THE STATE OF THE ART AND FUTURE PERSPECTIVES OF THE APPLICATION OF HYDROGEN I.C. ENGINES

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ABSTRACT

Due to the uncertainty of the overall fossil fuel availability, and the continuous consumption of the world's fossil fuel reserves, an alternative fuel economy needs to be deployed to guarantee our long-term (individual) mobility. Hydrogen has been identified as the most promising energy carrier to cope with this challenge. During the past 25 years, BMW Group has relentlessly pursued its activities in the hydrogen area, which has finally culminated in the launch of a fleet of hydrogen vehicles at the Expo 2000 World Exhibition.

A major task of the future research work is concentrated on the development of an advanced hydrogen internal combustion engine with absolute and specific power and torque characteristics exceeding those of today's gasoline or Diesel engines. The corresponding basic research is the focus of a cooperation between "BMW Group Research and Technology" in Munich and the "Institute for Internal Combustion Engines and Thermodynamics" of the Technical University in Graz. Besides the engine performance characteristics, emphasis is also placed on efficiency and emission aspects.

INTRODUCTION

The automobile era begun some 100 years ago with the invention of the motorized passenger carriage powered by an internal combustion engine. Since then, this technology has spread incessantly around the world and has significantly contributed to affect and to change our way of life. With about 600 million passenger vehicles in private hands all around the globe today – and currently with a worldwide production of approximately 55 million units per year – the automobile must be considered as the most popular invention ever made.

Today the automobile is part of our live and the privately owned vehicle has proven to be the key to our individual mobility. This individual mobility, allowing a person to travel to any place at any time, must be considered as a major privilege in the sense of our personal freedom. There is no need to say that persons in possession of this valuable privilege will try almost everything to save it in the future, whereas the population not yet in possession of this privilege will strive to acquire it. Accordingly, there is no reason to doubt a further significant worldwide expansion of the automobile during the next 100 years [1].

From a technical point of view, the automobile has dramatically evolved since the appearance of the first vehicle. This relates to the various vehicle systems, e.g. drive train, chassis, body, electric/electronic features, as well as to its functional aspects such as power or dynamic performance, handling, safety, comfort, ... and more recently variability, driver assistance, information and communication devices, personalization and adaptivity.

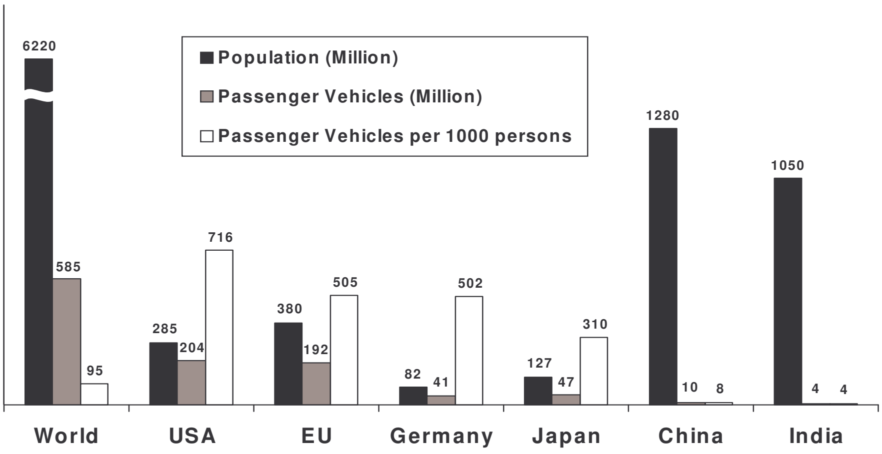
Despite this significant technological push, it is in some way astonishing that the reciprocating internal combustion engine has never had to face a real serious power source competitor since its implementation in the first automobile. It is true that there were some attempts to challenge this engine type, e.g. by electrical power sources, gas turbines or rotary internal combustion engines. But, even if praised at different times as "the revolutionary drive of the future", these technologies did not succeed to penetrate the automotive market. Nowadays, this market is completely dominated by technologically highly advanced reciprocating internal combustion engines operated in the Otto- or Diesel mode. Lately, the direct injection Diesel engine has experienced a tremendous customer acceptance and has become a real competitor to the gasoline engine. It will be highly interesting to observe the future market share between these two engine types, especially when bearing in mind their further respective technological development potential.

Or could it happen that a completely new power system will replace the "old-fashioned" combustion engine in the nearer future? How serious is the next challenge to be faced with the fuel cell power drive which has just appeared on the horizon? Will this be the final competitor and match winner, or will the internal combustion engine pursue its never-ending story of success?

THE CHALLENGES OF TODAY AND TOMORROW

There is no doubt that the automotive world is facing a series of meaningful challenges which need answers. In the following, just three fundamental ones will be addressed.

The first topic is related to the further worldwide expansion of the automobile. Thereby, it can be assumed that in the major industrialized regions (USA, EU and JP) the total number of vehicles, after reaching saturation at 500 to 700 cars per 1000 inhabitants (Fig. 1), will remain nearly constant. On the other hand, emerging nations such as China or India, grouping about one third of the total world population, will be affected by an unprecedented run on the automobile which in a mid term time frame could add another 300 million vehicles to the 600 million that already exist, which is an increase of 50% (!).



Sources: VDA-Jahresbericht 2001; Länderdatenbank; UNEP-Bericht; UPI 35 – Bericht; DSW-Grafik 2000

Fig. 1.Population in comparison to stock of passenger vehicles

Second, in order to secure the individual mobility the efficiency of the traffic infrastructure needs to be further increased, e.g. by the deployment of highly effective traffic managements systems [2]. This primarily applies to urban areas spread with a steadily increasing traffic density as well as to the long distance highway network.

The third topic relates to the environmental aspects of the automobile in the scope of an overall sustainable mobility scenario. This especially addresses the wide question of energy requirements and raw materials availability as well as emission and recycling considerations. This question does not only apply to the automobile environment but to any "consumer product or need" in a world driven by economy, industrialization and prosperity.

Topic number 3 clearly addresses from a long term view one of the possibly most crucial challenges of mankind on Earth:

Where do we get our energy supply from
once the fossil energy stocks are used up?

One possible alternative to fossil fuels is HYDROGEN, an energy carrier which could be produced on the basis of renewable energies such as sun, wind, water and geothermal energy. When burned with the oxygen of the air, it can supply the energy we daily need on-site, producing only clean water as a by-product. It is this vision of the realization of a CleanEnergy economy which has been pursued at BMW Group Research for 25 years [3].

TWENTY FIVE YEARS OF CONTINUOUS HYDROGEN RESEARCH AT BMW GROUP

It was at the beginning of the 1970s when the industrialized nations for the first time experienced the high risk of their dependence on fossil energies. It was during the so-called "oil crisis", when the availability of mineral oil was at a risk due to political reasons, when BMW Group took the decision to start its activities in the hydrogen area. The vision of a sustainable CleanEnergy hydrogen economy was developed at that time and has been relentlessly pursued up to now. In the scope of this vision a great effort was made to develop hydrogen vehicles and to operate them safely in a normal traffic environment. Twenty-five years of continuous development efforts have finally culminated in a small-series production of "5th-Generation Hydrogen Vehicles" presented at the Expo 2000 World Exhibition in Hannover. This vehicle fleet has since then covered 200.000 km on public roads.

At the start of the CleanEnergy Hydrogen Project, a thorough analysis was carried out examining different topics related to the overall layout of a future hydrogen vehicle. It was recognized that a hydrogen vehicle would only be accepted by customers if its "characteristics of daily operation and performance" were comparable to those of a conventional gasoline or diesel vehicle. Focusing on the typical aspects of a "fun to drive" BMW vehicle required the layout of a high performance car with excelling driveability characteristics.

Many alternatives were considered as to the type of propulsion, driveline and hydrogen storage systems to be used. It was found that the high performance and driveability criteria could only be met by the installation of a hydrogen internal combustion engine (Fig. 2). Moreover the high requirements concerning the range of operation of the vehicle could only be realized on the basis of a liquid hydrogen high energy density storage concept (Fig. 3).

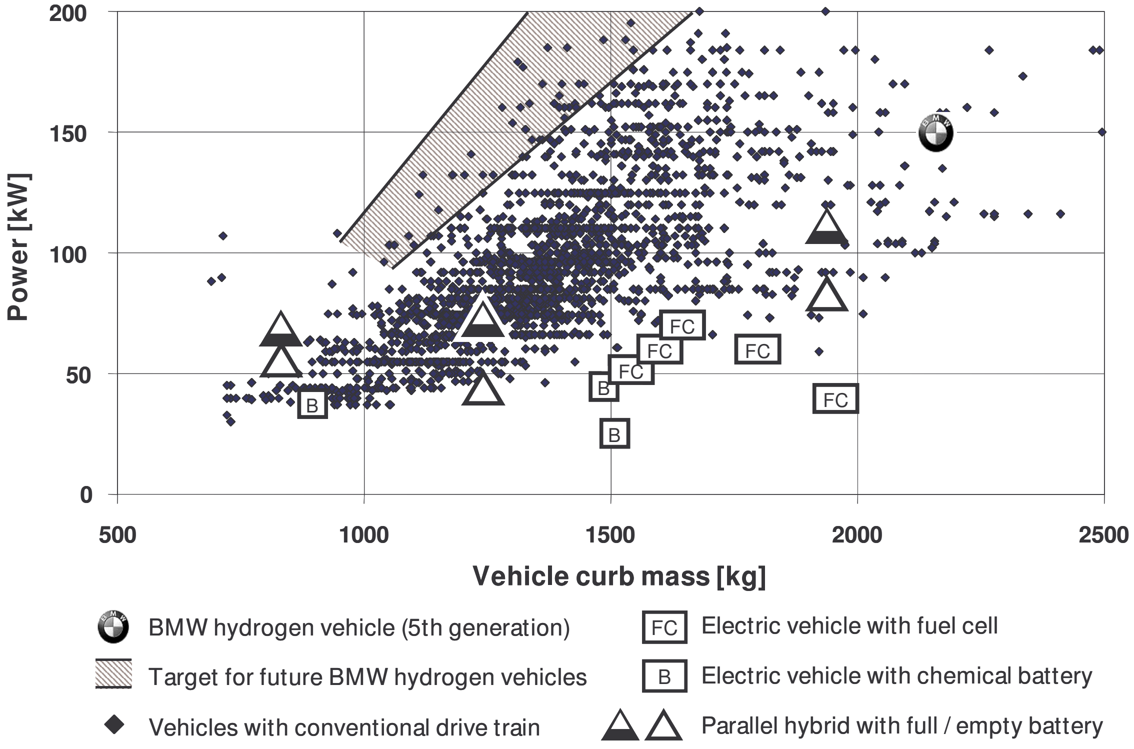


Fig. 2. Power/mass characteristics of vehicles with conventional and alternative drive train systems

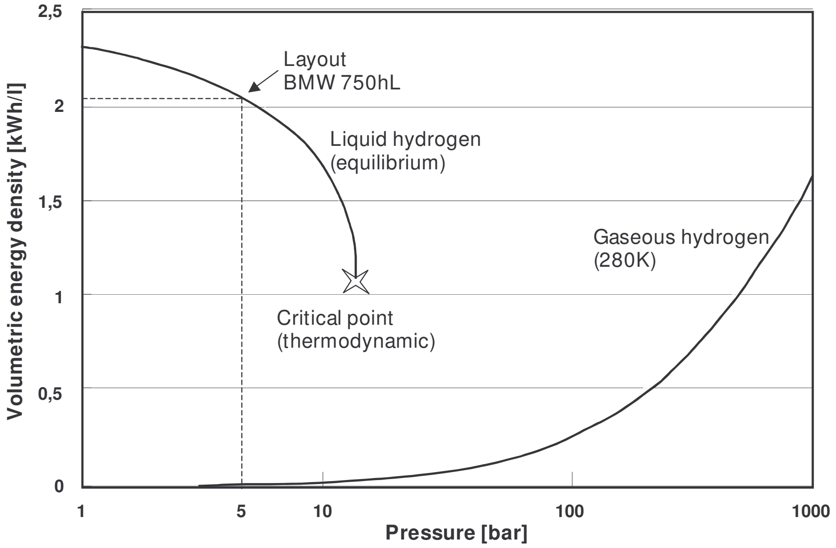


Fig. 3. Energy density of liquid and compressed hydrogen

The first generation hydrogen vehicle went into operation in 1979. It was a 4-cylinder BMW sedan. Its maximum power was at 60 kW and the top speed at 160 km/h. The range of operation was around 400 km.

The 5th generation vehicles [4], launched in 2000, are based on the series production BMW 750iL. Fig. 4 gives a detailed view of the vehicle concept. Its main hydrogen related components are

- the 12 cylinder internal combustion engine,
- the additional liquid hydrogen fuel tank located in the trunk,
- the APU (Auxiliary Power Unit) in the form of a 5kW/42V PEM (polymer electrolyte membrane) fuel cell system.

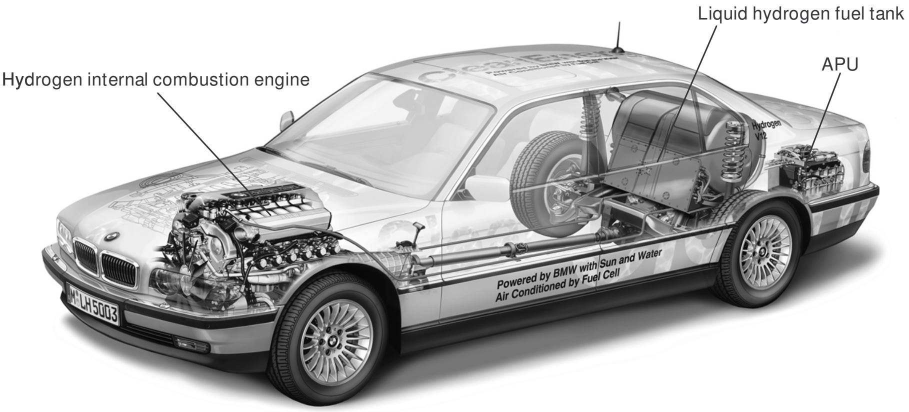


Fig. 4. Hydrogen system integration in the 750hL

The vehicle can be operated in a dual mode (hydrogen and gasoline) which allows to extend its range of operation from about 300 km in the hydrogen mode to a total of about 900 km. This dual mode feature is a necessity when operating the vehicle in the currently existing infrastructural environment with just a few hydrogen fuel stations available.

The engine is based on the series production V12 gasoline internal combustion engine [5]. The major changes realized in order to allow its operation in the hydrogen mode include the installation of an additional gaseous hydrogen injection system and a complete redesign of the ignition system. The external mixture formation and the sequential hydrogen injection system called for major modifications on the intake manifold as well as the integration of 12 electromagnetic injection valves with their corresponding control units. The technical characteristics of the engine installed in the vehicle fleet are listed in Tab. 1.

Tab. 1.Characteristics of the 12-cylinder engine

Engine Data		**BMW 12-cylinder gasoline**	**BMW 12-cylinder bi-fuel**
Displacement	[cm³]	5379	5379
Bore/Stroke	[mm]	85 / 79	85 / 79
Compression ratio	[-]	10.0 : 1	10.0 : 1
Valve timing	[°CA]	Int. 240 / 112 Exh. 240 / 109	Int. 240 / 112 Exh. 240 / 109
Fuel		SuperROZ 95	H_2 / SuperROZ 95
Power	[kW]	240 @ 5000rpm	150 @ 5800rpm*
Torque	[Nm]	490 @ 3900rpm	300 @ 3000rpm*
Engine management system		Bosch M5.2.1	Bosch M5.2.1

* in H_2 mode

The corresponding values clearly indicate that the hydrogen engine, even if featuring a 150 kW power output, is about 30% less powerful than the corresponding gasoline version. Results recently obtained in the scope of an Advanced Hydrogen Engine Cooperation between "BMW Group Research and Technology" and the "Institute for Internal Combustion Engines and Thermodynamics" at the Technical University of Graz have now indicated that there is plenty of room left for the development of hydrogen combustion engines to challenge any competing power-train technology [6, 7].

ADVANCED TECHNOLOGY OF FUTURE HYDROGEN INTERNAL COMBUSTION ENGINES

Focusing on the actually available (bi-fuel) hydrogen internal combustion engine technology, with a 30% power output penalty when compared to the gasoline operation mode, it must be questioned in how far this penalty can be compensated in the scope of an advanced hydrogen engine design. A first evaluation can be derived from the basic Eq. 1

$$p_i = \lambda_a \cdot H_G \cdot \eta_i \tag{1}$$

which allows the indicated mean effective pressure p_i in the cylinder to be determined as a function of the volumetric efficiency λ_a, the indicated efficiency η_i and the mixture calorific value H_G, which is defined as

$$H_G = \frac{H_U \rho_G}{\lambda L_{St} + 1} \qquad \approx \frac{H_U \rho_G}{\lambda L_{St}} \text{ (for } \lambda \geq 1;\ L_{St} >> 1) \tag{2}$$

in the case of mixture-aspirating engines (port injection/external mixture formation), or

$$H_G = \frac{H_U \rho_L}{\lambda L_{St}} \tag{3}$$

for air-aspirating engines (direct injection/internal mixture formation). In Eqs. 2 and 3 ρ_G denotes the density of the stoichiometric mixture, ρ_L the density of the air, H_U the lower calorific value of the fuel, L_{St} the stoichiometric air demand and λ the relative air/fuel ratio.

To better understand the overall situation, it is worthwhile to have a closer look at the physical properties of the new fuel being formed by gaseous hydrogen. As can be taken from Tab. 2, there are significant differences in the properties of gaseous hydrogen when compared to gasoline. Even though the comparison of the ratio between the lower calorific value H_U and the stoichiometric air demand L_{St} shows an advantage for hydrogen, the data indicates an 18% lower mixture calorific value in the external mixture hydrogen mode when compared to the gasoline situation. This effect has to be primarily attributed to the enormously low density of gaseous hydrogen, which entails a lower density of the air/fuel-mixture $\rho_{G,}$ and thus a lower mixture calorific value H_G.

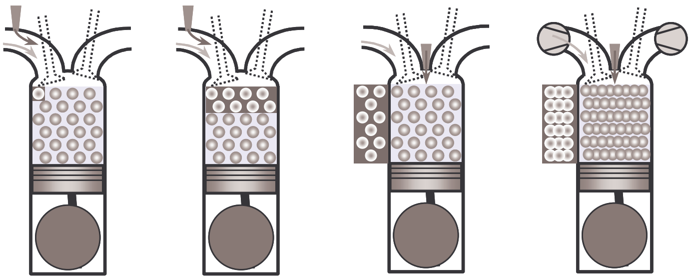
Tab. 2. Physical properties of hydrogen and gasoline

Properties		**Hydrogen**	**Gasoline**
Density ρ	[kg/m³]	0.09	730 - 780
Ignition limits in air	[Vol-%]	4 - 76	1 – 7.6
Minimal ignition energy	[mJ]	0.02	0.24
Self ignition temperature	[°C]	585	>> 350
Laminar flame velocity at λ=1	[m/s]	2.0	0.4 - 0.8
Density of stoichiometric mixture ρ_G	[kg/m³]	0.94	1.42
Stoichiometric air demand L_{St}	[-]	34.3	14.7
Lower calorific value H_U	[MJ/kg]	120	43.5
Mixture calorific value H_G	[MJ/m³]	3.2 ¹⁾ 4.5 ²⁾	3.9 ¹⁾ 3.8 ²⁾

¹⁾ Port Injection
²⁾ Direct Injection

This is in contrast to the internal mixture situation which yields a 17% higher mixture calorific value for hydrogen when compared to gasoline. In the internal mixture case the low density of hydrogen is not relevant since the pressurized hydrogen is fed to the cylinder by a direct injection system at a time when the intake valves are already closed. (Fig. 5)

Conditions:
λ = 1
n = const.
η_e = const.
T = const.



Fuel	gasoline	hydrogen	hydrogen	hydrogen
Concept	Port injection	Port injection	Direct injection	Supercharged direct injection
Mixture calorific value [MJ/m³]	3.9	3.2	4.5	≈ 7.8
Power output [%] (compared to gasoline)	100	82	117	≈ 200

Fig. 5. Cylinder charging concepts

According to Eq. 1 the engine power can be further increased by external supercharging which yields larger numbers for λ_a. But experimental investigations have shown that there is a limitation to supercharging in the external mixture formation situation due to the occurrence of combustion anomalies similar to those known from naturally aspirating hydrogen engines operated close to $\lambda=1$. This further underlines the advantageous power potential of H_2-DI internal combustion engines in comparison to mixture aspirating engines (Fig.6).

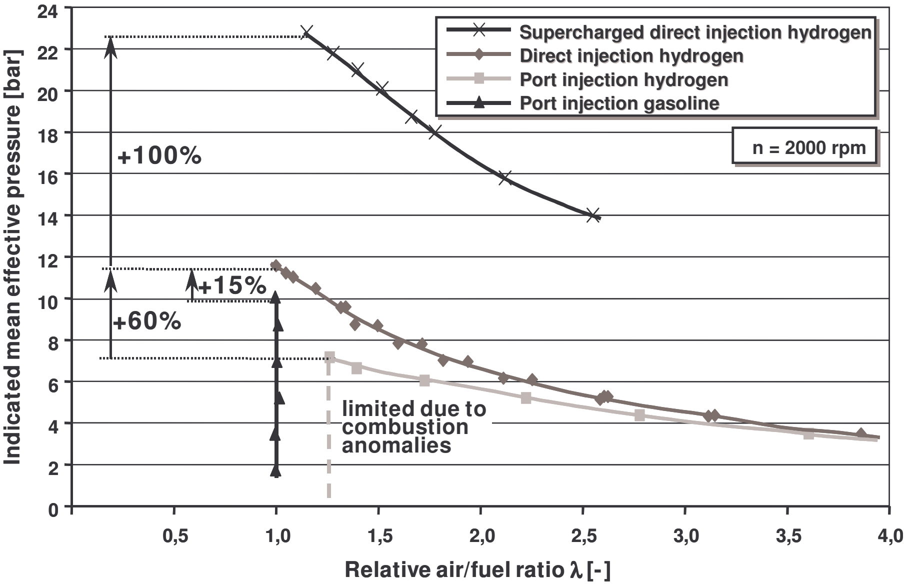


Fig. 6. IMEP for different cylinder charging concepts

A typical property of hydrogen is related to its ignition capabilities within a wide range of air/hydrogen ratios (Tab. 2). This allows the engine to be operated in a quality-controlled mode (Fig.6) even with a completely homogeneous mixture. The unthrottled mode of operation is beneficial to the engine's overall efficiency at part load conditions in two ways:

- the avoidance of throttling losses, and
- the increase of efficiency by leaner combustion.

Moreover, the high flame propagation velocity of air/hydrogen mixtures (Tab. 2) entails outstanding combustion properties. The comparison in Fig. 7 clearly indicates the significantly shorter combustion periods in the full-load range which are typical for hydrogen engines.

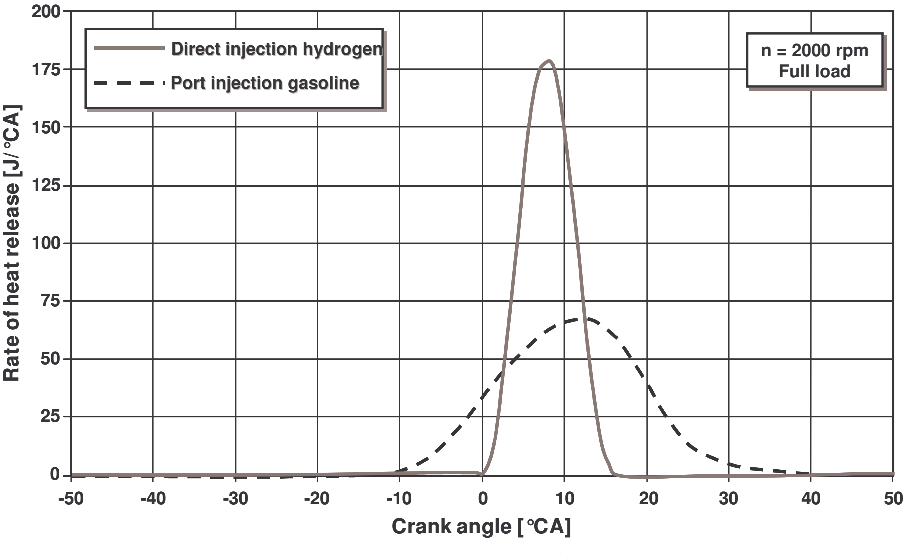


Fig. 7. Full load combustion behaviour

All in all, the obviously lower complexity of mixture formation leads to more flexibility in the combustion process. The direct injection engine allows both,

- the ignition timing, and
- the SOI (Start Of Injection) timing point

to be varied significantly, in order to achieve a highest engine power output or efficiency, or moreover, to even obtain full control of the combustion process by a sequential hydrogen injection at different timing points (Fig. 8).

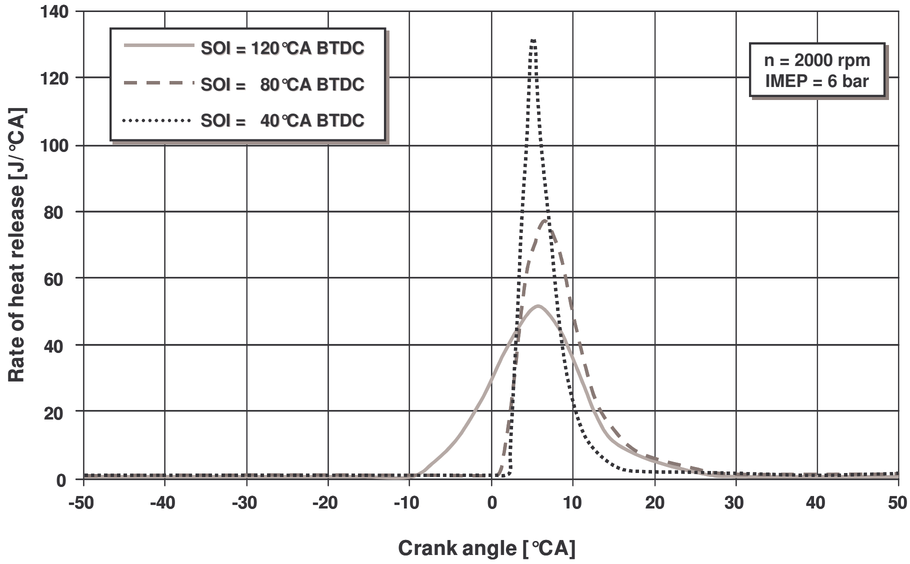


Fig. 8. Part load combustion behaviour with different start of injection

The direct injection of hydrogen provides the ideal approach for precise combustion control. After pre-injecting a small amount of hydrogen, the combustion process is initiated by external ignition. The ongoing process of combustion is then managed by the direct injection of hydrogen gas into the flame, allowing any knocking effects to be kept under control. Additionally further engine modifications, such as the increase of the compression ratio or the installation of a turbocharger, can be realized with the goal to raise the efficiency and to boost the performance.

The many results obtained from test bed investigations indicate that the supercharged DI hydrogen combustion engine has the potential to challenge both the gasoline engine with regard to the power output, as well as the turbo-diesel engine with regard to the torque characteristics (Fig. 9).

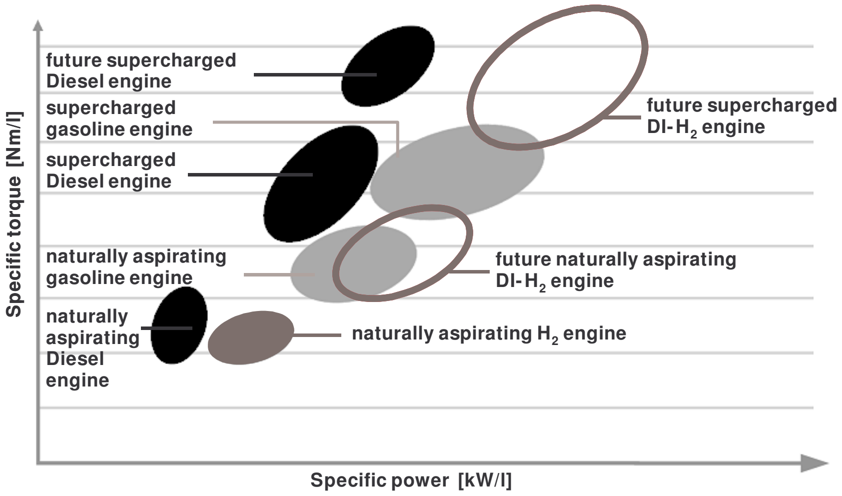


Fig. 9. Specific power and specific torque targets for future internal combustion engines

Moreover, due to the possibility to realize an ideal combustion control with high compression ratios, it is believed that – if additionally flanked by an overall efficient energy management – the effective efficiency of a hydrogen DI internal combustion engine at its best point can be raised up to 50% (Fig. 10).

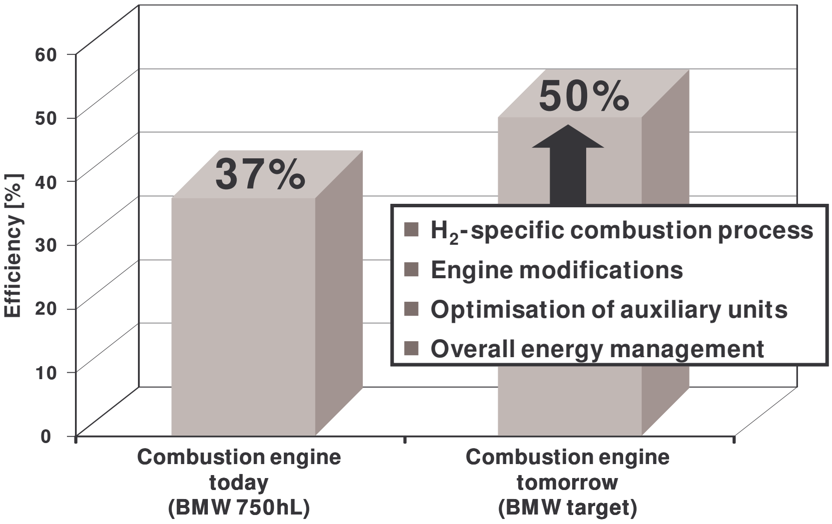


Fig. 10. Efficiency target for future direct injection hydrogen internal combustion engines

But how about the emissions? How about the formation of NO_x? Do they cast doubts on this technology? No, they don´t!

It is evident that, due to the lack of carbon in the hydrogen fuel, there are no HC, CO and CO_2 emissions, except from those traces produced by the combustion of a small amount of the engine lubricating oil. But due to the nitrogen in the normal air of the atmosphere there might be a formation of NO_x.

Intensive testing has indicated that operating a hydrogen combustion engine in a lean mode – at λ-values larger than 2.2 – does not produce any NO_x. Burning the air rich mixture entails that the temperature of NO_x formation (≈2200 K) is not reached in the combustion zone. If this temperature is exceeded at higher loads with $\lambda = 1 - 2.2$, NO_x is formed, as is indicated in Fig. 11.

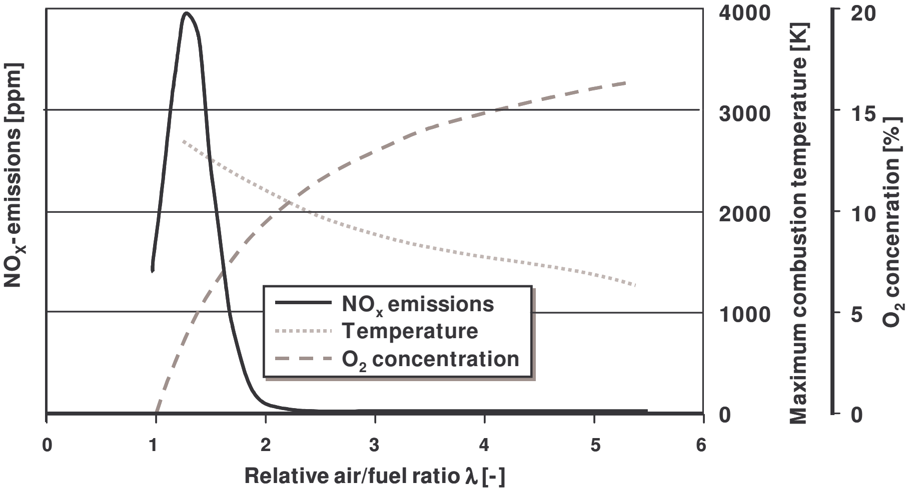


Fig. 11. Engine out NO_x-emissions

Two meaningful steps have been identified that allow the engine to be operated at full load without producing NO_x rich tailpipe emissions. First, it was experimentally determined that, at high engine loads, a late start of injection is beneficial for the avoidance of NO_x formation in the engine. On the other hand, a late start of injection entails a higher level of unburned H_2 emissions.The experiment has indicated that operating the hydrogen engine at full load with $\lambda = 1$ (stoichiometric mixture) allows an almost complete catalytic conversion of the NO_x and H_2 to N_2 and H_2O in the tailpipe, by means of a simple reduction catalyst. Accordingly, also at full engine load, NO_x tailpipe emissions can be reduced to a few ppm (Fig. 12).

Therefore, a conceivable engine operation strategy consists in a load dependent λ-adaptation. At part load conditions, a lean engine operation with $\lambda > 2.2$ is chosen. At higher loads – up to full load – the operation occurs at $\lambda = 1$, throttled as appropriate. This approach, avoiding the NO_x-emission critical range between $\lambda > 1 - 2.2$ and a complex NO_x storage catalyst, allows almost emission-free operation throughout the entire engine load and speed range (Fig. 12).

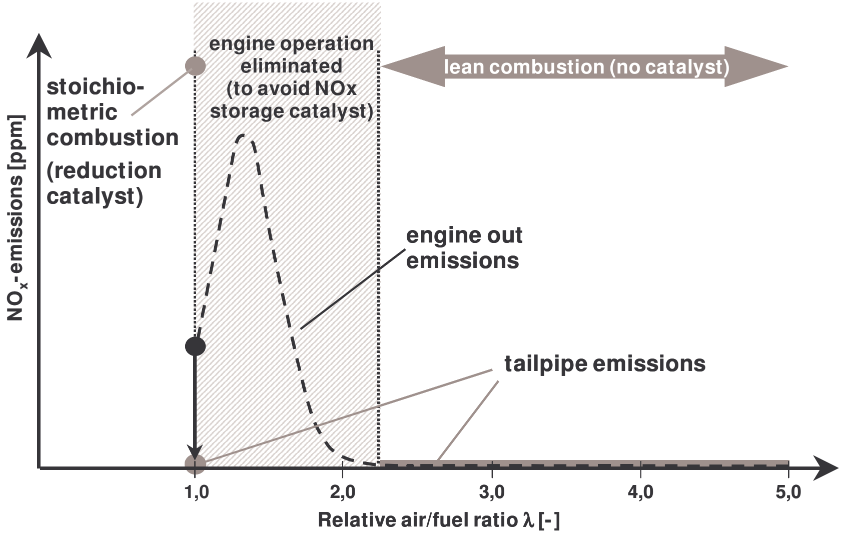


Fig. 12. Engine out and tailpipe emissions

CONCLUSION

For more than 100 years the reciprocating internal combustion engine has been significantly contributing to the (individual) mobility of mankind. Its automotive application has never been seriously challenged by alternative drive systems. Also, in the scope of a future hydrogen economy, the reciprocating internal combustion engine has a real chance to maintain its unique position. This uniqueness will be characterized by its high power density with regard to volume and weight, its high efficiency and nearly emission free operation. There is a great chance for the reciprocating hydrogen internal combustion DI engine to be the basis of our individual mobility for another 100 years.

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