

New and Innovative Combustion Systems for the H₂–ICE: Compression Ignition and Combined Processes

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ABSTRACT

Hydrogen nowadays is considered one promising energy carrier for future mobility scenarios. Its application as a fuel in ICEs greatly benefits from Direct Injection (DI) strategies, which help to reduce the disadvantages of PFI systems such as air displacement effects, knocking, backfiring and low power density. In SI-engines one appropriate way to increase efficiency is the reduction of wall heat losses by jet- and/or wall-guided mixture formation systems. In theory, Compression Ignition (CI) systems employing a diffusion type of combustion allow for a significant raise in compression ratio and, thus, are likely to excel the SI concept in terms of efficiency. The following paper deals with results obtained from investigations on H₂ Compression-Ignition (H₂–CI) combustion systems by employing both thermodynamic research engines and 3D CFD simulation.

INTRODUCTION

Nowadays, virtually all prototypes and small vehicle fleets using H₂ as a fuel in the passenger car area are based on stock SI engines, originally designed for gasoline or natural gas fueling. They are adapted for H₂–use by applying an external mixture formation strategy, in which H₂ is injected into the intake manifold where it mixes with aspirated air. This obvious approach allows for minimizing efforts when changing from conventional fuels to hydrogen, but it does not consider most of the unique properties of this fuel.

The density of hydrogen is outstandingly low, which leads to air–displacement effects within the intake system caused by the big volume fraction the fuel captures once it has expanded from fuel back pressure to the conditions within the intake port.

Although respectable efficiency-levels can be achieved at hydrogen PFI operation, PFI is severely limiting the IMEP–potential of the engine [1]. This problem can be partly resolved by e.g. supercharging or an increase of engine capacity. In addition, the huge amount of premixed fuel is likely to suffer backfiring in case of ignition by e.g. some hot spot in the combustion chamber during the intake phase.

Power densities comparable to those of modern gasoline fueled engines can be achieved by direct injection strategies, which in addition entirely inhibit backfiring. Figure 1 demonstrates that with the assumption of constant values of $\lambda = 1/\Phi$, n , η_e and T , the mixture calorific value – and thus power output – of a H₂–ICE in DI–operation even tops the respective value of a gasoline–PFI engine, which still is the most commonly used type of the gasoline fueled SI engine and therefore shall be taken as a reference. H₂–PFI due to the aforementioned restrictions is clearly inferior in terms of power output.

THERMODYNAMIC RESEARCH ENGINES

For thermodynamic analyses two single-cylinder four-stroke research engines are available. Both designs are derived directly from modern passenger car engines and – in their standard configuration – differ in terms of geometry inasmuch as the one which is normally used for investigation on SI combustion processes (H_2 -SI engine) features the typical layout of a gasoline engine with a pent roof cylinder head and a flat piston, whereas the one used for investigations on CI combustion systems (H_2 -CI engine) is equipped with a flat cylinder head and a piston bowl. The H_2 -SI engine was available from the EC funded research project HylCE, with the focus on the investigation of H_2 combustion processes for PFI and DI mixture formation strategies as well as Cryogenic Port Injection (CPI) concepts. For an initial set of experiments this engine was equipped with a special piston driving it to its maximum in terms of compression ratio. Despite the geometrical differences both engines are based on the same engine block. The basic data of both engines is given in Table 1.

		H_2 -SI	H_2 -CI
Cylinders	–	1	1
Bore	mm	84	84
Stroke	mm	90	90
Capacity	cm ³	499	499
Valves	–	4	4
Valvetrain	–	DOHC	DOHC
Compression Ratio	–	10.5 – 16.5 (adjustable)	18, 22 (piston bowl)

Table 1: Basic data of thermodynamic research engine

For H_2 -CI combustion processes with direct injection a brand new cylinder head, two different pistons and a new liner concept were designed. Figure 2 shows a cross-section of this H_2 -CI engine.

Assumption:

$\lambda_c = 1$
 $\lambda_a = \text{const.}$
 $\eta_a = \text{const.}$
 $n = \text{const.}$
 $V_H = \text{const.}$

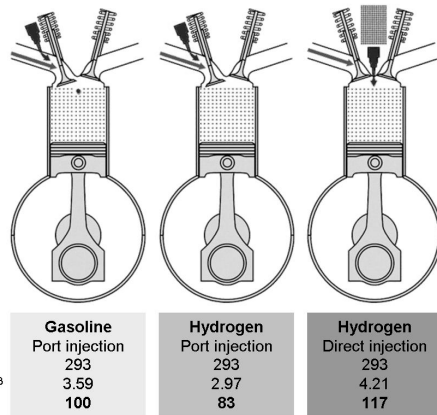


Figure 1: Power density potential of hydrogen (PFI & DI) versus gasoline PFI

Another advantage of DI-SI concepts is the ability to realize stratified mixtures, be it via wall-guided or jet-guided methods making functional use of geometrical designs of pistons and/or injector nozzle arrangements.

Regarding efficiency increase, DI combustion systems may minimize wall heat losses and ROHR – within certain limits – can be modeled, e.g. by the variation of SOI, the number of injections per cycle and fuel pressure. Though knocking phenomena can be significantly reduced with DI-SI injection systems, they still limit the potential to increase the compression ratio and therewith engine efficiency.

In the field of conventional HC-fueled passenger car engines the DI-Diesel engine provides top level efficiency. Thus, a further improvement of engine efficiency in the field of H_2 engines – theoretically – is likely to be achieved by imposing a diffusion type of combustion to the process, where the fuel, similar to a conventional Diesel ICE, is self-ignited due to sufficiently high temperatures within the combustion chamber. Given the extraordinary high self-ignition temperatures of H_2 /air-mixtures "combined" combustion processes take advantage of the conversion of a small amount of premixed fuel to raise the temperatures within the combustion chamber. In this way, a diffusion type of combustion can be achieved for the following second injection.

Due to the complexity of DI combustion processes development tools such as standard research engines and thermodynamic analyses have to be combined with laser-optical measurement methods and 3D CFD simulation.

This paper deals in detail with the achievements in the field of combustion-process development for hydrogen-fueled ICEs, obtained in close cooperation of the Institute for Internal Combustion Engines and Thermodynamics at Graz University of Technology with BMW Group Research and Technology in Munich, Germany.

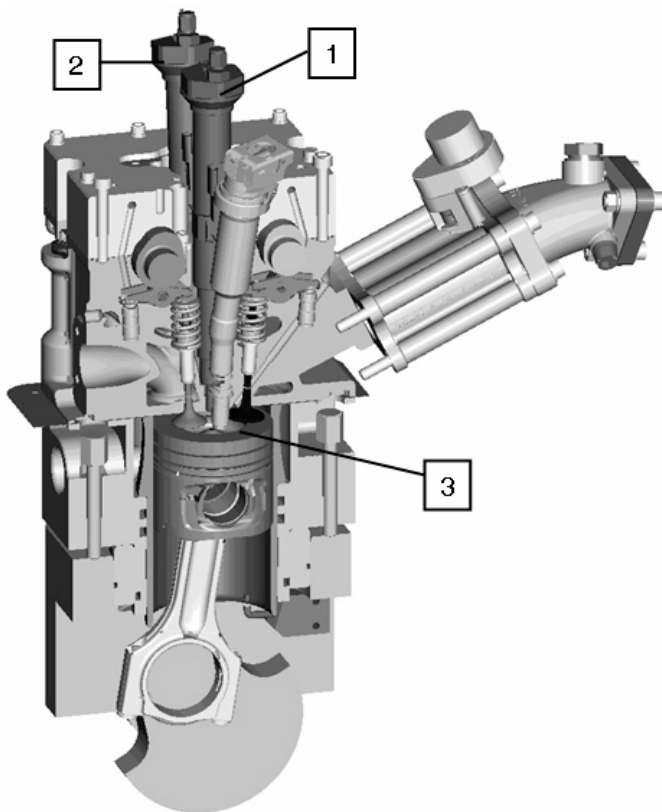


Figure 2: Cross-section of the H₂-Cl engine

For DI operation mode the engine features two possible positions for Injector-mounting, a central one (position 1 in Figure 2) and a lateral one (position 2 in Figure 2). Compression ratio on this engine can be adjusted via piston bowls (position 3 in Figure 2) of varying dimensions. The cylinder head also carries bores for a glow plug as well as a sparkplug. The latter can be used to securely burn the hydrogen/air-mixture in case compression ignition does not occur. The geometrical layout of this engine is shown in Figure 3.

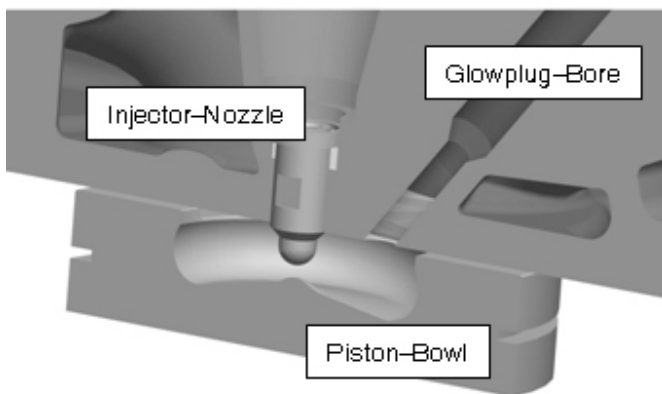


Figure 3: Combustion chamber layout of H₂-Cl engine

OPTICAL CHAMBER

For investigations on the jet pattern generated by the design of the injector nozzle an optically accessible high-pressure/high-temperature-chamber (Figure 4) has been applied. The chamber is shaped cylindrically with a bore of 300 mm and a height of 350 mm.

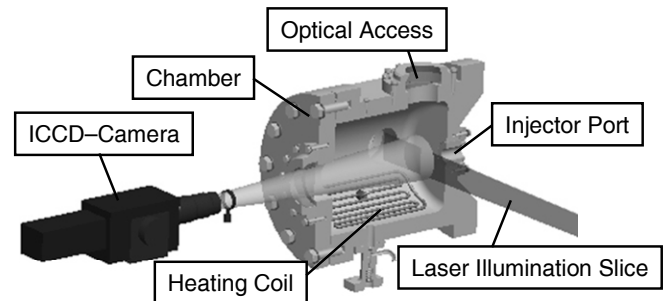


Figure 4: Optical chamber setup

To warm up the medium inside the unit is equipped with a heating element capable of delivering about 11 kW of heating power. The system features 4 optical accesses in the form of 4 windows with a diameter of 100 mm each. The basic data of the optical chamber is given in Table 2. For further detail on combustion chamber setup please refer to [2].

Volume	l	24.75
Shape	–	cylindrical
Diameter	mm	300
Length	mm	350
Opt. access	–	4 glass windows ø100 mm
Max. pressure	bar	100
Max. temp.	°C	750

Table 2: Basic data of the optical chamber

The precondition for the jet pattern measurement is the application of insitu non intrusive measurement methods. The most commonly used method, Laser Induced Fluorescence (LIF), will be described in the following.

LASER INDUCED FLUORESCENCE (LIF) – This is the most frequently used optical measuring method at Graz University of Technology. It is based on the detection of light emission from a fluorescing substance, which can either be a material to be detected or an additional species with an increased ability for fluorescence, the so called tracer. In the latter case the method is correctly called Tracer-LIF.

The tracer can be added to either the fuel or the aspirated air. Tracer substances that have proven suitable for investigation on H₂-ICEs are Triethylamine (TEA) and Trimethylamine (TMA).

The working principle mainly relies on selective energetic excitation of the tracer substance with the help of laser light of adequate wavelength. The electrons within the tracer substance are lifted to higher energetic states. During the following backdrop they again lose this energy in the form of light emission of a different wavelength, which then is detected by an ICCD–Camera system. Excitation is done by laser illumination slices, which are coupled into the chamber through its various optical accesses. For TEA and TMA a fluorescence emission spectrum is shown in Figure 5 for an excitation wavelength of 248 nm.

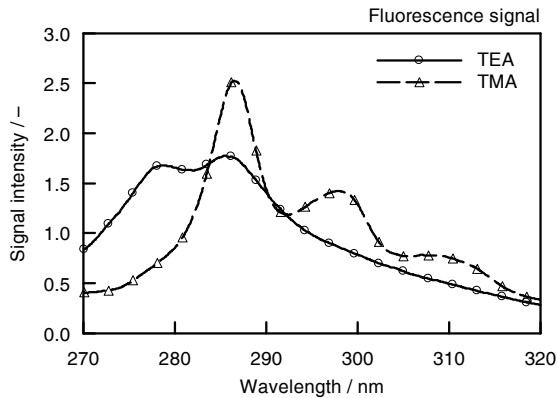


Figure 5: Fluorescence emission spectra for TEA & TMA

Given the same excitation wavelength and tracer concentration, the intensity of the LIF–signal still depends on ambient conditions, amongst others pressure and temperature. A correlation between tracer concentration (and with it A/F–ratio), signal intensity and ambient conditions is therefore needed to quantify results. For measures within the cylinder of an optical engine this can be achieved with the help of measurements carried out on the same engine at homogeneous operating points with known A/F–ratio and in–cylinder conditions. Due to the fact that the LIF–signal correlates linearly with the equivalence ratio, quantification of the measurements can be done even in stratified mixtures. For investigations of jet patterns quantification is not necessarily needed. The signal intensity in this case is only comparable with results in the same experimental series and indicates the amount of the tracer substance. Since calibrating the LIF–signal for A/F–ratio is one elaborate task [3] it is only done for measurements within an optical engine and not for investigations of jet patterns within the chamber.

INJECTION TECHNOLOGY

For high pressure H₂–injection a solenoid–driven concept by the Austrian company Hoerbiger Valve Tec (HVT) has been applied (Figure 6). One practical feature of this system is the possibility to change the injector nozzle making it an easy task to vary e.g. the number of bores, their diameters and their directions or to even alter the geometry of the bore(s). For investigations on CI combustion processes the units can be driven at H₂–pressures of up to 300 bar.

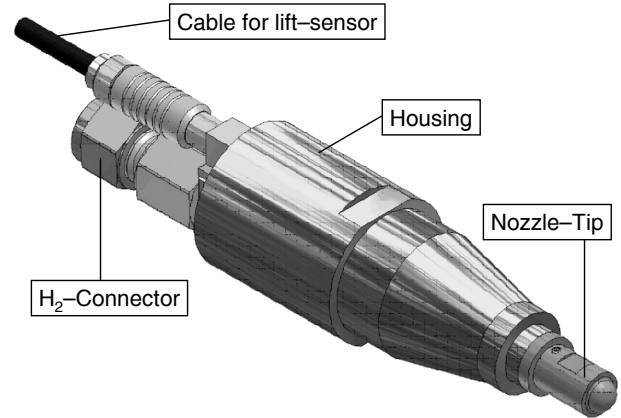


Figure 6: High–pressure H₂–injector by HVT

3D CFD SIMULATION

Compared to PFI combustion systems, in–cylinder processes are much more complex when DI is applied. Due to additional degrees of freedom like SOI, fuel–backpressure and number of injections per cycle mixtures are no longer necessarily homogeneous at ignition point. This results in a need for a deeper insight into in–cylinder processes. On the experimental side this can be achieved with an optical research engine, which, in combination with appropriate measurement methods, delivers information from small measuring volumes or 2D images from so called illumination slices. Due to glass components these engines are limited both in engine speed and load, their operation is expensive and, due to light refraction, they are normally limited to flat piston designs.

3D CFD simulation provides an arbitrary insight into the engine with respect to almost any thermodynamic and physical parameters which may be of interest. For CFD calculation on hydrogen fueled ICEs Graz University of Technology uses the FLUENT software package in version 6.3.26.

CFD is a numerical method and is based on mathematical models. All of the latter have been experimentally verified – mostly on excessively simplified setups to reduce the number of influencing parameters.

To setup an appropriate set of models for in-cylinder calculations experimental verification is inevitable. During these investigations the focus was laid on mixture formation due to the fact that without properly calculated mixture formation processes regarding the 3-dimensional distribution of excess air ratio within the combustion chamber any combustion model is doomed to fail. In that respect, the choice of the turbulence model has proven to be of utmost importance.

For an early injection SI operating point (Table 3) Figure 7 shows the distribution of excess air ratio at Ignition Point (IP) within the symmetrical plane of the SI optical engine of the institute as it is measured within the engine using the tracer-LIF method versus the calculated results using 3 different turbulence models.

Engine speed	min ⁻¹	1000
Excess air ratio	–	2.57
H ₂ pressure	bar	140
SOI	°CA	–120
IP	°CA	–10
Turb. models	–	Standard k _ε , Realizable k _ε , RSM

Table 3: Operating point data for turbulence-model comparison

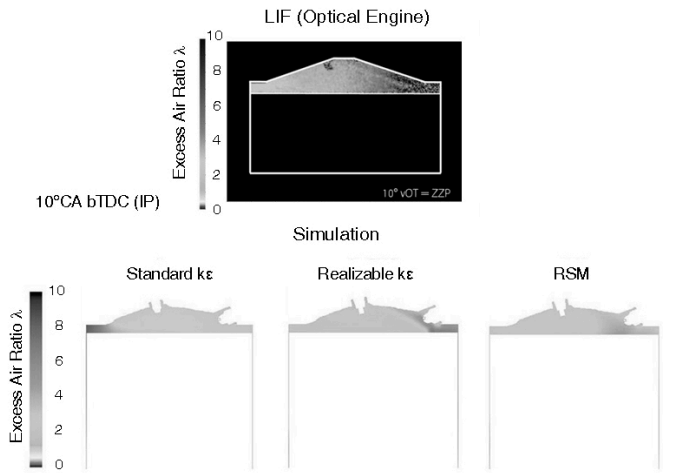


Figure 7: LIF vs. simulation (3 turbulence models)

Comparing the LIF-image shown in the upper half of Figure 7 with the more sophisticated turbulence models – Realizable- k_{ϵ} and RSM (Reynolds Stress Model) – sufficient accordance can be achieved both in the shape of the mixture cloud and in the distribution of local excess air ratio.

The standard k_{ϵ} -model – which is sort of a standard tool for CFD calculations in the field of technical engineering – even predicts wrong tendencies inasmuch as the mixture is calculated to be lean on the exhaust side (left hand side of each image in the picture) of the engine and rich on the intake side, whereas LIF shows the exact opposite.

The two more refined models correctly predict tendencies with RSM clearly standing out as the most accurate of all three models as it best matches the results of the measurements. This is especially true for early injection operating points in H₂–SI engines where the biggest eddies feature a length-scale of approximately the cylinder bore, whereas turbulence near the walls is heavily damped. The ability of the RSM-Model to handle turbulence anisotropically is especially beneficial in this case. Thus, RSM is established as the turbulence model of choice in case it provides enough numerical stability. If this is not granted, a Realizable- k_{ϵ} model is chosen as it also allows for sufficient accuracy.

STATE OF THE ART H₂–SI

For several years, the Institute for Internal Combustion Engines and Thermodynamics at Graz University of Technology and BMW Group Research and Technology have closely worked together to advance combustion system development for H₂–fueled SI–engines. The standard DI layout features a flat piston in combination with a multi-hole nozzle. Due to the exceptionally low density of hydrogen, injection pressures need to be above 100 bar in order to deliver sufficiently high masses of fuel into the combustion chamber. The multi-hole nozzle layout was designed to cover the entire chamber with H₂–jets. This could not be achieved due to the Coandă-effect [4, 5], which causes the jets to merge to a combined one shortly after injection. For late injection timing – with the general advantage of not having to compress the injected hydrogen – this leads to over-stratifications causing delayed combustion. In addition, knocking phenomena severely limit ignition timing and compression ratio.

One approach to spread a fairly homogeneous mixture over the combustion chamber, even at late injection timings, was the development of various nozzle geometries, the goal of which was to come close to a so called “perfect stratification” for SI engines featuring a $\lambda = 1$ core of the mixture for fast burn-rates and total fuel conversion. Pure air at the walls finally helps to minimize wall heat losses (Figure 8).

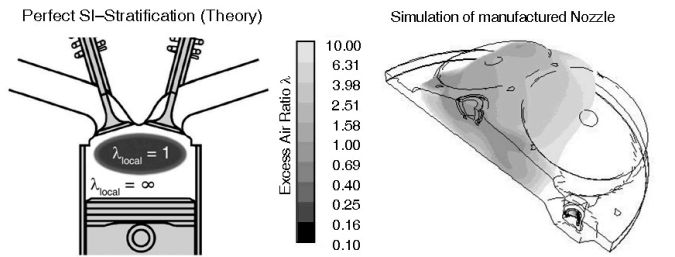


Figure 8: “Perfect stratification” at IP for H₂–SI engines

Another approach to minimize fuel-accumulation on the walls – especially within the quenching areas – is to redirect the injected gas towards the spark plug via the shape of piston bowls.

This is intended to help to reduce wall heat losses and to enable a fuel-rich mixture at the spark plug, while at the same time the mixture is intended to be kept within the piston bowl and not to capture significant space within the quenching areas. Referring to this, two different concepts are shown in Figure 9.

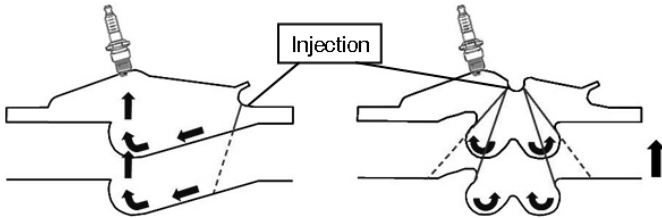


Figure 9: Wall-guided concepts for H₂-SI operation

While the spray guided mixture formation system, shown in Figure 8, managed to hold a significant advantage over the standard configuration, especially the ω -bowl concept severely suffered from delayed combustion due to massive over-stratification.

In general, premixed hydrogen in the combustion chamber leaves the combustion system susceptible for knocking phenomena, which are limiting the efforts to boost engine efficiency by raising the compression ratio and/or setting early ignition points. Small quenching distances of hydrogen in combination with a filled up chamber lead to increased wall heat losses, the effect of which is partly compensated by very fast burn rates. Late injection concepts help to minimize these tendencies; furthermore, operation with SOIs set later than 20 °CA bTDC suffer from delayed combustion driving the system further away from constant-volume combustion. In addition, the rate of pressure rise per °CA begins to reach unacceptable high values at very late SOIs.

With these results of long-term investigation on H₂-SI combustion processes, obtained with the help of both engine-measurement [6 – 12] and 3D CFD calculations [13], the challenge to further increase engine efficiency generates a demand for alternative concepts. Investigation on whether or not one of these may be the H₂-CI engine concept is subject of this paper.

THE “H2BVPLUS” PROJECT

To investigate the behavior of hydrogen as a fuel for Compression-Ignition and combined combustion processes in more detail, the project “H2BVplus” was started in 2007. The working title of the project is “Highly Efficient and Clean Combustion System for H₂-IC Engines for Automotive Application”.

The project is funded by the Austrian Federal Ministry for Transport, Innovation and Technology within its own “A3 Austrian Advanced Automotive Technology” program.

The work is carried out in close cooperation between the Institute for Internal Combustion Engines and Thermodynamics at Graz University of Technology in Graz, Austria, BMW Group Research and Technology in Munich, Germany, Hoerbiger Valve Tec GmbH in Vienna, Austria, and HyCentA Research GmbH in Graz, Austria.

PREREQUISITES FOR THE H₂-CI ENGINE

Regarding its use as a fuel for ICEs, three properties of hydrogen [12] are most outstanding. First, it has an exceptional low density, which necessitates a high-pressure injection to guarantee sufficient fuel-masses within the cylinder even at high engine loads. Second, are the wide ignition limits of H₂/air-mixtures from $\lambda = 0.14$ up to $\lambda = 10$, which allow for unthrottled operation within a wide operating range. Third, and for the use in a CI engine most important, is the high self-ignition temperature, which can be found to be $T_{AI} \approx 853$ K, which is significantly higher than the respective value of conventional Diesel fuels ($T_{AI} \approx 523$ K). Thus, literature can be found on CI operation of big and slowly revving engines [14] and on H₂-CI engines operated with ignition assist by Diesel fuel [15]. Diesel fuel is delivered into the combustion chamber in its liquid phase. Pressure levels up to 2000 bar guarantee for very good atomization resulting in droplets of small volume and comparatively big outer surfaces. The compression ratio has to be chosen in a way that enough heat is generated to enable temperature gradients, which drive thermal energy into the droplets to guarantee for both vaporization and ignition of the mixture.

Other than hydrogen, Diesel fuel is not a pure substance. It consists of virtually all sorts of hydrocarbons. Volatile substances with low evaporation as well as ignition-temperatures help to alleviate the CI-process. Once endothermic chemical processes are started further heat is generated to evaporate and burn non-volatile substances within the fuel.

For hydrogen, as being a pure chemical substance, the physical process itself is much simpler. Since the fuel is delivered into the combustion chamber in its gaseous form, evaporation heat is not needed and, thus, not extracted from the compressed air within the cylinder. The H₂ jets penetrating the combustion chamber mix with the surrounding air while thermal energy extracted from the charge is used to heat up the mixture. These processes have to proceed quickly to additionally guarantee for short ignition delays. Ignition delay is defined as the amount of time consumed between SOI and the first measureable increase of cylinder pressure.