INVESTIGATION OF MIXTURE FORMATION AND COMBUSTION PROCESSES IN A HYDROGEN FUELED DIESEL ENGINE

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1. Introduction

In cooperation of two chairs of the Technical University of Munich and MAN B&W AG as the industrial client a direct-injecting hydrogen Diesel engine with high efficiency and low emissions is being developed. The investigation is founded from the Bavarian Research Foundation and concerns the conversion from diesel fuel to hydrogen of a four stroke C.I. engine with stationary 900 rpm. The piston displacement is approx. 14 l per cylinder. The problem of this research to be confronted with is to develop a hydrogen engine with direct injection and compression ignition, which has not been realized yet. The chair A for Thermodynamics investigates and optimizes the mixing and combustion processes with laser optical measurements in stationary and non stationary setups. The engine behavior investigations are done on a single cylinder test engine at the chair for combustion engines of the Technical University Munich.

2. Experimental Setups

The mixture formation, the ignition and burning processes are investigated in two different experimental setups. The aim of the first experimental setup is to get information about the highly transient concentration distribution of hydrogen during the injection process. The experimental techniques used are an application of Laser-Induced Fluorescence (LIF) on tracer molecules and the Schlieren/Schatten method. The first setup is a combustion chamber (VVK) with equivalent dimensions to the planned ship C.I. engine, that is diameter of 240 mm and a volume which represents the volume in the cylinder at top dead center (Figure 1.). This chamber has a maximum of five windows, one at the bottom and four around the diameter, to give an optimal optical access for laser measurements. The pressurized hydrogen is injected into the cold compressed air through a hydraulic controlled needle valve. The experiments done with this setup leads to an optimization of the injection system, that is the number and position of the injection holes and also the injection direction.

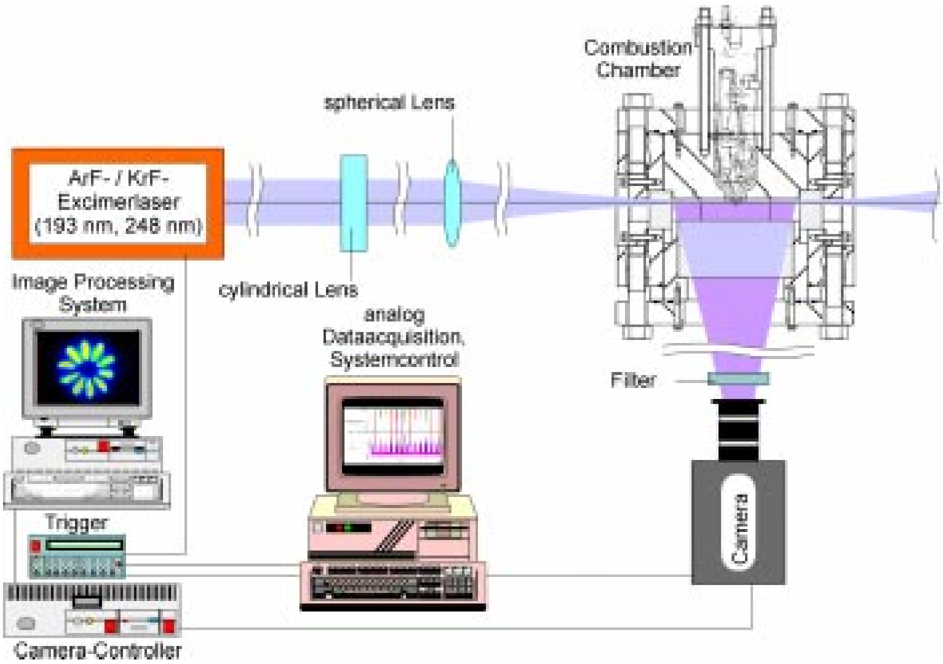

Figure 1.: Experimental setup for LIF measurements in the combustion chamber

The second setup is a single stroke rapid compression machine (EET) (Figure 2.) which simulates the compression stroke of the planned ship C.I. engine. It has an optical accessible combustion chamber and an moving piston with a quartz window. The machine has balanced masses, and allows the observation of the compression stroke with realistic piston velocities with sensitive optical measurement techniques. It has a cylinder capacity of 14 l, a compression end pressure up to 150 bar and a maximum combustion pressure up to 200 bar. The design of this setup allows a fast variation of experimental parameters, which means any compression ratios up to 25 can be adjusted. Swirl and turbulence in the combustion chamber can be induced through tangential inlets. Simple variation of experimental parameters like boost pressure, compression ratio, injection time, injection duration and nozzle geometry allow fast and effective examination of various boundary conditions.

The apparatus shown in figure 2 consists of two concentric pistons (piston 1 and 2) which are coupled through slots via hydraulic oil. The compression piston with the glass window is fixed to the piston 2. In the starting position the inner piston (piston 2) closes the connecting slots, which means both pistons are independent of each other. After opening a bypass valve the outer piston (piston 1), which is driven by compressed air, pushes the compression piston slowly into the combustion chamber. At the same time opens the inner piston the slots connecting both pistons, which leads to an acceleration of both pistons. Meanwhile compresses the compression piston with an speed up to 10 m/s the near the top dead center hydrogen is injected with 300 bar into this hot environment which leads to auto-ignition. The combustion will be observed by conventional measurement techniques and also with self fluorescence imaging with a high speed video camera, LIF and the Schlieren/Schatten method.

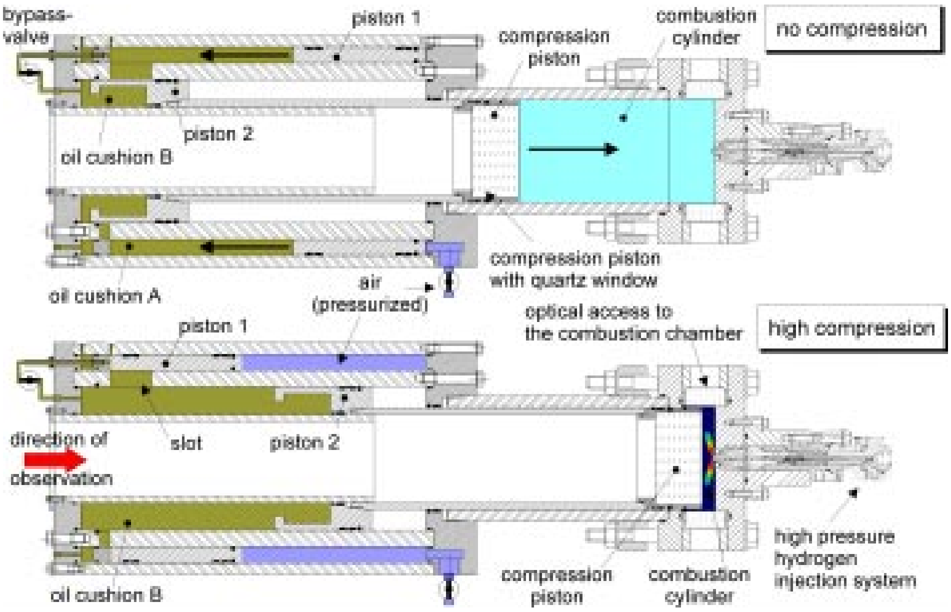

Figure 2.: Single stroke hydrogen rapid compression machine working according to Diesel's process

3. Experimental Data

The characteristics of using hydrogen instead of diesel oil or heavy oil as a fuel for large diesel engines have to be taken into consideration for adapting a combustion concept. The difference of hydrogen compared with conventional hydrocarbons lays in its wide limits of inflammability from 4 to 75 percent of volume hydrogen in air. The burning velocity of hydrogen can rise under adequate conditions to some hundred meter per second. These characteristics can be used to burn lean mixtures with low NO_x emissions nevertheless gaining a high efficiency. These properties can however lead to unwanted hard combustion or even to detonation. The fundamental knowledge of the influence of temperature, pressure, turbulence, gas composition and flow conditions is important to develop a gentle, effective and reliable combustion process.

3.1. MIXTURE FORMATION

Measurements to visualize the mixture formation of hydrogen in the combustion chamber are done in the first setup with laser induced fluorescence (LIF) on tracer molecules. These tracer molecules are unsaturated carbon bindings, which have a good cross section for excitation. This laser optical measurement technique is one of the modern contactless investigation method for gas flows. A pulsed KrF Excimer laser emits a laser beam with a wavelength of 248 nm. This laser beam is focused with a lens setup to a small lightsheet, which travels radial through the combustion chamber. The molecules in the lightsheet layer will be excited and emit light in all directions. A intensified CCD-camera records the emitted light through the window in the bottom of the combustion chamber. This measurement technique is very capable to visualize an unburned gas mixing process and gives a quantitative image of the mixing and the concentration distribution in a combustion chamber (Figure 3.).

The experiments in the first setup leads to an optimization of the injection system, i.e. the number and position of the injection holes and the injection direction as well. Figure 3. shows the LIF images of an high pressure hydrogen injection (300 bar) into cold pressurized air (100 bar) through a hydraulic controlled needle valve with a ten hole nozzle.

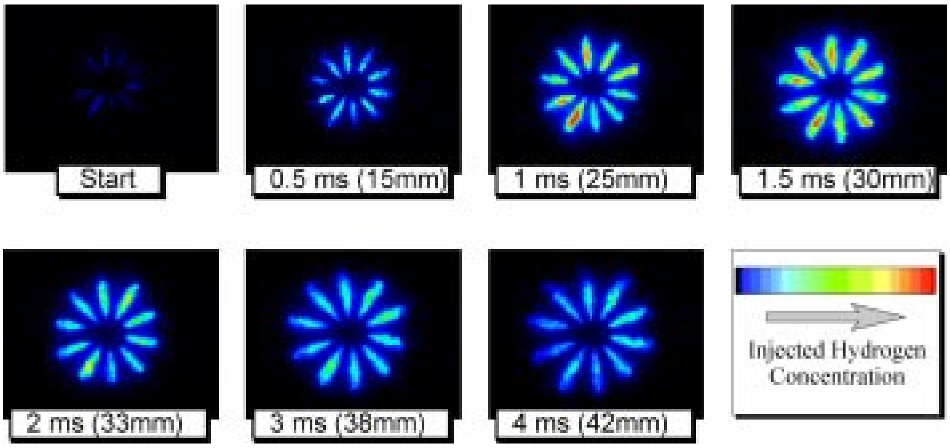

Figure 3.: Hydrogen distribution during injection visualized through LIF

3.2. COMBUSTION MEASUREMENTS

The experiments in the first setup also lead to information about the timing of the injection and the fuel mixture formation. These results were used in the experiments done in the second setup, the single stroke rapid compression machine. The effects of the mixture formation on the self ignition behavior and the combustion progress were investigated with laser optical measurements and high speed self fluorescence imaging. The injection is trigged on the piston stroke, so various points of injection around T.D.C. can be achieved. The injection system is a electronically triggered hydraulic controlled needle valve, injecting 300 bar hydrogen into the combustion chamber. It can easily be equipped with various types of nozzles, i.e. with different types and numbers of nozzles.

Figure 4. shows a characteristic combustion process with late internal mixture formation near the T.D.C. and compression ignition. The images taken with a frame rate of 13500 Hz show, that the ignition starts right after the beginning of the injection. The flame burns deflagrative along the injection jets during the hole injection duration. The

ignition delay time is short and the combustion chamber pressure rises moderately to a tolerably maximum.

Injecting hydrogen before the top dead center forms a good mixture but the combustion is detonative with maximum pressures in the combustion chamber up to several hundred bars.

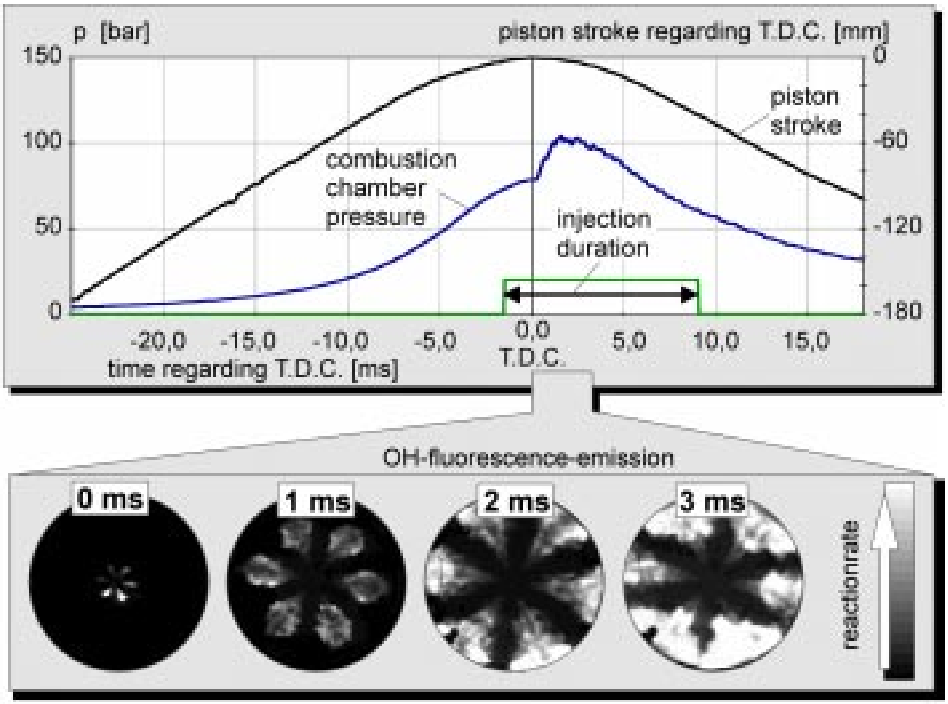

Figure 4.: Hydrogen injection near T.D.C., deflagrative combustion visualized with self fluorescence

3.3. NUMERICAL SIMULATIONS

Three dimensional numerical flow simulations with the code TASCflow from ASC are done complementary to the experimental investigations. These simulation allow a variation of different or additional parameters, which could not been easily adapted in the experiments. One of these parameters is the shape of the piston. In the experimental setups, only flat pistons are in use to allow optical access in direction of the stroke. Figure 5. shows a grid of a piece of the combustion chamber with an omega trough piston and a part of the injection nozzle with one hole. This grid has approx. 150 000 volume elements. A powerful HP workstation needs CPU time of approx. 500 hours to calculate 10 ms of simulation time of this very fine mesh. Also simulations with different kinds of swirl, different nozzle layouts and a variation of the boundary conditions have been calculated to gain information of the mixture formation and the temperature distribution. The analysis of the ignition delay has been implemented in the flow simulation with a zero dimensional simulation of the reaction kinetics, this is a code developed from J. Warnatz. This program calculates the ignition delay dependent on the temperature and concentration of hydrogen in air at a given pressure. This method allows the definition of areas of the injection jet where self ignition conditions are present. These simulation gain information to develop an optimized injection system at given compression ratios of engines which will be converted from diesel fuel to hydrogen.

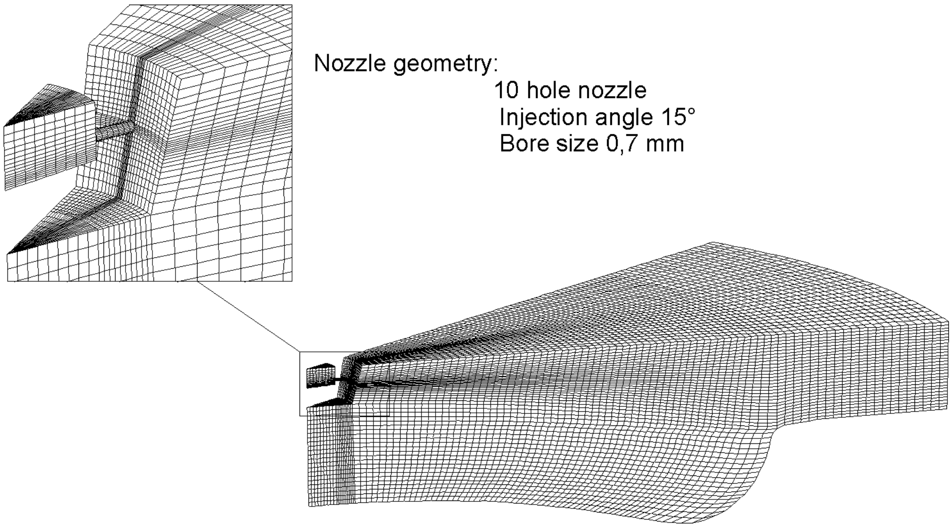

Figure 5.: Discrete geometry of the combustion chamber with utilization the rotational geometry

4. Conclusions

The developed experimental setups and the numerical simulations allow a detailed analysis of the mixture formation and of the combustion processes in a combustion ignition engine. With the experimental setups comparisons of different combustion concepts can be carried out. The results give immediate references for the improvement of nozzle layouts and combustion parameters. The experiments also show that the compression ignition with direct injection of hydrogen can be reached. The ignition delay depends on the compression ratio. With higher compression ratio a proof ignition can be realized. An injection of hydrogen near T.D.C. should be reached to avoid a good hydrogen-air mixture before the temperature for self ignition has arrived. If this can not be achieved, a hard combustion or detonation will be the result.

5. References

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