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Effect of Hydrogen Combustion on Tribology of Internal Combustion Engines

Ramin Rahmani[1*] and Homer Rahnejat[1,2]

[1] Wolfson School of Mechanical, Electrical and Manufacturing Engineering, Loughborough University, Leicestershire LE11 3TU, UK

[2] School of Engineering and Computing, University of Lancashire, Preston PR1 1JN, UK

* Corresponding author: R.Rahmani@lboro.ac.uk

Abstract

There is a growing expectation that cleaner alternative fuels such as hydrogen, biomethane and ammonia will progressively replace the traditional fossil fuels. Therefore, there is ~~a~~ great opportunity for hydrogen to play an important role, particularly in sectors of the economy that rely on internal combustion engines (ICEs), such as heavy-duty vehicles (HDVs), marine, off-road mobile machinery (NRMM), and in construction equipment. There is a growing body of research investigating the effect of hydrogen on engine materials and thermal performance. However, there has been a dearth of detailed analysis, particularly concerning tribological (friction, lubrication and wear) and lubricant performance in the presence of hydrogen and/or its combustion biproducts. Furthermore, comprehensive multi-scale studies, ranging from full vehicular tests down to tribometric assessment and precision surface characterisation of formed tribofilms, are still lacking. This paper aims to highlight the findings from recent in-depth studies of the authors.

1- Introduction

There is an ever-increasing demand for ultra-low-emission propulsion fuels. The main aim is to combat global warming caused by increased production of greenhouse gases (GHGs) such as carbon derivatives including CO_2 in the atmosphere along with reduction of emitted pollutants such as NOx and soot. Therefore, major OEMs are actively pursuing low and nominally zero emission propulsion systems for a range of applications including in the marine, agriculture, mining, construction and heavy-duty vehicle (HDV) sectors. For HDV and NRMM applications, battery-electric propulsion is often constrained by issues such as onboard energy storage density, charging/refuelling downtime, and payload penalties. There is also a trend to reduce the dependence on strategic materials, such as rare-Earth elements, which are extensively used in permanent-magnet traction motors employed in battery powered vehicles, as well as critical battery materials such as lithium, owing to the growing geopolitical tensions. Therefore, diversification in propulsion systems with tailored sources of power for different categories of applications is deemed to be a reasonable and a strategic way forward. Figure 1 shows that hydrogen is deemed to be one of the viable alternatives and a sustainable clean source of energy.

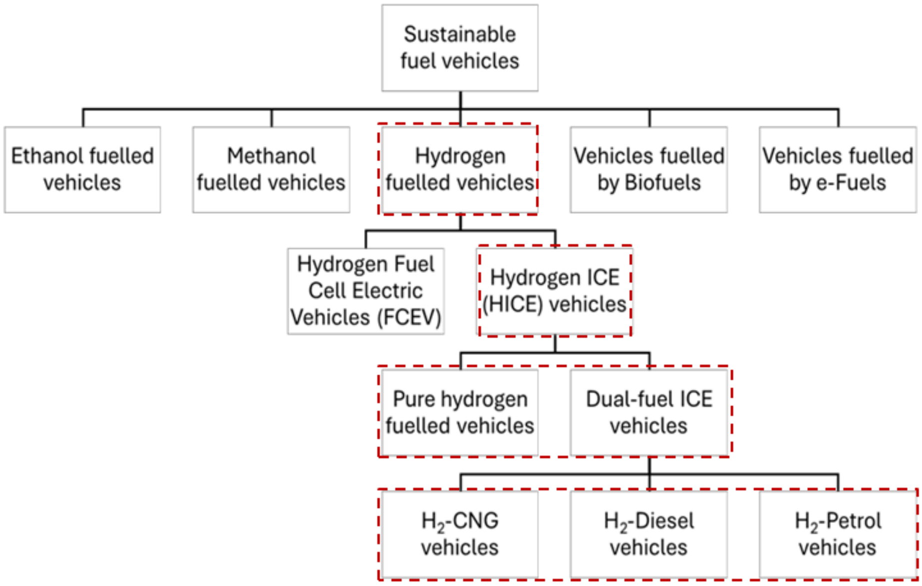


Figure 1: A classification of sustainably fuelled engines [1]

These stated fuels and the means of propulsion power can be obtained from various sources. Figure 2 depicts the main production methods for sources of energy. Crude oil is currently the main source of diesel fuel production. There are alternative more environmentally conscious methods to produce hydrogen gas such as the use of proton exchange membrane (PEM), powered by electricity produced from solar or wind energy.

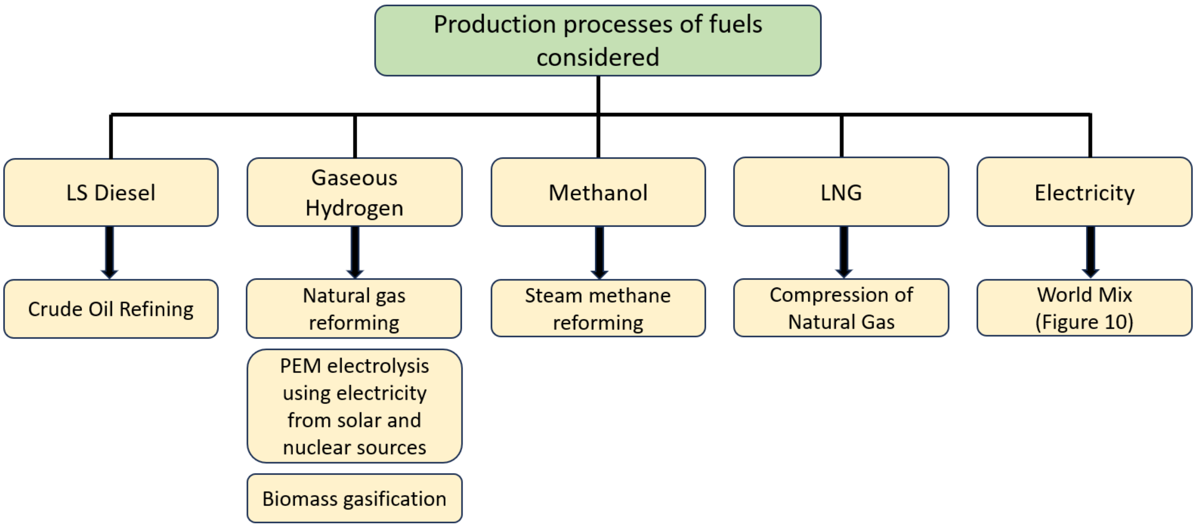


Figure 2: Production methods for various fuel types [2]

The existing methods of global electricity production is mainly based on fossil fuels. A recent study has shown that use of electricity to power HDVs produces comparable CO2 and even slightly higher CH4 emissions, based on a well-to-wheels (WTW) emissions life cycle analysis (LCA) than its low-sulphur diesel fuelled counterparts [2]. Similar observations can also be made if natural gas (NG) is used to produce hydrogen as shown in Figure 3. Furthermore, for the global electricity production sources, mainly based on fossil fuels (with around 36.7% contribution from coal and around 23.5% contribution from NG), the well-to-pump (WTP) energy consumption for electric HDVs is higher than that of diesel-fuelled counterparts [2], which results in an overall increase in the WTW energy consumption. Only electricity and hydrogen produced solely from renewable sources such as solar and biomass, as well as through nuclear power offer significantly lower WTW GHG emissions.

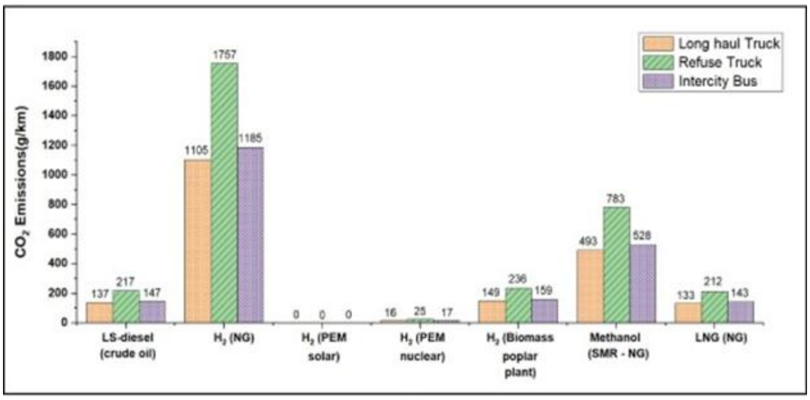


Figure 3: WTW LCA of CO_2 emission analysis using different fuel production methods [2]

A comparison of hydrogen with other fuels and energy sources in terms of energy content is provided in Table 1 [2]. Hydrogen has clearly the highest lower heating value amongst the different sources of fuel studied in Table 1. The high octane number for hydrogen yields excellent anti-knock combustion characteristics, combined with relatively low GHG emissions. These attributes make hydrogen a very competitive fuel for the ICEs. Nevertheless, it must be note that although hydrogen exhibits strong anti-knock potential in many SI operating regimes, assigning a single octane number is not straightforward and depends on the test method and operating conditions. However, the very low volumetric energy density of hydrogen compared with diesel or even LNG poses utilisation challenges that need to be overcome. Thus, the main engineering trade-off, from a combustion perspective, lies in the fact that hydrogen has the highest energy content per unit mass, but the lowest energy content per unit volume among the listed fuels.

Table 1: Energy content of various sources of energy for propulsion systems [2]

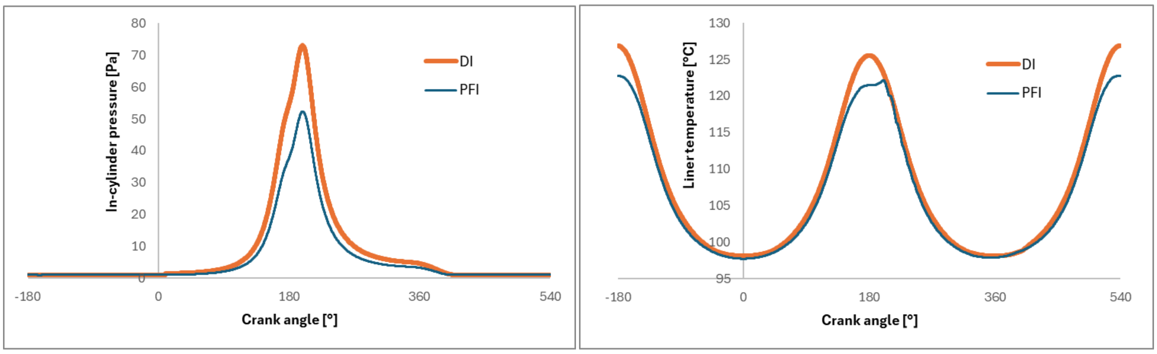
Fuel	Energy content (MJ/m^3)	Lower heating value (MJ/kg)	Octane / Cetane number
Hydrogen	10.8	120	130
LS Diesel	42,120	42.8	40-45
Methanol	17,964	19.7	112
LNG	20,988 – 24,012	49.4	120

2- Effect of hydrogen on frictional power loss

Whilst hydrogen combustion is studied in detail, the emphasis in most reported work has been on the primary aim of mitigating emissions through optimised use of hydrogen as a fuel. An overview of the progress and challenges, particularly on the combustion of hydrogen has been provided by Verhelst and Wallner [3] and more recently by Stepien [4]. Various studies on H2-diesel dual fuel ICEs' performance have been carried out for different percentages of H2 intake. It has been shown that the addition of hydrogen causes an increase in the combustion pressure peak by 7.7%, and an increase in the cumulative heat release rate of 3.5% for a H2-to-diesel fuel ratio of 20% [5, 6].

In general, there has been a dearth of research on the impact of hydrogen combustion on the tribological contacts in the ICEs, particularly on the lubricant rheology, physical chemistry and aging or degradation. Some of the representative investigations include the work of Pardo-García et al [7] who examined the effect of hydrogen combustion in a dual-fuel diesel-hydrogen ICE, showing that the presence of hydrogen reduced the emission of CO, HC and smoke, but decreased the lubricant viscosity by as much as 26%. There was also a decline in the Total Base Number (TBN) and an upsurge in the Total Acid Number (TAN) of the lubricant. These findings were in line with the previous research by Mathai et al [6] which reported similar trends in the TBN and TAN values in the case of engines fuelled with a mixture of hydrogen and compressed natural gas (CNG). Verhelst and Sierens [8] showed that the properties of engine oil were significantly affected. The concentration of various additives in the lubricant such as zincdialkyldithiophosphate (ZDDP), which is used as an anti-wear inhibitor, was significantly reduced along with almost complete disappearance of esters. In particular, employing direct hydrogen injection creates a demanding set of conditions from a tribological viewpoint in the various contact conjunctions such as in piston rings [9]. It also yields higher gas blow-by from the piston ring crevices [9].

A comparison of combustion pressure and temperature of port fuel-injected (PFI) and direct fuel-injected (DFI or DI) hydrogen is presented in Figure 4(a) and (b) respectively [9]. When hydrogen is used, the generated temperatures are generally expected to be higher due to a lack of evaporative cooling because of a phase change effect that is often seen in the case of liquid fuels such as gasoline and diesel [9]. It must be noted that the thermal response in general remains strongly dependent on the utilised equivalence ratio, fuel delivery strategy, and calibration details.



(a) (b)

Figure 4: Comparison of predicted (a) in-cylinder pressures and (b) cylinder liner temperatures based on different hydrogen fuel delivery systems [9]

Figure 5 shows that the prevalent regime of lubrication during top dead centre (TDC) reversal is boundary and mixed regime of lubrication due to a drop in the piston velocity at the vicinity of the TDC (Figure 5a) along with increased normal load due to a rise in combustion pressure (Figure 4a). The duration of boundary regime of lubrication has a significant effect on the frictional losses of the engine (Figure 5c). As it can be seen from Figure 5(b), the boundary regime of lubrication, with nominal lubricant film thickness to the root mean square (RMS) asperity height ratio, $\lambda \leq 1$, occurs from 20° crank angle to the TDC in the compression stroke to 30° crank angle past the TDC in the power stroke. This is a significant portion of the 4-stroke cycle and is primarily the result of generated pressure and temperatures with H_2 combustion in this case. Figure 5(c) shows that with both the fuel delivery types, DFI and PFI, the TDC reversal is dominated by the boundary regime of lubrication and more so in the case of DI engine.

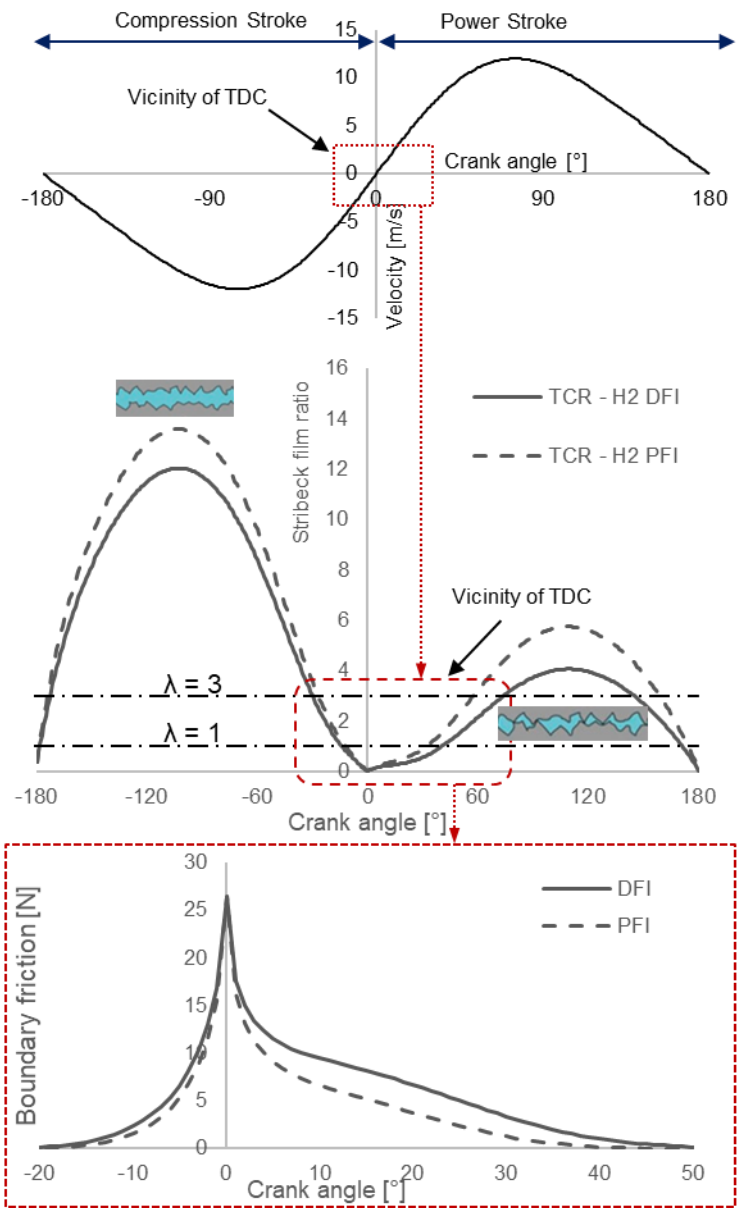


Figure 5: Predicted prevalence of mixed and boundary regimes of lubrication and increased friction at the vicinity of TDC with H2 as fuel [9]

As the largest share of engine frictional losses occurs in piston-cylinder system [10, 11], with a significant portion at the TDC reversals, the effect of fuel type and delivery system in the combustion chamber becomes important. It is clear that attention should be paid to fuel type and delivery system in order to minimise the extent and duration of boundary regime of lubrication. Figure 6 shows the energy loss due to friction through use of different fuels in the same engine [12] with larger share of energy loss belonging to the hydrogen fuelled engine using direct fuel injection strategy.

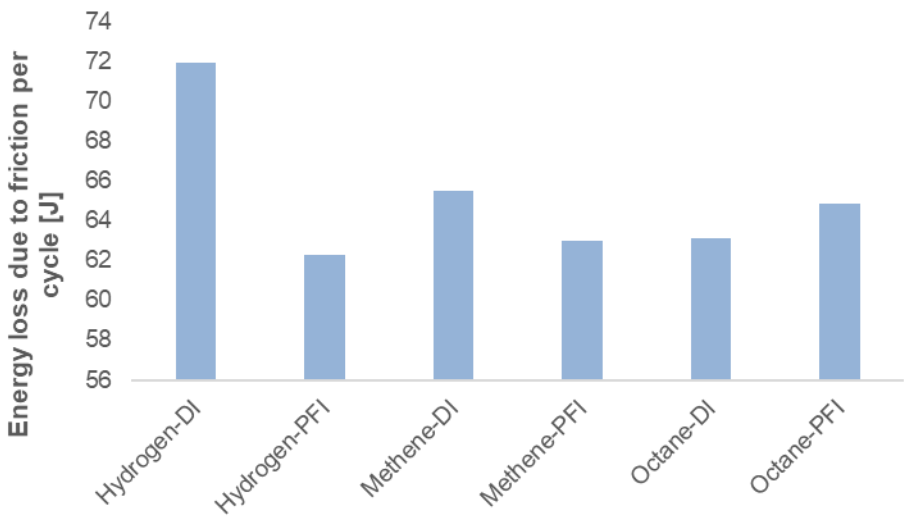


Figure 6: Cyclic frictional losses with different fuel sources and delivery to the combustion chamber [12]

3- Effect of hydrogen on lubricant quality

With hydrogen fuel, lubricant viscosity is reduced owing to the higher combustion temperatures, which also leads to the higher temperature in the tribological conjunctions. Furthermore, lubricant thermal and physio-chemical degradation [6,7] can yield lower operational viscosity. This means lower lubricant film thickness and reduced load carrying capacity in the contacts ensue, particularly in the vicinity of TDC (e.g., in the case of piston ring and cylinder liner contact). This results in a greater tendency for boundary regime of lubrication with greater instances of direct contact of counter face surface asperities. This is clear in the results of Figure 5(c) and 6. With boundary regime of lubrication tribofilms formed on the counter face surfaces affect the boundary friction. The lubricity of these tribofilms is a function of their constituents/composition, promoted by the adsorption/bonding of the surface-active lubricant additives. The process is a function of temperature, pressure and shear activation [13-15]. Therefore, the effect of fuel on lubricant chemistry, particularly its additive content is very important, not only in terms of boundary friction, but also with regards to the wear of contacting surfaces.

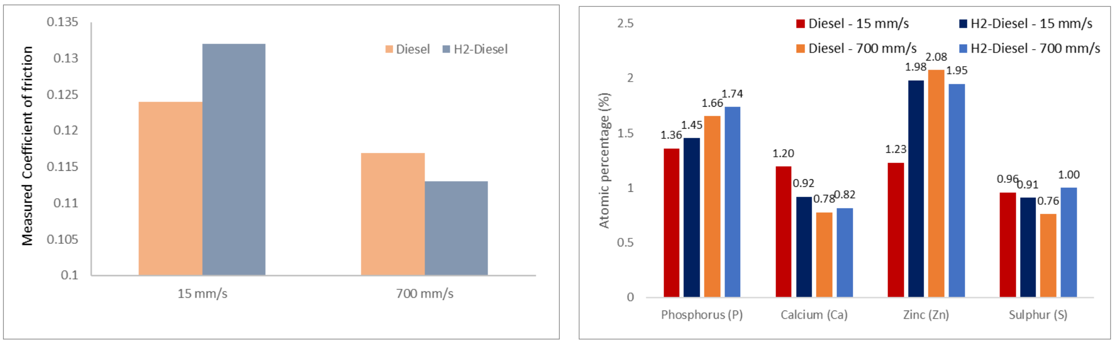
Hydrogen or H_2-assisted engines have been reported to produce more wear particles than the conventional gasoline or diesel engines in their lubricants. A comprehensive study of the effect of hydrogen on engine lubricants has been carried out in [16, 17] where lubricant samples from dual H_2-diesel 6 litre truck engines (with approximately 20% H_2) were siphoned after intervals of time corresponding to 2,000 km operation and chemically analysed, and compared with the same engine types operated with pure diesel fuel. Table 2 provides a comparison of wear metal content for H2-diesel and pure diesel fuelled engines with identical power and displacement IC engines.

Table 2: Typical results of wear metal analysis in lubricant samples from diesel and dual fuel H_2 – diesel engines (data extracted from [16, 17])

Parameter	Unit	Lubricant from diesel fuelled engine	Lubricant from H_2-assisted diesel fuelled engine
Al	**mg/kg**	1.1	3.3
Sn	**mg/kg**	0.0	0.3
Pb	**mg/kg**	0.0	0.0
Cu	**mg/kg**	0.9	1.7
Fe	**mg/kg**	6.6	14.0
Cr	**mg/kg**	0.3	0.9
Mo	**mg/kg**	7.4	14
Ni	**mg/kg**	0.1	0.2
Mn	**mg/kg**	0.3	0.4

Lubricant samples from dual H_2 – diesel or CNG engines also show a higher TAN. The increased water content associated with hydrogen combustion may promote hydrolytic and corrosive processes. Water content along with oxidation/nitration products and blow-by-derived acidic species, can contribute to TAN rise and additive degradation. Thus, owing to the presence of generated water by the combustion of hydrogen [6, 16], the lubricant may become more acidic and potentially impact key lubricant additives such as ZDDP (Figure 7).

In terms of direct impact of hydrogen gas on lubricants, a few controlled tribometric studies have been carried out in the presence of hydrogen gas to study its effect, particularly on the formation of tribofilms from the lubricant additives [15, 18]. However, the lubricant samples used were not from an operating engine, thus were not subjected to the shear degradation and aging in a real engine environment. The research reported in [16, 17] used lubricant samples directly from engines of HDVs with either dual fuel or equivalent pure diesel fuel. The lubricant samples were then subjected to tribometric tests, and the measured frictional variations were presented in the form of Stribeck curves. Figure 7 shows lower friction in the case of lubricant extracted from engine subject to H2-diesel fuel combustion under sliding higher speeds [17]. The conditions tested correspond to part of cam-flat tappet contact pressure conditions experienced in typical valvetrain systems under pure sliding conditions [19-21]. Tribofilm compositions for two different running speeds are also shown in Figure 7, obtained using X-ray Photoelectron Spectroscopy (XPS) of disc surfaces. Differences in surface chemistry (e.g. Zn-rich versus Ca-rich species) suggest condition-dependent additive participation. Formation of Ca-rich tribofilms shows the creation of conditions for the adoption of calcium mainly from dispersant and detergents in the lubricant under the tested conditions. In particular, the drop in zinc content compensated by a notable rise in calcium in the case of diesel engine lubricant under low speed tribometry conditions. However, in the case of lubricant obtained from H2-assisted engine lubricant, zinc content on the surface has not been adversely impacted. Since the conditions in the tribometric tests were at lower operating temperature than that is usually encountered in a real engine, the breakdown of ZDDP, potentially due to hydrolysis effect, could have increased the presence of Zn. Furthermore, a reduction in the formed glassy phosphorous layer is evident in both cases under low speeds pertaining to higher prevalence of boundary regime of lubrication.



(a) (b)

Figure 7: Measured (a) friction in tribometric tests of engine lubricant samples under different sliding speeds, and (b) XPS analysis results of the disc surfaces (data extracted from [17])

4- Concluding Remarks

Studies have shown that hydrogen combustion increases the water content of lubricant, leading to its increased acidity (TAN). Combustion of hydrogen can also lead to increased lubricant thermal and physio-chemical degradation resulting in lower effective viscosity, thus reducing load carrying capacity of the contacts. The higher liner temperatures, particularly under direct fuel injection strategy can also exacerbate the problem. The reduced load carrying capacity leads to increased boundary interactions and propensity of the surfaces to wear, as evidenced by the increased presence of wear particles in tested engine lubricants. The created acidic environment and increased presence of water in the lubricant could also interfere with intended formation of protective anti-wear additives. These preliminary findings suggest the need for a thorough investigation of lubricants extracted from hydrogen fuelled and hydrogen assisted dual fuel engines to understand adverse consequences of use of hydrogen as a fuel in the ICEs. Furthermore, there is a need for developing lubricants that are specifically formulated to mitigate such adverse effects in the presence of hydrogen combustion.

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