared with traditional oil-based hydraulic oils, HFCs have superior fire resistance, stability, environmental friendliness, heat transfer, material compatibility, and cost effectiveness; however, there are also disadvantages. Most notably, the lubrication performance, anti-wear performance, and corrosion resistance of HFCs are inferior to those of oil-based hydraulic fluids. In addition, HFC wear and corrosion resistance degrade further in marine environments, significantly limiting HFC applications. High-salinity conditions not only reduce the lubrication between friction pairs but also accelerate electrochemical corrosion in friction-pair contact areas. This decreased friction corrosion performance directly affects the transmission efficiencies of hydraulic systems and greatly reduces the service lifetimes of key components of marine equipment. Therefore, improving the overall performance of HFC in the marine environment by optimizing additive formulations and technological transformation strategies has become an important research focus in the field of hydraulic transmission.

Many studies have focused on improving the lubrication properties of HFC bases, that is, water–EG solutions. Additives can significantly enhance the anti-friction and anti-wear capabilities, yielding exceptional lubrication performance [80–82] and enabling operation under extreme conditions for extended periods [16, 83–86]. At present, additives for water–EG solutions can be broadly categorized into three groups: ionic liquids, nanoparticles, and organic additives (Table 2).

Ionic liquids have distinctive physical and chemical properties, such as high thermal stability, nonvolatility, nonflammability, and high conductivity [112]. These properties make ionic-liquid additives for hydraulic fluids rich in hydrogen bonds, polar groups, and negative charges useful. Crucially, these additives enhance the adhesion of hydraulic fluids to friction surfaces [82, 94, 113, 114], thereby improving their friction and wear performance. In terms of the structure–activity relationship with respect to performance, the cations in ionic liquids do not markedly affect the high-pressure or anti-wear performance. In contrast, anions have a greater effect on the frictional properties, mainly by affecting the hydrogen bonding, van der Waals forces, electrostatic adsorption, solvation, and other interactions between molecules at the surface interface, which affect their frictional behavior at the sliding peak [82]. Gelatin, which contains abundant carboxylic acid groups, can form strong hydrogen

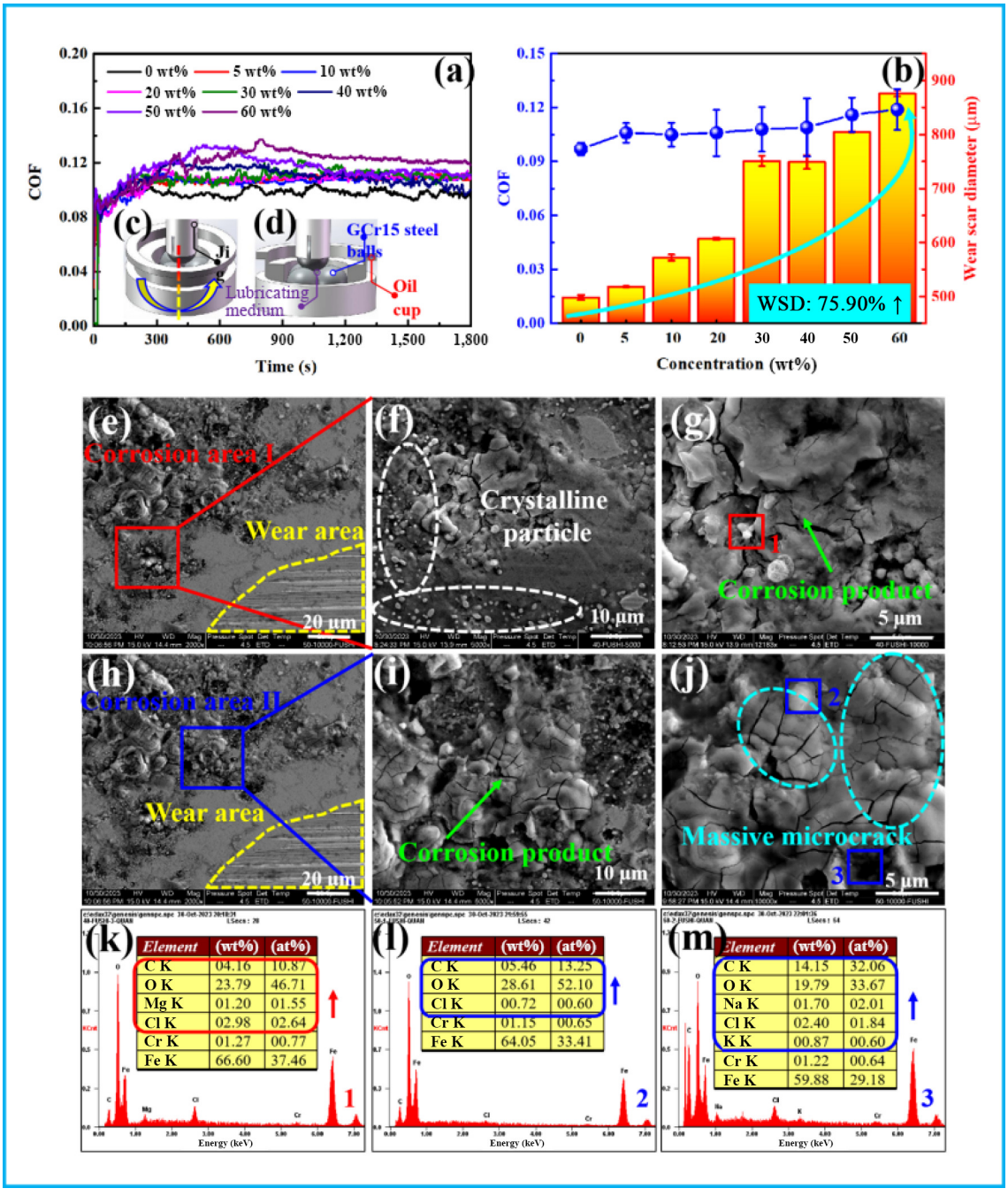

Fig. 11 (a) Effects of various seawater contents on HFC COF, (b) average COF and average wear-spot diameter under different seawater concentrations, (c) side and (d) sectional views of the four-ball friction corrosion test device (the friction test rotates counterclockwise), (e–j) microscopic morphologies, and (k–m) elemental composition results for different regions of the friction pair. Reproduced with permission from Ref. [78], © The Authors 2024.

bonds with hydrophilic surfaces, enhancing the adsorption performance of hydraulic fluids and reducing friction and wear [115]. Furthermore, an environmentally friendly diamine–stearate ionic liquid was added to a water–EG solution, and point-contact experiments were conducted on sapphire stainless-steel discs under a load of 1 N; the COF and δ were reduced by 76% and 80%, respectively (Fig. 14(a)) [83]. In addition, Jiang et al. [116] tested the frictional properties of phosphate ionic liquids as additives in aqueous EG solutions using an SRV high-temperature friction and wear tester. Their experiments demonstrated that phosphate ionic liquids can effectively enhance the anti-friction performance of water–EG solutions under a 200-N load. Additionally, X-ray photoelectron spectroscopy (XPS) analysis revealed that the ionic liquid formed a friction reaction film containing phosphorus, effectively reducing the shear resistance and achieving anti-friction and anti-wear effects, as shown in Fig. 14(b). In addition, Dong et al. [117] developed and synthesized an ionic liquid additive based on thiadiazole derivatives and confirmed its significant anti-friction and anti-wear effects through SRV friction and wear testing. TEM-based analysis of the friction-pair cross section revealed the formation of a 2-μm ultrathick friction reaction film in the wear area (Fig. 14(c)). Owing to their unique physical and chemical properties [118], ionic liquids are widely used as lubricating additives. However, there are disadvantages, such as significant differences in their solubilities in hydraulic oils with different polarities and, potentially, high corrosiveness [119]. These areas will be a key focus of future research.

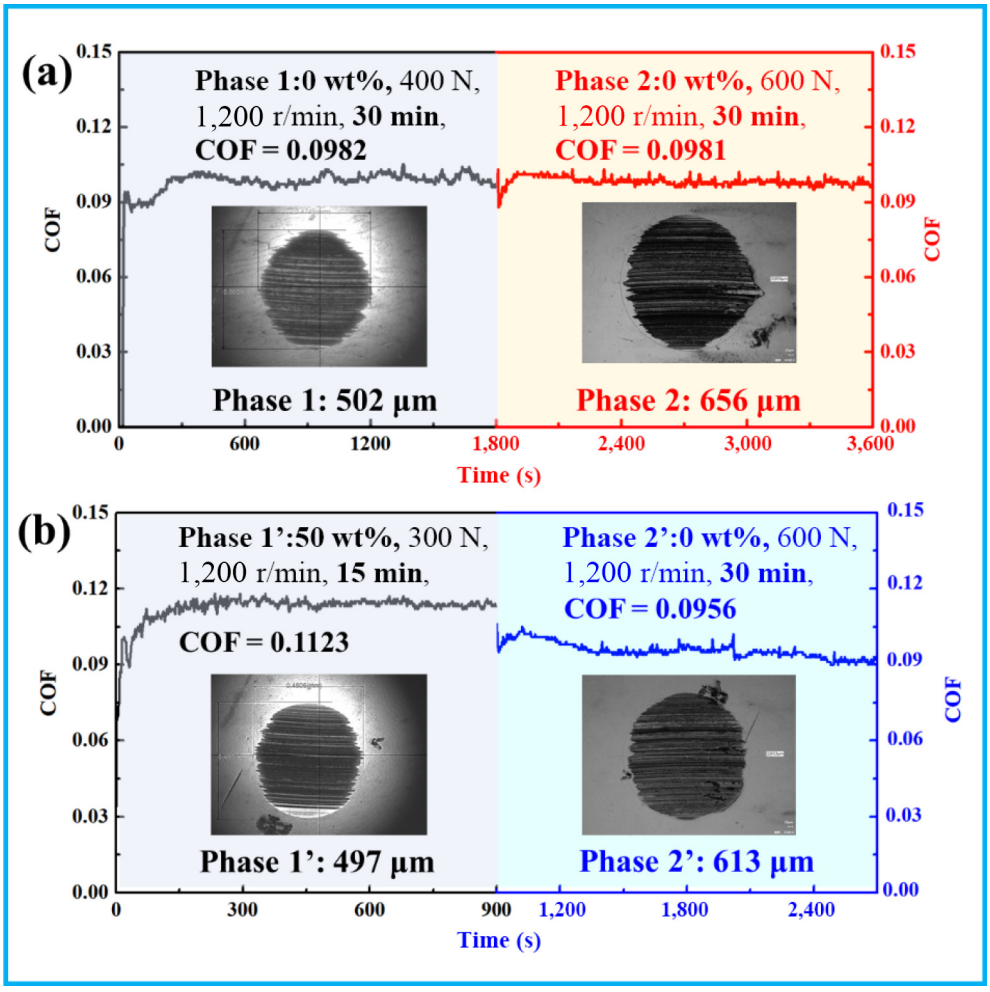

Fig. 12 Comparison of tribological properties of HFC samples with varying seawater contents after operation: (a) 0 and (b) 50 wt%. Reproduced with permission from Ref. [78], © The Authors 2024.

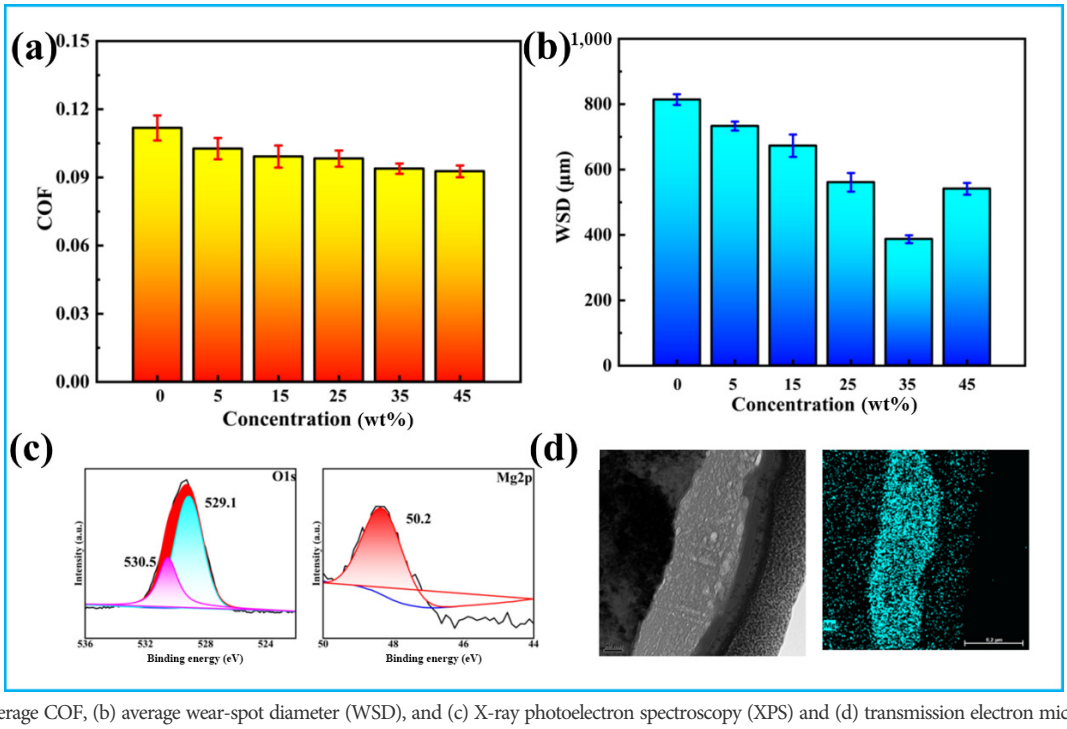

Fig. 13 (a) Average COF, (b) average wear-spot diameter (WSD), and (c) X-ray photoelectron spectroscopy (XPS) and (d) transmission electron microscopy (TEM) results for friction pairs following experiments involving HFC with 35–45 wt% seawater.

Table 2 Effects of additives on tribological properties of EG solutions [16, 80–111]

Type	Additive name	Additive concentration	Condition	Effect	Author (year)	Limitation
Ionic liquid additive	Phosphonate ionic liquid	1 wt%	Ceramic–steel; 20 N	Effectively improve anti-wear performance	Khanmohammadi et al. (2023) [81]	Poor anti-wear performance at high loads
	Ammonium/quaternary phosphonium salt functional ionic liquid	1 wt%	GCr15 steel–steel; 100 N	Effectively improve anti-wear performance	Xu et al. (2024) [82]	The load-bearing capacity is relatively poor
	Stearic acid salt ions	0.5 wt%	Sapphire ball–steel disc; 1 N	Reduce friction and increase friction reduction effect by 76% and 80%, respectively	Avilés et al. (2022) [83]	Only applicable to working conditions with small loads
	Phosphorus-free ionic liquids	0.5 wt%	AISI52100 steel–steel; 100 N	Certain anti-corrosion and lubrication characteristics	Zheng et al. (2022) [84]	The load-bearing capacity is relatively poor
	[Choline][Proline]	50 wt%	Si_3N_4–100CR6 steel; 2 N	Effectively improve anti-wear performance	Hua et al. (2021) [85]	Poor anti-wear performance at high loads
	PDMAn	2%	GCr15 steel–GCr15 steel; 300 N	Achieve COF < 0.01 at high speed	Zheng et al. (2022) [86]	The shorter the alkyl chain is, the worse the performance will be
	[Choline][Proline]	3 wt%	AISI52100 steel–100CR6 steel; 2 N	Achieving superlubricity under low humidity	Hua et al. (2022) [87]	Poor anti-wear performance at high loads
	DMAP4	15 wt%	GCr15 steel–GCr15 steel; 196 N	Achieve COF < 0.01	Zheng et al. (2022) [88]	Applicable only under specific conditions (< 250 N, > 1,200 r/min)
	$Li(PEG)PF_6$	0.8 wt%	GCr15 steel–GCr15 steel; 1–4 N	COF = 0.008	Ge et al. (2023) [89]	The applied load is relatively low
	Ser–CA/CQDs	2.0 wt%	AISI 52100 steel–AISI 52100 steel; 100-300 N	The wear scar volume decreases by 51.97%	Yang et al. (2025) [90]	COF is high
Nano-additive	SiO_2/TiO_2	1.5 wt%	SiC ring–Si_3N_4 ring; 500 N	COF as low as 0.0005	Xu et al. (2025) [80]	Only applicable to working conditions with low loads
	Protic ionic liquids (PILHB)	0.1 wt%	Steel–steel; 50–300 N	Effectively improve anti-corrosion and anti-wear performance	Su et al. (2021) [91]	The friction reduction effect is not significant
	Nanodiamond	0.55 wt%	Steel–steel; 100 N	COF decreased by 31%	Elomaa et al. (2013) [92]	The anti-wear effect is not significant
	Graphene oxide	0.083–0.332 wt%	Silicon nitride ball–diamond-like carbon coating; 3 N	COF decreased by 94.7%	Yi et al. (2021) [93]	Only applicable to working conditions with small loads
	Silica/graphene oxide	0.125 wt%	Steel–steel; 68.9 N	COF decreased by 38%	Singh et al. (2014) [94]	The friction and wear performance shows no significant degradation
	Granular γ-AlOOH/h-BN nanoparticles	0.03–0.15 wt%	GCr15 steel–steel; 100 N	COF decreased by 55.46%	Liu et al. (2025) [95]	Only applicable to working conditions with low loads
	6NP-CDs and eNP-CDs	0.2 wt% 6NP-CDs and 0.5 wt% eNP-CDs	GCr15 steel–steel; 392 N	COF decreased 51.73 and 59.9%, respectively	Wang et al. (2025) [96]	Poor extreme pressure performance
	Graphene	0.125 wt%	Steel–steel; 68.9 N	The COF and wear volume decreased by 38% and 31%, respectively	Gao et al. (2022) [97]	The friction and wear performance shows no significant degradation
	$MPEGOCS_2K$-CuS	2 wt%	GCr15 steel–GCr15 steel; 98–490 N	COF decreased by 59%	Hua et al. (2024) [98]	Poor anti-wear performance at high loads
	Aqueous graphene oxide	0.1%	SiC–SiC steel; 40 N	COF = 0.020	Gui et al. (2024) [99]	Low bearing capacity
	U-MoS_2	0.1 wt%	AISI E52100 steel–AISI 4130 low-carbon steel; 5 N	COF (0.057) was reduced by 84%	Kabir et al. (2025) [100]	Low bearing capacity
	Graphene-oxide nanoflakes (GONFs)	5%	Si_3N_4–SiO_2; 2–4 N	Achieve COF < 0.01	Yang et al. (2025) [101]	Low bearing capacity
Organic additives	Sulfur-containing triazine derivatives	2 wt%	Steel–steel; 98–392 N	Effectively improve extreme pressure performance	Wu et al. (2017) [16]	The anti-wear effect is not significant

(Continued)

Type	Additive name	Additive concentration	Condition	Effect	Author (year)	Limitation
Organic additives	Lithium citrate	0.5 wt%	Silicon nitride sphere–amorphous carbon film; 1–11 N	Realize super lubrication with almost zero wear	Sun et al. (2023) [102]	Only applicable to working conditions with small loads
	Fructose	50 wt%	AISI 52100 steel–steel; 3–8 N	Realize super lubrication with almost zero wear	Ma et al. (2021) [103]	Only applicable to working conditions with small loads
	Plant oil-based phosphate esters	2 wt%	Steel–steel; 200 N	Increased friction reduction effect by 72.6%	Ding et al. (2019) [104]	The anti-wear effect is not significant
	Ibuprofen compounds	2 wt%	AISI 52100 steel–steel; 392 N	Effectively improving corrosion resistance, with certain anti friction and anti-wear properties	Wang et al. (2017) [105]	The anti-wear effect is not significant
	Eichhornia crassipes carboxymethyle cellulose (EC-CMC)	1.5 wt%	AISI 52100 steel–steel; 40–100 N	COF = 0.0547	Opia et al. (2021) [106]	Low bearing capacity
	Soybean Oil	1%	SAE-AMS 6440 steel–steel; 2 N	COF = 0.135, WSD was reduced by 39.42%	Zetra et al. (2021) [107]	Low bearing capacity
	Cu-BTC@Ag MOF nanocrystals	0.5 wt%	GCr15 steel–GCr15 steel; 60 N	Lubricant decreased by 18.8%, and its wear volume decreased by 32.7%	Wang et al. (2023) [108]	Low bearing capacity
	DDACe $(((C_{12}H_{25})_2N^+(CH_3)_2[CeCl_4]^-)$	35.43 wt%	Steel–steel; 10 N	COF = 0.006	Chen et al. (2023) [109]	Low bearing capacity
	Glycerol	40%	Steel–steel; 3–6 N	COF = 0.0057–0.0087	Ma et al. (2024) [110]	Low bearing capacity
	Polymer-based proton ionic liquid	1 wt%	AISI 52100 steel–steel, Si_3N_4/glass; 100 N	COF ≈ 0.08	Duan et al. (2025) [111]	Low bearing capacity

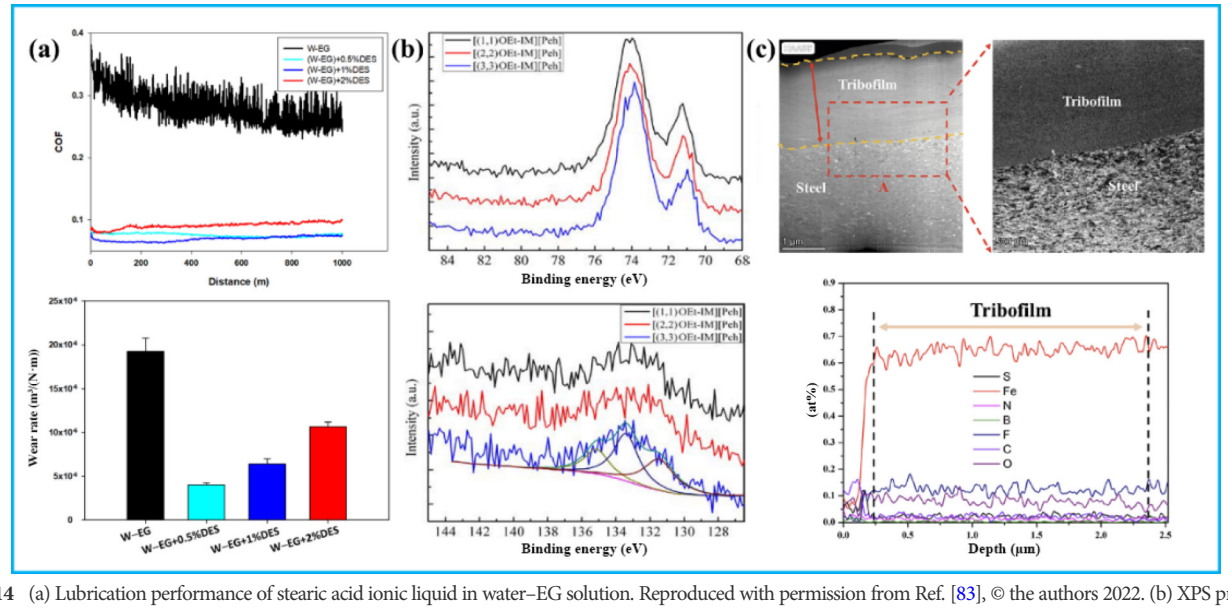

Fig. 14 (a) Lubrication performance of stearic acid ionic liquid in water–EG solution. Reproduced with permission from Ref. [83], © the authors 2022. (b) XPS profiles showing formation of friction reaction film promoted by a phosphate ionic liquid. Reproduced with permission from Ref. [116], © Emerald Group Publishing Limited 2013. (c) TEM images of ultrathick friction reaction film generated by thiadiazole-derivative ionic liquid. Reproduced with permission from Ref. [117], © Elsevier B.V. 2024.

Owing to their unique physical and chemical properties, such as surface, quantum size, low volume, and macroscopic quantum-tunneling effects, nanoparticles have been widely utilized in tribological studies [80, 91–96, 120–122]. In particular, the incorporation of nanodiamond particles as additives can enhance the anti-friction and anti-wear performance of the lubricating medium [92, 123–126]. For example, Elomaa et al. [92] found that nanodiamonds were incorporated into a film on the application of friction, significantly improving the tribological properties of EG-based HFC. Similarly, Guzman Borda et al. [127] further improved the anti-friction and anti-wear performance of hydraulic oil using copper nanoparticles deposited in the friction contact area during mechanical action. Liu et al. [128] used graphene oxide quantum dots as nanosized additives in a water–EG solution to achieve enhanced lubrication, reducing its running-in time and wear rate by 95.7% and 90%, respectively

(Fig. 15(a)). During the friction process, the oxidized graphene quantum dots adhere to the contact surface, forming a friction reaction film that increases the lubricating effect. In addition, Xu et al. [80] exploited the "fluid lubrication" and "ball bearing" effects of SiO_2 and TiO_2 nanoparticles in a ceramic EG solution system to shorten the break-in time and achieve macroscopic superlubricity (Fig. 15(b)). Overall, nanoscale additives can effectively enhance the viscosity and lubrication of hydraulic oils, exert a ball-bearing effect in lubricating media, significantly reduce equipment wear, and serve as efficient and environmentally friendly lubricating additives. However, the dispersibility of nanosized additives remains a fundamental problem that has not yet been resolved.

In addition to ionic liquids and nanosized additives, organic additives are commonly used to enhance the anti-friction and anti-wear properties of water–EG solutions [16, 102–105]. Organic solvents can enhance the adsorption of water–EG solutions, enabling the formation of a more stable and dense lubricating film on the friction surface, thus enhancing the friction and wear performance. Figure 16(a) shows that the addition of ibuprofen to a water–EG solution significantly enhances the solution adsorption and contact angle, yielding a favorable anti-friction effect under a load of 400 N [105]. By introducing vegetable-oil-based additives to a water–EG solution, Ding et al. [104] achieved reductions of 72.6% and 27.2% in the COF and δ, respectively. XPS analysis confirmed that the additive created an adsorption film comprising carbon and esters, which enhanced the tribological properties of the water–EG solution (Fig. 16(b)). Organic solvents can also improve the anti-friction and anti-wear properties of water–EG solutions by producing friction reaction films. For example, the lubrication performance of sodium sulfate as an additive in a water–EG solution was examined using a four-ball friction and wear tester [129], revealing that sodium sulfate increased the final nonseizure load of the water–EG solution. Subsequent scanning electron microscopy (SEM) and XPS analyses confirmed that reactions with sodium sulfate generated compounds, including Na_2O, Na_2SO_4, and $FeSO_4$, on the friction pair surface, effectively preventing direct contact between the friction pair and reducing wear. The formation of friction reaction films prevents direct contact between the rough peaks of friction pairs and enhances the anti-friction and anti-wear performance of hydraulic oils. However, organic solvents are often highly toxic and contribute to environmental pollution.

Although many single additives have been used in water–EG solutions, each has limitations. A single additive can improve the anti-friction and anti-wear effects of a water–EG solution under low-load conditions but shows reduced effectiveness under extreme conditions. Furthermore, the use of additives in HFC has not been validated sufficiently. Therefore, to broaden the scope of HFC applications under extreme operating conditions, we have conducted a series of screening studies on compound additives.

First, the use of benzotriazole and an organic molybdenum compound (TM-104) as combined additives in a water–EG solution significantly improved the anti-friction and anti-wear performance of the lubricating medium. This compound additive reduced the COF and δ of the water–EG solution by more than 60% and 90%, respectively. This improvement was attributed primarily to the synergistic effect of the benzotriazole and organic molybdenum. That is, the additives formed a Mo-containing friction reaction film in the wear area of the friction pair. The film exhibited low nano-hardness and a low elastic modulus, which enhanced the extreme pressure performance and load-bearing capacity of the flame-retardant hydraulic fluid. Additionally, a combination of ammonium phosphate salts and organic molybdenum was found to significantly enhance the anti-friction and anti-wear properties of water–EG solutions. The microstructures and elemental compositions of the friction-pair wear areas after friction experiments with different solutions were analyzed using SEM. The use of composite additives resulted in a smoother wear area and the formation of a Mo-containing friction reaction film. This effectively reduced the shear resistance, further enhancing the anti-friction and anti-wear performance of the water–EG solution.

Although HFCs have been extensively utilized in marine equipment, current additives for HFC are ineffective at reducing friction and anti-wear properties in the marine environment.

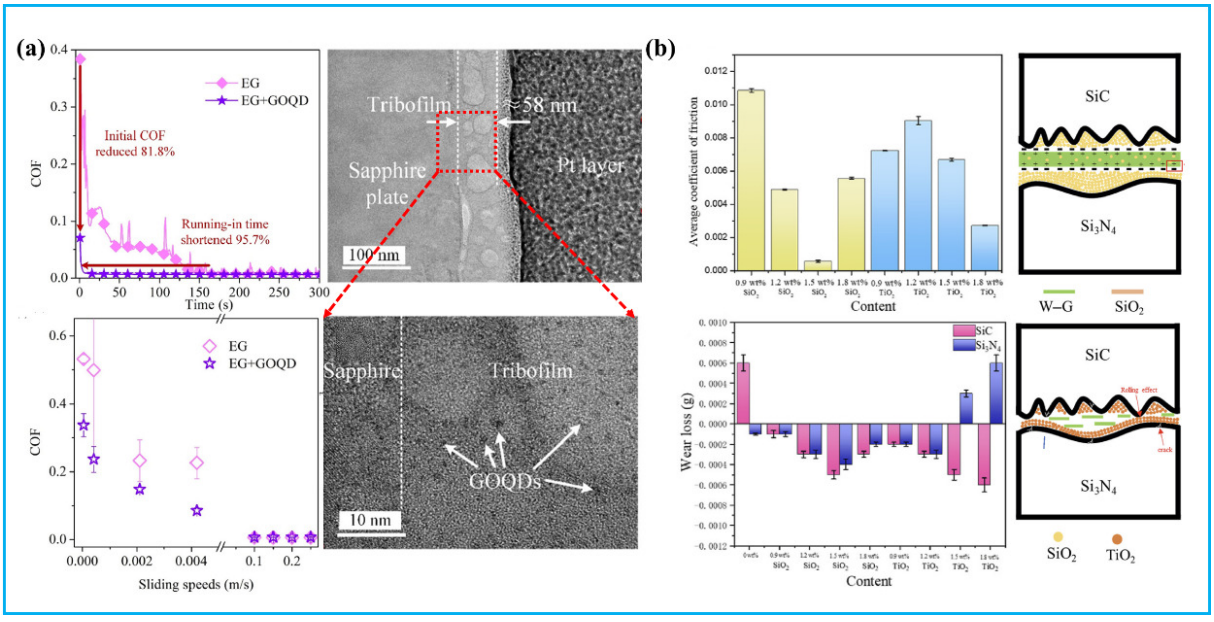

Fig. 15 (a) Friction and wear performance of graphene oxide as an additive in water–EG solution. Reproduced with permission from Ref. [128], © Elsevier Ltd. 2022. (b) SiO_2 and TiO_2 nanoparticle enhancement of the tribological properties of water–EG solutions, enabling superlubricity. Reproduced with permission from Ref. [80], © Elsevier B.V. 2025.

Therefore, we have conducted further testing to assess the efficacy of compound additives in seawater. Figure 17(a) shows a significant increase in the HFC COF when HFC is mixed with seawater. Subsequently, upon adding the compound additive, the COF significantly decreased. Compound additive 2 also exhibited good anti-wear effects (Fig. 17(b)). Thus, compound additives can effectively improve the tribological properties of water–EG solutions, providing a more reliable HFC for use under the harsh working conditions of the marine environment.

The most recent research results show that compound additives can effectively improve HFC's anti-friction and anti-wear performance. However, nonflammable hydraulic fluids must not

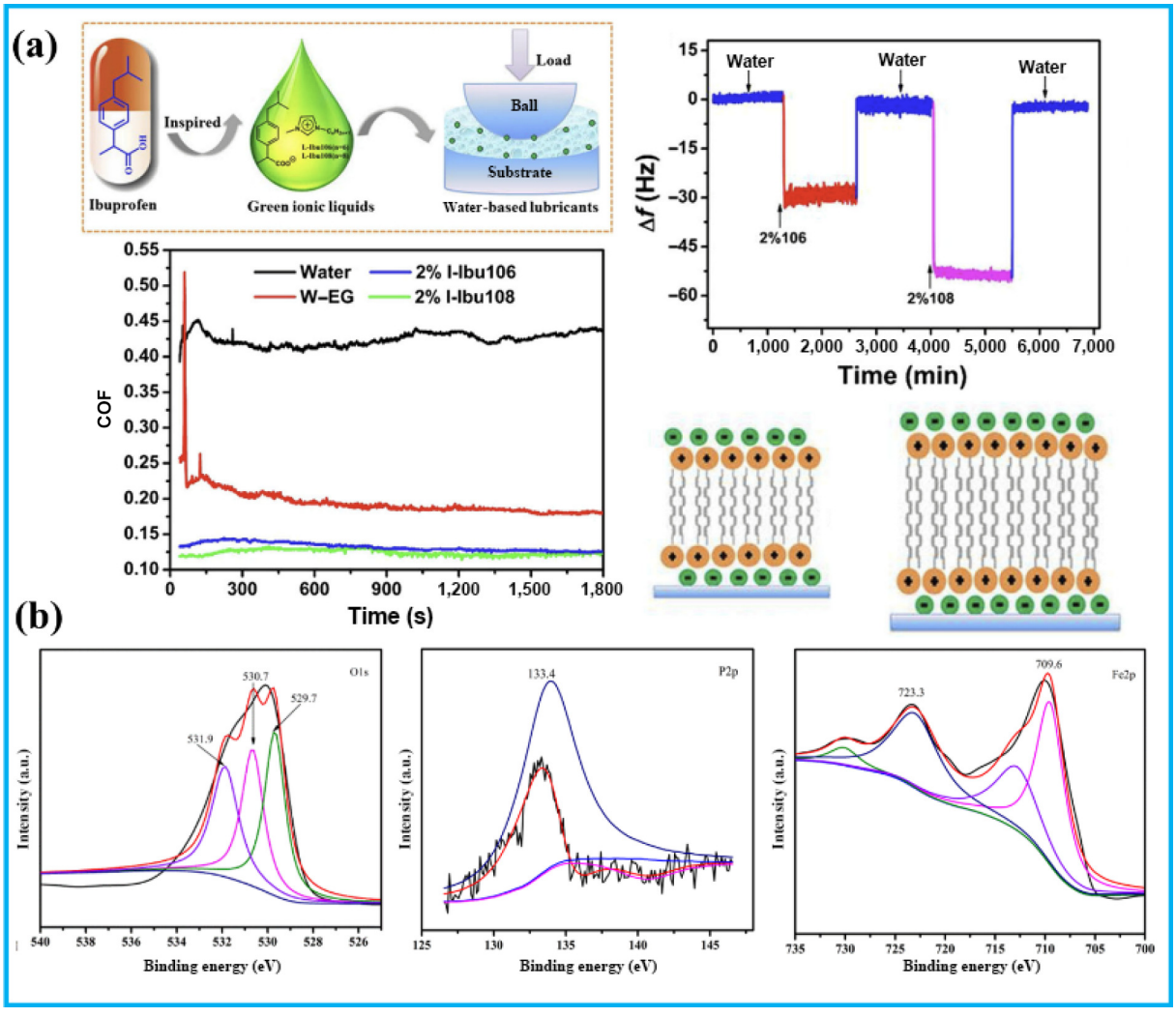

Fig. 16 (a) Lubrication performance of ibuprofen as an additive. Reproduced with permission from Ref. [105], © Springer Science Business Media New York 2017. (b) Plant-oil-based additives promote formation of friction reaction films (XPS characterization). Reproduced with permission from Ref. [129], © Tech Science Press 2019.

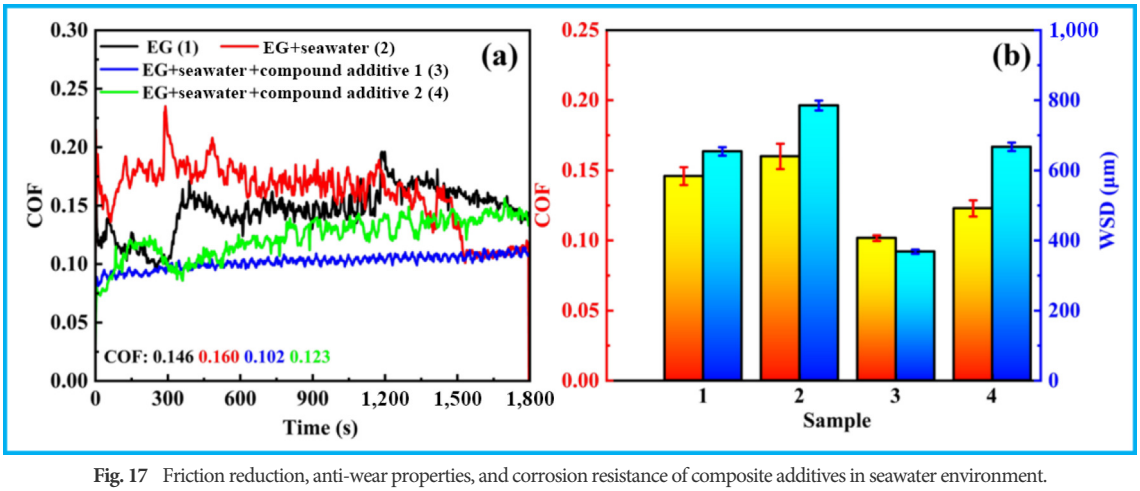

Fig. 17 Friction reduction, anti-wear properties, and corrosion resistance of composite additives in seawater environment.

only meet friction and wear requirements but also achieve the necessary viscosity, corrosion resistance, and thermal performance. Currently, characterization and validation of the additional physicochemical properties of additives employed in flame-retardant hydraulic fluids are ongoing. However, further investigation is needed to elucidate the formation and development processes of the friction reaction films produced by these additives. Additionally, their mechanisms of action must be explored further.

5 Conclusions and prospects

In this review, we summarize the fundamental characteristics of HFCs and their modifications. The following conclusions are drawn.

(1) The water content strongly influences the physicochemical properties of water–EG solutions, including viscosity, friction, lubrication, and wear behavior. Therefore, the optimal ratio should be determined. As the water content increases, the viscosity and adsorption decrease, whereas the wetting and lubricating properties increase significantly. At an EG concentration of 50 wt%, a $[H_2O]_m$–$[EG]_n$ structure forms, significantly improving lubrication and anti-wear properties. This enhancement is attributed primarily to the formation of a more stable hydrogen-bond network between water and EG upon mixing, enabling superlubricity within a shorter running-in period. Furthermore, a decrease in the friction performance of commercial HFCs under extreme operating conditions (load > 490 N, speed > 2,400 r/min, and temperature > 70 °C) was observed. At present, limitations remain regarding HFC applications.

(2) Seawater alters the physical and tribological properties of HFCs, including their physicochemical behavior. It also affects friction, wear, and oxidation-induced corrosion. Notably, seawater infiltration modifies the viscosity and thermal properties, directly impacting the adsorption characteristics. The effect of seawater infiltration on tribological properties is complex. When the seawater content exceeds 40 wt%, severe electrochemical corrosion occurs on the friction pair surface, degrading lubrication and increasing wear. However, Mg^{2+} and Ca^{2+} ions in seawater readily generate a friction–corrosion reaction film during the running-in process. This film reduces direct contact between rough regions on the friction pair surface and minimizes wear.

(3) Improvements in the tribological properties of water–EG solutions by additives and compound additives are discussed, along with their respective mechanisms. Ionic, liquid, nanoscale, and organic additives enhance lubrication to varying degrees, but their effects are limited under extreme conditions. Notably, the synergistic use of benzotriazole and organic molybdenum effectively enhanced the anti-friction and anti-wear performance of water–EG solutions. The COF and δ decreased by more than 60% and 90%, respectively. These improvements increase the potential for commercial HFC applications under extreme operating conditions and in the marine environment.

Overall, this review provides a valuable reference for future research on improving the friction and wear properties of HFCs in marine environments and expanding their applications under extreme operating conditions. Future research directions are summarized in Fig. 18.

5.1 Multiscale numerical simulations and mechanism investigation

Future studies should employ advanced multiscale simulation methods (e.g., molecular dynamics, first-principles calculations, and finite element analysis) to establish refined models of HFC systems. Key research priorities include investigations of (1) the interfacial behaviors of green additive formulations under complex conditions (high pressure, high speed, and variable temperature), (2) the dynamic formation mechanisms and evolution of tribofilms, (3) friction-reduction and anti-wear mechanisms at the microscopic scale, and (4) the structure–performance relationships between additive molecular structures and tribological properties. These approaches will

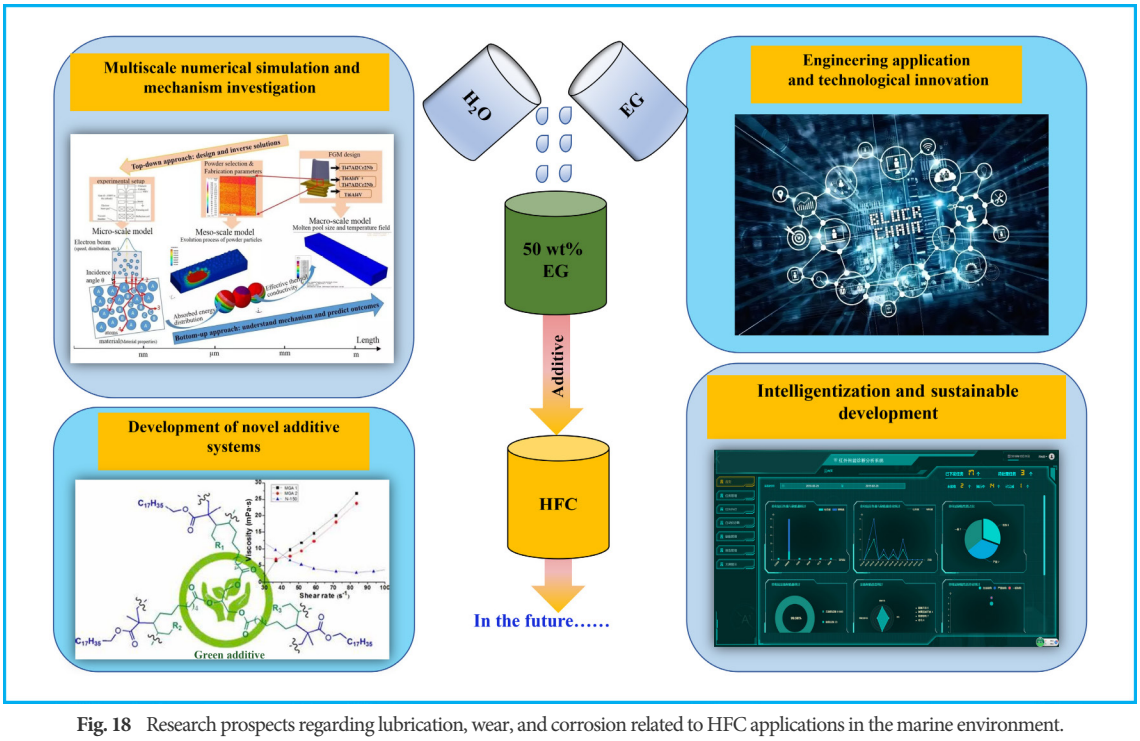

Fig. 18 Research prospects regarding lubrication, wear, and corrosion related to HFC applications in the marine environment.

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overcome the limitations of traditional experimental methods and provide novel theoretical perspectives on HFC lubrication mechanisms.

5.2 Engineering applications and technological innovation

Practical engineering solutions should be developed from fundamental insights into additive lubrication mechanisms. (1) Surface modification technologies should be advanced. In particular, break-in parameters should be optimized to promote the *in situ* generation of high-performance tribofilms, and functional coatings (e.g., diamond-like carbon and nanocomposite coatings) should be developed. (2) System energy efficiency should be optimized by establishing predictive models of frictional energy consumption and developing intelligent lubrication control systems. (3) Associated economic benefits should be assessed, including quantification of energy-saving benefits and evaluation of carbon-reduction potential. These innovations could significantly reduce frictional energy losses and δ, thereby extending equipment service lifetimes and improving energy efficiency.

5.3 Development of additive systems

Targeted additive formulations should be designed for specialized applications. (1) In the marine environment, high-efficiency corrosion-inhibitor blends and seawater-stable additive systems are needed. (2) For extreme conditions, wide-temperature-range (from −50 to 200 °C) stabilizers and high-load anti-wear additives are needed. (3) For eco-friendly applications, biodegradable formulations and low-toxicity alternatives should be explored. These developments will expand HFC applications to aerospace, deep-sea equipment, and polar exploration.

5.4 Smart technology and sustainable development

(1) Smart monitoring systems should be developed, including internet-of-things-based real-time lubrication status monitoring and intelligent early-warning systems. (2) Recycling technologies, such as HFC regeneration and novel waste-fluid treatment processes, should be investigated. (3) Standardization should be established through the development of industry-standard formulations and the commercialization of technological achievements.

These research avenues have scientific importance and will provide essential technological support for the green transition and "dual carbon" goals of the manufacturing industry. Cross-disciplinary innovation will drive HFC technology toward higher efficiency, environmental sustainability, and smarter technologies.

Acknowledgements

This project was supported by the Tribology Science Fund of the State Key Laboratory of Tribology in Advanced Equipment (No. SKLTKF24B02), the Natural Science Foundation of the Jiangsu Higher Education Institutions of China (No. 24KJB460033), the National Natural Science Foundation of China (No. 52405222), and the Yangzhou Innovation Capability Enhancement Program (No. YZ2022170).

Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

References

[1] Willmer S W. Classification of lubricants and hydraulic fluids. *Ind Lubr Tribol* **23**(3): 92–95 (1971)

[2] Chen H Q. Classification and product standards of hydraulic oil. *Hydraulics Pneumatics & Seals* **5**: 17–18 (2007) (in Chinese)

[3] Khaksar F, Manavi P N, Ardalan A A, Abedi E, Saleh A. Concentration of polycyclic aromatic hydrocarbons in zooplanktons of Bushehr coastal waters (north of the Persian Gulf). *Mar Pollut Bull* **140**: 35–39 (2019)

[4] Uddin S, Fowler S W, Saeed T, Jupp B, Faizuddin M. Petroleum hydrocarbon pollution in sediments from the Gulf and Omani waters: Status and review. *Mar Pollut Bull* **173**: 112913 (2021)

[5] Yarahmadi H. Oil pollution threatens Persian Gulf marine life. *Science* **383**(6683): 599 (2024)

[6] Li C S, Wang J H, Song K C, Zhang W T. Application of water ethylene glycol refractory hydraulic fluid in ship hydraulic systems. *Acta Petrolei Sinica* **25**(9): 103–106 (2009) (in Chinese)

[7] Lian X, Xiao F, Liu X. Aflas tetrafluoroelastomer/EPDM water resistant ethylene glycol hydraulic oil performance. *The World Rubber Industry* **41**(05): 11–14 (2014)

[8] Wang D, Li Z Y, Zhu Y Q. Lubrication and tribology in seawater hydraulic piston pump. *J Mar Sci Appl* **2**(1): 35–40 (2003)

[9] Nguyen Thanh Tran T, Zhao M S, Geng S J, Ivey D G. Ethylene glycol as an antifreeze additive and corrosion inhibitor for aqueous zinc-ion batteries. *Batter Supercaps* **5**(6): e202100420 (2022)

[10] Kumar R M, Baskar P, Balamurugan K, Das S, Subramanian V. On the perturbation of the H-bonding interaction in ethylene glycol clusters upon hydration. *J Phys Chem A* **116**(17): 4239–4247 (2012)

[11] Singh T, Jain M, Ganguli D, Ravi K. Evaluation of water glycol hydraulic fluids: A tribological approach. *J Synth Lubr* **23**(4): 177–184 (2006)

[12] Wang J M, Xu C, Wang J H, Li C S, Zhao G Q, Wang X B. Tribological properties of three S-alkyl-N,N-dicarboxymethyl dithiocarbamates as additives in water–glycol hydraulic fluid. *Tribol Trans* **56**(3): 374–384 (2013)

[13] Da Q A, Yao C J, Zhang X, Li L, Lei G L. Reservoir damage induced by water-based fracturing fluids in tight reservoirs: A review of formation mechanisms and treatment methods. *Energy Fuels* **38** (19): 18093–18115 (2024)

[14] Seiler J, Hackmann J, Lanzerath F, Bardow A. Refrigeration below zero °C: Adsorption chillers using water with ethylene glycol as antifreeze. *Int J Refrig* **77**: 39–47 (2017)

[15] Xiao D C, Deng Y P, Wang Z Y, Jiang Z W, Liu Y S. Kinematic viscosity prediction of polyalkylene glycol in a deep-sea environment from molecular dynamics. *J Chem Eng Data* **68**(12): 3162–3172 (2023)

[16] Wu Y L, He Z Y, Zeng X Q, Ren T H, de Vries E, van der Heide E. Tribological properties and tribochemistry mechanism of sulfur-containing triazine derivatives in water-glycol. *Tribol Int* **109**: 140–151 (2017)

[17] Goto T, Yin S, Sato T, Tanaka T. Morphological control of zinc oxide and application to cosmetics. *Int J Nanotechnol* **10**(1/2): 48 (2013)

[18] Ekman A, Börjesson P. Life cycle assessment of mineral oil-based and vegetable oil-based hydraulic fluids including comparison of biocatalytic and conventional production methods. *Int J Life Cycle Assess* **16**(4): 297–305 (2011)

[19] Schneider M P. Plant-oil-based lubricants and hydraulic fluids. *J Sci Food Agric* **86**(12): 1769–1780 (2006)

[20] Wang Z Q, Cao J T, Ren X G, Zhang B, Ye R H. Comparative study of the tribological properties of CFRPEEK, stainless and carbon steel in high water-based fluid. *Tribol Trans* **66**(5): 895–905 (2023)

[21] Lovrec D, Tič V. Cellulose filters in industrial processes and compatibility with ionic liquids. In: *New Technologies, Development and Application V*. Berlin (Germany): Springer, 2022: 297–307.

[22] Chen G Q, Zhang C Y, Huang Q, Yu Q L, Yang Z Z, Zhou C Y, Yan X Y, Wang R Z, Yu B, Cai M R. Novel phosphate organic guanidine salt water-based additive with integrated anti-friction, anti-wear and anti-corrosion properties. *Tribol Lett* **70**(2): 33 (2022)

[23] Shill S K, Al-Deen S, Ashraf M, Garcez E O, Subhani M, Hossain M M. Resistance of geopolymer, epoxy and cement mortar to

hydrocarbon-based synthetic engine lubricant, hydraulic fluid, jet fuel and elevated temperatures. *Constr Mater* **2**(1): 15–26 (2022)
[24] Holmberg K, Erdemir A. Influence of tribology on global energy consumption, costs and emissions. *Friction* **5**(3): 263–284 (2017)
[25] Wang P J, Wu J B. Performance analysis of poppet valves in deep-sea hydraulic systems: Considering viscosity–pressure characteristics. *J Mar Sci Eng* **13**(6): 1177 (2025)
[26] Chen J, Tian T, Li J J, You Z J. Effects of operating parameters and particle friction on water usage of deep-sea manganese nodules hydraulic conveying equipment. *Powder Technol* **442**: 119850 (2024)
[27] Liu T S, Liu Y J, Huang S T, Xue G. Influence of the hydraulic power take-off system on the dynamic response and power output of a wind-wave hybrid system. *Appl Ocean Res* **154**: 104359 (2025)
[28] Holmberg K, Andersson P, Erdemir A. Global energy consumption due to friction in passenger cars. *Tribol Int* **47**: 221–234 (2012)
[29] Holmberg K, Andersson P, Nylund N O, Mäkelä K, Erdemir A. Global energy consumption due to friction in trucks and buses. *Tribol Int* **78**: 94–114 (2014)
[30] Kao M J, Tien D C, Jwo C S, Tsung T T. The study of hydrophilic characteristics of ethylene glycol. *J Phys Conf Ser* **13**: 442–445 (2005)
[31] Wang Y, Li F B, Fang W H, Sun C L, Men Z W. Study of hydrogen bonding interactions in ethylene glycol-water binary solutions by Raman spectroscopy. *Spectrochim Acta Part A* **260**: 119916 (2021)
[32] Zhang J B, Zhang P Y, Ma K, Han F, Chen G H, Wei X H. Hydrogen bonding interactions between ethylene glycol and water: Density, excess molar volume, and spectral study. *Sci China Ser B* **51**(5): 420–426 (2008)
[33] Loskutov V V, Kosova G N. Molecular structure of an ethylene glycol–water solution at 298 K. *Russ J Phys Chem* **93**(2): 260–264 (2019)
[34] Loskutov V V. Concentration dependence of the viscosity activation energy of aqueous ethylene glycol mixtures. *J Solut Chem* **50**(3): 427–442 (2021)
[35] Zhang N, Li W Z, Chen C, Zuo J G, Weng L D. Molecular dynamics investigation of the effects of concentration on hydrogen bonding in aqueous solutions of methanol, ethylene glycol and glycerol. *Bull Korean Chem Soc* **34**(9): 2711–2719 (2013)
[36] Ninni L, Camargo M S, Meirelles A J A. Water activity in poly (ethylene glycol) aqueous solutions. *Thermochim Acta* **328**(1–2): 169–176 (1999)
[37] Baudot A, Odagescu V. Thermal properties of ethylene glycol aqueous solutions. *Cryobiology* **48**(3): 283–294 (2004)
[38] Zahn M, Ohki Y, Fenneman D B, Gripshover R J, Gehman V H. Dielectric properties of water and water/ethylene glycol mixtures for use in pulsed power system design. *Proc IEEE* **74**(9): 1182–1221 (1986)
[39] Risnes R, Madland M V, Hole M, Kwabiah N K. Water weakening of chalk: Mechanical effects of water–glycol mixtures. *J Petrol Sci Eng* **48**(1–2): 21–36 (2005)
[40] Li L Z, Gong P, Bai P P, Wen X L, Meng Y G, Ding J N, Tian Y. Impact of water content on the superlubricity of ethylene glycol solutions. *Lubricants* **11**(11): 466 (2023)
[41] Wang Y J, Zhao N N, Fang B Z, Li H, Bi X T, Wang H J. Effect of different solvent ratio (ethylene glycol/water) on the preparation of Pt/C catalyst and its activity toward oxygen reduction reaction. *RSC Adv* **5**(70): 56570–56577 (2015)
[42] Wojnarowicz J, Opalinska A, Chudoba T, Gierlotka S, Mukhovskyi R, Pietrzykowska E, Sobczak K, Lojkowski W. Effect of water content in ethylene glycol solvent on the size of ZnO nanoparticles prepared using microwave solvothermal synthesis. *J Nanomater* **2016**: 2789871 (2016)
[43] Azmi W H, Usri N A, Mamat R, Sharma K V, Noor M M. Force convection heat transfer of Al_2O_3 nanofluids for different based ratio of water: Ethylene glycol mixture. *Appl Therm Eng* **112**: 707–719 (2017)
[44] Weng L D, Chen C, Zuo J G, Li W Z. Molecular dynamics study of effects of temperature and concentration on hydrogen-bond abilities of ethylene glycol and glycerol: Implications for cryopreservation. *J Phys Chem A* **115**(18): 4729–4737 (2011)
[45] Zhou F, Yue B, Wang Q Z, Wang X L, Koshi A, Kato K. Tribological properties of a-CN_x coatings sliding against SiC balls in ethylene glycol aqueous solution. *Lubr Sci* **22**(6–7): 225–236 (2010)
[46] Li J J, Zhang C H, Deng M M, Luo J B. Reduction of friction stress of ethylene glycol by attached hydrogen ions. *Sci Rep* **4**: 7226 (2014)
[47] Kudo R, Ootani Y, Fukushima S, Ozawa N, Kubo M. Neural network molecular dynamics simulation on friction-induced chemical reactions of Si_3N_4 in water and ethylene glycol environments. *Chem Lett* **53**(7): upae114 (2024)
[48] Liu S S, Wang Y C, Huang H L, Huang G L. A review on corrosion and corrosion inhibition behaviors of magnesium alloy in ethylene glycol aqueous solution. *Corros Rev* **41**(6): 649–658 (2023)
[49] Lian Z X, Li X G, Xu J K, Yu H D. Durable slippery liquid-infused porous surfaces for effective corrosion protection of aluminum alloy in ethylene glycol-water solutions. *Surf Coat Tech* **484**: 130850 (2024)
[50] Du C H, Yu T T, Wu Z S, Zhang L Q, Shen R L, Li X J, Feng M, Feng Y G, Wang D A. Achieving macroscale superlubricity with ultra-short running-in period by using polyethylene glycol-tannic acid complex green lubricant. *Friction* **11**(5): 748–762 (2023)
[51] Gong P, Zhang W T, Wen X L, et al. Frictional performance of water-glycol fire-resistant hydraulic fluid. *Tribology* **62**: 1095 (2024) (in Chinese)
[52] Zhou Z J, Zhou X C, Huang Q P, Liu X S, Wang L, Xing S P. Impact of oil-water emulsions on lubrication performance of ship stern bearings. *Sci Rep* **14**: 31478 (2024)
[53] Sun Q L, Liu Y W, Deng L, Wang J G, Feng D. Dynamic response of deepwater test string under fluctuations in axial force and internal pressure. *Sci Rep* **13**: 11718 (2023)
[54] Liu C, Zhou C K, Tan L P, Cui J G, Xiao W S, Liu J, Wang H Y, Wang T. Reliability analysis of subsea manifold system using FMECA and FFTA. *Sci Rep* **14**: 22873 (2024)
[55] Liang H, Totten G E. Corrosive wear in hydraulic systems: An overview. In: *Hydraulic Failure Analysis: Fluids, Components, and System Effects*. Totten G E, Wills D K, Feldmann D G, Eds. Montgomery (USA): ASTM International, 2001: 119–133.
[56] Yu S J, Cao J, Li S X, Huang H B, Li X J. The tribological and mechanical properties of PI/PAI/EP polymer coating under oil lubrication, seawater corrosion and dry sliding wear. *Polymers* **15**(6): 1507 (2023)
[57] Zhang P, Liu X J, Lu W L, Zhai W Z, Zhou M Z, Wang J. Fretting wear behavior of CuNiAl against 42CrMo4 under different lubrication conditions. *Tribol Int* **117**: 59–67 (2018)
[58] Zhang P, Lu W L, Liu X J, Zhai W Z, Zhou M Z, Jiang X J. A comparative study on torsional fretting and torsional sliding wear of CuNiAl under different lubricated conditions. *Tribol Int* **117**: 78–86 (2018)
[59] Xiao D C, Deng Y P, Wang Z Y, Li T H, Liu Y S. Viscosity evolution of water glycol in deep-sea environment at high pressure and low temperature. *J Mol Liq* **387**: 122387 (2023)
[60] Wu J B, Li L. Influence of ambient pressure on sealing performance of O-ring in deep-sea hydraulic system. *Ocean Eng* **245**: 110440 (2022)
[61] Schatzberg P, Felsen I M. Effects of water and oxygen during rolling contact lubrication. *Wear* **12**(5): 331–342 (1968)
[62] Zhang P, Wang J. Torsional fretting wear behavior of PVD TiCN coated CuNiAl blade bearing in oil and artificial seawater. *Coatings* **9**(2): 140 (2019)
[63] Lee J S, Ray R I, Lowe K L, Jones-Meehan J, Little B J. An evaluation of microbial growth and corrosion of 316L SS in glycol/seawater mixtures. *Biofouling* **19**(sup1): 151–160 (2003)
[64] Guo Y N, Wang P F, Shi X F, et al. Experimental study on the effects of lubricating oil moisture on bearing performance. *Lubr Eng* **43**(12): 27–32 (2018) (in Chinese)
[65] Xia Y Q, Zhao X P, Wu H. Study on wear resistance and friction reducing properties of turbine oil. *Lubricating Oil* **30**(6): 15–18 (2015) (in Chinese)

[66] Liu H, Xu H, Zhang Y, Ji H, Ge Y, Ellison P, Jin Z. The influence of sea water in oil emulsion on bearing performance. *P I Mech Eng J—J Eng* **223**(3): 457–468 (2009)
[67] Yan S, Lin B, Zhang X F, Wang A Y, Zhou X X. Investigation of the running-in process of silicon nitride sliding in aqueous solutions of ethylene glycol. *Tribol Int* **90**: 386–392 (2015)
[68] Zhuo X, Cao J, Huang H B, Liu L, Suo X K, Ye P Q, Abbas Z. Cavitation erosion resistance and tribological performance of PAI/PI/EP soft coating on 20CrMo. *Wear* **536–537**: 205176 (2024)
[69] Xiao B, Zheng X L, Zhou Y, Yao D, Wan Y. Tribological behaviors of the water-lubricated rubber bearings under different lubricated conditions. *Ind Lubr Tribol* **73**(2): 260–265 (2021)
[70] MacDonald J. Marine turbine oil system maintenance. *Lubr Eng* **21**: 429–432 (1965)
[71] Wang Z Q, Gao D R. Comparative investigation on the tribological behavior of reinforced plastic composite under natural seawater lubrication. *Mater Des* **51**: 983–988 (2013)
[72] Zheng L. Corrosion in hydraulic fluids for subsea applications. Ph. D. Thesis. Leeds (UK): University of Leeds, 2009.
[73] Yang H Y, Yang J, Zhou H. Research on materials of piston and cylinder of water hydraulic pump. *Ind Lubr Tribol* **55**(1): 38–43 (2003)
[74] Nie S L, Huang G H, Li Y P. Tribological study on hydrostatic slipper bearing with annular orifice damper for water hydraulic axial piston motor. *Tribol Int* **39**(11): 1342–1354 (2006)
[75] Yamamoto Y, Takashima T. Friction and wear of water lubricated PEEK and PPS sliding contacts. *Wear* **253**(7–8): 820–826 (2002)
[76] Zheng L, Neville A. Corrosion behavior of type 316L stainless steel in hydraulic fluid and hydraulic fluid/seawater for subsea applications. *Corrosion* **65**(2): 145–153 (2009)
[77] Gong P, Wen X L, Bai P P, Yue L, Ding J N, Tian Y, Li L Z. Influence of low concentration seawater on the friction corrosion performance of water–glycol fire-resistant hydraulic fluid. *J Bio Tribo Corros* **10**(3): 49 (2024)
[78] Wen X L, Peng G, Bai P P, Yuan N Y, Yue L, Meng Y G, Tian Y, Li L Z, Ding J N. Tribocorrosion behavior of GCr15 steel in water–glycol fire-resistant hydraulic fluids (HFC) containing seawater. *J Mater Res Technol* **30**: 4682–4691 (2024)
[79] Wang J Z, Yan F Y, Xue Q J. Tribological behavior of PTFE sliding against steel in sea water. *Wear* **267**(9–10): 1634–1641 (2009)
[80] Xu R Z, Deng Y P, Jiang X C, Liu Y S. Superlubrication and wear behavior of SiC/Si_3N_4 induced by nanoparticles in water–glycol. *Wear* **572–573**: 206007 (2025)
[81] Khanmohammadi H, Wijanarko W, Espallargas N. The role of tribofilm chemical composition on wear of austenitic stainless steel lubricated with water-glycol containing ionic-liquids as additives. *Wear* **520–521**: 204672 (2023)
[82] Xu F, Li H L, Tian B Y, Cui K, Dong R, Fan M J, Cai M R, Zhou F, Liu W M. Towards superior surface behavior, tribological and mechanical response by the green, functional ionic liquid water–glycol lubricating system. *Tribol Int* **193**: 109363 (2024)
[83] Avilés M D, Sánchez-Rodríguez C, Pamies R, Bermúdez M D, Carrión-Vilches F J, Sanfelix S G, Kjøniksen A L. New water–ethylene glycol lubricants with stearate ionic liquid crystal additive. *Lubricants* **10**(10): 241 (2022)
[84] Zheng D D, Su T, Ju C. Influence of ecofriendly protic ionic liquids on the corrosion and lubricating properties of water–glycol. *Tribol Int* **165**: 107283 (2022)
[85] Hua J, Björling M, Larsson R, Shi Y J. Controlling friction in ionic liquid/glycerol aqueous solution lubricated contacts by adjusting CO_2 and water content. *Tribol Int* **161**: 107070 (2021)
[86] Zheng Z W, Liu X L, Yu H X, Chen H J, Feng D P, Qiao D. Insight into macroscale superlubricity of polyol aqueous solution induced by protic ionic liquid. *Friction* **10**(12): 2000–2017 (2022)
[87] Hua J, Björling M, Larsson R, Shi Y J. Controllable superlubricity achieved with mixtures of green ionic liquid and glycerol aqueous solution via humidity. *J Mol Liq* **345**: 117860 (2022)
[88] Zheng Z W, Liu X L, Huang G W, Chen H J, Yu H X, Feng D P, Qiao D. Macroscale superlubricity achieved via hydroxylated hexagonal boron nitride nanosheets with ionic liquid at steel/steel interface. *Friction* **10**(9): 1365–1381 (2022)
[89] Ge X Y, Wu X D, Shi Q Y, Song S Y, Liu Y F, Wang W Z. Study on the superlubricity behavior of ions under external electric fields at steel interfaces. *Langmuir* **39**(51): 18757–18767 (2023)
[90] Yang Z Z, Li P Y, Li X L, Chen G Q, Ren H H, Wang B, Zhang R Y, Guo H, Zhang Y. Macroscopic tribological properties and molecular simulation study of carbon quantum dots modified by ionic liquids. *Carbon* **238**: 120236 (2025)
[91] Su T, Song G J, Zheng D D, Ju C, Zhao Q. Facile synthesis of protic ionic liquids hybrid for improving antiwear and anticorrosion properties of water–glycol. *Tribol Int* **153**: 106660 (2021)
[92] Elomaa O, Hakala T J, Myllymäki V, Oksanen J, Ronkainen H, Singh V K, Koskinen J. Diamond nanoparticles in ethylene glycol lubrication on steel–steel high load contact. *Diam Relat Mater* **34**: 89–94 (2013)
[93] Yi S, Chen X C, Li J J, Liu Y F, Ding S L, Luo J B. Macroscale superlubricity of Si-doped diamond-like carbon film enabled by graphene oxide as additives. *Carbon* **176**: 358–366 (2021)
[94] Singh V K, Elomaa O, Johansson L S, Hannula S P, Koskinen J. Lubricating properties of silica/graphene oxide composite powders. *Carbon* **79**: 227–235 (2014)
[95] Liu R, He L L, Li S Y, Ge C H, Li W X, Zhang X D. Preparation and tribological behavior of γ-AlOOH/hexagonal boron nitride composites as additives in water-based lubricant. *J Mater Eng Perform* **34**(12): 11324–11333 (2025)
[96] Wang H Y, He Z Y, Qiu K, Xiong L P, Li L L, Liu J. Enhanced tribological properties of ethylene glycol-based lubricants by nitrogen–phosphorus Co-doped carbon dots. *Lubricants* **13**(1): 8 (2025)
[97] Gao Q L, Liu S W, Hou K M, Li Z P, Wang J Q. Graphene-based nanomaterials as lubricant additives: A review. *Lubricants* **10**(10): 273 (2022)
[98] Hua K Y, Yu H X, Zuo X Y, Zhou F, Zhang X. CuS nanoparticles capped with $MPEGOCS_2K$ for applications as lubricants and antiwear additives. *ACS Appl Nano Mater* **7**(17): 20454–20463 (2024)
[99] Gui P T, Long W, Cai X M, Yin Y T, Wang W Y, Wang P Y. Influence analysis of lubrication and friction reduction of graphene oxide lubricant at SiC interface. *Colloid Surf A* **691**: 133897 (2024)
[100] Kabir M H, Dias D, Marjuban S, Avais M, Castaneda H, Liang H. Effects of urea-functionalized MoS_2 on hydrophilic lubrication. *Tribol Int* **203**: 110384 (2025)
[101] Yang K, Xiong Y H, Wu G J, Lin H B, Tang J, Wu C, Chen H L, Wang Y Q. Multi-dimensional nano-additives for their superlubricity: Tribological behaviors and lubrication mechanisms. *Adv Materials Inter* **12**(9): 2400796 (2025)
[102] Sun S Y, Yi S, Li J J, Ding Z M, Song W, Luo J B. Lithium citrate triggered macroscopic superlubricity with near-zero wear on an amorphous carbon film. *ACS Appl Mater Inter* **15**(15): 19705–19714 (2023)
[103] Ma Q, Wang S J, Dong G N. Macroscale liquid superlubricity achieved with mixtures of fructose and diols. *Wear* **484–485**: 204037 (2021)
[104] Ding H Y, Yang X H, Xu L N, Li M, Li S H, Xia J L. Tribological behavior of plant oil-based extreme pressure lubricant additive in water-ethylene glycol liquid. *J Renew Mater* **7**(12): 1391–1401 (2019)
[105] Wang Y R, Yu Q L, Cai M R, Shi L, Zhou F, Liu W M. Ibuprofen-based ionic liquids as additives for enhancing the lubricity and antiwear of water–ethylene glycol liquid. *Tribol Lett* **65**(2): 55 (2017)
[106] Opia A C, Kameil A H M, Syahrullail S, Mamah S C, Izmi M I, Hilmi C D Z, Bakar A R A, Saleh A A. Tribological behavior of organic formulated polymer concentration effect in bio-based lubricant using high-frequency reciprocating rig. *Jurnal Tribologi* **30**: 44–60 (2021)
[107] Zetra Y, Hariyanto R A B, Firmansyah R A, Perry Burhan R Y, Pusparatu. Lubricity performance of ethylene glycol ester from

soybean oil as a lubricity enhancer bio-additive for low-sulfur diesel fuel. *Mal J Fund Appl Sci* **19**(4): 481–493 (2023)
[108] Wang Y Y, Zhang G L, Yang D, Li Y, Yin W, Weng Y B. Electronic-control friction behavior of porous metal-organic framework@Ag nanocrystals as self-repairing lubricant additive. *ACS Appl Mater Inter* **15**(29): 35732–35740 (2023)
[109] Chen S W, Sun H, Liu J, Wang J Y, Lu H S, Hao J C, Xu L, Liu W M. A dual-responsive microemulsion with macroscale superlubricity and largely switchable friction. *Mater Horiz* **11**(7): 1668–1678 (2024)
[110] Ma Q, Liang M D, Xu X, Yan C P, Wang H F. Towards direct superlubricity and negligible wear with polyalcohol lubricant mixtures of ethylene glycol and glycerol for steel tribopairs. *Appl Surf Sci* **663**: 160151 (2024)
[111] Duan Y B, Liu X, Guo P X, Chen Q, Cai M R, Zhou F. Halogen-free poly(ionic liquid) water-based lubricant additive with superior viscosity-building and lubricating properties. *ACS Appl Polym Mater* **7**(10): 6240–6249 (2025)
[112] Hagiwara R, Ito Y. Room temperature ionic liquids of alkylimidazolium cations and fluoroanions. *J Fluor Chem* **105**(2): 221–227 (2000)
[113] Mu L W, Shi Y J, Ji T, Chen L, Yuan R X, Wang H Y, Zhu J H. Ionic grease lubricants: Protic [triethanolamine][oleic acid] and aprotic [choline][oleic acid. *ACS Appl Mater Inter* **8**(7): 4977–4984 (2016)
[114] Mu L W, Shi Y J, Hua J, Zhuang W, Zhu J H. Engineering hydrogen bonding interaction and charge separation in bio-polymers for green lubrication. *J Phys Chem B* **121**(22): 5669–5678 (2017)
[115] Christendat D, Abraham T, Xu Z, Masliyah J. Adhesion forces between functionalized probes and hydrophilic silica surfaces. *J Adhes Sci Technol* **19**(3–5): 149–163 (2005)
[116] Jiang D, Hu L T, Feng D P. Tribological behaviors of novel crown-type phosphate ionic liquids as lubricants for steel/aluminum contacts. *Ind Lubr Tribol* **65**(4): 219–225 (2013)
[117] Dong J Y, Sun Q H, Zhang S W, Zhang E H, Ma W W, Wang Y N, Li W M, Wang X B. Synthesis and tribological study of a novel thiadiazole derivative as multifunctional lubricant additive. *Colloid Surf A* **707**: 135825 (2025)
[118] Zhou Y, Qu J. Ionic liquids as lubricant additives: A review. *ACS Appl Mater Inter* **9**(4): 3209–3222 (2017)
[119] Qu G N, Fang H L, Liu L, Li Y, Zhang S W, Yang H M, Hu L T. High-performance protic ionic liquids as additives in lubricating oils with varying polarity. *Tribol Int* **191**: 109157 (2024)
[120] Gan L H, Chen L W, Zhang Y X. Preparation of silica aerogels by non-supercritical drying. *Acta Phys-Chim Sin* **19**(6): 504–508 (2003)
[121] Liu W, Zhong W, Du Y W. Research progress in nanocomposites with core/shell structures. *Materials Reports* **21**: 59–61 (2007) (in Chinese)
[122] Yang J R, Yin X L, Wang W, Wang T. Comparative research on nano-additives' tribological performance in lubricating oil. *Journal of Chang'an University (Natural Science Edition)* **31**: 95–97 (2011) (in Chinese)
[123] Xu T, Zhao J Z, Xu K. The ball-bearing effect of diamond nanoparticles as an oil additive. *J Phys D Appl Phys* **29**(11): 2932 (1996)
[124] Chu H Y, Hsu W C, Lin J F. The anti-scuffing performance of diamond nano-particles as an oil additive. *Wear* **268**(7–8): 960–967 (2010)
[125] Peng D X, Kang Y, Hwang R M, Shyr S S, Chang Y P. Tribological properties of diamond and SiO_2 nanoparticles added in paraffin. *Tribol Int* **42**(6): 911–917 (2009)
[126] Valeryevna Gubarevich A, Usuba S, Kakudate Y, Tanaka A, Odawara O. Frictional properties of diamond and fullerene nanoparticles sprayed by a high-velocity argon gas on stainless steel substrate. *Diam Relat Mater* **14**(9): 1549–1555 (2005)
[127] Guzman Borda F L, de Oliveira S J R, Seabra Monteiro Lazaro L M, Kalab Leiróz A J. Experimental investigation of the tribological behavior of lubricants with additive containing copper nanoparticles. *Tribol Int* **117**: 52–58 (2018)
[128] Liu Y, Yu S, Li J, Ge X, Zhao Z, Wang W. Quantum dots of graphene oxide as nano-additives trigger macroscale superlubricity with an extremely short running-in period. *Mater Today Nano* **18**: 100219 (2022)
[129] He Z Y, Xiong L P, Liu J N, Han S, Wu Y L, Zeng X Q. Tribologicalproperties of no active sulfur-containing sodium sulfonate asadditive in water–glycol fluid. *J Balk Tribol Assoc* **23**: 139–151 (2017)

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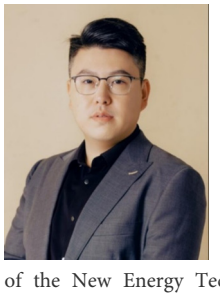

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