Title:
Hydrogen HPDI system applied on a High Efficiency Heavy Duty Diesel Engine

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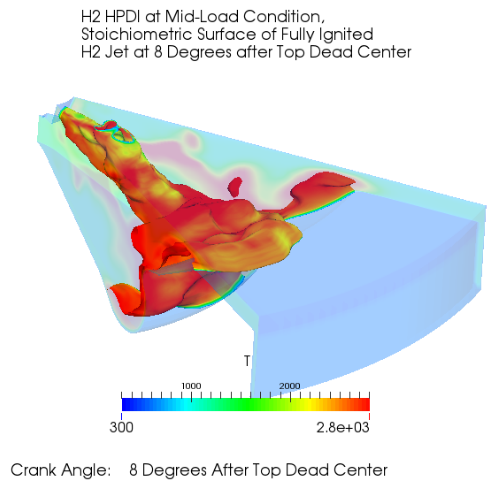
Westport Fuel Systems (WFS) has earlier this year entered into a cooperation with a major OEM regarding the application of the H2 HPDI (High Pressure Direct Injection) system on the latest 13L high efficiency, high performance heavy duty diesel internal combustion engine. As a first step in this cooperation, the benefits of the **Westport H2 HPDI** system were assessed on the engine through a detailed combustion modelling study.

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 cycle direct injection of gaseous fuel (in this case hydrogen) at high pressure (~300 bar). A small quantity of pilot fuel (e.g., diesel) injection at a similar pressure precedes the injection of hydrogen and acts as an ignition source. The hydrogen then burns with a traditional diffusion flame. The injection of both fuels is accomplished via WFS's proprietary dual concentric needle HPDI injector design. By utilizing diesel cycle thermodynamics, the HPDI fuel system operating on H2 exceeds the already high thermal efficiency and power density of the base diesel engine.

2. Description of the Engine Simulation Method

Westport Fuel Systems carried out a simulation study on a heavy duty diesel engine. Results were obtained using WFS's 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 H2. 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 H2 fuel.



during the power stroke.

3. H2 HPDI Simulation Results and Discussion

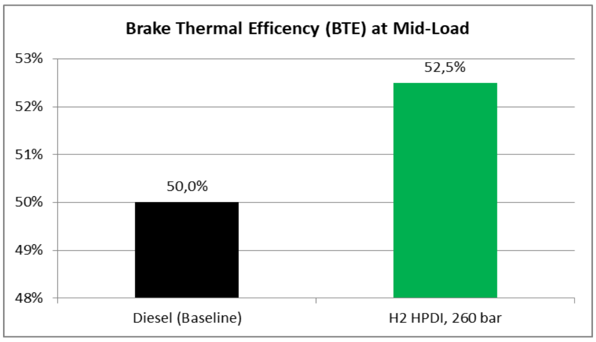
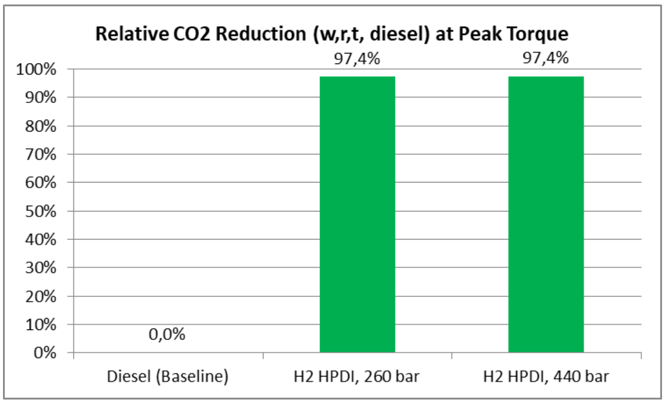


Figure.2 Brake Thermal Efficiency at mid-load condition.

Preliminary results from CFD Simulation show comparison between diesel and hydrogen (H2) HPDI. Baseline simulation is made on a diesel combustion system designed to achieve 50% BTE. As seen from Figure 2, the H2 HPDI at mid-load (50% load) condition demonstrates a brake thermal efficiency (BTE) of 52.5% with 260 bar gas injection pressure. This corresponds to a 5% reduction in fuel consumption. Similarly, at peak torque condition (not shown in the figure) the H2 HPDI brake thermal efficiency (BTE) was 50.1% with 290 bar gas injection pressure. Increasing the fuel injection pressure for H2 HPDI to 440bar, peak torque BTE was 51.4%.



For the full-load condition (Figure 3) about 97.4% reduction in tail pipe CO_2 was observed relative to pure diesel combustion. The tailpipe CO_2 emissions (tank to wheels) for H2 HPDI is due to the use of diesel pilot. Visualization of the residual CO_2 in the combustion chamber for H2 HPDI as shown by CFD model (Figure 4) clearly indicates a drastic reduction compared to diesel combustion. WFS currently has activities ongoing to further reduce the pilot quantity substantially from the current levels and thereby improve the tailpipe CO_2 reduction. Other pilot fluids are currently under further investigation.

Engine out NOx (before the exhaust aftertreatment system) at peak torque was comparable to the diesel baseline with 290 bar injection pressure. Fuel injection pressure, timing, & EGR have been demonstrated as effective measures for bringing engine-out NOx to low levels without soot formation and other issues related to low NOX diesel combustion. This opens up for an engine tuning combining low tailpipe NOx emission with super high efficiency as well as high power and torque.

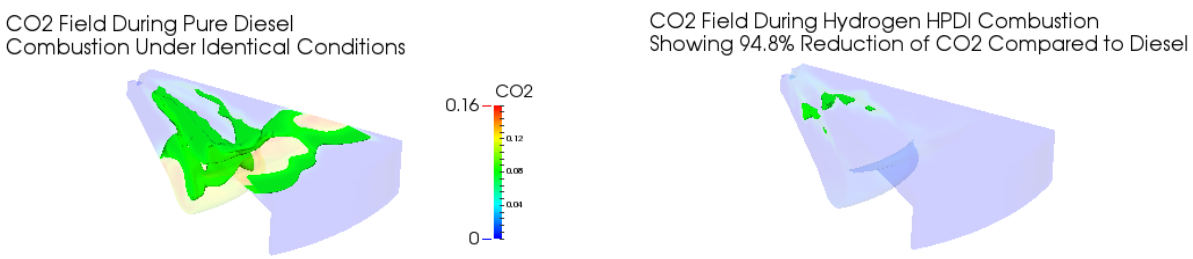


Figure.4 CFD visualization residual CO_2 mass fraction in the engine combustion chamber during the power stroke at 10 degrees after top dead center - for pure diesel combustion (left) and pure H2 HPDI combustion (right).

Several factors associated to the physical and chemical properties of hydrogen fuel, which are generally a drawback to spark ignited H2 engines, are actually beneficial in combination with the H2 HPDI system. They include lower equivalence ratio at given air flow and load, significant contribution to work due to expansion of compressed hydrogen near top dead center before the piston starts to move down during the power stroke, high tolerance to fuel-rich combustion, high flame speed and high diffusivity of hydrogen.

4. Summary and Path Forward

WFS have examined the combustion properties of hydrogen as an alternative, zero-carbon fuel for internal combustion engines for heavy duty applications. Combustion modelling has demonstrated that HPDI combustion offers the highest power density, highest efficiency and is the most robust system for using hydrogen in an internal combustion engine for heavy duty applications. H2 HPDI provides near-zero CO_2 emissions in its current configuration, with further CO_2 reduction opportunities identified for future studies and development. The H2 HPDI system has already been tested on HD combustion engines with good results, and the upcoming testing on the latest HD engines will be very exciting.

The fact that H2 HPDI solves a lot of issues operating a combustion engine with H2 while delivering excellent performance and efficiency makes it a promising path forward and enables a short time to market.

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

- Higher torque and power density than diesel due to the absence of knock
- 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 translates into short time to market
- No difference in thermal and mechanical load to combustion chamber, crank train and exhaust train compared to diesel operation
- Lubricity and safety: No combustible H2/Air mixture and water vapor passing the ring pack into the crankcase