Hydrogen HPDI™ System Applied on a High-Efficiency Heavy-Duty Diesel Engine

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Westport Fuel Systems (WFS) and Scania CV AB (Scania) has since early 2021 had an ongoing cooperation regarding the application of the H_2 HPDI™ (High Pressure Direct Injection) system on the latest 13L CBE1 high-efficiency, high-performance heavy-duty diesel internal combustion engine. In this cooperation, Scania and WFS have unveiled and confirmed some disruptive attributes regarding compression-ignited hydrogen engines.

1. Description of HPDI Technology

HPDI with pilot ignition is a commercially available technology originally developed for heavy-duty natural gas engines. Fuel injection relies on late (close to top dead center) cycle direct injection of gaseous fuel (in this case hydrogen) at moderate pressure (~300 bar). A small quantity of pilot fluid (1-3% on energy basis) injection at a similar pressure precedes the injection of hydrogen and acts as an ignition source. It can be considered as a liquid sparkplug. The hydrogen then burns with a traditional diffusion flame. The injection of the fuel and the pilot is accomplished via WFS (Westport Fuel Systems) proprietary dual concentric needle HPDI injector design.

By utilizing diesel cycle thermodynamics, the HPDI fuel system operating on H_2 exceeds the already high thermal efficiency and power density of the base diesel engine.

2. Description of the Engine Simulation Method

Westport Fuel Systems (WFS) carried out a simulation study on the engine. Results were obtained using WFS in-house state-of-the-art engine combustion CFD solver, which utilizes a proprietary turbulent combustion model with detailed chemical kinetic mechanisms. The model predictions have been validated against experimental engine test data over a wide range of operating conditions on multiple engine platforms for pilot-ignited gaseous fuel combustion over the last 15+ years including H_2. Figure 1 shows the CFD visualization of the fully ignited hydrogen jet as the HPDI combustion is unfolding in the engine cylinder at mid-load condition (50% load at 1200 RPM). The CFD tool has been critical in investigating and optimizing HPDI combustion for H_2 fuel.

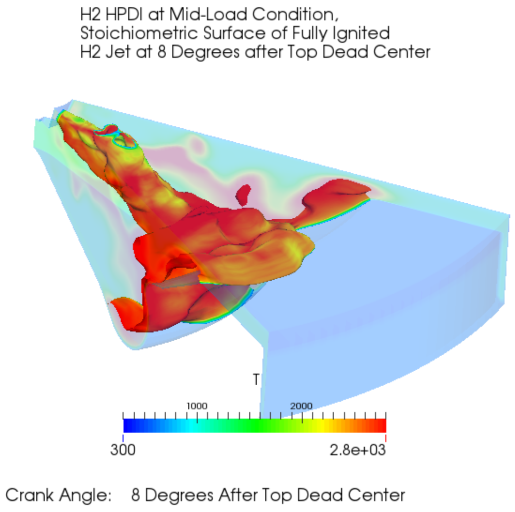


Figure.1 CFD visualization of the H_2 jet ignition

3. H_2 HPDI Simulation & Test Results

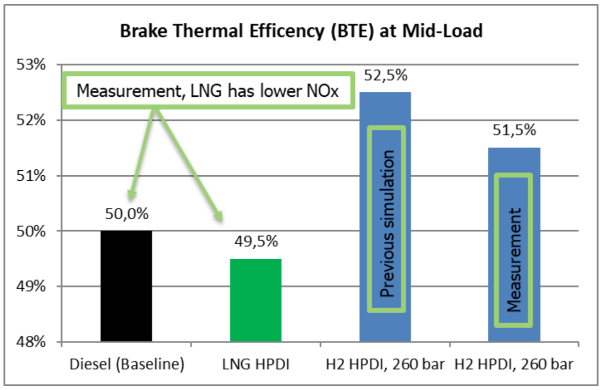


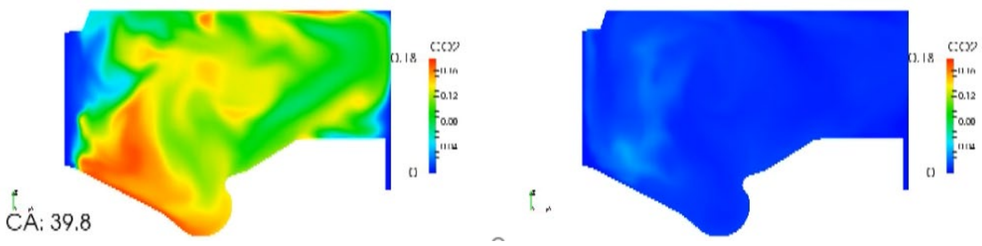
Figure.2 Brake Thermal Efficiency at mid-load condition.

Recent test results show the comparison between diesel and hydrogen H_2 HPDI. The baseline test is made on a diesel combustion system designed to achieve 50% brake thermal efficiency (BTE). As seen from the table, simulated data of the H_2 HPDI at mid-load (50% load) condition demonstrates a BTE of 52.5% with 260 bar gas injection.

In real tests, the injection timing must be retarded to achieve the same engine out NOx emissions as the diesel reference. Despite this, an impressive 51.5% BTE is achieved.

CO_2 reduction

In the case with H_2 HPDI, the H_2 requires much less energy to ignite than methane. This enables a significant reduction in pilot fluid amount, and during some conditions probably eliminating the need of a pilot fluid injection. In the visualization below, it can be seen that CO_2 is more or less avoided in the case of H_2 HPDI combustion.



CO_2 concentration in diesel combustion

CO_2 concentration in H_2 HPDI combustion

Figure.3 CFD visualization of CO_2 fraction in the engine combustion chamber during the power stroke at 40

Several factors associated with the physical and chemical properties of hydrogen fuel that is generally a drawback to spark-ignited H_2 engines is actually beneficial in combination with the H_2 HPDI system. They include lower equivalence ratio at given air flow and load, significant contribution to extracted work due to expansion of compressed hydrogen near top dead center increasing the pressure during the power stroke, high tolerance to fuel-rich combustion, high flame speed and high diffusivity of hydrogen.

4. Thermal efficiency

The H_2 HPDI system offers another quantum leap in efficiency of the combustion engine and positions itself as a promising alternative for HD truck propulsion. The remarkable efficiency of the H_2 HPDI can be explained by several effects:

1. H_2 is quite bulky and has low density. By injecting H_2 at top dead center, a significant amount of molecules (moles) are added, aka Molar Expansion. Just expanding them during the expansion stroke generates power and increases the efficiency. You can say that the ICE utilizes the work stored in the pressurized onboard H_2 tank. Seen from the ICE's perspective, this is free energy.
2. H_2 burns very fast which enables a very favorable heat release, which gives rise to a high Effective Expansion Ratio, which ultimately promotes efficiency.
3. The low injection pressure (compared to diesel) induces less motion into the combustion chamber. This reduces the thermal losses and the heat load on the combustion chamber.

5. Power density

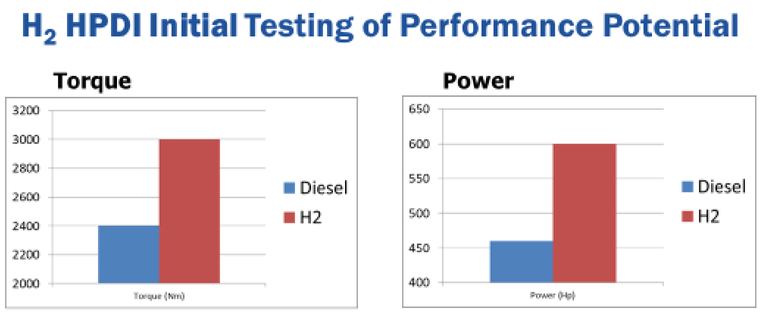
One of the significant benefits with H_2 HPDI is that it reveals the potential of the H_2 fuel to enable a combustion engine with high power and torque density. The reason of this is to find in the properties of H_2 combustion.

$$\mathbf{O_2 + 2H_2 = 2H_2O \quad => \quad 3.5\ MJ/kg\ air}$$

$$\mathbf{O_2 + 0{,}69CH_{1{,}8} = 0{,}69CO_2 + 0{,}62H_2O \quad => \quad 2.9\ MJ/kg\ Air}$$

It can be seen in the formula above that for a given amount of air (in this case, only the oxygen part is shown), H_2 is able to release more energy than diesel fuel.

Recent tests have indicated a 15-20% increase in power and torque over the standard diesel engine, without violating peak cylinder pressure, exhaust gas temperature or other engine limitations.


H_2 HPDI Initial Testing of Performance Potential

Torque

Power

Torque and power comparison of 13-liter engine with diesel and with H_2 HPDI
(engine limitations like PCP, exhaust temp, and boost pressure kept below limit)

6. Torque response and low end torque

In order to make a useful source of power for propulsion, not only the power and efficiency is of importance. In order to get good drivability of the truck, a flat torque curve with low end torque and transient response is critical. This is currently very demanding for spark-ignited premixed concepts. On the contrary, H_2 HPDI offers significant improvements. In a typical diesel engine, there is a functionality called “smoke limiter”.

Maximum injected fuel quantity – with respect to smoke – is limited in a positive transient while waiting for boost pressure build-up. For a methane engine, the maximum amount of injected fuel is limited by methane slip.

H_2 combustion is very forgiving in comparison. It burns quickly with high combustion efficiency with a very short HR tail, and the only product is water. The lack of carbon in the fuel means that there is no smoke limit, which enables stoichiometry in positive transients, and thus very fast torque build-up.

The absence of a smoke limit also allows stoichiometry to be applied at full load and low rpm, typically 500 to 900 rpm, as long as thermal and NVH limits are not exceeded. Stoichiometry, of course, results in a high torque. Together with very agile transients, this contributes to very good drivability.

To this can be added the previously described fact that a combustible mixture of H_2 and air has a Heating Value – at a given λ – which is 25% higher (on mass basis) compared to hydrocarbons, including alcohols. This further contributes to fast transients and high steady state torque.

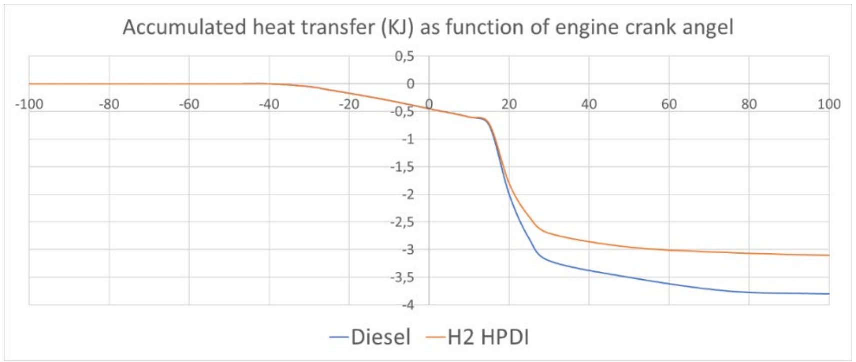
Last but not least, direct injection of H_2 allows for very late post-injections in transients – typically SOI @ 90 °CA after TDCf – which contributes to a significantly faster charge pressure build-up, as well as providing the opportunity to deliver massive heat output at high temperature to the exhaust aftertreatment immediately after a cold start.

The very late post-injections are made possible by the fact that the fuel is carbon-free and that the penetration of the spray is limited. Together, this means that the late phasing of the post-injections is not limited by soot build-up in the oil, as is the case for diesel.

It should be added that stoichiometry is applicable to a heterogeneous spray driven H_2 combustion system without a penalty in engine out NO_X. This is not the case for homogeneous flame front-based H_2 combustion systems, where the engine out NO_X penalty becomes very large at stoichiometry.

7. Heat load on engine components

The initial tests with hydrogen with the H_2 HPDI showed significantly lower exhaust temperature. The higher efficiency is one of the reasons among others. However, with the higher adiabatic flame temperature of H_2 compared to diesel, it can be expected to have a higher thermal load on the combustion chamber material. In fact, this is overcompensated by the lower turbulence induced by H_2 HPDI injection compared to diesel injection.



This can be seen in the simulation in the graph above.
H_2 HPDI uses 50-70 bar higher pressure than cylinder pressure while diesel injection utilizes several thousand bar to avoid sever smoke emissions. It's a completely different magnitude. The lower momentum of the combustion gases in the H_2 case means two things.

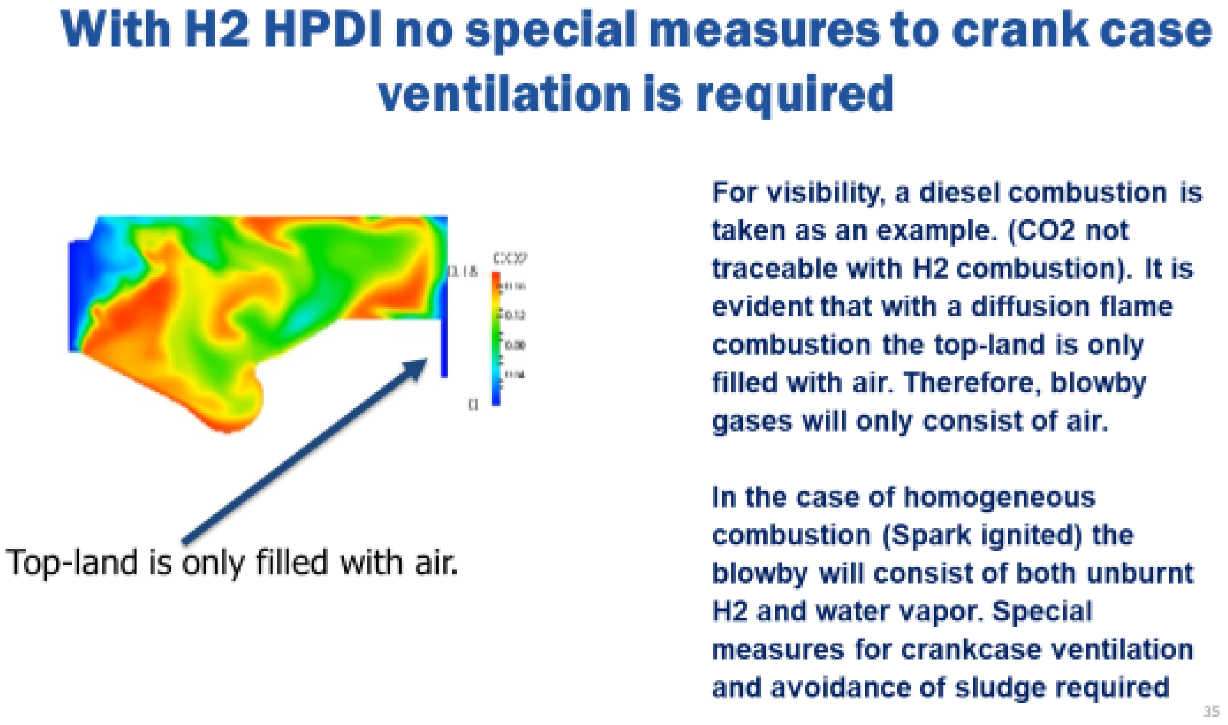
-Less heat transfer to the combustion chamber walls, resulting in lower thermal load of the structure.

-Less heat transfer to the combustion chamber walls, which equals higher engine efficiency.

8. Crank case ventilation

H_2 HPDI is based on late injection of the hydrogen gas into the combustion chamber and thus stratified charge with subsequent spray-driven combustion, just like a conventional diesel. This means that the blow by gas contains extremely little H_2 and relatively little combustion products, and thus there is no need for forced/active crankcase ventilation to avoid explosions in the crankcase and degradation of the oil due to dilution with water and subsequent lubricity issues.

Please note that the combustion products for H_2 contain 2.7 times more water compared to diesel.



With H2 HPDI no special measures to crank case ventilation is required

Top-land is only filled with air.

For visibility, a diesel combustion is taken as an example. (CO2 not traceable with H2 combustion). It is evident that with a diffusion flame combustion the top-land is only filled with air. Therefore, blowby gases will only consist of air.

In the case of homogeneous combustion (Spark ignited) the blowby will consist of both unburnt H2 and water vapor. Special measures for crankcase ventilation and avoidance of sludge required

9. Commonality with diesel base engine, H_2 and methane engine

From a commercial perspective, commonality is very important if a certain technology should be brought to the market.

If HPDI is used for gaseous fuels, i.e., CNG and H_2, the commonality between these fuels and diesel becomes maximum from an engine perspective. The only engine component that is not identical between these three engines – diesel, CNG and H_2 – is the fuel injector. If you want to access the last tenths of BTE, you can introduce small changes to the following components:

- Intake port (swirl)
- Piston bowl shape
- Number of holes in the pilot fluid nozzle
- Turbine size

This is absolutely not necessary though.The underlying mechanism for this extreme commonality between these three engines lies, of course, in the fact that all three operate according to the same basic combustion principle, i.e. late injection, stratified charge and spray-driven combustion.

One can simply describe it as all fuels release the same combustion enthalpy at the same crank angle in the same air mass. The external gas exchange system will essentially not notice any difference regardless of which of the three fuels are being burned.

The EATS will operate according to the same principle for all three engines.

10. Hydrogen embrittlement

One of the challenges with hydrogen is the reaction with different materials. Hydrogen embrittlement is a known phenomenon. The big advantage with H_2 HPDI is the fact that H_2 is kept in the fuel system. As soon as it is introduced into the combustion chamber, it ignites, combusts and turns into water vapor. The engine components are never exposed towards hydrogen.

11. Exhaust aftertreatment system and thermal management

In a modern combustion engine, the emissions are more or less zero when the engine and aftertreatment is warm. This means that a majority of the total emissions are emitted during warm-up phase. A lot of research and development has been invested to make the warm-up phase as short and clean as possible. H_2 HPDI offers several options in this area as the system permits combustion with very low air excess ratio and very late injection timing.

In addition, H_2 direct injection enables very late post-injections – typically SOI @ 90 °CA after TDCf – which helps deliver a massive high-temperature heating effect to the exhaust aftertreatment immediately after a cold start.

The very late post-injections are made possible by the fact that the fuel is carbon-free and that the penetration of the spray is limited. Together, this means that the late phasing of the post-injections is not limited by soot build-up in the oil, as is the case for diesel.

12. Summary and path forward

The H_2 HPDI system has been examined on different internal combustion engines as a zero-carbon fuel for heavy-duty applications. A first set of prototype vehicles has been assembled with impressive results.

The fact that H_2 HPDI solves at lot of issues operating a combustion engine on H_2 – while delivering excellent performance and efficiency – makes it a promising path forward with respect to the climate, and enables a short time to market at a very low development and production cost.

The most prominent advantages using the Westport Fuel Systems H2 HPDI can be summarized as:

- Higher torque and power density than diesel due to the characteristics of H_2 as a fuel.
- Even higher efficiency than the excellent efficiency of a diesel engine.
- Only the fuel system is replaced and major changes to the engine and aftertreatment system are avoided, which translate into short time to market and low total cost of ownership.
- No difference in thermal and mechanical load to combustion chamber, crank train and exhaust system compared to diesel operation.
- Lubricity and safety: No combustible H_2/air mixture and water vapor pass through the ring pack into the crankcase.