Challenges facing lubricants for hydrogen and ammonia fuelled combustion engines

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1. Introduction

Legislative and societal pressures are pushing for rapid global greenhouse gas reductions. The transportation sector is a major contributor of carbon emissions and technical solutions for low and zero carbon transportation must be found to meet carbon reduction aspirations while maintaining the personal mobility, public transport, and goods freight expectations of today. Many governments around the world have made commitments to deliver net zero and as a consequence of this, there is significant interest in low and zero carbon fuels which will deliver feasible and affordable tailpipe emission reductions. We describe where we expect to see liquid zero carbon fuels used directly in internal combustion engines, the operational challenges that they bring to the engine and how lubricants can help address these challenges.

2. Zero carbon fuels for internal combustion engines

Decarbonisation options for the heavy freight industry are limited. Battery electric vehicles are unable to store energy at sufficient density to rival the carrying capacity and range expectations of today's fossil fuelled freight, and fuel cell technology comes at high cost, low proven durability, and poor efficiency at high load. In contrast to these challenges, a freight vehicle equipped with an internal combustion engine running on zero-carbon fuel can deliver high efficiency at full load, on a durability-proven powertrain and a competitive freight capacity. A vehicle equipped with a zero carbon fuelled internal combustion engine also allows established vehicle manufacturers to use existing supplier relationships, technical skills, manufacturing facilities and vehicle and engine platforms. It is expected that the ability to reuse existing competencies and facilities will provide a lower research and development cost and ultimately a competitive and quick route to decarbonising the freight industry.

Hydrogen can be formed easily by electrolysis of water from green energy power generation such as solar and wind power and it is widely anticipated to be the zero-carbon chemical energy carrier of the future. However, hydrogen has a relatively low energy density compared to existing fossil fuels and will need to be stored as a compressed gas or even a cryogenic liquid to provide sufficient range and carrying capacity for heavy freight such as long haul on-road trucks. Such storage requires high cost fuel storage systems which will add to vehicle cost, and each conversion step of hydrogen from a low compression gas to high compression to cryogenic liquid has an energy cost which will materialise as a higher fuel cost.

The alternative approach to deliver high energy density low carbon fuel is to convert hydrogen to another chemical carrier with more favourable energy density and handling characteristics. Methanol and ammonia both remain as a liquid at much higher temperatures than hydrogen, however burning methanol will release carbon emissions and should only be considered a transitionary fuel to zero carbon transportation. Both fuel options have an energy cost penalty to create from hydrogen which puts a higher price on the fuel but lower cost on fuel storage for both the fuel supplier and on the vehicle cost [Figure 1].

We therefore anticipate that long-haul heavy duty trucks and off-highway equipment will adopt hydrogen as the primary zero carbon fuel of the future, with deep sea shipping adopting ammonia. Methanol is likely a transitionary fuel which will see high use in marine from now out to late 2030s, and some regional use in heavy duty trucks where it is available as a by-product of coal power generation. Coastal shipping has potential to see fragmentation caused by regional differences in cost and availability of low carbon fuels.

Legislation typically drives adoption of zero emission transport, and for marine this legislation is still in its infancy. Both the International Maritime Organization and European Union are drafting legislation, however both adoption and enforcement on a global scale is challenging. Potentially the marine industry could see a consumer-lead adoption, with networks like Cargo Owners for Zero Emission Vessels (coZEV) committing to zero emission shipping by 2040, ahead of any legislative framework. In contrast, the legislation frameworks for reducing and monitoring carbon emissions from on and off-highway truck applications is well established, and here we see much greater technology maturity, with many vehicle and engine manufactures committing to start of production of hydrogen vehicles within the next five years. We will describe the challenges of running combustion engine on true zero carbon fuels ammonia and hydrogen.

3. Zero carbon fuel internal combustion engine challenges and solutions

3.1 Water accumulation

Hydrogen generates over four times as much water as diesel during combustion for the same energy output, while ammonia produces more than twice the levels of diesel [Figure 2]. The majority of the water will be evacuated from the combustion chamber into the exhaust, but some will enter the crankcase and mix with the lubricant. Oil and water is immiscible and will separate over time, forming a higher density, lower layer of water and a lower density upper layer of oil. The water phase is a

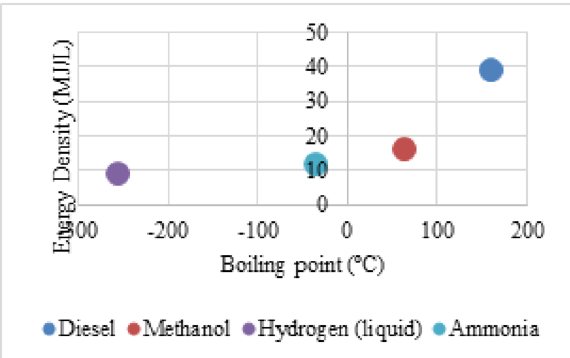

Fig. 1 Energy density plotted against boiling point

significant concern for engine lubrication as it will be extracted by the oil pick up and pumped around the engine. Water provides inadequate lubrication, an insufficient boiling point, poor ability to solubilise and suspend combustion derived deposits and can corrode many of the metals found in an engine.

Typically water is removed from the lubricant as an engine naturally heats up, regenerating the lubricant to restore the expected level of lubricity, however the cost and availability of zero-carbon fuels may mean that early adopters run their vehicles for a shorter duration than traditional diesel fuelled vehicles and this could prevent the removal of water. Any accumulation of water may create a negative perception which could act as a barrier to wider spread adoption of zero-carbon fuelled combustion engines. Off-highway applications may see much shorter utilisation and pose the greatest risk of water accumulation.

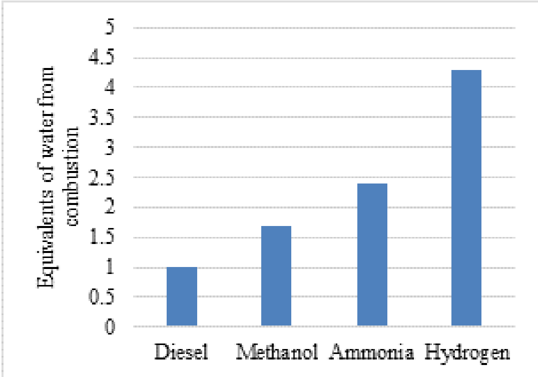

Fig. 2 Relative water produced at equivalent energy release

3.2 Fuel-economy and lubricant-derived emissions

Fossil fuels offer high energy density, mature and available distribution infrastructure, and easy storage at ambient temperatures. In contrast to these attributes ammonia must be refrigerated and hydrogen must be stored as a compressed gas or cryogenic liquid to provide sufficient range, requiring tanks which come at a much higher cost than fossil fuel tanks. Zero carbon fuel pricing is currently volatile and exemplified by hydrogen expecting a sixfold increase in 2021 [1]. Finally the production, distribution and refilling infrastructure is in its infancy, although significant investment is planned[2].

We anticipate that ammonia and hydrogen fuelled vehicles will be under significant pressure to deliver high fuel economy to offset the fuel cost, availability, and high on-vehicle storage cost. The lubricant can enable improved fuel efficiency though reduced hydrodynamic viscosity and lower boundary friction. A reduced hydrodynamic viscosity may cause bearing wear or lead to high lubricant-derived carbon emissions, however reduced boundary friction through careful additive chemistry selection can provide further fuel efficiency benefits without deleterious consequences to engine emissions or lifespan.

Combustion of hydrogen or ammonia emits water and nitrogen oxides, either directly from burning ammonia, or from nitrogen in the air. Nitrogen oxides can easily be managed with in-engine calibration or downstream with selective catalytic reduction, however there is also a risk of lubricant entering the combustion zone by leakage past the piston rings or valve stem. lubricant present in the combustion chamber will create very low levels of carbon in the tailpipe and this contribution to emissions could the challenge positioning of these vehicles as zero emission vehicles. The lubricant may be redesigned to reduce carbon emissions by increasing the viscosity and rheology of the lubricant, reducing the carbon intensity of the base oil by using esters, polyethylene or polyalkylene glycols or by addressing the carbon lifecycle assessment of the lubricant through the use of bio-derived or re-refined base oils.

3.3 Pre-ignition

Hydrogen has very low ignition energy which can cause internal combustion engines fuelled on hydrogen to experience spontaneous ignition of the fuel ahead of a spark event. This is known as pre-ignition and will reduce the power output of the engine, negatively affecting fuel economy, engine performance and operator experience of the vehicle. Very high pressure pre-ignition gasoline pre-ignition events have caused engine damage, with bent connecting rods, cracked pistons and damaged piston rings observed. Hydrogen pre-ignition is a similar phenomena and has potential for similar engine damage, however the absence of commercially representative engines has limited the ability to obverse engine damage in the real world to date.

Pre-ignition can occur when there are hot spots within the combustion zone that can trigger ignition of the hydrogen fuel. These hot spots could be a consequence of engine hardware design and it is anticipated that both the spark plug and piston crown may need redesign to eliminate hot spots. Lubricant-derived deposits can also insulate metal surfaces to create hot spots. Finally, lubricant droplets ejected from the piston rings into the combustion chamber can initiate ignition. We have focused on oil-droplet pre-ignition control by investigating the impact of lubricant composition on pre-ignition.

We have observed statically differentiated pre-ignition performance in hydrogen combustion engines, and confirmed that the understanding from gasoline low-speed pre-ignition is not directly applicable to hydrogen environments, with different responses to chemical composition. Further work is needed to understand and minimise hydrogen pre-ignition through lubricant design.

4. Summary

Zero-carbon fuelled internal combustion engines offer a credible route to decarbonising the heavy freight industry, while making use of existing supplier and manufacturing infrastructure. The use of zero carbon fuels in combustion does create challenges for the engine and lubricant, particularly the management of water accumulation and corrosion of metals exposed to water, pre-ignition of hydrogen and the management of high on board fuel storage costs, high fuel costs and low availability, which demands high fuel efficiency. Research is underway to resolve these in time for commercial use of these zero carbon fuels.

References

1) https://www.powermag.com/blog/hydrogen-prices-skyrocket-over-2021-amid-tight-power-and-gas-supply/
2) https://www.h2stations.org/