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Hydrogen Opposed Piston Engines

There are three potential pathways to enable carbon-free ground transportation: battery electric vehicles (BEV); fuel cell electric vehicles (FCEV); and internal combustion engines (ICE) using a combination of renewable fuels and/or carbon capture and storage.

Barring a significant technical breakthrough, the weight and recharging time of BEVs make them unsuitable for long haul applications, leaving FCEV and ICE vehicles as the only solutions with long-term commercial potential. This document summarizes the potential advantages of the opposed-piston engine operating on renewable hydrogen. The discussion is divided into two sections: a comparison of FCEV[1] and hydrogen ICE (H2-ICE); and a comparison of conventional engines and opposed piston engines operating with hydrogen combustion.

The ideal powertrain will emit zero CO_2 and zero criteria emissions; can be fabricated, operated, and serviced with zero CO_2 and zero other harmful pollutants; and will be cost-effective to purchase, operate, and service. The costs - of purchase and of ownership - are important. Mass impact requires mass adoption. Mass adoption will occur more easily and more rapidly if the solutions are cost effective.

It should be clear that creating a truly carbon-free transportation solution along any of the three viable pathways will take a lot of time and money, and all pathways represent significant technical risk. As a result, all the viable pathways should be developed and considered until a truly sustainable solution is available.

Summary

- Hydrogen may be the best fuel for truly sustainable long-haul transportation.
- There are two, viable, long term hydrogen power options – Fuel Cells and Internal Combustion Engines. Properly configured engines, like fuel cells, emit essentially zero criteria emissions.
- Hydrogen opposed piston engines have an inherent efficiency advantage over conventional internal combustion engines with an efficiency approaching or exceeding that of fuel cells.
- Hydrogen opposed piston engines, especially in direct drive form are much less complex and have a cost advantage over fuel cells.
- The OP Hydrogen engine should be developed and evaluated as a zero emission long-haul solution.

"An opposed-piston engine with hydrogen combustion could well provide the best known thermal efficiency from a reciprocating engine, with the potential to match the in-vehicle efficiency of a hydrogen fuel cell. If so, it is a valuable potential option for long haul transit in our quest for sustainable transportation."

James Turner, MEng, PhD, CEng, FIMechE, FSAE
Professor of Mechanical Engineering
Clean Combustion Research Center
King Abdullah University of Science and Technology

[1] This note studies Proton Exchange Membrane (PEM) fuel cells. Solid oxide fuel cells operate at a much higher temperature (600°C - 1000°C) which for the foreseeable future makes them impractical for vehicles both because of the lengthy startup time and challenge managing the high temperatures.

Hydrogen Fuel Cell vs. Hydrogen ICE

The appeal of a hydrogen fuel cell is easy to see – a carbon-free fuel is used to efficiently generate energy with only water as an emission. But the details matter.

Fuel cell advantages:

Hydrogen fuel cells have two major advantages over H2-ICE: benign emissions and high efficiency. For H2-ICE to be a practical alternative, they need to match or nearly match fuel cells on these two dimensions.

> "The direct injection 2-stroke engine could be a very promising and interesting option for hydrogen combustion to achieve "Zero" NO_x because of its advantages of high power density and inherent much lower NO_x emissions. These 2-stroke advantages are even more significant with an Opposed Piston engine, thanks to its higher power density and efficiency."
>
> Pierre Duret
> Former Director Powertrains & Sustainable Mobility, IFP School (France)

Emissions:

Some of the criteria emissions from petroleum-based engines are eliminated when using hydrogen as a fuel. Since there are no carbon molecules in the fuel, neither unburned hydrocarbons nor particulate matter is a concern[2]. The only criteria emission of concern is NO_x.

If hydrogen combustion is sufficiently lean – with an air/fuel equivalence ratio (lambda) ≥ 2.2[3] - very low levels of NO_x are created, as shown in Figure 1.[4] So a reciprocating engine, operating sufficiently lean, will produce very little NOx and may be able to meet ultralow NOx tailpipe requirements without an aftertreatment system. Papers from BMW[3] and Hydrogen Energy Research Lab[5] show that sufficiently lean hydrogen combustion in properly designed combustion chamber results in close to zero NO_x. Compared with conventional hydrogen ICE, the opposed-piston engine has a significant advantage for low NO_x hydrogen combustion as discussed below.

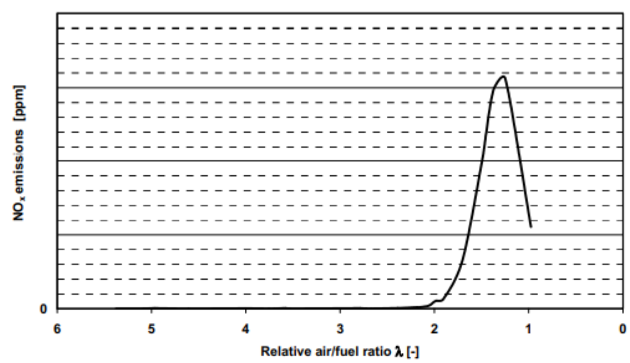


Figure 1: NOx vs Air Fuel Ratio in Hydrogen Combustion

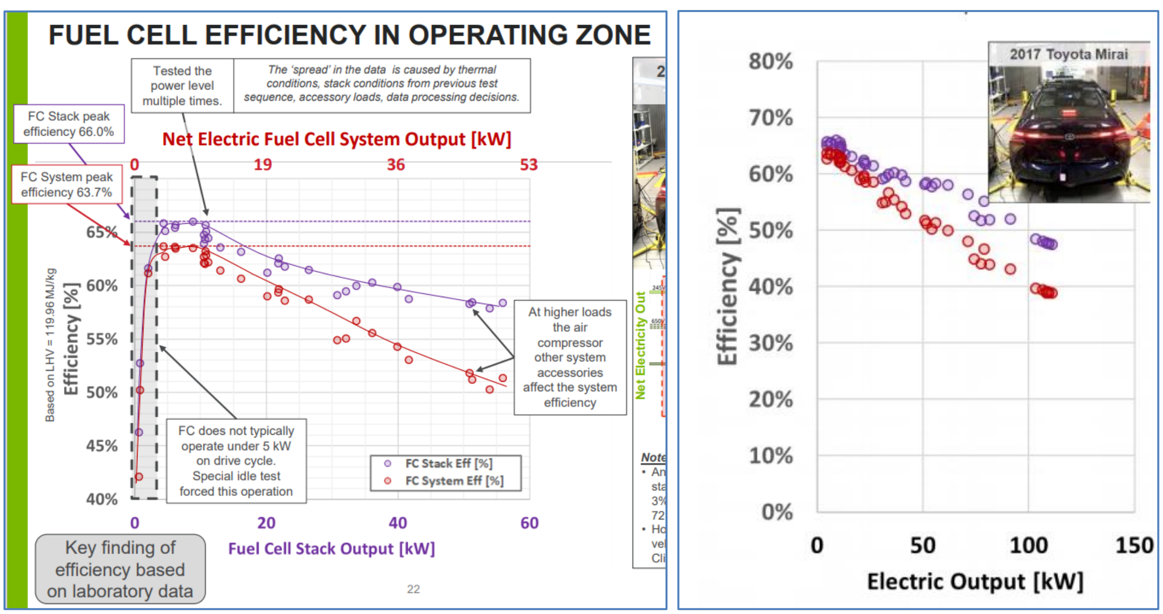
[2] That is, they are not a concern from fuel combustion. As discussed later in the document, reciprocating engines consume a small amount of lubricating oil so small quantities of HC, CO, PM, and PN may be created.
[3] Reference is to a trapped lambda condition.
[4] Figure 1 is from Eichlseder, H., Wallner, T., Freymann, R., Ringler, J., "The Potential of Hydrogen Internal Combustion Engines in a Future Mobility Scenario," SAE Paper 2003-01-2267. 2003.
[5] Yamane, K., "Hydrogen Fueled ICE, Successfully Overcoming Challenges through High Pressure Direct Injection Technologies: 40 Years of Japanese Hydrogen ICE Research and Development," SAE Paper 2018-01-1145. 2018.

Another tailpipe emission to consider is CO_2. While a reciprocating engine operating on hydrogen does not generate CO_2 from combustion, reciprocating engines require lubrication, and a small portion (generally around 0.05% of the fuel) of the lubricating oil will get into the combustion chamber and will be combusted, forming CO_2. To account for lubricating oil combustion, the EU sets a limit of 1 g CO_2 / kWh for zero CO_2 powertrains. Both conventional and OP engines exhibit low oil consumption so it is expected they will emit far less than this limit when operating on hydrogen fuel.

Efficiency:

To be a practical alternative to fuel cells, H2-ICEs needs to match – or get very close – to fuel cells in terms of efficiency. While fuel cells have high peak efficiency – around 60% - there are two balancing factors. For one, fuel cell efficiency declines with load, as noted in Figures 2 and 3. Diesel engines have historically been designed to operate efficiently at high loads. Since commercial vehicles primarily operate a high load, H2-ICE may be particularly well suited for high load commercial vehicle operation.

Second, system efficiency is the important factor, not the efficiency of the energy conversion unit. For fuel cells to operate efficiently, they must operate at higher than ambient air pressure. The air compressors used to pressurize the fuel cell system consume significant parasitic energy, particularly at high load. Argonne National Laboratory's Center for Transportation Research[6] explored this effect by measuring fuel cell stack and fuel cell system efficiency on a 2017 Toyota Mirai.



Figures 2 and 3: Fuel Cell Stack and System Efficiency from ANL Report

[6] "Technology Assessment of a Fuel Cell Vehicle: 2017 Toyota Mirai," Argonne National Labs, Report # ANL/ESD-18/12

The measured results show fuel cell stack efficiency below 50% and fuel cell system efficiency dropping below 40% at high loads. The sharp drop in system efficiency is due to parasitic losses to the air compressor and other system accessories.

In addition, fuel cells generate electricity and electric motors are used to generative tractive power which results in a double conversion loss. Since engines generate rotating power they can be directly coupled to a drive train, reducing energy conversion losses.

As shown in the map below, the heavy duty opposed-piston diesel engine (configured for ultralow NO_x) has peak thermal efficiency of just below 50%, centered around high load areas of the operating map, with broad areas of high efficiency (>45% brake thermal efficiency). Achates Power expects close to the same level of thermal efficiency with hydrogen as a fuel.

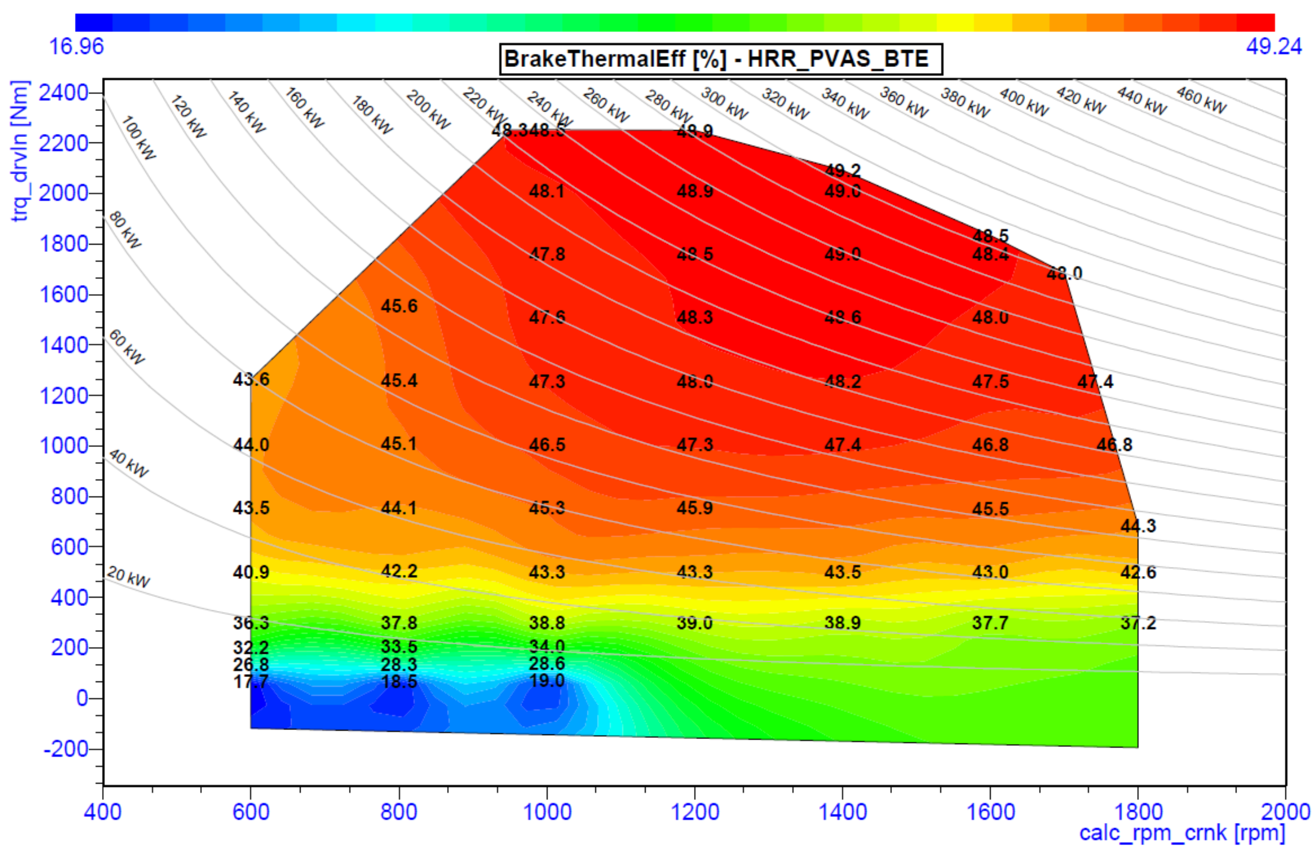


Figure 4: Brake Thermal Efficiency Map of Achates Power Heavy Duty Opposed Piston Engine

Conclusion:

Properly configured hydrogen engines – particularly opposed-piston engines coupled directly to a mechanical drivetrain – can emit low criteria emissions and may come close or match them in efficiency, particularly in commercial vehicle applications.

Fuel cell challenges:

Fuel cells have several challenges that may impede broad adoption: purchase cost, reliability, and fuel purity.

Purchase cost:

Purchase cost is important, of course, because it significantly impacts adoption. While the cost of fuel cells is expected to drop significantly with economies of scale and experience, it is almost certain that H2-ICE will have a sustainable cost advantage for the foreseeable future. Because hydrogen engines are derived from existing engines they have built-in economies of scale advantages beyond material cost differences.

A recent report from Ricardo[7] estimates that a 44 metric ton heavy duty truck requires 200 kW fuel cell and a 160 kWh battery for 800 km range. Ricardo estimates the cost of the fuel cell and battery in 2020 is $110,000. If, as they predict, fuel cell costs fall by 2/3 and battery costs are cut in half by 2030, the solution will cost $44,000. A comparable Diesel engine solution, including aftertreatment system, is around $20,000. It is not certain what the cost of a hydrogen-ICE will be but as a first order estimate the base engine it is likely to be nearly the same as today's Diesel engines (without the hydrogen storage system, which is present on both FCEVs and hydrogen ICE). In addition, because of advantages of lean, low NOx combustion (outlined below) H2-OPEs are expected to have reduced aftertreatment system requirements resulting in a lower cost system

Even as the cost of the fuel cell significantly decreases it will still face a substantial cost disadvantage compared to an H2-ICE.

Reliability:

According to the U.S. Department of Energy:

> *"Fuel cell stack durability in real-world environments is currently about one third of what is needed for commercialization. Durability has increased substantially over the past few years from 29,000 miles to 57,000 miles, but experts believe a 150,000-mile expected lifetime is necessary for FCVs to compete with gasoline vehicles.*
>
> *"Cold-weather operation can also be problematic since fuel cell systems always contain water, which can freeze at low temperatures, and must reach a certain temperature to attain full performance. FCVs can now start and operate in sub-freezing temperatures, but there are still some performance concerns.*
>
> *"Finally, contaminants can degrade fuel cell performance and durability, so it is unclear what level of purity of hydrogen and intake air will be required for FCVs to operate reliably in real-world conditions.[8]"*

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[7] "Fuel Cell: A sustainable clean solution for long haul commercial vehicles," https://comveh.ricardo.com/about-automotive/resources/fuel-cell-a-sustainable-clean-solution-for-long-haul-commercial-vehicles
[8] https://www.fueleconomy.gov/feg/fcv_challenges.shtml

Note that commercial vehicle engines are currently expected to operate reliably for 1,000,000 miles.

Fuel Purity

The preferred fuel cell configuration for long haul trucks is Proton Exchange Membrane (PEM). As noted by the DOE statement on reliability (above) PEM fuel cells require almost pure hydrogen.

> *"Another advantage of the ICE concerns the 98% to 99% level of purity required for the H2, whereas it is almost 100% in fuel cell. So this means that the H2 used for a fuel cell would also be more expensive to produce and to distribute. "*
>
> Pierre Duret
> Former Director Powertrains & Sustainable Mobility, IFP School (France)

Hydrogen OPE vs. Conventional Hydrogen Engine

Technical Challenges

The two main technical challenges for H2-OPE are fuel injection and ignition source.

Fuel Injection

OP engines utilize direct injection after ports closure to avoid the risk of fuel short circuiting out the exhaust. High pressure injectors for hydrogen are challenging because the small molecule size of the gas lends itself to leakage, but direct injection enables high compression ratios for improved efficiency and increased power and torque. Direct injection also avoids the risk of backfire.

Several companies are developing hydrogen high pressure injectors, including Bosch[9] and Westport Fuel Systems.[10]

Ignition Source

Hydrogen has high resistance to autoignition, making it unsuitable for compression ignition. A spark plug, or other ignition source, is generally required. Achates Power prefers compression ignition in its OP engines because it enables combustion in the middle of the combustion chamber for clean, efficient combustion and minimal heat loss. The addition of a spark plug is a new design element. Fortunately, the OP engine has room for multiple spark plugs around the cylinder circumference. Coupled with the fast flame speed of hydrogen combustion, stable and robust combustion can be expected from spark ignition in an OP engine.

OPE Engine Advantages:

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[9] "Hydrogen Engines for Future Passenger Cars and Light Commercial Vehicles," MTZ Magazine Volume 82 February 2021, pps 43-48

[10] "Total Cost of Ownership (TCO) Analysis for Heavy Duty Hydrogen Fueled Powertrains," https://wfsinc.com/file_library/files/wpt-wfsinc/20201225_Westport_AVL_Whitepaper_Hydrogen_HPDI_final.pdf

The OP engine has significant advantages for hydrogen combustion compared to conventional engines, including high efficiency, low NOx, high power density, and low cost.

High efficiency:

OP engines have inherent efficiency advantages compared to conventional engines. These advantages have been studied by a number of organizations, including Achates Power[11], General Motors[12], Honda, University of Bath[13], and University of Modena[14]. As the GM paper notes "The efficiency advantages of the opposed piston two-stroke engine are mainly because of lower in-cylinder heat losses due to elimination of the cylinder head and lower surface area to volume ratio". This is particularly important for hydrogen combustion because hydrogen combustion is hotter[15] (see Figure 5) and gets closer to the combustion chamber surface (that is, it has a shorter quenching distance) than diesel or gasoline combustion.

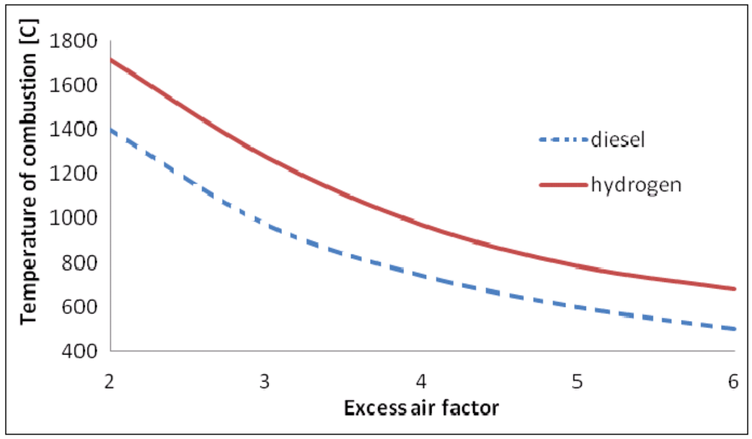

Figure 5: Figure from Seediek, et al

High efficiency is an important factor as hydrogen fuel is likely to be more expensive than Diesel fuel (for the same energy). Improving efficiency, therefore, will help transition to a hydrogen economy by reducing the cost of utilizing the fuel.

Low NO_x

As noted above, a reciprocating engine operating sufficiently lean (lambda ≥ 2.2) generates very little NO_x.

[11] Herold, R., Wahl, M., Regner, G, Lemke, J., "Thermodynamic Benefits of Opposed-Piston Two-Stroke Engines," SAE 2011-01-2216. 2011.
[12] Warey, A., Gopalakrishnan, V., Potter, M., "An Analytical Assessment of the CO2 Emissions Benefit of Two-Stroke Diesel Engines," SAE 2016-01-0659. 2016.
[13] Turner, J., Head, R., "Analysis of Different Uniflow Scavenging Options for a Medium-Duty 2-Stroke Engine for a U.S. Light-Truck Application," ASME ICEF 2018. 2018.
[14] Mattarelli, E., Cantore, G., Rinaldini, C., Savioli, T., "Combustion System Development of an Opposed-Piston 2-Stroke Diesel Engine," 72nd Conference of the Italian Machines Engineering Association, ATI2017. 2017.
[15] Seediek, I., Elgohary, M., Ammar, N., "The Hydrogen-fuelled internal combustion engines for marine applications with a case study," Shipbuilding Volume 66 Number 1, 2015. ISSN 0007-215x

Conventional engines can generally achieve sufficiently lean levels up to about 50% load[16]. Above 50% load - as shown in Figure 6 - conventional engines with hydrogen combustion must reduce the air-fuel ratio for high power density, typically to stoichiometry (lambda = 1) which generates high levels of NO_x. Conventional engines, therefore, must control the air-fuel ratio between lean and stoichiometric and will require NO_x aftertreatment systems to meet ultralow NO_x regulations.

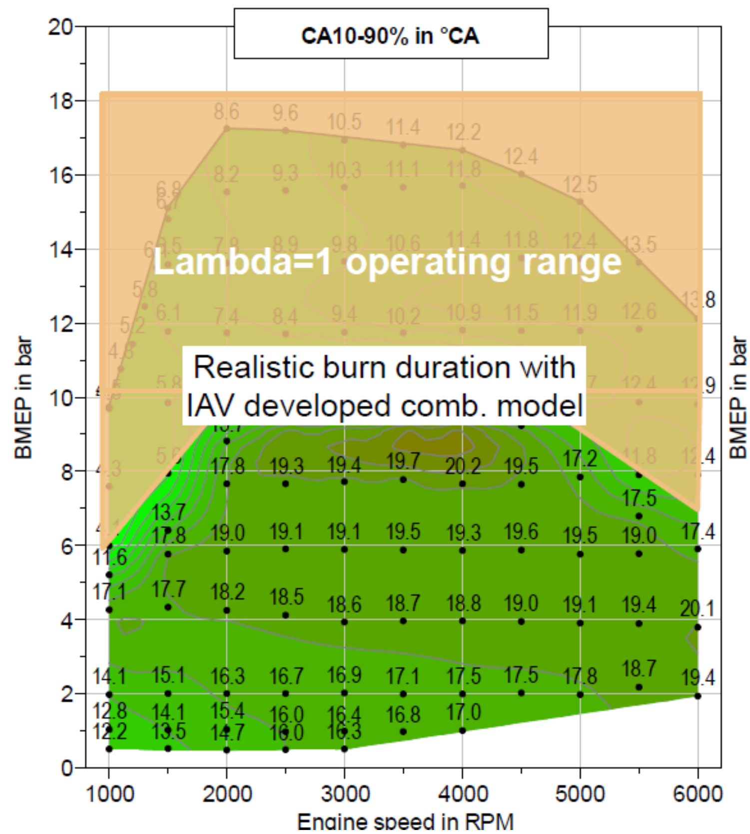

Figure 6: Operating Conditions of Conventional Engine with H2

By contrast, the opposed-piston engine operates naturally lean because as a two-stroke engine it can better optimize between displacement and brake mean effective pressure (BMEP). Because combustion occurs in every cylinder in every revolution in a two-stroke engine (twice the frequency as a four-stroke engine) it has inherently high power density. This power density advantage can be used to reduce displacement (reducing size and cost) or BMEP (which, among other things, allows an engine to run lean at the same boost levels). In practice, OP engines designed by Achates Power takes advantage of both – smaller displacement and lower BMEP than conventional engines of the same power and torque.

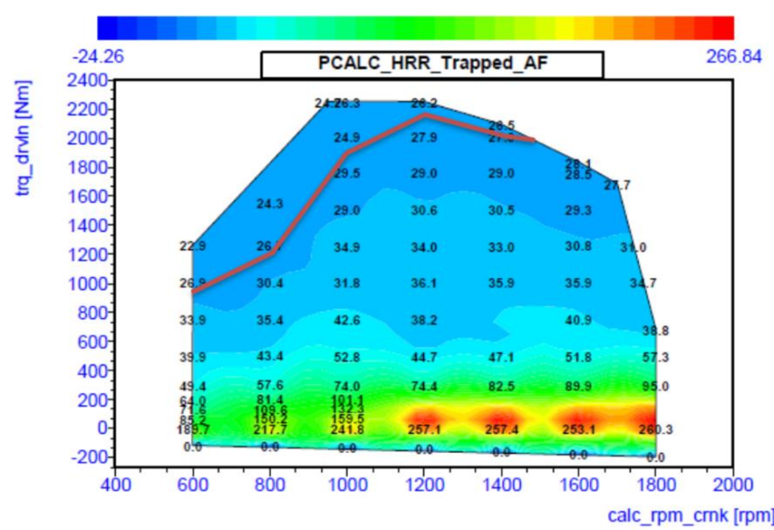

Figure 7: Air/Fuel Ratio of Heavy Duty Diesel OP Engine

[16] Rezaei, R., Hayduk, C., Sens, M., Fandakov, A., Bertram, C., "Hydrogen Combustion – A Puzzle Piece of Future Sustainable Transportation!", SIA Powertrain & Energy, November 2020.

Figure 7 shows the trapped air-fuel (A/F) ratio across the speed-load map of a 10.6L opposed piston engine operating with Diesel fuel. An A/F ratio above 27:1 with Diesel fuel matches the low NOx criteria of A/F lambda of 2.2 or greater for hydrogen. Nearly the entire operating range is already sufficiently lean for low NO_x hydrogen combustion. Just a small amount of additional boost will enable low NO_x operation in the full range.

The OP engine has another low NOx advantage. Trapped exhaust gas (EGR) has the same effect of reducing NOx formation for hydrogen as it does for Diesel fuel. External EGR can be challenging for hydrogen combustion since the high fraction of water in the exhaust can lead to condensation problems. The OP engine, however, has the ability to dynamically control scavenging and trapped conditions. This leads to a naturally high burned residual fraction (internal EGR) that both dilutes the charge to inhibit NO_x formation and helps prevent autoignition. Figure 8 shows the trapped residual in an OP Diesel engine. Internal EGR is the ideal NOx inhibitor since it provides the benefits without extra pumping work or condensation concerns.

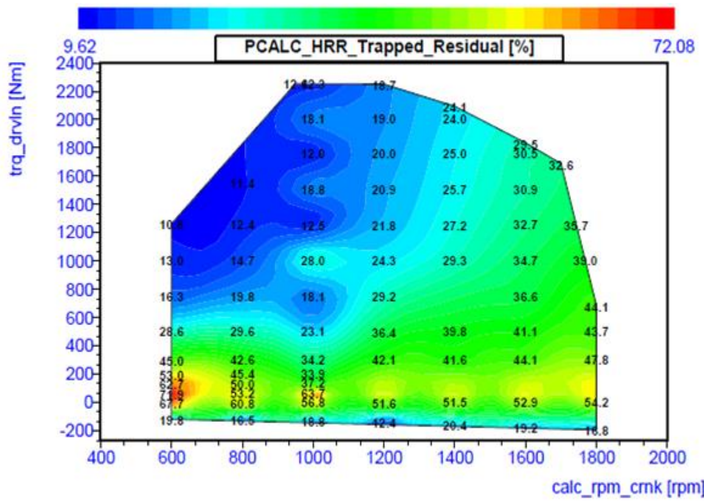

Figure 8: Trapped Residual in OP Diesel Engine

High Power Density

Lean hydrogen combustion has lower power density compared to gasoline or Diesel fuel. As noted above, however, as a two-stroke engine the OP engine has a favorable tradeoff between displacement and BMEP enabling operation at higher power density without excessive peak cylinder pressures.

Low cost:

The H2-OPE may have a significant cost advantage vs. H2-ICE. As noted above, the H2-OPE operates lean across the full operating range of the engine and therefore emits very little NO_x. It is likely possible to meet ultralow NOx regulations without any aftertreatment system, a significant advantage over H2-ICE.

Conclusion:

There are no ideal powertrains. Batteries, fuel cells, and engines all require energy to build and operate, and cost money to manufacture, utilize, and service. Hydrogen opposed-piston engines, however, offer many attractive features since they can operate efficiently with very low criteria emissions. Since it will have a significant cost and reliability advantage over hydrogen fuel cells for an indefinite period of time, the platform should be considered and developed as a viable option for an important transition to carbon-free and sustainable transportation.

For more information about Achates Power contact Larry Fromm fromm@achatespower.com