HYDROGEN C.I. LARGE BORE FOUR STROKE ENGINE: IGNITION AND COMBUSTION PROCESS ANALYZED WITH HIGH SPEED OPTICAL MEASUREMENT SYSTEMS

Dipl.-phys. Peter Prechtl; Dipl.-Ing. Frank Dorer; Dr.-Ing. Dr.-Ing. E.h. Franz Mayinger
Lehrstuhl A für Thermodynamik, Technische Universität München,
D-85747 Garching, Germany
Dr.-Ing. C. Vogel; Dr.-Ing. v. Schnurbein
MAN B&W DIESEL AG, Stadtbachstr. 1, D-86153 Augsburg, Germany

1. INTRODUCTION

The simple reaction of hydrogen and oxygen into water as a clean method for energy conversion, the high energy density, the wide ignition ranges and the high burning velocities have been the reason for people to investigate the usability of hydrogen as a fuel for internal combustion engines for a long time. Short overviews are given in [1,2]. In the last years, extensive research has been done with different concepts on the application of hydrogen for engine use. A summary over German activities is given in [3]. The method of internal mixing and compression ignition combines the advantages of the high efficiency of a diesel engine and the clean combustion of hydrogen and oxygen. For this combustion method, however, one main problem has to be solved which is the auto-ignition of hydrogen. A variety of studies on this topic has shown that a reliable running C.I. engine can not be realized yet [4,5,6,7]. In a cooperation of MAN B&W Diesel AG and two departements of the Technische Universtät München a large bore four-stroke engine running with hydrogen is being developed. The research project is supported by the Bayerische Forschungsstiftung (Bavarian Research Foundation). The Lehrstuhl für Verbrennungskraftmaschinen (department of internal combustion engines) investigates the behavior of a single cylinder test engine. The Lehrstuhl A für Thermodynamik (department of thermodynamics) investigates the injection and combustion process with modern optical measurement techniques in a rapid compression machine (RCM) under realistic conditions. As mentioned above, the ignition of hydrogen under internal mixing conditions is the key process for a reliable engine operation. Due to this fact it is main subject of the current research activities.

2. EXPERIMENTAL INVESTIGATIONS

In a first phase the experiments are carried out in the RCM by varying of the compression ratio, the load pressure and the flow condition (variation of the swirl and the turbulence). The compression ratio reaches a value up to 22, the compression end pressure is between 5 and 11 MPa. The temperature reaches values over 950 K. The hydrogen is injected with a pressure between 25 and 33 MPa and a maximum injection duration of 15 ms. In a next step the influence of the injector geometry is analyzed. For these experiments nozzles with a hole number of 6 up to 24 and a slot nozzle with nearly equivalent cross-sections are manufactured. These measurements are carried out under the same pressure conditions.

Experimental Setup

The experimental setup used for these investigations is based on an fully optically accessible rapid compression machine (RCM). The machine simulates a single compression stroke under realistic conditions. This experimental set-up allows a variety of investigations under different conditions. It is simple to replace the injection device or the nozzle geometry. The compression ratio, the load, the intake temperature as well as the injection timing can be varied. In addition to that fact a swirl or a turbulence can be engendered in the combustion chamber. On the top of the combustion chamber the original electro-hydraulic-controlled injection device for pressurized hydrogen is mounted. The hydrogen is supplied from single bottles and from bundles. The hydrogen is compressed with a 30 MPa piston compressor, and it is stored in a small high pressure tank before the injection. The optical access to the combustion chamber of the RCM is realized through a large quartz window in the bottom of the piston and additional windows in the cylinder walls. The RCM allows a maximum combustion pressure over 20 MPa. This set-up allows the use of optical measurement techniques, such as the laser induced fluorescence (LIF/LIPF) [8] for the detection of several species like OH, and fast imaging techniques, such as the high speed digital video and Schlieren techniques to visualize the mixing and combustion process. A typical set-up using the high speed video camera is shown in figure 1. The dimensions of the machine are in a 1:1 scale to the single cylinder test engine which has a piston displacement of about 14 liters and a power output of approximately 180 kW. The velocity of the piston of the rapid compression machine corresponds to the piston speed of the engine with 800 – 900 RPM near the TDC. The emitted light (self-fluorescence) from the ignition and the combustion process is observed using a digital high speed camera at a frame rate of 13,500 Hz. In addition to the conventional data such as the pressure, the piston displacement, the needle lift and other required signals the images are stored digitally. In a next step the data is analyzed, combined with the images and recorded to a digital mpeg-film. These films give a good impression of the location and the spatial distribution of the ignition and the combustion process. This method contributes to a better understanding and an efficient improvement of the combustion concept.

Results and discussion

In the first series of experiments it has been shown that the compression ratio has a significant influence on the ignition delay. Higher temperatures lead to shorter ignition delays. However, large variations of the ignition delays have been observed in all the experiments. The ignition occurs statistically distributed in the combustion chamber. The analysis of the films proves the assumption that an ignition of a single jet does not lead to the ignition of other hydrogen jets as it is shown in figure 2. It has also been observed that several jets have not ignited. It can be inferred that different areas of combustible hydrogen mixtures of the injected jets in a single compression cycle can have different ignition delays. As a result, cycle to cycle variations in the pressure recordings are expected and the possibility of miss-fire can not be excluded. Possible reasons can be statistical effects on the ignition due to the compression end temperatures near the auto-ignition temperature of hydrogen and the varying mixing conditions. It is likely that there is an influence of the purity of the pressurized hydrogen, the intake-air or of the leakage in the injection system on the ignition. All three possibilities were analyzed. The results show that there is no contamination of the hydrogen compression and of the high pressure storage system. Furthermore, the air supply system has also no contamination. The injection device has a oil sealing system which was suspected to leak impurifications of oil into the injected hydrogen. The installation of another injector with dry sealings has no significant impact on the statistical ignition behavior. But it has to be taken into account that the hydrogen is used in the same way as it is delivered from a commercial gas supplier. That means it is delivered as a compressed gas and it is not as chemically clean as the liquid hydrogen (the boiling temperature of liquid hydrogen is 20 K). The phenomenon of the auto-ignition, which is difficult to realize, and the variations of the ignition delays were also observed and discussed by other researchers working on that topic [6, 7, 4, 2]. The ignition delays estimated from calculations of hydrogen air mixtures with zero dimensional calculations [9 - 11] are in a range of 2 ms at compression end temperatures over 1050 K. Siebers [12] reports ignition delays in his experiments of 0.5 ms at temperatures of 1200 K.

An enhanced flow field in the combustion chamber, which can be realized through a swirl or a turbulence, improves the reliability of the ignition and reduces the variations of the ignition delays. Due to the critical injection of the hydrogen [13] into the combustion chamber and its high speed in the nozzle outlets of about 1400 m/s (which is the speed of sound), the injected jets are not deflected in the vicinity of the outlets. Owing to the strong slow-down of the injected hydrogen a significant influence on the penetration direction can be observed at a distance of 50 mm from the nozzle.

In order to run the engine under similar conditions like a diesel engine with a high compression ratio and late gaseous injection a nozzle geometry with 6 or more holes is set up. All the experiments with hole numbers up to 10 show that a burning jet hardly ignites his neighbor jet. As discussed above, this behavior leads to large variations in the pressure recordings. As a result of these observations a nozzle system with a spatially connected combustible mixture distribution is set up. Experiments with nozzles with 18 holes or a slot show a much better combustion behavior as those with 6 to 10 holes. Once auto-ignition occurs, the flame propagates very fast over all injected jets. Due to the equivalent cross-section of the nozzles the diameter of the holes decreases with the increase of the number of holes. A smaller bore diameter reduces the momentum of the injected hydrogen significantly ($\sim d^2$). Owing to a smaller momentum the jet is slowed down faster and a reduced penetration speed of the jets can be observed. Due to the smaller speed the auto-ignition begins in the vicinity of the nozzle. The best ignition behavior is observed with a slot nozzle. Figure 3 illustrates the ignition process of a nozzle with a slot height of 100 um. Under these conditions an earlier and saver ignition can be achieved. On the other hand a longer combustion duration is observed. The flow conditions have significant influence on the combustion process. Nozzle geometries with low jet velocities and large ignitable areas have good auto-ignition properties but induce insufficient conditions for a fast and effective overall combustion. The flow energy for the mixing process is lost in highly throttling nozzles. The nozzles with 6 holes show, in contrast to nozzles with more bore holes, better combustion properties as soon as the hydrogen is ignited. The combination of both advantages leads to the application of nozzles with a series of large and small bores. The existence of the small bores ensure an early and reliable ignition in the vicinity of the nozzle and a fast flame propagation which ignites the surrounding jets. The large bores, however, cause a high momentum of the injected hydrogen which leads to good mixing. Figure 4 illustrates the ignition and the combustion process of a combined 18-hole nozzle with 6 x 0.6 mm and 12 x 0.4 mm bores. A fast flame propagation around the nozzle is achieved within 0.6 milliseconds. In addition to that fact a faster penetration of the jets from the large bore holes to the wall of the cylinder is observed which results in a more efficient use of the whole combustion chamber. Nozzles of these types are, at the present situation, the best combination of a reliable ignition and efficient combustion. However, the variations of the ignition processes and the pressure rise rates are higher than those observed in real diesel engines. In addition to that fact an improvement of the ignition of the hydrogen near the nozzle can be expected using slow opening valves. These types of valves are used in modern combustion concepts of Common-Rail diesel engines with which the pressure rise rates can be controlled and the emissions can be reduced.

Although an operation of a C.I. engine using hydrogen seems to be possible under the above discussed conditions, alternative ignition devices should still be considered. The low ignition energy of hydrogen suggests the use of a spark plug ignition under late internal mixing conditions. The varying auto-ignition behavior of the hydrogen because of possible impurifications can lead to pre-ignitions under early-injection conditions. Due to this fact S.I. hydrogen engines have a reduced compression ratio of about 10 [14 15, 16]. The possibility of setting up a configuration with late internal mixing and spark ignition, as that used in a new generation of GDI engines, is also of great interest. For this reason experiments have been setup with small modifications to the cylinder head of the RCM which is the insert of a spark-plug. With the same nozzle geometry and a reduced compression ratio, the auto-ignition can be avoided, which enables a reliable and a fast ignition of the hydrogen. Due to the optimized arrangement of the holes in the nozzle a fast flame propagation around the nozzle is achieved within 1 ms. Figure 5 shows a spark ignited combustion. The spark-plug timing is set to the beginning of the hydrogen injection. With a late injection and an immediate, ignition high compression ratios can be realized as opposed to external or early internal mixing.

3. CONCLUSIONS

The developed set-up for the investigations of a hydrogen-fueled large bore C.I. engine with a high pressure injection system allows a detailed analysis of all relevant processes.

The modern optical techniques enable the analysis of the mixing, the ignition and the combustion processes. The results obtained with this setup contribute to a better understanding of the very fast processes. Furthermore this setup allows an efficient testing and development of engine components. The auto-ignition of hydrogen has been observed. High pressures and temperatures have a positive influence on a short ignition delay. Turbulences and swirls support the propagation of the flame over the whole combustion chamber and regulate the combustion for smoother pressure rates. At present, combined nozzles containing 18 bores with different diameters seem to be the best injection geometry for small variations of the ignition delay and of the pressure. However, the current ignition behavior of hydrogen in a C.I. engines without ignition sources is not applicable yet. Therefore it still requires further improvement for a smooth and safe engine operation. Modern injection concepts with their possibilities of pilot-injection and slow-opening rates offer additional options for improvement. However, further ignition sources for hydrogen under late internal mixing conditions have to be considered and should be investigated. A discussion of the experiments, carried out using the single-cylinder test-engine, is presented by the Lehrstuhl für Verbrennungskraftmaschinen [17]. A detailed study of the mixing process is given by F. Dorer in [18].

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FIGURE 1: EXPERIMENTAL SET-UP USING THE RAPID COMPRESSION MACHINE (RCM) AND A HIGH SPEED VIDEO CAMERA TO OBSERVE THE IGNITION AND COMBUSTION PROCESS

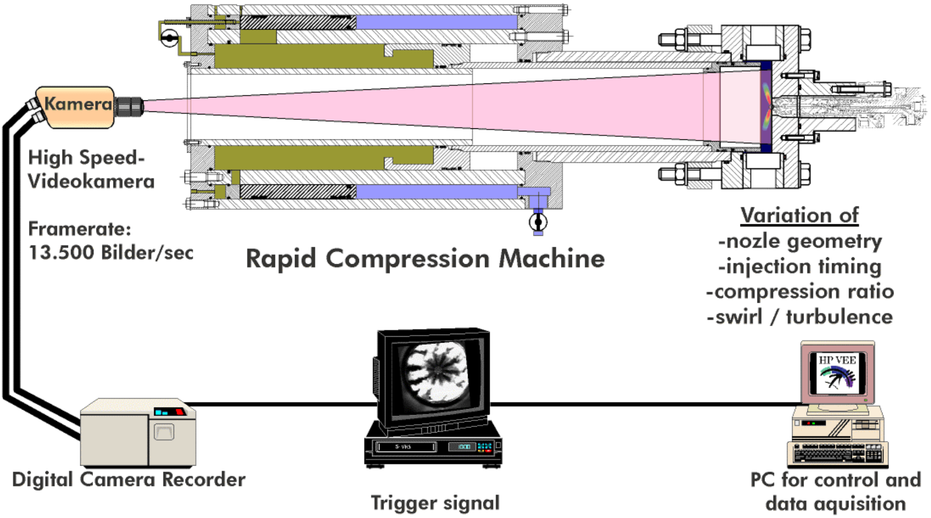

FIGURE 2: TYPICAL IGNITION PROCESS OF A 6 HOLE NOZZLE

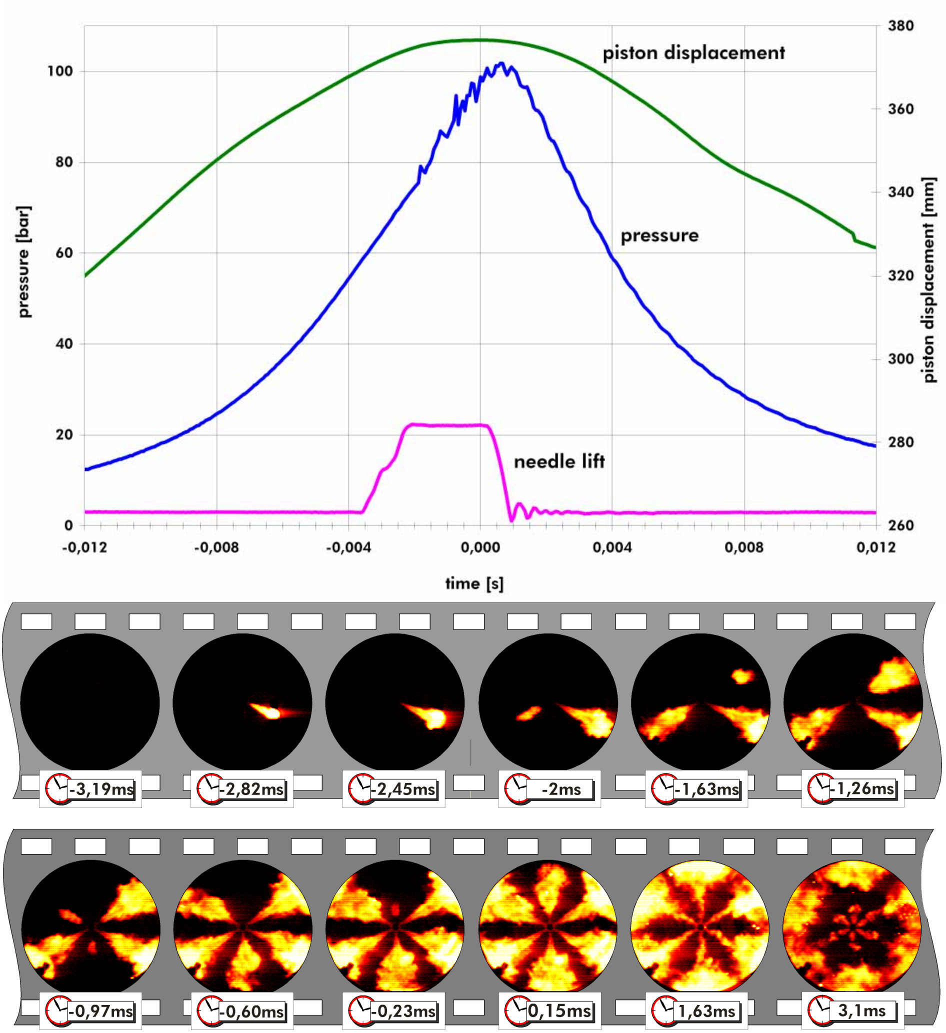

FIGURE 3: TYPICAL IGNITION PROCESS OF A SLOT NOZZLE WITH A SLOT HEIGHT OF 100 UM; FLAME PROPAGATION AROUND THE NOZZLE WITHIN 0.4 MS

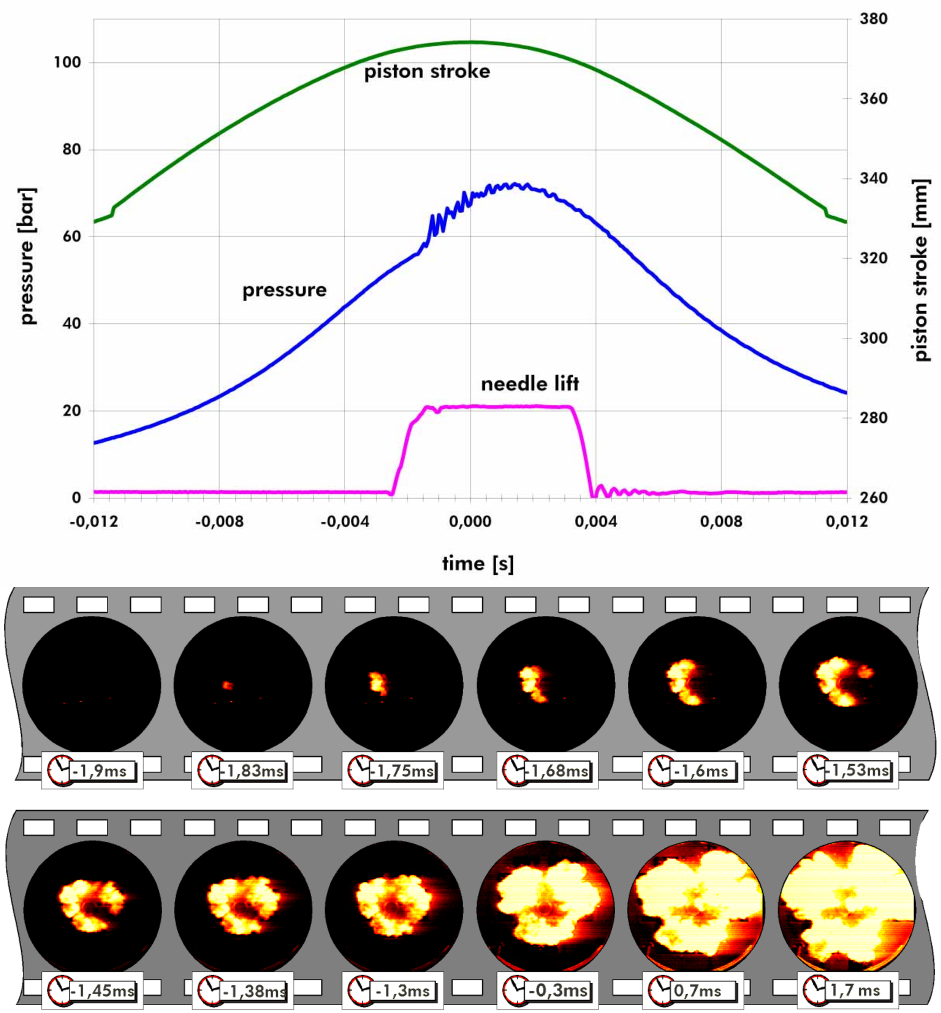

FIGURE 4: TYPICAL IGNITION PROCESS OF A COMBINED NOZZLE WITH 6 X 0.6 AND 12 X 0.4 MM; FAST FLAME PROPAGATION, FAST COMBUSTION AND GOOD SPATIAL USE OF THE ENTIRE COMBUSTION CHAMBER

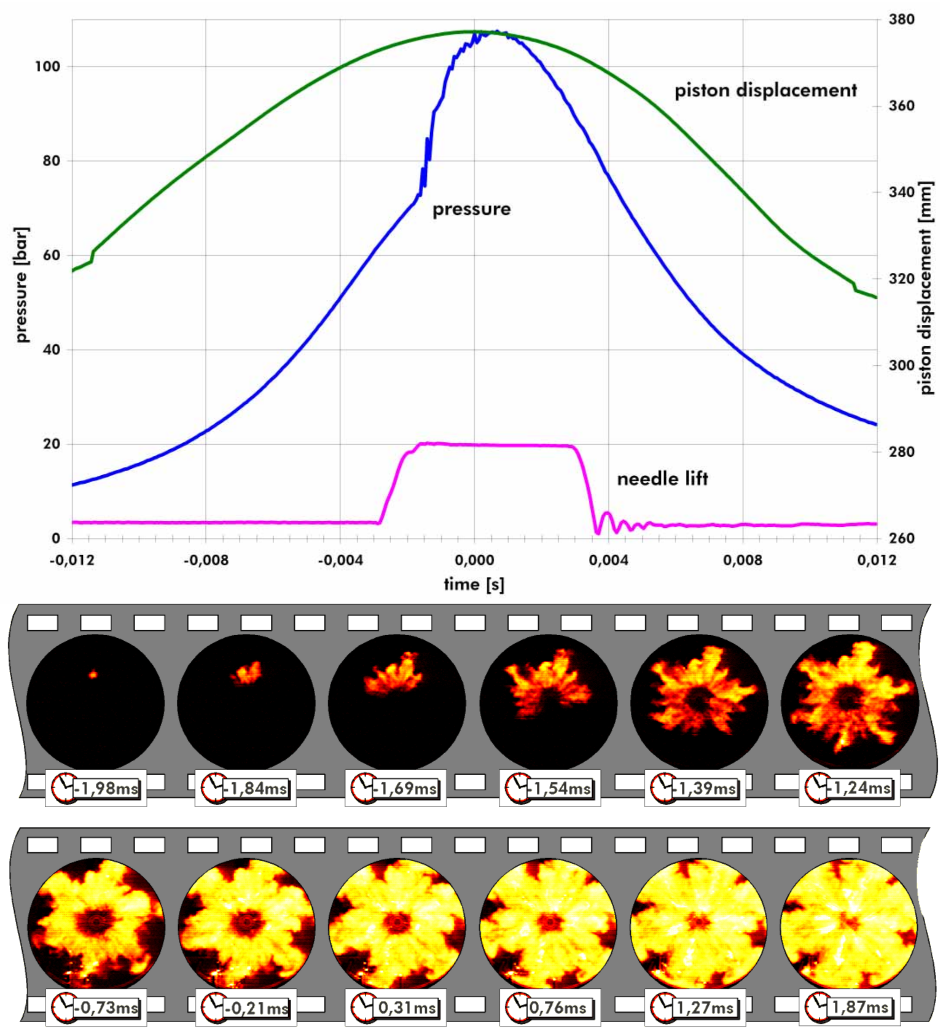

FIGURE 5: SPARK IGNITION OF A LATE INJECTED HYDROGEN JET