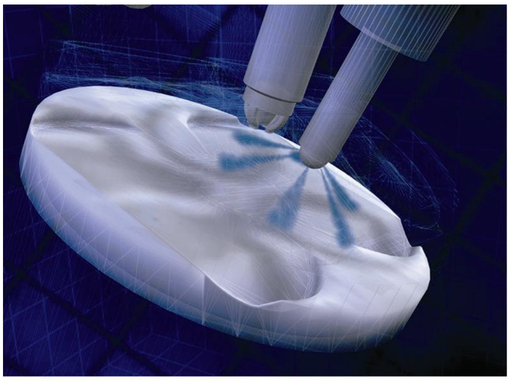
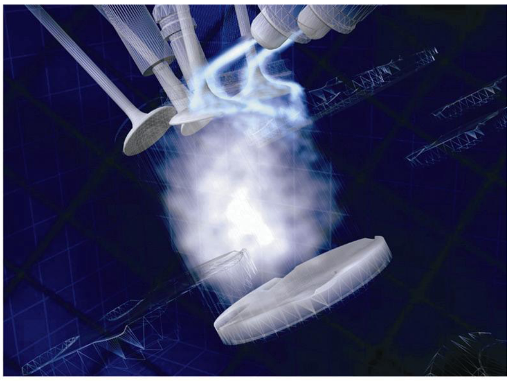
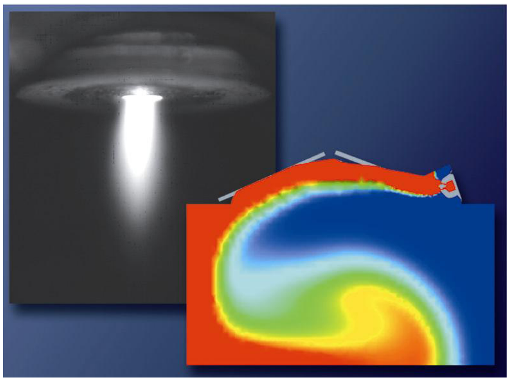
HyICE
Hydrogen Internal
Combustion Engine

February 2007

Summary of an Integrated Project in the 6th Framework Programme of the European Commission

HyICE

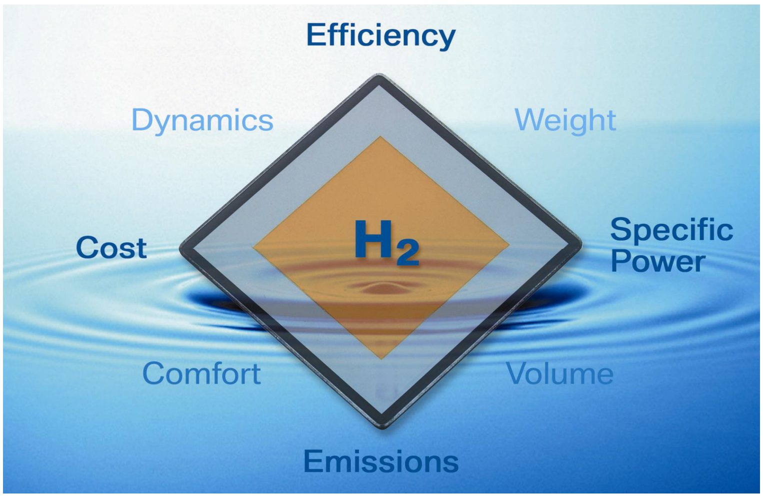
Optimization of the Hydrogen Internal Combustion Engine


Overview

The goal of HyICE is to optimize a concept for an internal combustion engine (ICE) which has the potential to outdo both, gasoline and Diesel engines with respect to efficiency and power density.
For this purpose the two most promising principles of mixture formation, Direct Injection (DI) and Cryogenic Port Injection (CPI), have been studied.
With a specific power output of 100kW per liter of displacement and an efficiency of 42% both engine concepts are already now exceeding current gasoline engines regarding power density as well as efficiency although the maximum possible values have not been achieved yet.
One major result of the project is that each concept has its specific advantages and the choice to be taken depends on the goals to be achieved:
The CPI aims for near-term economic drive trains, while, as a result of complexity and the large amount of calibrating parameters, DI offers the potential to exceed even the limits of CPI, however there is need for further fundamental research work.
To open up the whole potential of this outstanding fuel Hydrogen a dedicated, highly efficient ignition system has been developed.
A commercial CFD-solver has been toughened up to the calculation with Hydrogen to support the development process also of future production engines. The models for mixture formation and combustion have been adapted and validated also by the use of optical equipment.
In the USA the ICE is considered a valid option for Hydrogen-propulsion as well. To extract the maximum benefit out of efforts and investments made on both sides of

the Atlantic Ocean an information exchange between automobile industry and researchers from Europe and the USA is arranged, ensuring the exchange of important and valuable know-how.
The project outcomes have been published on a variety of different technical and also on political platforms ensuring the dissemination and exploitation of the gained knowledge. For training issues 13 Ph.D. students and 20 graduands as well as 17 trainees were integrated in the development work of the project.



Right of way for Hydrogen

1 Motivation and Targets

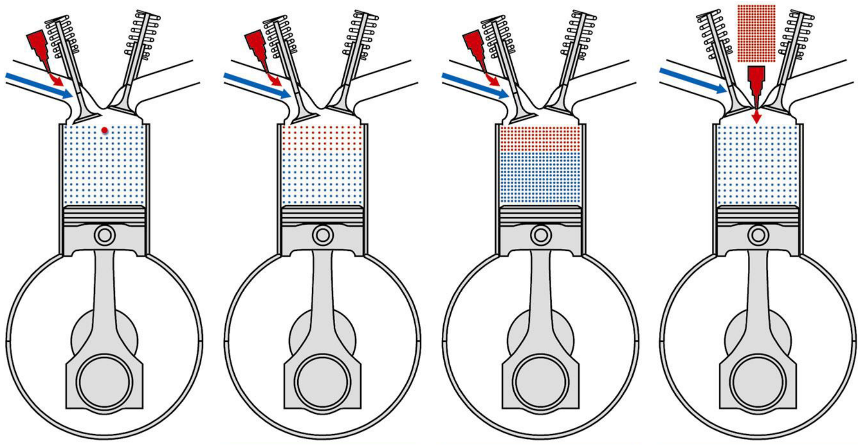
As the only carbon free fuel, Hydrogen releases no CO_2 during combustion. In the European Commission Strategic Research Agenda, chapter 2.4 it is stated that "Hydrogen can be used in adapted internal combustion engines already in the near future".
The internal combustion engine is ideally suited for the transition to the hydrogen economy since it offers:

- high efficiency
- high power density
- low cost
- capability for bi-fuel-operation in a transition phase
- high potential for a fast mass-market introduction.

Contemporary Hydrogen cars and buses in small series: MAN Hydrogen bus, Ford H_2 V-10 E-450 shuttle, BMW Hydrogen 7

Today's Hydrogen engines based on port injection technology suffer from a significantly reduced power density. The injection of the required large volume of gas into the intake manifold leads to a displacement of air, reducing the power potential by 20% compared to liquid fuels. Nevertheless, as illustrated in the following image, two new approaches promise the potential to even outperform conventional fuels.

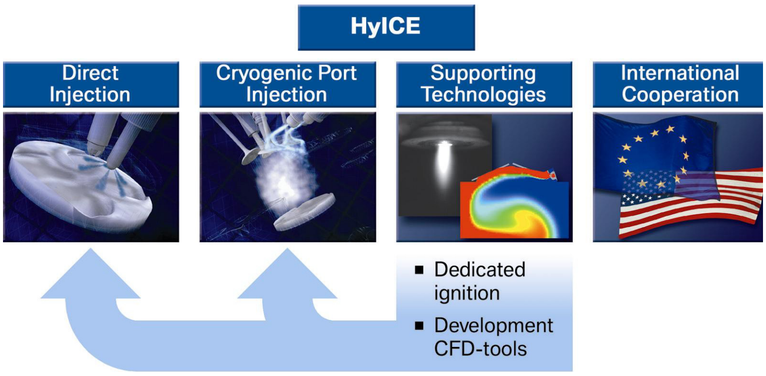
By mixing cryogenic Hydrogen gas (-240°C) with the aspirated air (cryogenic port injection), the mixture can be cooled down and thus the energy content inside the combustion chamber increases.



Potential of specific power of various engine concepts

Fuel	Gasoline	Hydrogen	Hydrogen	Hydrogen
Concept	Port Injection	Port Injection	Cryo. Port Injection	Direct Injection
Charge Temp. [K]	293	293	210	293
Spec. Power [%]	**100**	**82**	**115**	**117**
	"State of the Art"		"Research"	

The injection of Hydrogen directly into the combustion chamber (direct injection) after the full amount of air has been aspirated and the intake valves have closed is practiced already today at Diesel engines and more and more at gasoline engines too.
Both approaches allow for roughly 15% higher power output than corresponding engines fed by fossil fuels and therefore are represented in the project structure, each forming a separate subproject.



Organization

Another subproject is delivering supporting technologies, necessary for both concepts:
Since Hydrogen engines are operated by quality control a dedicated ignition system is advantageous, which can deal with rich as well as with very lean mixtures.
With increased complexity of engine technology simulation tools have continuously gained importance. Therefore a suitable and validated CFD solver is needed also for the optimization of H_2 combustion engines.
The subproject "International Cooperation" has established a bridge between the European consortium members and Ford Motor Company, Dearborn (Ford) and its associates in the USA, being connected in a very similar Hydrogen engine research project.

2 HyICE Consortium

To exploit the theoretic potential of a Hydrogen ICE, in 2004 eleven European partners came together with the ambitious goal to outperform gasoline and Diesel engines regarding efficiency and power density by a dedicated design within three years. This could favorably be achieved by incorporating each one's specific know-how. Industrial partners like BMW Group Research and Technology, Munich (BMW) and MAN Nutzfahrzeuge, Nuremberg (MAN) brought in their background for vehicle application by specifying the components and by carrying out engine tests.
With Volvo Technology Corporation, Gothenburg (Volvo) the use of Hydrogen on a new type of Free Piston Energy Converter with the potential for very high efficiencies could be evaluated.
New advanced components for fuel injection and the ignition system were developed by the suppliers Hoerbiger ValveTec, Vienna (HVT) and Mecel Engine Systems, Åmål (Mecel). For investigations in mixture formation and combustion, Graz University of Technology (TUG)

Partners BMW Group Research and Technology, MAN, Ford, VOLVO, TU Graz – Graz University of Technology, ANSYS, ifp, HOERBIGER, irion management consulting, Universität der Bundeswehr München, Mecel Engine Systems

and University of Armed Forces Munich (UBW) provided their know-how for sophisticated measurement techniques and simulation tools.
Beside experimental investigations on the combustion process, one major task was the adaptation of calculation models for premixed as well as for diffusion flame combustion to the special behavior of Hydrogen. For premixed combustion this was done by Institut Francais du Pétrole, Paris (IFP), while a model for diffusion flames was adapted by UBW.
Ansys Germany, Otterfing (Ansys) provided their commercial CFD solver CFX as common CFD platform in which the adapted models were implemented.
The “International Cooperation” with the bridge piers Ford Research Centre Aachen respectively Ford Motor Company, Dearborn/Michigan (Ford) and the associated Argonne National Laboratory (ANL), Chicago/Illinois and Sandia National Laboratories (SNL), Livermore/ California, funded by the Department of Energy, Washington D.C., led to a prolific exchange of development contents.

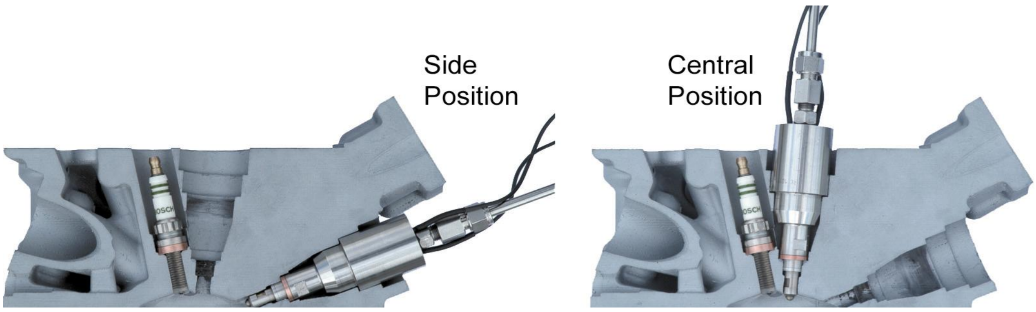
All administrative management duties were done by Irion Management Consulting, Konstanz.

3 Activities and Results

3.1 Direct Injection

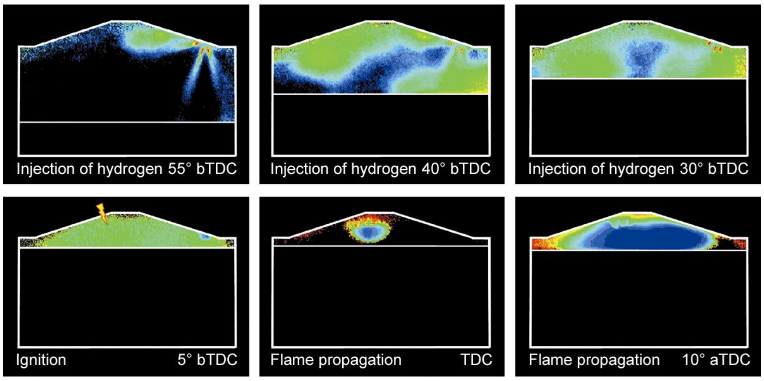
3.1.1 High-Pressure Direct Injection

The investigations in HyICE evaluated the potential of Hydrogen high-pressure direct injection (HP-DI) concerning efficiency and power density. Specific advantages beneath the high power density are opened up by a wide field of possibilities for optimizing the hydrogen combustion process. Only with high-pressure injection, the injection timing can be varied within a wide range and thus controlled fuel stratification can be realized.
Within HyICE, extensive experimental work was carried out at TUG, employing a single-cylinder research engine in a modern passenger car configuration and a likewise transparent engine allowing insights into the mixture formation and combustion process.



HVT: Positioning of H_2-HP-DI-injector

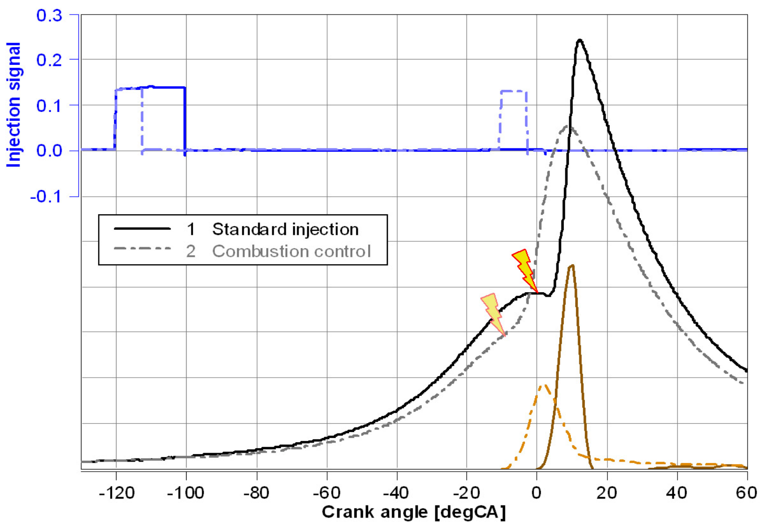
The best possible mixture preparation regarding efficiency could be pointed out with the definition of a perfect stratification. Further activities on improved injection strategies were carried out to approach this idealized benchmark stratification.



TUG: H_2-HP-DI, Optical measurements

By means of new injection strategies, thus controlling the combustion process, a method has been developed to significantly improve the noise behavior which is of utmost importance in a passenger car application. At a certain operating point with multiple injections, pressure rise as well as maximum pressure can be limited. High-pressure direct injection shows vast potential by optimizing the mixture formation process. However, high-pressure DI also poses some challenges starting from pressure supply to injector stability. Nevertheless the investigations within HyICE proved high potential concerning the key issues of improving efficiency and avoiding NO_X-emissions.

TUG: H_2-HP-DI, Combustion control

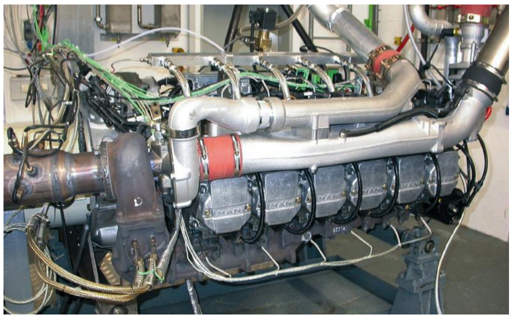


3.1.2 Low-Pressure Direct Injection

The important advantage of the low-pressure direct injection (LP-DI) is the reduced complexity of the fuel supply and its components, thus making a development to a higher level of maturity possible. As MAN is planning to equip a fleet of hydrogen urban buses within the follow-up project HyFLEET:CUTE with DI-technology, this question was of utmost interest. But compared to the high-pressure concept described before, this technology, of course, cannot offer as many degrees of freedom as the former.

Within HyICE, the new 12.8l six-cylinder engine was specifically designed for Hydrogen operation. In a combined effort of 3D-CFD simulation at MAN and optical measurements at UBW and TUG, several injector nozzles were investigated and a suitable configuration for good homogenisation was found.

By help of a turbocharger, a remarkable maximum power output of 200kW and an effective efficiency of 42% were achieved very quickly. The chosen lean burn concept still offers a lot of potential for further optimization.



MAN: Inline six-cylinder engine with H_2-LP-DI

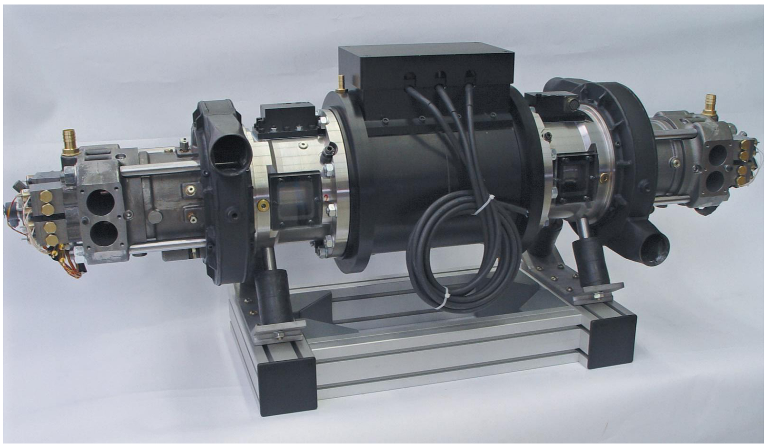
Low-pressure DI can provide many of the advantages of high-pressure DI while being closer to series-production readiness. As the injectors and the fuel storage tend to be more voluminous due to the lower density of Hydrogen, this concept is better suited for commercial vehicles such as city-buses.

3.1.3 DI Injectors

A major task is the design modification of the DI injectors for Hydrogen. One primary function is the precise metering of the required fuel mass during a very short injection time of a few milliseconds. The design of all HyICE injectors is based on a proven gas valve concept of HVT. Throughout several injector generations most challenges could be solved. The solenoid actuator showed impressive performance concerning switching times. A needle bouncing effect during the closing phase has been observed but different approaches for low- and high-pressure DI injectors have already been performed by HVT in follow-up projects in order to solve this problem.

3.1.4 Transferability to Other Engine Concepts

The principle of the free piston energy converter is based on a freely oscillating piston between two opposite combustion chambers. By using a linear electrical machine, the movement of the piston can be converted directly into electrical energy.

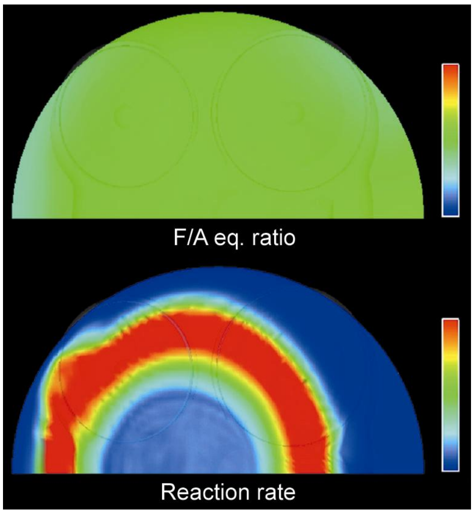


Volvo: Free piston engine

At Volvo, a prototype based on this concept was built up within the European research project "FPEC" for Diesel-HCCI operation. With Hydrogen, this concept has the potential for excellent efficiency by the new degree of freedom of controlling the piston movement via the electrical machine. Within HyICE, simulations for H_2-operation predicted an indicated efficiency of 55%.

3.2 Cryogenic Port Injection

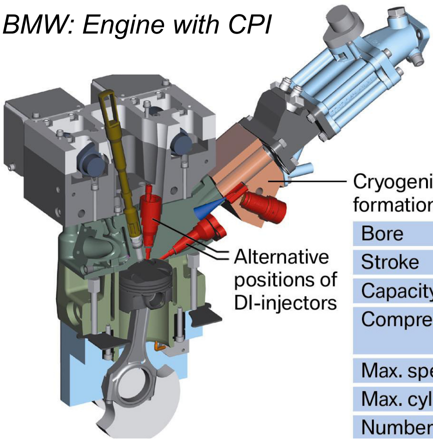
In contrast to direct injecting hydrogen engines, for the cryogenic port injection (CPI) the low pressure range of a liquid Hydrogen tank is sufficient. This concept takes advantage of the external mixture formation of Hydrogen and air by making use of the coldness.
At the same time the concept of liquid Hydrogen storage and CPI forms a technically straightforward system, therefore supporting the attempt to build economic Hydrogen vehicles.
Within HyICE detailed experimental investigation in the mixture formation and the combustion process, as well as validation and adaptation work on CFD tools have been combined into the development of a combustion system for CPI.



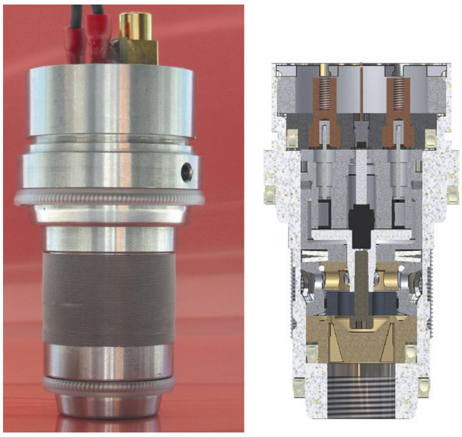
IFP: CFD results

Specifically designed cryogenic injectors, an anti-icing nozzle design and an optimized injection strategy provide a homogeneous air/Hydrogen mixture with maximum cooling effect.
The result is an increase in specific power by 25% compared to Hydrogen port injection at ambient temperatures, thereby reaching the level of current gasoline PFI engines. Moreover the engine range of good efficiency is substantially expanded.
The combustion process itself shows a very stable behavior. Thus the CPI engine is predestined for operation with higher compression ratios – leading to a further increase in efficiency – and turbocharging.
With increased compression ratio an indicated efficiency of 44% has been demonstrated, further improvements may be expected. Turbocharged operation with extreme specific power output has also been investigated, whereby 100kW per liter of displacement have been reached.

BMW: Engine with CPI



Bore	84 mm
Stroke	90 mm
Capacity	500 cm³
Compression ratio	adjustable 9.0 – 13.5 (16.5)
Max. speed	6000 rpm
Max. cylinder pressure	150 bar
Number of valves	4



HVT: Cryogenic Injector

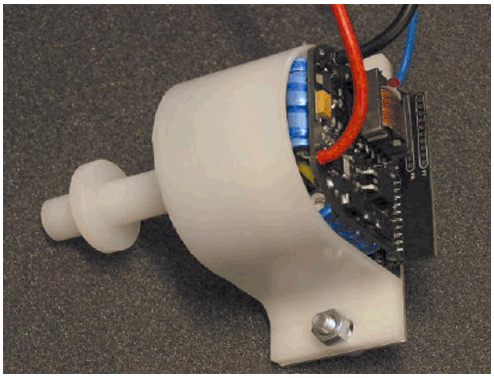
The work on the H_2-CPI engine was very successful and shows impressive results, the expectations have been partly exceeded and the challenges could mostly be solved. Moreover, the maturity of the injectors and the status of the development of the combustion system already prove the potential to apply them to a multi-cylinder engine for a first vehicle application.

3.3 Supporting Technologies

A series of development topics that support the work on the different combustion systems have been summarized in an accompanying subproject.

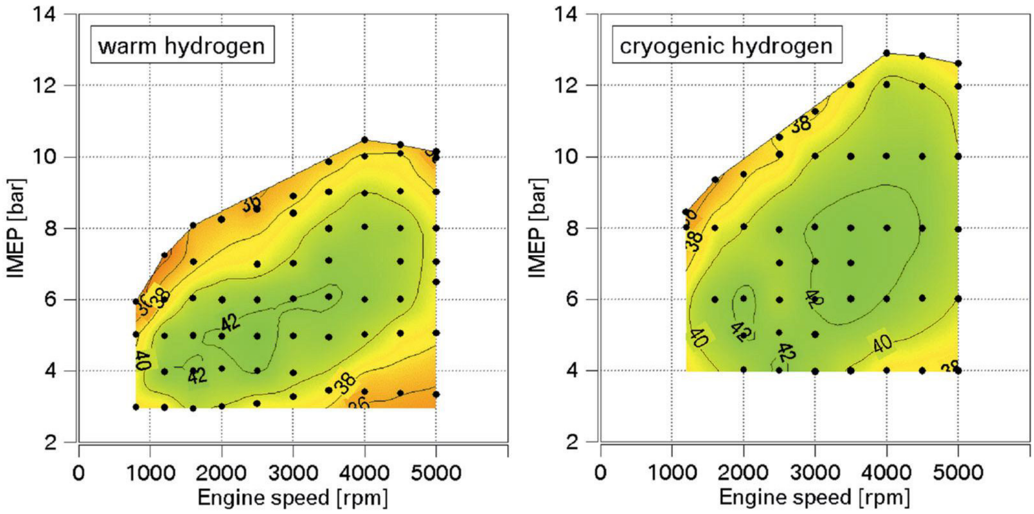
Dedicated Ignition System

As a Hydrogen ICE can be operated throughout a wide range of air-to-fuel ratios, a specific ignition system is necessary to benefit from this advantage. Within HyICE a very flexible and powerful ignition system has been developed, which is designed to combine high efficiency, high energy transfer to the gas and low heating of the electrodes in order to avoid hot-spots in the combustion chamber.



Mecel: Dedicated H_2 ignition system

The full potentialities of the ignition system could not be exploited yet, further engine testing is necessary for an optimization of the ignition parameters.
An integrated ion-current sensing circuit allows for the detection of in-cylinder



BMW: Results with CPI

combustion evolution and might be used as an input signal for a cylinder individual closed loop ignition control.

CFD Adaptation

CFD-calculation today is a standard at the development departments of any engine manufacturer.

All available tools, however, were focused on petrol based fuel and none of them has been validated under engine conditions for Hydrogen application.

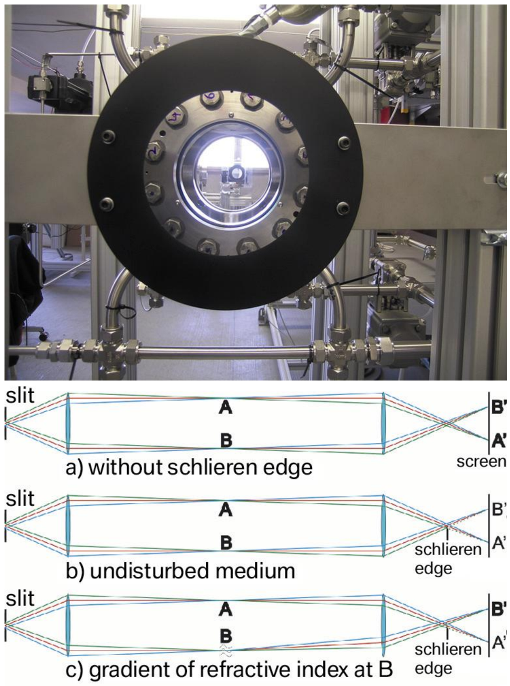
So, for optimizing the engine concepts as well as to support the development process of future production engines a suitable CFD solver is needed.

3D calculation models have been adapted to mixture formation and combustion by IFP and UBW, whereas the specific properties of Hydrogen were taken into account. These models were validated by data from literature and experiments and integrated into a solver, usable for the optimization of gas exchange, mixture formation and the combustion processes. This Hydrogen proven CFD tool is a major result of the project, and it will be delivered by a commercial supplier, ensuring support and maintenance also in future upgraded versions.

Optical Measurement Techniques

In addition and as a prerequisite to the development of simulation tools, also new measurement techniques were developed and applied particularly for Hydrogen.

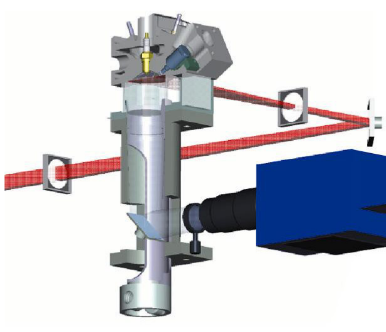
At UBW a mixing chamber test bed was designed and built up to gain detailed information about the turbulent mixture formation. Gas injections at different temperature and pressure levels can be performed. They are recorded by use of a Schlieren imaging system in combination with an electronic high speed camera. The great advantage of this system, compared e.g. to commonly used stroboscopic systems, is the capability to generate large data bases with high accuracy – important for averaging – and even more the possibility to observe typical behavior of single injections like swirl generation and degeneration in series of consecutive images.

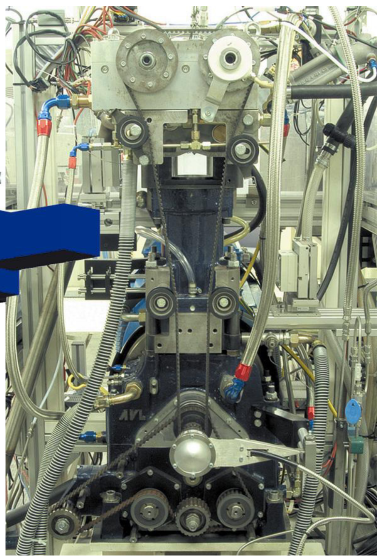


UBW: Equipment for Schlieren measurements

At TUG, an optical engine was employed for these investigations. The visualisation of the mixture formation and combustion process was made possible by adapting the methods of Laser-Induced Fluorescence (LIF) and Raman-Spectroscopy for the use with Hydrogen. With this measurement method, for the first time detailed insights into the processes within a Hydrogen engine became possible.

The resulting 2-dimensional images form an important input for improving both the combustion process itself and the simulation tools adapted within HyICE.





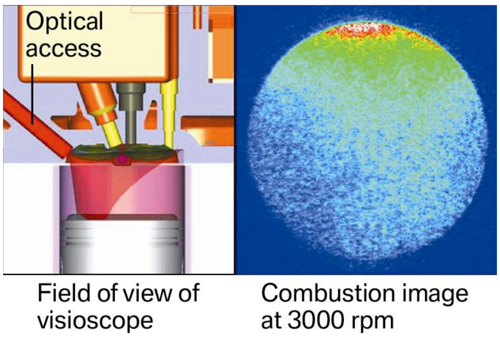
TUG: Optical measurement techniques

3.4 International Cooperation

Ford: International cooperation EU-USA

The international cooperation between the European consortium members and Ford and its associates in the USA was intended to provide an interchange of know-how and thus accelerate the development of the Hydrogen engine.

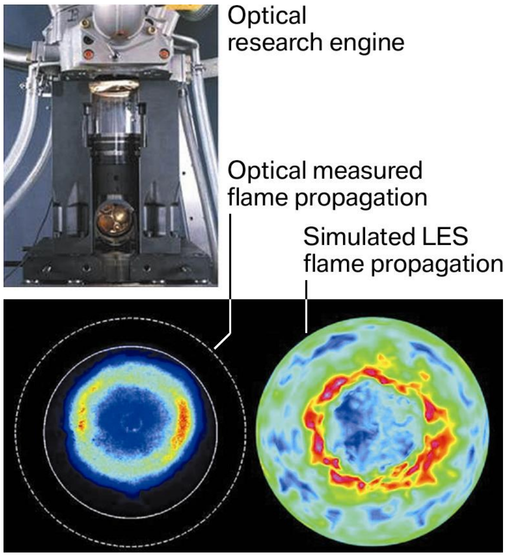
Within HyICE, Ford provided information on engine testing. With these results, important insights into the influence of different injector nozzle geometries and the compression ratio could be obtained. At the National Laboratories cooperating with Ford and funded by the US Department of Energy, research activities were carried out on fundamental questions concerning the Hydrogen combustion process. At ANL a research engine was employed which provides optical access through an endoscope, thus delivering insights into the engine even under critical high-load conditions.



ANL: Ford single-cylinder engine with optical access

The activities at SNL consisted of investigations with an optically accessible engine and advanced simulation techniques.

With the experimental results, the effect of the injection strategy on the combustion process could be shown by means of fluorescence of chemical species appearing in the reaction zone, thus pointing out the distribution of the combustion process.



SNL: Results of the optical research engine

The very ambitious Large Eddy Simulation (LES) modeling approach pursued by a research group at SNL had the goal of pointing out future potentials of an even more refined simulation. Due to its high computational expense, this work goes even beyond the targets of HyICE, giving an outlook to future possibilities of 3D-simulation of complex Hydrogen combustion processes.

4 Conclusion and Outlook

In summary it can be ascertained that in the range of high-power vehicles, HyICE technologies can:

- Answer the customer's demand regarding both fuel efficiency and engine performance.
- Enable the development of products which can be sold at a reasonable price.
- Offer the chance of rapid dispersal of mass market Hydrogen vehicles, provided that the related infrastructure is available and that the political basic conditions are favorable.

HyICE delivers basic inputs for further projects. Already started are:

- HyFLEET:CUTE is also a project within the 6th Framework Research Programme and covers the operation of 47 Hydrogen powered buses in regular public transport service in 10 cities on three continents. 14 of these buses are powered with internal combustion engines, of which 10 are equipped with a low-pressure direct injection system based on the know-how gained within HyICE.

- H2BVplus aims for a "Highly Efficient and Clean Combustion System for Hydrogen Internal Combustion Engines for Automotive Application". This two-year research project is nationally funded by the Austrian government, has been started in January 2007 and incorporates the HyICE partners TUG, HVT and BMW. High-pressure direct injection technology provides a basis for the work which is focused on H_2 self-ignition respectively a so-called hybrid combustion-system.

Further projects are already planned to be proposed to the European JTI initiative related to Hydrogen application:

- A HyICE successor project, focusing on high-pressure direct injection in combination with spark ignition.

- The CPI concept could already be applied to a monofuel multi-cylinder engine which serves as a drive unit for a research vehicle.

Given the advantages and convincing properties of a Hydrogen driven reciprocating piston engine already to be observed today, it is generally expected that this engine will take on a firm position in the market and will be successful in the long turn, particularly in extra-urban traffic.

All involved partners in an alphabetical order:

- ANSYS Germany GmbH, Germany
- BMW Forschung und Technik GmbH, Germany (Coordinator)
- Ford Forschungszentrum Aachen GmbH, Germany
- Hoerbiger ValveTec GmbH, Austria
- Institut Français du Pétrole, France
- Irion Management Consulting GmbH, Germany
- MAN Nutzfahrzeuge AG, Germany
- Mecel AB, Sweden
- Technische Universität Graz, Austria
- Universität der Bundeswehr München, Germany
- Volvo Technology Corporation AB, Sweden

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