Conference Summary

Hydrogen for Sustainable Mobility Forum

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Why H_2-ICE?

Interest in hydrogen fueled internal combustion engines is increasing in major automotive markets, driven by various regulatory and commercial drivers:

- Tailpipe CO_2 regulations for both light- and heavy-duty vehicles : H_2-ICE offers near-zero tailpipe CO_2
- Hard-to-electrify segments such as long-haul transport will require alternative solutions
- Provide a market for hydrogen and refueling infrastructure while fuel cell vehicles become more prevalent. H_2-ICE enables change from conventional fossil fuels while using mostly existing engine hardware.
- H_2 can serve as an energy carrier (or feedstock to other e-fuels) to balance the supply-demand mismatch between regions which can produce and use green electricity.

Challenges

- Availability of green H_2: The potential for H_2 to decarbonize transport ultimately rests on the fuel being derived from green sources and not from the current steam methane reforming. The amount of green H_2 produced today is very small compared to the requirement, and the cost is very high.
- NOx emissions are produced and will require diesel-like after-treatment. Particulate emissions are low compared to diesel but a filter might be required for European PN standards. H_2 slip needs to be addressed and requires an oxidation catalyst.

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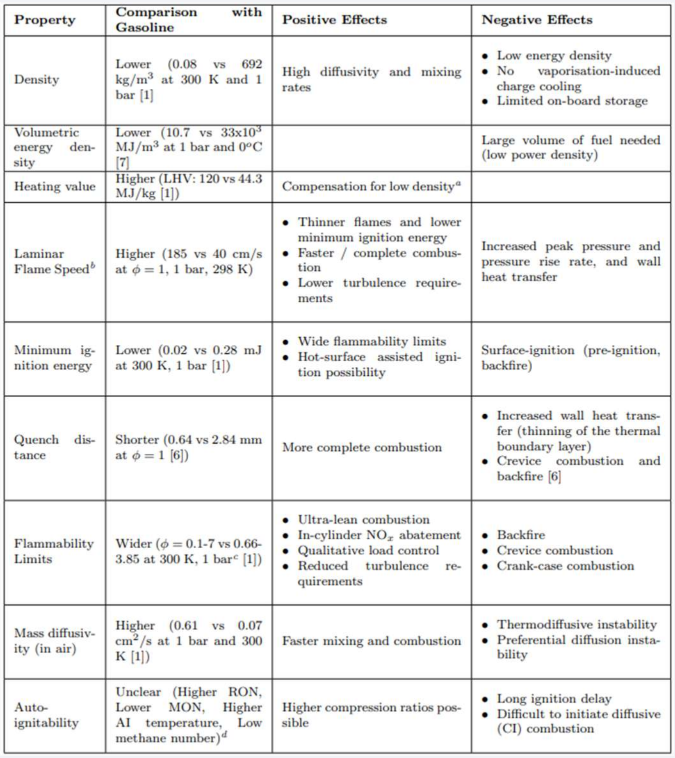
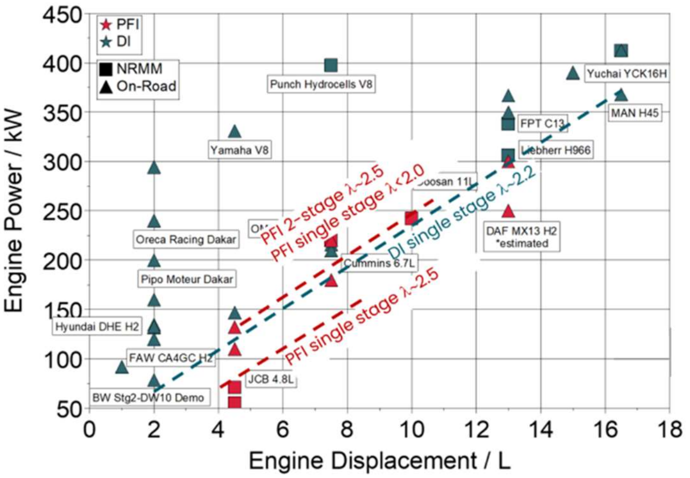
Comparison of H_2 as an ICE fuel to gasoline



Property	Comparison with Gasoline	Positive Effects	Negative Effects
Density	Lower (0.08 vs 692 kg/m^3 at 300 K and 1 bar [1]	High diffusivity and mixing rates	• Low energy density • No vaporisation-induced charge cooling • Limited on-board storage
Volumetric energy density	Lower (10.7 vs $33x10^3$ MJ/m^3 at 1 bar and 0°C [7]		Large volume of fuel needed (low power density)
Heating value	Higher (LHV: 120 vs 44.3 MJ/kg [1])	Compensation for low density[a]	
Laminar Flame Speed[b]	Higher (185 vs 40 cm/s at $\phi = 1$, 1 bar, 298 K)	• Thinner flames and lower minimum ignition energy • Faster / complete combustion • Lower turbulence requirements	Increased peak pressure and pressure rise rate, and wall heat transfer
Minimum ignition energy	Lower (0.02 vs 0.28 mJ at 300 K, 1 bar [1])	• Wide flammability limits • Hot-surface assisted ignition possibility	Surface-ignition (pre-ignition, backfire)
Quench distance	Shorter (0.64 vs 2.84 mm at $\phi = 1$ [6])	More complete combustion	• Increased wall heat transfer (thinning of the thermal boundary layer) • Crevice combustion and backfire [6]
Flammability Limits	Wider ($\phi = 0.1$-7 vs 0.66-3.85 at 300 K, 1 bar[c] [1])	• Ultra-lean combustion • In-cylinder NO_x abatement • Qualitative load control • Reduced turbulence requirements	• Backfire • Crevice combustion • Crank-case combustion
Mass diffusivity (in air)	Higher (0.61 vs 0.07 cm^2/s at 1 bar and 300 K [1])	Faster mixing and combustion	• Thermodiffusive instability • Preferential diffusion instability
Auto-ignitability	Unclear (Higher RON, Lower MON, Higher AI temperature, Low methane number)[d]	Higher compression ratios possible	• Long ignition delay • Difficult to initiate diffusive (CI) combustion

Engine Advances



FEV showed that 45 different H_2-ICE engines from 29 different manufacturers are currently being developed, for both on-road and non-road applications. Smaller, light-duty engines are mostly PFI, and larger > 13L engines are mostly DI, while the medium-duty engines have a mix of both technologies.

The key targets for improving H_2-ICE are performance, emissions and efficiency, and these influence the choice of technologies such as air handling (boost, EGR), fuel injection (PFI, LP-DI, HP-DI), after-treatment (TWC/SCR/PF), engine design and combustion (spark/compression ignition, lean/ultra-lean, compression ratio, etc.)

For commercial vehicle applications, low-P DI is favored currently and efficiencies > 44% have been achieved.

IFPEN provided an update on the various research activities and capabilities relevant to H_2-ICE.

- Previous research on a single-cylinder engine has shown that NOx emissions can be near-zero at mean air-to-fuel ratio (λ) of 2.8, increasing non-linearly at $\lambda < 2.2$. A consortium of leading suppliers and OEMs is working on developing a dedicated 4 cylinder 2.3L engine for light-duty application. Target is operation at $\lambda = 2.5$ for very low NOx emissions.
- A port-injected, 8L, 6-cylinder engine is being developed for demonstration with a 19-ton truck. Effective efficiency of >40% was achieved and engine-out NOx emissions measured at 0.6 g/kWh on the WHTC, an order of magnitude below diesel.

The combination of stoichiometric operation and use of a TWC-only after-treatment is possible as well, as was shown by **Ferrari**, on a 500-cc single cylinder engine with direct injection at 5 – 40 bar. Specific power of 140 kW/l was achieved, and it required the use of port water injection to avoid preignition. Compared to lean combustion, the indicated efficiency is lower for stoichiometric.

CFD modeling capabilities are being used to optimize fuel injection and mixing, both critical for further efficiency gains and emission reduction. As an example, **IAV GmbH** showed that the use of a “jet cap” for injecting fuel can help improve fuel-air mixture homogenization and NOx emission reduction by an order of magnitude.

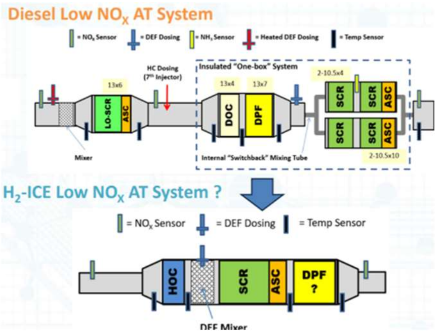
FPT presented their Cursor xC13 (13L) prototype H_2-ICE, developed on a multi-fuel platform for diesel, natural gas and H_2. The engine uses low pressure (30-40 bar) DI and lean combustion with SCR after-treatment. The engine delivers ~ 475 hp peak power and 2,200 Nm peak torque. Optical diagnostics is being used to evaluate the various root causes of pre-ignition.

No discussion of H_2 is complete without cost considerations of green H_2. **Punch** showed their analysis which concludes that the cost of H2 needs to drop to €5/kg to be competitive with diesel. Fuel cell vehicles are more expensive than H_2-ICE, but their higher efficiency makes the total cost of ownership (TCO) comparable, so expect fuel cells to provide stiff competition. Punch also showed their 6.6L V8 engine, targeting a wide range of applications including gensets and non-road engines. The engine uses port-fuel injected H_2, along with NOx control strategies such as high-P cooled EGR and retarded spark timing.

NOx Control

The current preferred technology for NOx control is Cu-SCR, same as for diesel engines. Still, H2-ICE will require further optimization to overcome specific challenges. **Southwest Research Institute (SWRI)** is leading an effort in this regard. There is room for simplification and downsizing given the absence of soot emissions, lower engine out NOx emissions and lack of hydrocarbon emissions.

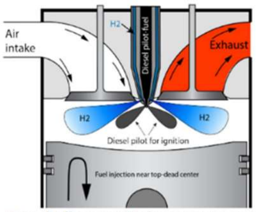
On the other hand, the higher water content is known to adversely affect low temperature SCR conversion. H_2 slip is an issue given the global warming potential of H_2 and increases the propensity for N_2O emissions.



AVL showed the use of stoichiometric operation with water injection as a pathway to achieve similar efficiency as lean combustion, while using a simpler after-treatment. High water content in exhaust can be used to advantage here, with water condensed out from the exhaust using a heat exchanger. Other than a TWC, a passive SCR is added to convert NOx using NH_3 generated during rich operation. This λ=1 operation with water injection and a late injection strategy was shown to deliver similar power as the reference gasoline engine and achieve 150 kW/l power for a 2L race car engine. For heavy-duty, 50.5% BTE was achieved on a 13L engine using lean combustion and high-P DI. Increase in compression ratio (to 23:1) and further improved turbocharger efficiency is predicted to raise the BTE to 51.7%.

At the core of this concept is the HPDI fuel injection system, which was discussed in more detail by **Westport Fuel Systems**. It includes a pilot diesel injection to promote ignition, followed by H_2 injection at high pressure. The amount of diesel injection must be optimized to qualify H_2-ICE as a ZEV in Europe. The use of high P injection is combined with EGR to reduce NOx. A "smart tank" using a compressor is required to enable driving ranges > 500 km. Simulations predict a range of 900 km with a smart tank with 80 kg fuel.

High-pressure (100-600bar) direct-inj.
Pilot-fuel or pre-chamber ignition



Key challenges: High-pressure pump, NOx, fuel compression energy

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