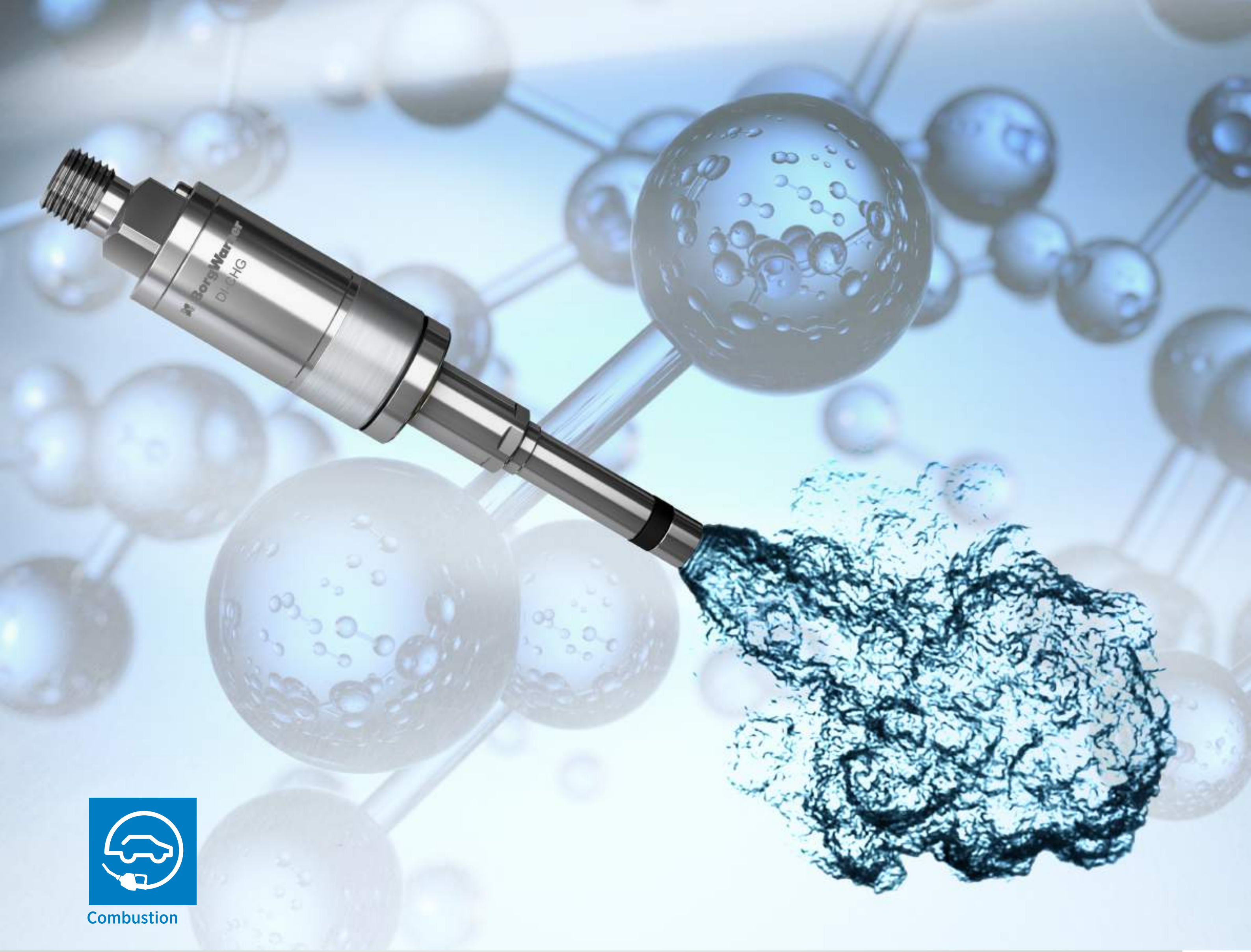

Decarbonizing the Automotive Sector with Hydrogen

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BorgWarner is developing hydrogen powertrains that can meet the demands of both current and future emissions regulations in the automotive industry.

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Introduction

Despite efforts to reduce fuel consumption, emissions from motor vehicles continue to increase. More than a tenth of global CO_2 emissions related to energy usage can be attributed to passenger cars, with almost as much originating from commercial vehicles. Recent European Union proposals aim to totally decarbonize the light duty automotive sector by 2035, and a similar goal for heavy duty vehicles is planned. To achieve these targets, reliance on diesel and gasoline must be replaced by a focus on cleaner and more efficient energy options.

Powertrain Options to Reduce CO_2 Emissions

The Hydrogen Fuel Cell (H_2FC) Vehicle and the Hydrogen Internal Combustion Engine (H_2ICE) both have the potential to reduce CO_2 emissions to zero. Data for a 40-ton commercial vehicle equipped with each of these powertrains are compared with those of a Battery Electric Vehicle (BEV) in Figure 1.

Why Choose Hydrogen?

Compared to the BEV, a hydrogen powertrain offers the advantage of lower weight, which makes the vehicle more energy efficient and increases its freight carrying ability. Refueling is also faster; a hydrogen powered commercial vehicle can be filled in about 20 minutes, whereas recharging the BEV takes almost two hours even at a peak charge rate of 1MW.

H_2ICE is a fast-to-market powertrain solution that requires only minor adjustments to the existing internal combustion engine to meet both zero emission CO_2 targets and future emissions regulations. BorgWarner acts as a hydrogen technology solution provider to

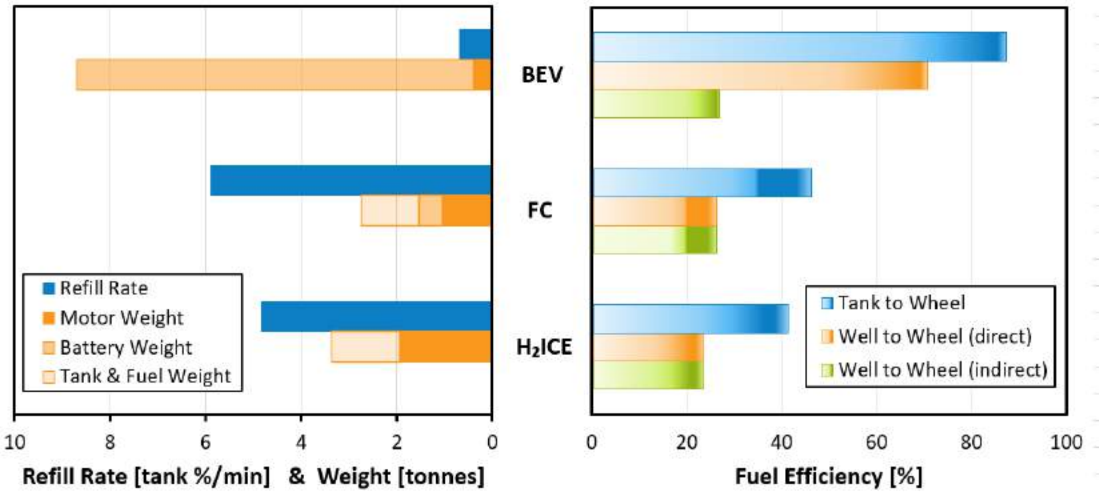

Fig. 1: Comparative data for zero CO_2 powertrains

OEMs in all vehicle segments. From passenger cars to light and heavy-duty commercial transport for both on- and off-road vehicles, customers have access to individual components or complete turnkey applications integrating the entire hydrogen injection system including controller, software and calibration.

Hydrogen Injector Positioning and Fuel Pressure Considerations

Because hydrogen has quite different fuel characteristics than diesel or gasoline, it is vital to specify the injection system correctly with regard to fuel injector positioning and fuel system pressure. Figure 2 shows the system architecture for both port injection and direct injection layouts. Under stoichiometric conditions (where the ratio of air to fuel should ensure complete combustion), injection into the inlet port may displace up to 30% of the incoming charge, which reduces cylinder filling efficiency and decreases power output. In contrast, direct injection into the cylinder after the intake valve closes avoids this deficiency, and also prevents engine backfire – a potential hazard with H_2ICE – since no fuel enters the inlet manifold.

The injection system operating pressure influences both the rate of fuel injection and the width of the injection window. High pressures give higher injection rates and longer injection windows thus supporting higher power applications. For medium pressure systems, operating below 50 bars, a compressor is unnecessary. For pressures in excess of 150 bars, a compressor must be added to the injection system to avoid an increase in tank empty pressure, which would decrease the usable fuel tank capacity. The compressor also consumes engine power, but this is more than offset by the higher engine thermal efficiency. This is because an engine equipped with a high-pressure system may use a higher compression ratio as well as later injection timing for reduced piston compression work and better knock resistance. The disadvantage to employing higher system pressures is that later injection timings also result in lower air-fuel mixture uniformity due to shorter mixing time, which increases NO_x emissions.

Low, medium and high-pressure injection solutions for hydrogen propulsion systems are being developed by BorgWarner. Of these, the medium pressure direct injection system is considered to be an ideal starting point for H_2ICE applications, enabling the desired combustion control and emissions levels to be achieved with only moderate system complexity.

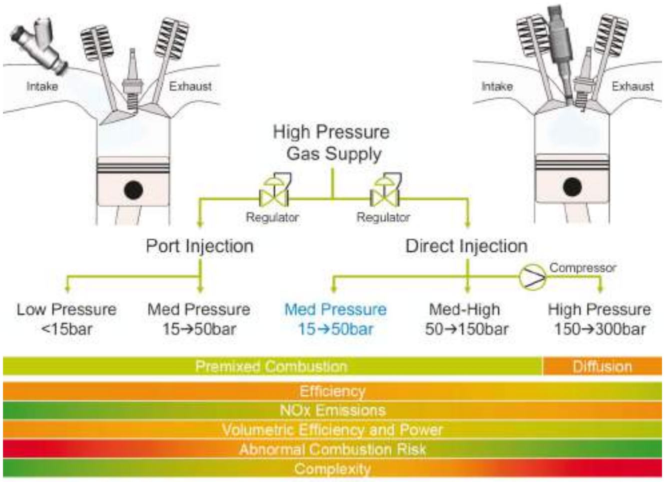

Fig. 2: System architecture options for gaseous fuels

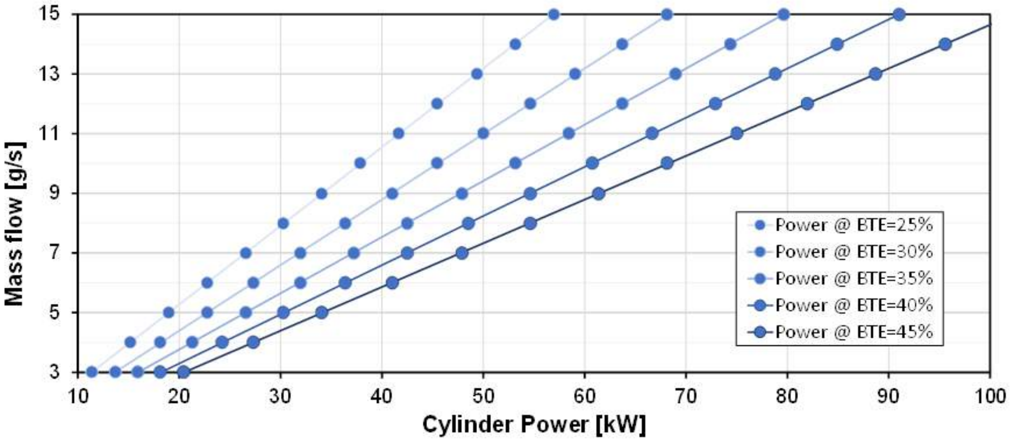

Fig. 3: Injector flow and engine power capability

Hydrogen Injector Choice

The hydrogen flow requirements to achieve various power targets with a medium pressure direct injection system and a 100° crank angle injection window are shown in Figure 3.

Two types of medium pressure injectors have been developed by BorgWarner to cover the various flow and power ranges needed for passenger car and commercial vehicle applications. DI-CHG10 is package compatible with 7.5mm tip GDi injectors and suitable for outputs up to 60kW per cylinder. The larger DI-CHG15 injector (Figure 4) has a 9.8mm tip but is able to increase flow and power capability to ~90kW per cylinder for heavy duty vehicle engines.

The DI-CHG injectors feature a solenoid-operated valve which opens outwards, ensuring robust injector sealing against high in-cylinder pressures. The valve also provides a large cross-sectional area for high flow rates, which together with a minimized internal pressure drop enables the injector to meet high cylinder power targets. The injector materials and coatings have been selected for compatibility with hydrogen, and robust performance. To allow the engine to operate throughout its full load range with accurate quantity control, either pressure modulation or software control of the injectors can be employed. The latter is proposed to enable control of the injector even within its ballistic operating range while maintaining a constant injection pressure. This constant pressure approach enables reduced pressure losses in the regulator and lowers the overall system complexity.

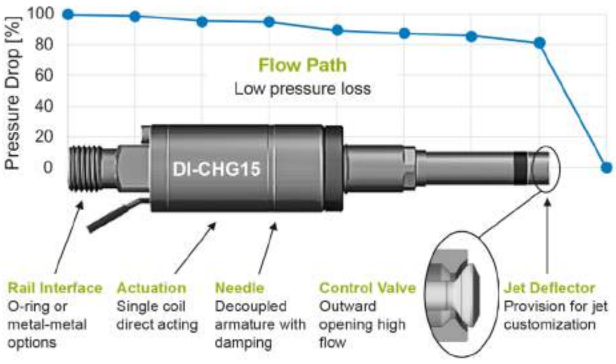

Fig. 4: The DI-CHG15 medium pressure injector suits applications developing up to 90kW per cylinder

New Control System for H_2ICE

BorgWarner has combined current gasoline direct injection (GDi) and diesel software modules with new hydrogen modules and an optimized injector drive wave form to produce a controller and software package for H_2ICE powertrains. The combined operating system includes strategies for stoichiometric and lean combustion and is sufficiently flexible to incorporate system variations such as exhaust gas recirculation (EGR), knock detection and water injection.

Air-Fuel Mixing Control

Optimized air-fuel mixing is essential to achieve efficient combustion. Injector position and charge motion characteristics are unique to each engine, impacting the process of mixture formation. As a result, a control of the hydrogen jet targeting with a jet deflector fitted to the injector nozzle, as shown in Figure 5 may be necessary to improve mixture homogeneity. Computational fluid dynamics (CFD) is an essential tool to first predict the flow of the hydrogen jet, then to understand how the mixture in the cylinder develops, and finally to guide the design of an optimized jet deflector. The outcome of this optimization process will be improved mixture homogeneity in particular at high load operation conditions, where it is critical to minimize NO_x emissions.

Practical Assessment of Combustion Performance

During the development of a working H_2ICE model, BorgWarner converted a four-cylinder 1.5 liter GDi engine to burn hydrogen in place of gasoline. The standard fuel injectors were replaced with DI-CHG injectors, and the gas rail volume was increased to compensate for the lower density of hydrogen compared to gasoline, thereby ensuring gas pressure stability. A number of useful observations were made during testing:

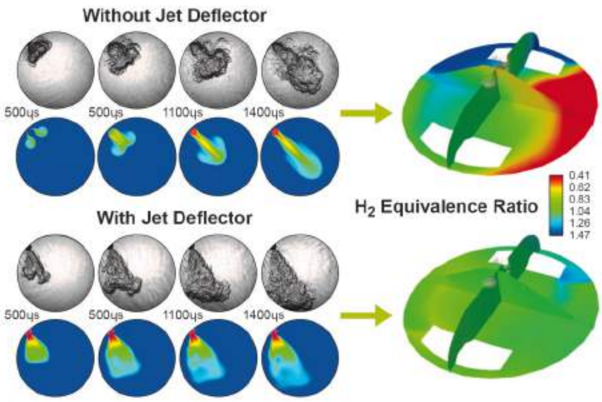

Fig. 5: Effect of injector nozzle jet deflector on gas jet formation

- Hydrogen exhibits wide combustion limits for both combustion phasing and lambda
- Engine-out emissions are well below prescribed limits under most operating conditions
- In lean combustion mode, NOx emissions reduce to near zero levels
- Even allowing for typical oil consumption, carbon based emissions from an H_2ICE engine are insignificant compared to diesel or gasoline exhaust gases.

Summary

It is possible to adapt existing internal combustion engines for operation with hydrogen using a medium pressure, direct injection system architecture. BorgWarner has developed new fuel injectors and control hardware/software for this purpose and produced a working model of an H_2ICE. This has demonstrated that CO_2 and NO_x emissions can be reduced to near zero levels using hydrogen as an alternative to diesel or gasoline. It can therefore be considered a viable powertrain solution for automotive applications and is able to support rapid decarbonization of the sector.

In addition to road vehicles, hydrogen technology may also be used in power generation, agricultural, aviation, construction, marine and/or recreational applications. BorgWarner acts as a hydrogen technology solution provider to OEMs in all segments, ensuring that its customers have access to products and support ranging from individual components to complete turnkey applications integrating the entire hydrogen injection system.

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