HYDROGEN INTERNAL COMBUSTION ENGINE WITH HIGHEST EFFICIENCY

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Abstract.
Zero emission transport solutions are key on net zero objectives. On commercial vehicles three main propulsion systems were defined as zero emission: battery-electric, fuel cell and hydrogen internal combustion engine (H2-ICE). Due to high efficiency, especially on high load operations, application suitable durability, lower sensitivity on hydrogen purification and reduced costs, H2-ICE is receiving high attention.

The first generation of hydrogen engines for commercial vehicles follow spark ignited engine combustion processes, which are operated lean with intake manifold or low-pressure direct injection. The achievable efficiencies and power densities are limited due to the combustion system characteristics.

Due to Total Cost of Ownership (TCO) and range requirements, an alternative combustion process is required, to bring H2-ICE efficiency closer to diesel engine combustion. It involves hydrogen to be injected under high pressure near top dead center. During the presentation, the ways to derive such a highly efficient hydrogen engine from a diesel engine will be shown.

The available or necessary approaches to initiate the diffusion combustion of the hydrogen are also discussed to show maximum efficiency in the hydrogen combustion engine, targeting 50% or higher brake thermal efficiency (BTE). Evaluations on the effective benefit of different compression ratios and different air boosting levels were assessed in transient dyno tests and will be presented and commented in the paper.

Keywords: H2-ICE, HPDI, Pilot Fluid

1 Commercial hydrogen engine combustion concepts

Long term Green House Gases (GHG) and CO2 targets are linked to carbon neutral transport solutions. On commercial vehicles three main propulsion systems are in a strong position as zero emission: battery-electric, fuel cells and hydrogen internal combustion engines (H2-ICE). In a holistic approach, the energy and emission demand on new batteries cells are too high to produce new vehicles or maintenance for durability. It is given by the high dependence on critical minerals. Due to that, H2-ICE is becoming a strong complementary solution, especially for high load applications [1, 2, 3]. Once H2-ICE is the one with the lowest TCO (lowest acquisition and maintenance costs) and highest durability (minimum 3 times higher) than other zero emission solutions, it has becoming focus on commercial vehicles.

The first generation of hydrogen engines for commercial vehicles follow spark ignited engine combustion processes, which are operated lean with intake manifold or low-pressure direct injection [2, 3, 4, 5]. Although these engine concepts are characterized by low injection pressures which means advantages regarding the necessary hydrogen storage concepts, the achievable efficiencies and power densities are limited due to the combustion process. That demands an engine design with higher volumetric displacement to achieve the required power level and transient performance [6].

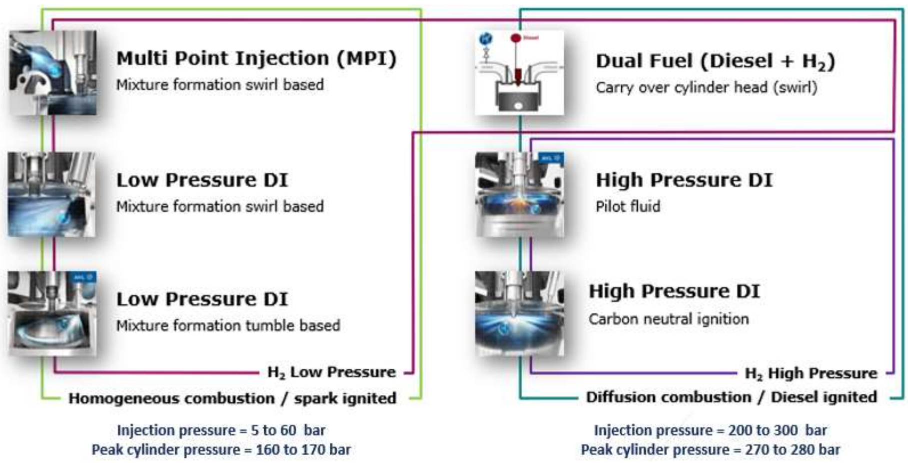

Fig. 1. Different injection strategies for H2 internal combustion engines. Adapted from [2].

To achieve a significant increase in efficiency, an alternative combustion process is required that comes close to Diesel engine combustion. To accomplish this, the hydrogen must be injected under high pressure near to top dead center, which is enabled by high pressure direct injection systems [7, 8], such as Westport's HPDI^{TM} product. As shown in Figure 1, the combination of hydrogen with a hydrocarbon as ignition fuel is a possibility to have a robust system. In the same way for a zero emission option at a complete cycle, Diesel can be substituted by HVO. For low carbon strategies, Diesel cycle combustion of hydrogen is possible in two main ways: Hydrocarbon pilot (minimum pilot fluid content to support mixture ignition) or an alternate ignition source like a glow plug. The use of Diesel cycle to burn hydrogen can enable efficiency in a combustion engine exceeding 50% BTE [6 and 9].

In terms of material development, spark ignition H2-ICEs will need solutions to reduce weight and size. As higher volumetric displacement is necessary to deliver the required power and torque, packaging can become an issue. Mechanical and thermal loads are below Diesel levels, which indicate an easy carry over of materials. On the other hand, the HPDI design is more demanding from mechanical and thermal perspectives, e.g. peak firing pressure can be up to 280 bar and injection pressures 300 bar. This brings the material selection into high focus for HPDI design.

The presence of hydrogen in the combustion chamber creates a risk of hydrogen embrittlement on the exposed parts of the chamber. Improved cast iron and stainless steel alloys are being developed to enable same high durability to Hydrogen than Diesel [10]. However, the diffusion flame combustion of the HPDI^{TM} system should allow the H2 to be fully combusted before any significant engine component exposure considering the pilot fluid concept as illustrated in Figure 2. Only the fuel system itself would be constantly exposed to H2 [6].

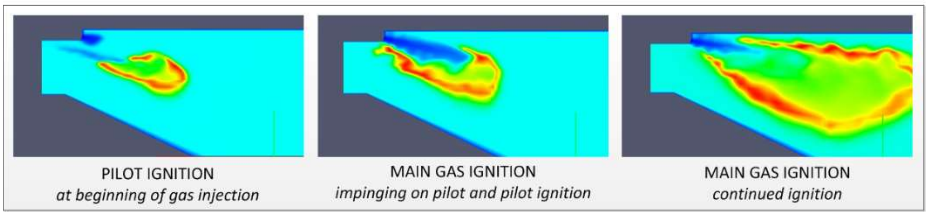

Fig. 2. Steps of ignition with the pilot fluid injection concept.

2 Demonstrator platform

It was decided to use existent Diesel platform to transform it on a HPDI H2-ICE version, which main data is presented in Figure 3 below:

ignition	charging	cyl.	VH	EGR	max. torque	rated power
[-]	[-]	[-]	[l]	[-]	[Nm]	[kW]
reference diesel engine		6	~13	cooled	2500	340

Fig. 3. Main data of series Diesel engine used as platform.

A summary of key steps is presented in Figure 4.

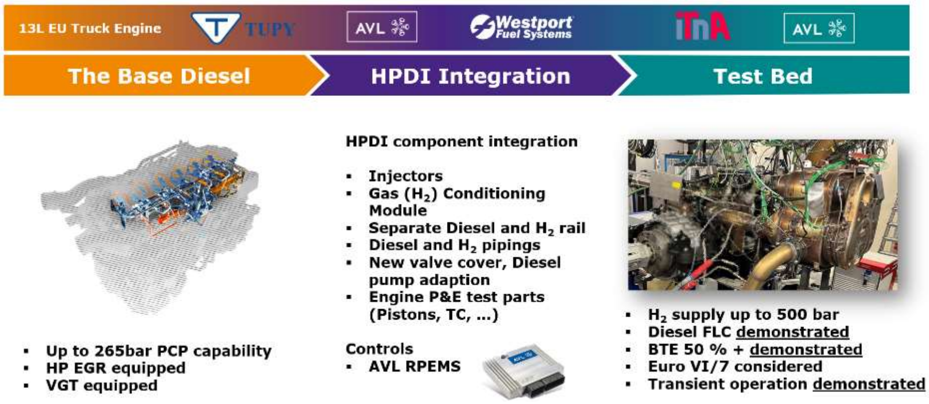

Fig. 4. Overview of the H2-HPDI Demonstrator Program and its Contributors [9]

The selected platform was already high loaded, 265bar on peak cylinder pressure (PCP) using already Compact Graphite Iron (CGI) alloy at cylinder head. Pistons were maintained on the performance tests are original steel grade material. Only variations on compression ratio that demanded new designs, but no material change.

The demonstration of the necessary vehicle components has not been part of the program. The current approach foresees a 700bar tank system, and an integrated gas module, as a buffer tank, and a mobile compressor which extends the drive range if the tank pressure falls below the demanded injection pressure.

3 Test results

The baseline series production 13L in-line six HD Diesel engine for the H2-HPDI Demonstrator shows highest brake thermal efficiency (BTE) of 47.6 % before any adaptions on the engine. HPDI concept used Diesel as pilot fluid. After equipping the base line engine with Westport HPDI 2.0 fuel injection system measurements with hydrogen showed a brake thermal efficiency of 48.7 % which is an increase in brake thermal efficiency of +1.1 % (Figure 5). The increased BTE was achieved due to additional expansion work and reduced friction because of lower injected Diesel quantity and lower injection pressure (between 200 and 350 bar). The test engine was equipped with an external Diesel supply unit with Diesel at requested rail pressure. The HP- and LP-Diesel-pump of the engine was disconnected which led to increased brake thermal efficiency since Diesel pump friction loss of around 0.3 % (evaluated in strip-down analysis) was not considered.

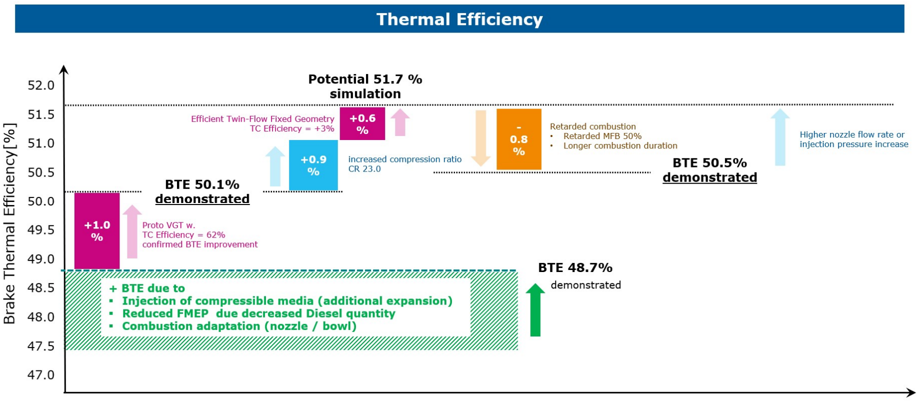

Fig. 5. Brake thermal efficiency improvement – demonstrated and potential results.

To increase the brake thermal efficiency, the serial VGT turbocharger was exchanged by an improved VGT turbocharger with efficiency of 62%. With the exchanged VGT turbocharger a brake thermal efficiency of 50.1 % was demonstrated [9].

For further brake thermal efficiency increase an estimation has been conducted on base of 1-D simulations and comparable engine measurements (Figure 9). According to the estimation a brake thermal efficiency of 51.7 % could be identified with increasing the compression ratio with 23.0 and installing a high efficiency turbocharger. The increased compression ratio was realized with a new piston with adapted piston bowl shape for best hydrogen jet and piston interaction. To improve the gas exchange, a high efficiency fixed turbine geometry turbocharger with efficiency of 68 % (twin scroll layout with wastegate) was installed and combined with a double flooded EGR system to ensure proper EGR-rates for lowest emissions. A Miller valve timing promises additional 0.1 % increase of brake thermal efficiency. However, test results showed 50.5% BTE due to retarded combustion. The use of higher nozzle flow rate or injection pressure increase could cope with this releasing the potential increase. Any how the demonstration of +2.9% on BTE compared to Diesel is an important milestone to high efficiency hydrogen combustion engines.

The hydrogen injection pressure was adjusted to about 200-300 bar, depending on the peak cylinder pressure. The injection pressure was adjusted 50-80 bar higher than the peak cylinder pressure to ensure an overcritical pressure ratio between injection pressure and cylinder pressure for the Start of Injection. Furthermore, NO_X emissions rise with a higher injection pressure, whereas efficiency has a sweet spot with falling efficiency when raising or lowering injection pressure.

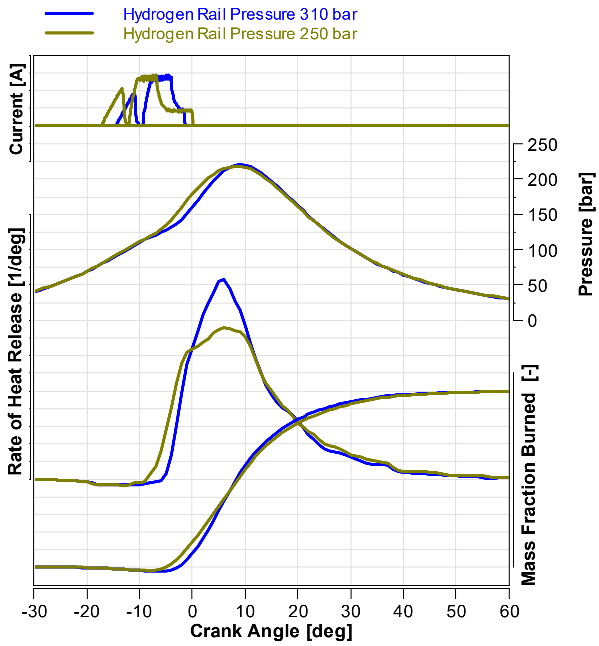

Fig. 6. Injector current, cylinder pressure and rate of heat release for 1200rpm, 21 bar BMEP from [9].

The measurement data indicate Diesel-like behavior of the H2-HPDI combustion concept in terms of NOx emissions and exhaust gas temperature level. Consequently, the aftertreatment concept meeting Euro 7 legislation according to the Draft Agreement of 12/2023 (limit values displayed in Table 1 will look like the currently proposed Diesel system architectures (Figure 7). As the H2-HPDI combustion concept tends towards higher NOx emissions EAS concept 2 in Figure 7 is the most suitable configuration to meet the emission targets and limits.

Tab. 1. Limit values in the WHTC cold/hot and RDE limits for EURO VI E and Euro 7 (based on draft agreement)

Pollutant emissions	WHTC		RDE	
	Euro 7 Draft Agreement WHTC c/h combined (1/7 vs. 6/7) 20.12.2023	EU VI Limits WHTC c/h combined (1/7 vs. 6/7)	Euro 7 Draft Agreement 20.12.2023 ISC c/h combined (1/7 vs. 6/7)	EU VI Limits ISC combined (1/7 vs. 6/7)
-	per kWh	per kWh	per kWh	per kWh
NOx in mg	200	460	260	690
PN_{10} in #	6x10^11	6x10^11 (PN 23)	9*10^11	9.78*10^11 (PN 23)
NH_3 in mg	60	10 (ppm)	85	N/A
N_2O in mg	200	N/A	260	N/A
CH_4 in mg	500	500	650	750
CO in mg	1500	4000	1950	600
NMOG in mg	80	160 (NMHC)	105	240 (NMHC)
HCHO in mg	N/A	N/A	N/A	N/A
PM in mg	8	10	-	N/A

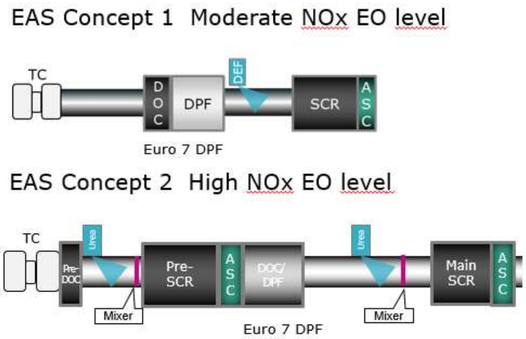

Fig. 7. Possible system architecture for a Euro 7 compliant aftertreatment system for the H2-ICE HPDI combustion concept.

The Euro 7 PN10 limit (**Erro! Fonte de referência não encontrada.**) requires the integration of a particle filter in the exhaust aftertreatment system even for the HPDI concept. However, the expected low level of soot emissions eliminates the need for active soot regeneration. SCR desulfurization and Urea deposit removal procedures can be performed by exotherm HC oxidation on the Diesel Oxidation Catalyst (pre-DOC) respecting the temperature limits of the downstream components. Typically, in a Diesel exhaust aftertreatment system with two SCR systems, the dosing of the AdBlue dosing systems is varied to enable passive soot oxidation on the DPF when the operating conditions are favorable and usually the pre-SCR catalyst volume is lower compared to the main-SCR volume. As the soot emissions for the H2-HPDI combustion concept are considerably lower compared to the Diesel combustion the above-mentioned design and operation guidelines do not necessarily apply for an exhaust aftertreatment system specifically designed for an H2-HPDI engine. In the recent measurement campaign at AVL an aftertreatment system corresponding to the concept 1 configuration in Figure 7 was applied and its performance was measured in the WHTC c/h. In **Erro! Fonte de referência não encontrada.** the results are graphically compared to Euro VI and Euro 7 emission limits. While the Euro VI NOx emissions are already reached the Euro 7 limits could be reached by adapting the EAS configuration and implementing heat-up strategies on the engine side.

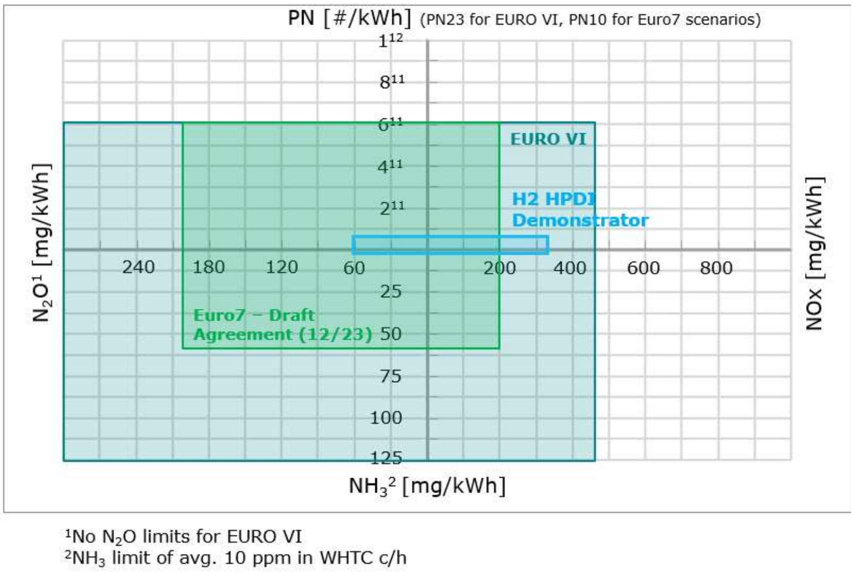

Fig. 8. NOx, N2O and NH3 emissions in WHTC c/h.

In terms of max. power and max. torque, results are illustrated in Figure 9.

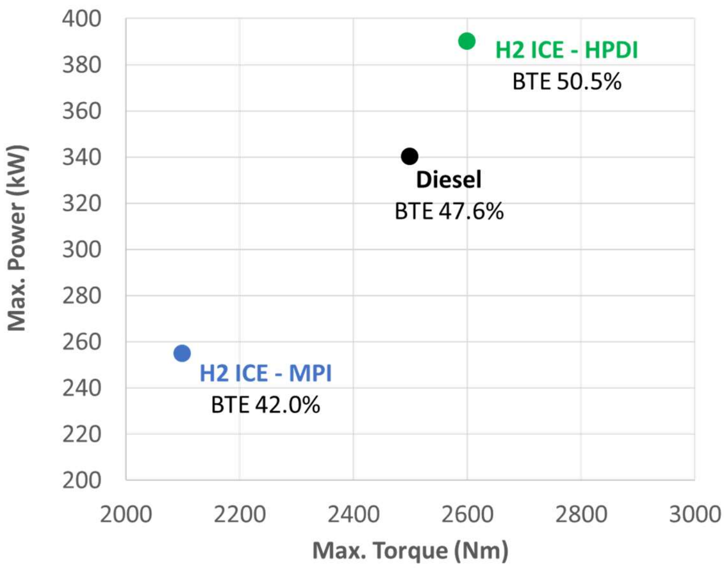

Fig. 9. Power and torque comparison with different powertrain concepts (same 6 cylinder 13L design).

The tank to wheel (TTW) CO_2 reduction from Diesel Engine was 97.5% in full load conditions. Use of sustainable paraffine fuel (e.g.: HVO, e-diesel) is also possible as pilot fluid for well to wheel (WTW) further reduction. These results are in line with the proposed limits of Zero Emission Vehicle (ZEV) in Europe of 5 g/ton-km CO2e. H2-ICE with HPDI shows potential to attend even lower values like 1 g/ton-km CO2e.

4 Conclusions and next steps

H2-ICE is a promising carbon neutral solution for commercial vehicle transportation. Its high performance at full load conditions combined with lower cost and much higher durability are factors for a significant advantage over other carbon neutral solutions.

In a common project of AVL, TUPY, Westport and ITnA (TU-Graz) a H2-ICE with HPDI demonstrator was designed, built up and tested under transient conditions. A brake thermal efficiency above 50% was demonstrated, with further hardware upgrades thermodynamic calculations promise almost 52% BTE [11]. The demonstrated full load curve is identical to a typical Diesel, enabling even higher power levels with transient torque built up calibrated to be identical to series. H2 combustion can release 24% more energy compared to diesel for a given airflow. It combined with the fact that H2 combustion do not produce smoke, the smoke limiter is no longer needed. Then transient torque builds up time can be reduced with approx. 50% compared to the baseline diesel.

Fuel efficiency is a major contributor to optimize total cost of ownership for heavy duty vehicles, therefore high-pressure direct injection is an enabler to achieve carbon neutrality with highest efficiency for high load operation profiles combined with the robustness needed for commercial vehicle applications.

The H2-ICE HPDI engine did run on a hydrogen energy ratio of 97.5% in full load conditions. A liquid pilot has turned out to be the only robust measure to ensure stable and robust conditions for an auto ignition of the hydrogen. It allows GHG reduction in line with proposals of ZEV in Europe.

A further degree of freedom and therefore potential for future combustion system development regarding NO_X-emission and max. cylinder pressure is seen in application of a combustion control with moderated injection rate.

For the P&E demonstration on the engine test cell all engine related HPDI components did show adequate reliability (engine run time limited to several 100hrs). The vehicle must foresee a 700bar Tank system, an integrated gas module, as a buffer tank, and a mobile compressor which extends the drive range if the tank pressure falls below the demanded injection pressure.

Further evaluations are focused on durability tests. It can be on vehicles or dyno and further project organization is being planned.

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