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FKFS和IFS氢能车辆驱动系统研究

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摘要：本文介绍氢气在交通运输领域的相关应用，以氢气直喷(H_2-DI)内燃机的开发过程为例，阐述斯图加特汽车工程与车辆发动机研究所(FKFS)和斯图加特大学汽车工程学院(IFS)的研究工作。在单缸乘用车发动机试验台上研究氢气高压直喷特性(FVV项目)，目标是实现氢气发动机在当量混合条件下稳定运行，从而以较低的增压需求输出较大功率。当发动机在高负荷条件下工作时，当量混合比更容易导致爆震现象。为了防止末端气体发生预反应，喷射氢气将在点火上止点(TDCF)前不久开始，随后由火花塞点燃。喷射持续时间以及喷射的最大质量流量都将在不同程度上影响燃烧的持续时间。此外，本研究还探讨了氢气燃烧过程中所存在的问题，如较高的氮氧化合物排放量，以及未燃氢气进入排气系统等。

关键词：氢气；内燃机；直喷；当量燃烧

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The Investigation of Hydrogen-Based Vehicle Propulsion Systems at FKFS and IFS

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Abstract: The defossilisation of transport is of central importance for meeting global climate targets. In addition to introducing battery-electric vehicles that today are mainly intended for individual and local passenger transport, fuels based on renewable resources offer the possibility of fulfilling energy-intensive transport tasks with low global greenhouse gas emissions. Hydrogen produced from renewable energy is gaining particular importance here, as its use in mobile applications ensures not only overall low global warming potential but also the lowest tailpipe greenhouse gas emissions. In this paper, the various aspects of the use of hydrogen in vehicles are briefly presented and the work at FKFS and IFS is illustrated using the development of an H_2-DI combustion process for ICE applications as an example. The presented FVV research project investigates a high-pressure direct injection concept on a single-cylinder passenger car engine test bench. It aims to operate a spark-ignited engine near stoichiometric conditions to produce a significant power output with low boost pressure demand. However, for a hydrogen engine, a stoichiometric mixture leads to an increased knocking tendency towards higher loads. To avoid pre-reactions in the end gas, the injection starts shortly before TDCF and the hydrogen jet is ignited by the spark plug. The injection duration and therefore the maximum hydrogen mass flow through the injector nozzle influence the combustion duration. Challenges of the investigated hydrogen combustion process are, among others, the higher NO_X emission level compared to the lean operation and the hydrogen slip into the exhaust system.

Keywords: hydrogen; internal combustion engine; direct injection; stoichiometric combustion

1 Hydrogen Powered Vehicles

As part of the efforts to avoid CO_2 emissions in road traffic, battery-electric vehicles are currently in the foreground in the sector of passenger cars and light duty vehicles. In the area of heavy commercial vehicles, battery-electric drives will initially not be the preferred solution due to the high battery capacity required for this (>1 MWh), the associated increase in load (>45 t), the high charging power required

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(>1 MW), the nevertheless limited range (<650 km) and the charging times needed that will be eliminated in the context of the introduction of automated driving.

The electrical supply of heavy-duty electrical vehicles (HD-BEV) during travel requires the installation of an overhead line infrastructure at least on long-distance routes. Since Catenary-Trucks have to use two parallel overhead lines the supply of electrical power is limited (voltage) which makes the expansion of long motorway sections necessary and is associated with high costs.

So, from today's point of view, the use of hydrogen from renewable sources as an energy carrier represents an important possibility to realize high ranges and short filling times without local CO_2-emissions. Due to the high efficiencies that can be achieved 63%~65%, operation with fuel cells (PEM) as energy converters is envisaged in the medium to long term. However, the efficiencies of currently available PEM fuel cell systems drop sharply at high continuous power levels (<45%) and large amounts of heat have to be dissipated via the vehicle cooling system. With a 15~20 K lower temperature level of the coolant circuit compared to combustion engines, this poses great challenges for the thermal management of the vehicles, e. g. when driving up steep gradients over a longer period of time (e. g. crossing the Alps). In addition, an increase in the annual mileage of heavy commercial vehicles, as is to be expected due to the increasing establishment of automated driving in long-distance traffic, will lead to significantly higher demands on the cycle stability of fuel cell systems.

For this reason, the use of hydrogen in combustion engines for heavy commercial vehicles is becoming increasingly important. Here, engines are used which are usually based on diesel engines or on natural gas engines derived from diesel engines. If not already done, these are converted to petrol-engine combustion processes. This usually includes the application of an ignition system, the reduction of the compression ratio, the adaptation of the piston geometry and the application of a mixture formation system for gaseous fuels. Today, external mixture formation systems (PFI) are often used, as they are easier to adapt and allow a high degree of homogenization. The associated effects such as lower mixture heating values, higher knock tendency as well as the danger of backfiring and pre-ignition make the development of systems for internal mixture formation (H_2-DI) necessary. Current developments concentrate on systems that operate at pressures between 15 and 30 bar. One reason for this is that gaseous fuels such as hydrogen are preferably stored in pressure accumulators in the vehicle at pressures between 300 and 700 bar, and the use of low rail pressures ensures a long vehicle range. Due to high losses (approx 7% for H2 @ 1-200 bar) during the compression of compressible media, recompression of the gas in the vehicle has not been attempted up to now.

2 Hydrogen Combustion Process

So, the current research and development of hydrogen combustion processes mainly focuses on lean direct injection operation to minimize engine-out NO_X emissions[1-2]. Lean combustion comes along with a significant additional boost pressure demand to reach high engine loads. Therefore, the herewith presented research project investigates near-stoichiometric hydrogen combustion with direct injection[3]. However, Ref. [4] and [5] report a higher risk of pre-ignition or knocking for premixed engine operation at low air-to-fuel equivalence ratios and higher loads. Late compression stroke injection offers the possibility to avoid premixing and, thereby, pre-reactions. In particular, the project strives for a jet-guided combustion process using a spark-ignited hydrogen jet. The experimental investigations are carried out at a hydrogen engine test bench at the FKFS.

A passenger car gasoline engine (Mercedes-Benz M 254) is the basis for the single-cylinder research engine with a displacement of 500 cm^3. The adaption to hydrogen includes only minimum changes without mechanical modifications. The relative positioning of the injector and spark plug is optimized for a jet-guided gasoline combustion process. The injector is mounted vertically near the central position of the combustion chamber, and the spark plug is positioned between the intake and exhaust valves[6]. The outward-opening Bosch HDEV4 piezo-controlled gasoline injector is adequate for fundamental investigations with high-pressure hydrogen (gaseous) direct injection. However, for short hydrogen injection durations of about 10°CA in non-premixed jet-guided mode, the cross-section of this injector is merely adequate for low engine speeds and loads.

Fig. 1 shows a schematic view of the experimental setup. The external charging unit delivers a pressure of up to 3 bar absolute, and the conditioning system controls the intake air temperature. The intake plenum and throttle flap reduce pulsations in the air path. An exhaust flap allows for an adjustment of the resulting exhaust back pressure. 300 bar bottle bundles provide hydrogen that the pressure regulator reduces to a maximum rail pressure of 200 bar. In addition to the measurement of temperatures and both static and dynamic pressures, a Horiba exhaust gas analyzer and an H_2 mass spectrometer are installed. For safety reasons, an active crankcase ventilation system provided by Hengst reduces accumulated H_2 below the piston.

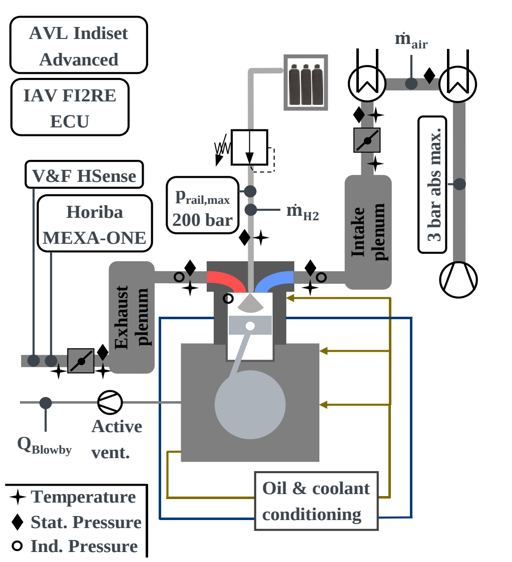

Fig.1 Schematic SCE experimental setup[3]

The air-to-fuel equivalence ratio is calculated from the measured oxygen content of the exhaust gas using Eq. (1)[7]. This equation assumes complete fuel conversion, generating inaccurate results for incomplete stoichiometric combustion. Therefore, the first experiments are performed with a slightly over-stoichiometric air-to-fuel equivalence ratio of 1.1.

$$\lambda_{O_2}=\frac{[O_2]-1}{4.7733[O_2]-1}$$

For future tests, a recently published modified equation considering the products of incomplete combustion is a promising option to control a stoichiometric operating point accurately[1].

Fig. 2 illustrates the intended injection and ignition strategy. For an ignition timing variation, a definition of the ignition timing relative to the injection duration is beneficial.

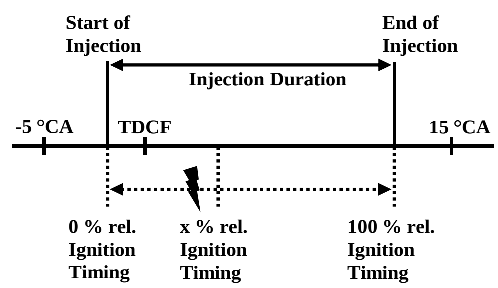

Fig.2 Schematic explanation of injection timing and ignition timing relative to the overall injection duration

Fig. 3 shows the cycle-averaged cylinder pressure signal and calculated heat release rate for a variation of the ignition timing for a 1 500 min^{-1} and 5 bar IMEP operation point at an air-to-fuel equivalence ratio of 1.1. The maximum rail pressure of 198 bar for this specific mass flow enables the minimum injection duration for the given injector and operating point. For this study, MFB 50 is kept constant at 8° aTDCF, which leads to an adjustment of the injection timing between the presented cases. The colored bars in the upper graph illustrate the injection phases and the arrowheads the spark timings.

For the earlier ignition timings, a fast conversion of the already injected fuel results in a first peak in the HRR, but the rate drops to a lower level for the remaining injection time. Ignition timing at EOI leads to a fast fuel conversion with the highest peak in HRR

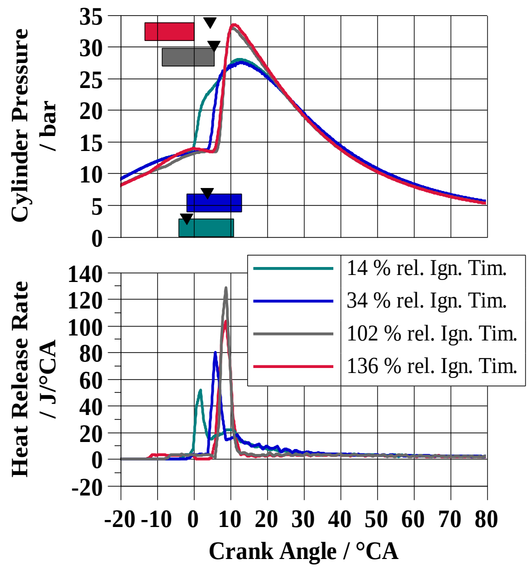

Fig.3 Cylinder pressure and heat release rate (average of 200 working cycles) for a variation of the relative ignition timing (1 500 min^{-1}, 5 bar IMEP, λ =1.1, 8 °CA aTDCF MFB50)

due to rich conditions at the spark plug.

Fig. 4 presents significant correlations for the variation of the relative ignition timing. Early ignition favors combustion instability, as can be seen from an increased coefficient of variation for IMEP, p_{max} and MFB50, combined with a long combustion duration and a low maximum pressure gradient. This enables an advantage in NO_X emissions but reduces indicated efficiency simultaneously. For relative ignition timings of 50% to 70 %, the H_2 slip into the exhaust system decreases encouraged by accelerated flame propagation, but pressure gradients rise to an unacceptable level. Further investigations, like a variation of the MFB50 timing, will be performed for the different cases to find a compromise between cylinder pressure gradient, H_2 slip into the exhaust manifold and indicated efficiency. A combustion control with multiple injection pulses similar to Ref. [9] could be a promising option to reduce the cylinder pressure gradient. The study shows the feasibility of a jet-guided combustion process with near stoichiometric conditions for the given operating point. For this research engine and operating point, the NO_X engine-out emissions are an order of magnitude smaller compared to the homogeneous operation at an air-to-fuel equivalence ratio of 1.1. Nevertheless, an exhaust gas aftertreatment system, which is not part of this project, is inevitable for NO_X tailpipe emission reduction. Ref. [4] and [8] discuss NO_X reduction with H_2 as a reducing agent and the challenge to mitigate NH_3 and N_2O slip.

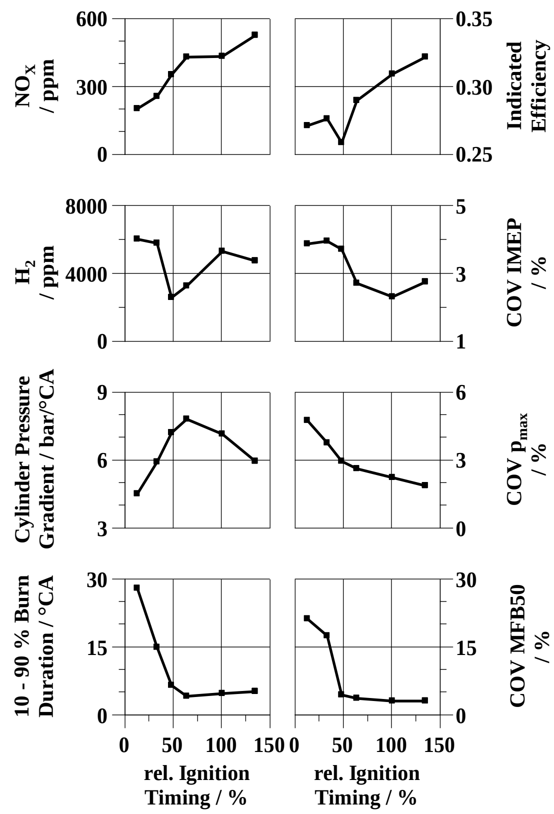

Fig.4 Significant measurements for a variation of the relative ignition timing (1 500 min^{-1}, 5 bar IMEP, λ= 1.1, 8 °CA aTDCF MFB50)

3 Conclusion

In this paper the concept of high-pressure direct injection for a hydrogen-fueled ICE is introduced. First results show the feasibility of a jet guided combustion process with near stoichiometric conditions.

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Abbreviations:

aTDCF—After top dead center firing
°CA—Degree crank angle
DI—Direct Injection
EOI—End of injection
HRR—Heat release rate
IMEP—Indicated mean effective pressure
MFB50—50 % mass fraction burned
SOI—Start of injection

References:

[1] LEJSEK D, *et al*. Mixture formation and combustion in a passenger car engine with low pressure H_2 direct injection[C]// 19th Symposium Sustainable Mobility, Transport and Power Generation. Graz: 2023.

[2] GEILER J N, *et al*. H_2 engine hybrid powertrain for future light commercial vehicles[C]// 10 International Engine Congress. Baden-Baden: 2023.

[3] BEYER A, *et al*. A non-premixed hydrogen combustion process using a spark-ignited hydrogen jet [C]// 2023 Conference on Powertrains With Renewable Energy Carriers. Stuttgart: 2023. (to be published)

[4] KAPUS P, *et al*. Hydrogen for internal combustion engines—a viable alternative for passenger car propulsion [C]// 19th Symposium Sustainable Mobility, Transport and Power Generation. Graz: 2023.

[5] STERLEPPER S, *et al*. Concepts for hydrogen internal combustion engines and their impications on the exhaust gas aftertreatment system[J]. Energies, 2021, 14(23): 8166. https://doi.org/10.3390/en14238166.

[6] VOLLRATH O, *et al*. The new Mercedes-Benz in-line six-cylinder gasoline engine with 48 V electrification[J]. MTZ Worldwide, 2018, 79: 54. https://doi. org/10.1007/s38313-018-0015-7.

[7] LEJSEK D, *et al*. Thermodynamic analysis of hydrogen engines with port fuel- and direct injection [C]// 18th Symposium Sustainable Mobility, Transport and Power Generation. Graz: 2021.

[8] BORCHERS M, *et al*. Selective catalytic reduction with hydrogen for exhaust gas after-treatment of hydrogen combustion engines[J]. Topics in Catalysis, 2023, 66: 973. https://doi.org/10.1007/s11244-022-01723-1.

[9] GERBIG F, *et al*. Potentials of the hydrogen combustion engine with innovative hydrogen-specific combustion processes[C]// FISITA World Automotive Congress. Barcelona: FISITA, 2004.