# HIGH PRESSURE HYDROGEN INJECTION SYSTEM FOR A LARGE BORE 4 STROKE DIESEL ENGINE: INVESTIGATION OF THE MIXTURE FORMATION WITH LASER-OPTICAL MEASUREMENT TECHNIQUES AND NUMERICAL SIMULATIONS

Dipl.-Ing. F. Dorer; Dipl.-phys. P. Prechtl; Dr.-Ing. Dr.-Ing. E.h. F. 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

Legislative restrictions and aspects of future markets enforce worldwide research in the fields of application-oriented hydrogen technology. The knowledge of the $CO_2$-emission and the pollutant burden of current energy systems require the development of new concepts. The use of hydrogen as a fuel in Diesel engines incorporates high efficiency [1] and low pollutant emissions. This combination represents a further step of development on our way to a hydrogen economy. MAN B&W Diesel AG is known to be one of the leading manufacturer of large bore Diesel engines. These engines were worldwide used as propulsion systems on ships and in combined heating and power stations. In these fields the question also arises, in which way the new hydrogen technology can be used in the future.

In a cooperation of two departments of the Technische Universität München and MAN B&W DIESEL AG, as the industrial partner, a directly injecting hydrogen Diesel engine with a high efficiency and low emissions is being developed. The investigation is founded by the Bavarian Research Foundation and deals with the conversion from diesel fuel to hydrogen of a four stroke C.I. engine with stationary 900 rpm. The piston displacement is approximately 14 l per cylinder. The objective of this research is the development of a hydrogen engine with a direct injection and a compression ignition which has not been realized yet in such dimensions. The Lehrstuhl A für Thermodynamik (department for thermodynamics) investigates and optimizes the mixing and combustion processes in stationary and non-stationary setups by means of optical measurement techniques. The engine behavior investigations are performed on a single cylinder test engine at the Lehrstuhl für Verbrennungsmotoren und Kraftfahrzeuge (department of combustion engines) of the Technische Universität München.

## 2. EXPERIMENTAL INVESTIGATIONS

Contrary to diesel-fueled C.I. engines the fuel of a hydrogen powered engine is injected in a gaseous way. The feature of hydrogen compared to that of diesel oil or heavy oil as a fuel for large diesel engines has to be considered in order to adapt a combustion concept. The difference between hydrogen and conventional hydrocarbons consists in its wide limits of inflammability from 4 to 75 percent by volume hydrogen in air. The burning velocity of hydrogen can rise, under adequate conditions, up to some hundred meters per second. These characteristics can be used to burn lean mixtures with low $NO_X$ emissions while gaining a high efficiency. These properties, however, can lead to unwanted hard combustion or even to detonation. The fundamental knowledge of the influence of the temperature, the pressure, the turbulence, the gas composition and the flow conditions is indispensable for the development of a gentle, effective and reliable combustion process. The knowledge of the mixture formation of the internal mixing process, which is discussed in this paper, is of major importance for the design of a new burning concept.

## Experimental Setup

The mixture formation, the ignition and the burning processes are investigated in two different experimental setups. The aim of the first experimental setup is to obtain information about the highly transient concentration distribution of hydrogen during the injection process. The Laser-Induced Fluorescence (LIF) on tracer molecules has been used as the main measurement technique. The first setup is a constant volume combustion chamber (VVK) with the equivalent dimensions as the planned large bore C.I. engine, which implies that the volume in the VVK equals the volume in the cylinder at the top dead center (Figure 1). This chamber has a maximum of five windows, one at the bottom and four around the diameter, which gives an optimal optical access for the laser measurements. The pressurized hydrogen is injected into the cold pressurized air through a hydraulic controlled needle valve. The experiments conducted with this setup lead to an optimization of the injection system which is mainly the number and the position of the bore holes and also the injection direction. The second experimental setup is a rapid compression machine which simulates the compression stroke of the large bore 4 stroke diesel engine. This setup is used to investigate the ignition and the burning processes, which will be discussed in the other paper [8].

In the first setup measurements are performed by means of the laser induced fluorescence (LIF) technique in order to visualize the mixture formation of hydrogen in the combustion chamber of a large scale diesel engine. This optical measurement technique is one of the modern non-intrusive investigation methods for gas flows. Tunable laser light is used for selective excitation of an electronic transition in a molecule or in an atom. The electronic structure of molecules changes at this transition. The energy difference between the molecules in the excited state and the molecules in the ground state are quite remarkable. Once excited, the molecule changes back to the less energetic states where different vibration energy levels can be reached. This phenomenon is called fluorescence [2]. The amount of energy which is required to excite hydrogen molecules can not easily be provided by the modern laboratory equipment. By using tracer molecules, which are mixed into hydrogen in extremely low amounts, information about the local hydrogen distribution can be obtained. These tracer molecules are unsaturated carbon bindings which have a good cross-section for excitation. A pulsed KrF Excimer laser emits a rectangular laser beam with a wavelength of 248 nm. This laser beam is focused by means of a lens setup into a small lightsheet which travels in the radial direction through the combustion chamber. The molecules in the lightsheet layer are excited and then emit light in all directions in a very short period of time ($10^{-8}$ ms). An intensified CCD-camera records the emitted light through the window in the bottom of the combustion chamber. This measurement technique is very capable of visualizing unburned gas mixing processes and therefore gives a quantitative image of the mixing and the concentration distribution with a high spatial and temporal resolution in a combustion chamber (Figure 2).

## Results and discussion

When describing the injection method, it can be said, that in a direct injecting engine the fuel is injected near the top dead center (TDC). For the determination of the amount of the injected fuel out of the injection duration, the pressure ratio of the injected gaseous fuel pressure to the compression end pressure has to be higher than the critical pressure ratio. This means that the velocity of the injected fuel is the speed of sound in each bore hole of the nozzle [3]. When looking at the investigated engine, it is evident that a fuel pressure of 30 MPa hydrogen is required.

The experiments in the first setup lead to an optimization of the injection system, such as the number and the position of the injection holes as well as the injection direction. Figure 2 shows the LIF images of an high-pressure hydrogen injection (30 MPa) into cold pressurized air (10 MPa) through a hydraulic-controlled needle valve with a ten hole nozzle. The penetration depth can be obtained from the hydrogen concentration which is shown in figures 2. In order to determine the penetration depth of a single injection jet, the injection valve with a single hole nozzle has been located on the cylinder wall. Therefore the whole diameter of the combustion chamber can be used. In order to simulate the same molecule density as that found in engine conditions, 30 MPa hydrogen is injected in cold (300 K) pressurized air of 3 MPa. Figure 3 gives the results of this measurement. Figure 4 shows a comparison of the penetration depth at given moments after the onset of the injection at nozzles with different numbers of bore holes, while the critical cross-section area remains the same.

The experiments describing the hydrogen distribution (Figure 2, 3 and 4) show, that immediately after the onset of the injection the propagation velocity is so high, that after 1.0 ms the injection jet will have crossed almost half of the cylinder diameter. When using nozzles with a high number of bore holes, the momentum of each jet decreases while the critical cross-section area remains the same. This means that the propagation velocity reduces faster whereas in the vicinity of the nozzle the impact of the bore hole diameter is slight. The objective of our experiments is the formation of a diffusive flame along the injection jets. This objective results from the tendency of hydrogen to detonate under premixed conditions. In order to avoid a more or less premixed combustion it is necessary to situate conditions for an ignition and a steady flame in the vicinity of the nozzle. Therefore it is essential to reduce the propagation velocity immediately after the onset of injection. In modern Diesel-fueled C.I. engines with Common-Rail injection systems the steepness of the opening slope of the needle valve is adjustable. This concept can also be used in hydrogen-fueled C.I. engines. At the Lehrstuhl A für Thermodynamik a new injection valve for hydrogen has been developed. The rising and closing time of the needle valve can be adjusted. Therefore the propagation velocity can be reduced by using a slower opening slope of the needle valve. First examinations of the influence of the adjustable steepness of the needle opening on the mixture formation will be carried out in the second quarter of 1998.

## 3. NUMERICAL SIMULATION

Three-dimensional numerical flow simulations with the code TASCflow from ASC are performed complementary to the experimental investigations. These simulations allow a variation of different or additional parameters which could not easily be adapted in the experiments. One of these parameters is the shape of the piston. In order to reduce the CPU time only one injection jet is calculated with utilization by means of the rotational geometry. In the experimental setups only flat pistons allow the 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 approximately 150 000 volume elements. A powerful HP workstation needs CPU time of approximately 500 hours to calculate 10 ms of simulation time of this very fine mesh. Also simulations with different kinds of swirls, different nozzle layouts and a variation of the boundary conditions have been calculated in order to gain information about the mixture formation and the temperature distribution (figure 6 and figure 7). The analysis of the ignition delay has been implemented in the flow simulation with a zero-dimensional code of the reaction kinetics, which is a code developed by Warnatz and Maas [4] [5] (figure 7 and figure 8). This program calculates the ignition delay which depends on the temperature and the 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 existent. These simulations give information about how to develop an optimized injection system at given compression ratios of engines which are converted from diesel fuel to hydrogen.

### Results and discussion

Figure 5 shows the numerical simulation of an injection of 30 MPa hydrogen into hot (1050 k) pressurized air of 10 MPa. In the upper part an injection without a swirl is shown, whereas in the lower part an injection with a swirl is observed. In both cases the injected hydrogen spreads to half of the combustion chamber diameter within the first two milliseconds. Regardless of the existence of a swirl, the injection jets are very similar in the first 2 ms. This behavior results from the high propagation velocity in the first milliseconds. Later on the influence of the swirl can be observed in a better mixing.

When calculating the ignition delay with the Maas code using a given air pressure of 10 MPa the results are obtained for different air-fuel rations as it is shown in figure 8. At a temperature of 1000 K and an air-fuel ration of 4 the ignition delay results in 2 ms. When implementing the zero-dimensional reaction-code in the numerical simulation of the hydrogen injection (figure 6)it is observed, that at a given air-fuel ration of 4 and a temperature of 1000 K the minimum ignition delay is at 5.5 ms. A decrease of the ignition delay can be achieved only through a higher air temperature [6] which leads to a higher compression ratio or an higher intake air temperature at a given compression ratio. The minimum ignition delay which can be realized at a temperature of 1050 K is 2.5 ms at an air-fuel ration of 4. When looking at the calculated minimal ignition delay, there is no significant influence of a swirl, a lower injection pressure or a different number of bore holes. The reason for this fact is that the ignition delay is determined from the local temperature and concentration. These calculations show areas of mixed cold hydrogen (350 K) and hot air (1000 – 1050 K) where a minimal ignition delay at a concentration of 10 % hydrogen occurs, independent of the flow conditions. Figure 6 shows the calculated values for the temperature distribution, the velocity field and the resulting ignition delays at an air temperature of 1050 K and an ambient air pressure of 10 Mpa.

A comparison between the calculated hydrogen distribution and the experiments conducted in the constant-volume combustion chamber implementing laser induced fluorescence is shown in figure 8. The deviation of the single experimental data points from the calculated values is due to the fact, that all laser induced fluorescence experiments are single-shot experiments. This means that only one picture can be taken during the injection duration, because of the maximum repetition rate of the excimer laser. Considering the fact that hydrogen is injected in cold and lower pressurized air in order to simulate the same molecule density, the experimental data are in good agreement with the numerical simulation.

## 4. CONCLUSIONS

The investigations of the mixture formation for a hydrogen fueled large bore 4 stroke compression ignition engine allow a detailed analysis. The experimental investigations and the numerical simulations show, that the compression ignition with direct injection of hydrogen can be realized. The results give immediate references for the improvement of nozzle layouts and other motor parameter such as the compression ratio. The ignition delay depends on the compression ratio or the intake air temperature. With a higher compression ratio a save and fast ignition can be realized. The increase of the numbers of nozzle bore holes, entails a decrease of the momentum of each hydrogen jet. This leads to good conditions for an ignition near the nozzle and reduces the possibility of a premixed, detonative combustion. However, a compression ignition hydrogen engine can be realized with minor changes to the engine and major changes to the injection system.

## REFERENCES

[1] Krepec T., Giannacopoulos T., Miele D. Int. J. Hydrogen Energy, Vol. 12, No. 12, 855-861, 1987

[2] Eckbreth A.C. Laser Diagnostics for Combustion Temperature and Species, Abacus Press, 1988

[3] Stephan K., Mayinger F. Thermodynamik, 12. edition, Springer, Berlin, 1986

[4] Warnatz J., Maas U. Technische Verbrennung, Springer-Lehrbuch, 1993

[5] Maas U., Warnatz J. Ignition Processes in Hydrogen-Oxygen Mixtures, Combustion and Flame 74, 53-69, 1988

[6] Siebers D., Naber J. Hydrogen Combustion under Diesel Engine Conditions, XI World Hydrogen Conference, 1503-1512, 1996

[7] Dorer F., Prechtl P., Mayinger F. Investigation of Mixture Formation and Combustion Processes in a Hydrogen Fueled Diesel Engine, Hypothesis II, August 1997

[8] Prechtl P., Dorer F., Mayinger F. Hydrogen C.I. Large Bore 4-Stroke Engine: Ignition and Combustion Processes Analyzed with High Speed Optical Measurement Systems, XII World Hydrogen Conference, Argentina, 1998

**FIGURE 1. • EXPERIMENTAL SETUP FOR LIF MEASUREMENTS IN THE COMBUSTION CHAMBER**

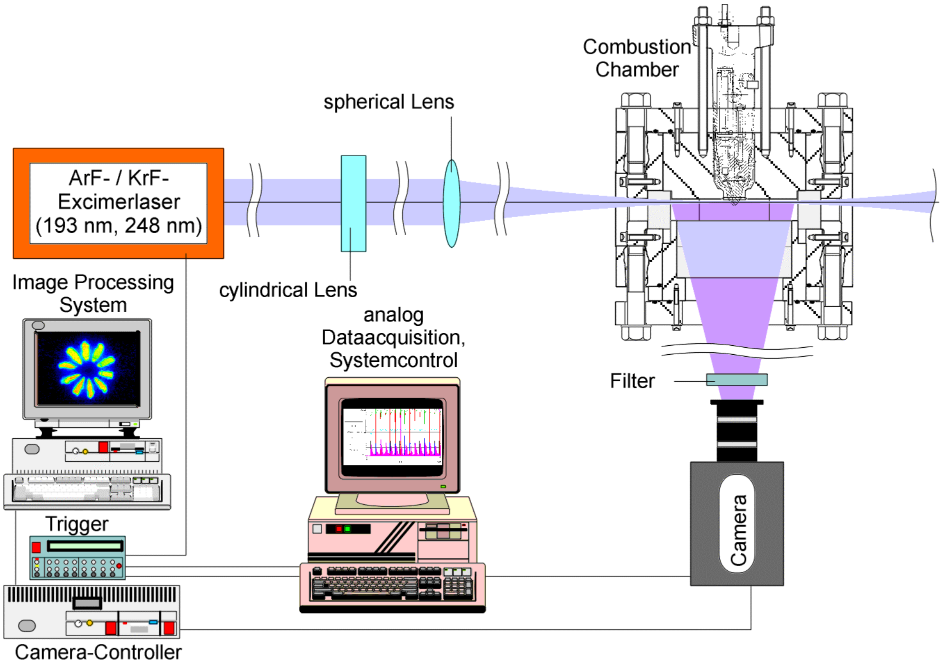

FIGURE 2. • HYDROGEN DISTRIBUTION DURING INJECTION VISUALIZED THROUGH LIF

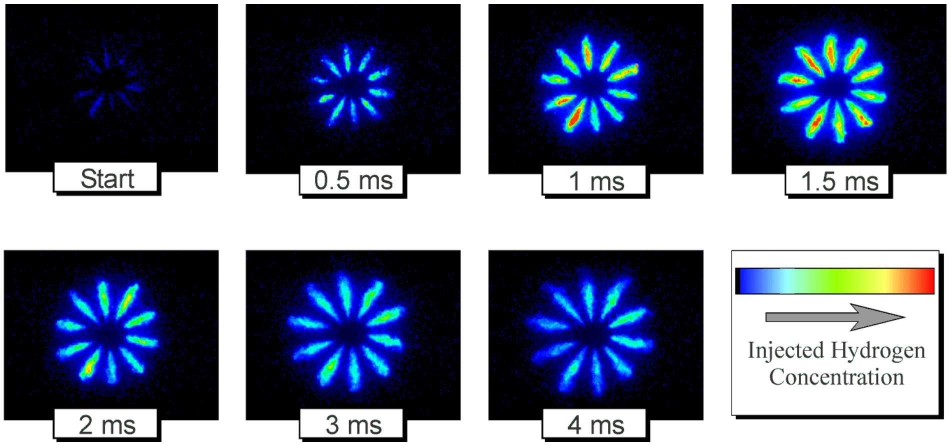

FIGURE 3. • DETERMINATION OF THE PENETRATION DEPTH OF A SINGLE INJECTION JET

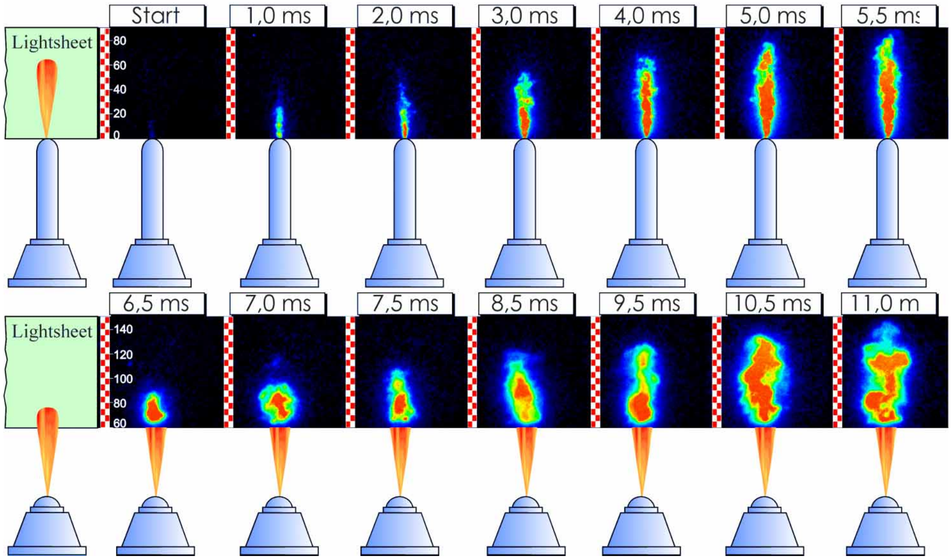

FIGURE 4. • COMPARISON BETWEEN DIFFERENT NUMBERS OF BORE HOLES AT A GIVEN CRITICAL CROSS-SECTION AREA

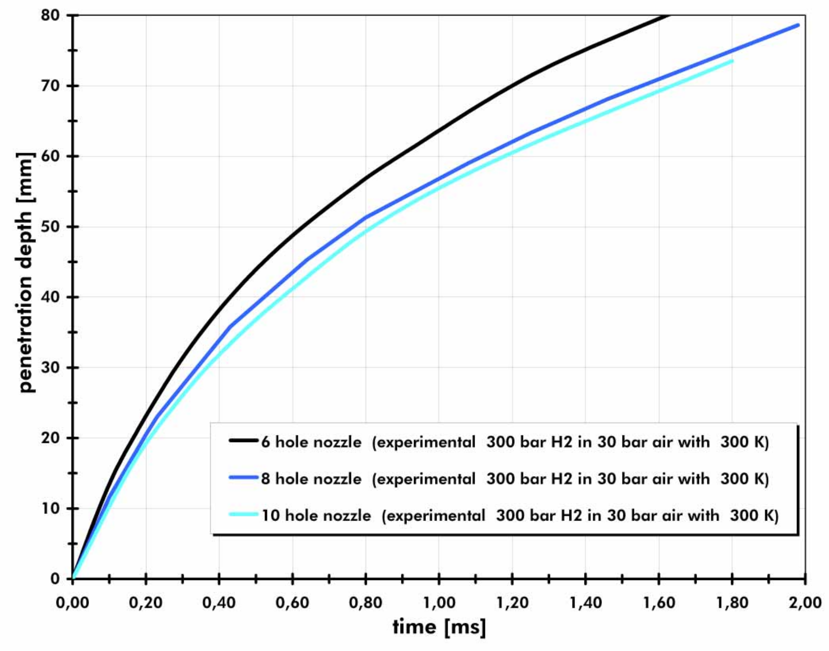

FIGURE 5. • DISCRETE GEOMETRY OF THE COMBUSTION CHAMBER USING THE ROTATIONAL GEOMETRY

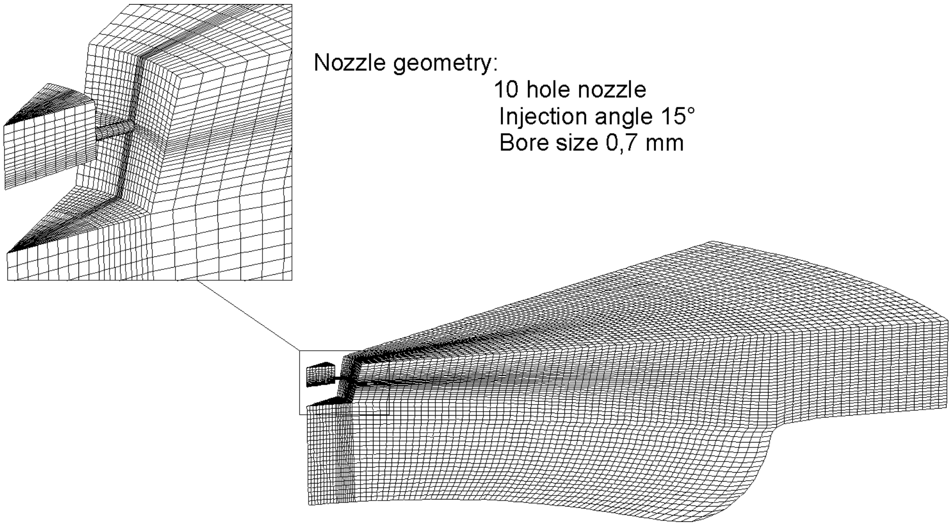

FIGURE 6. • RESULTS OF THE NUMERICAL SIMULATION WITH A FLAT PISTON; TOP WITHOUT A SWIRL AND BOTTOM WITH A SWIRL

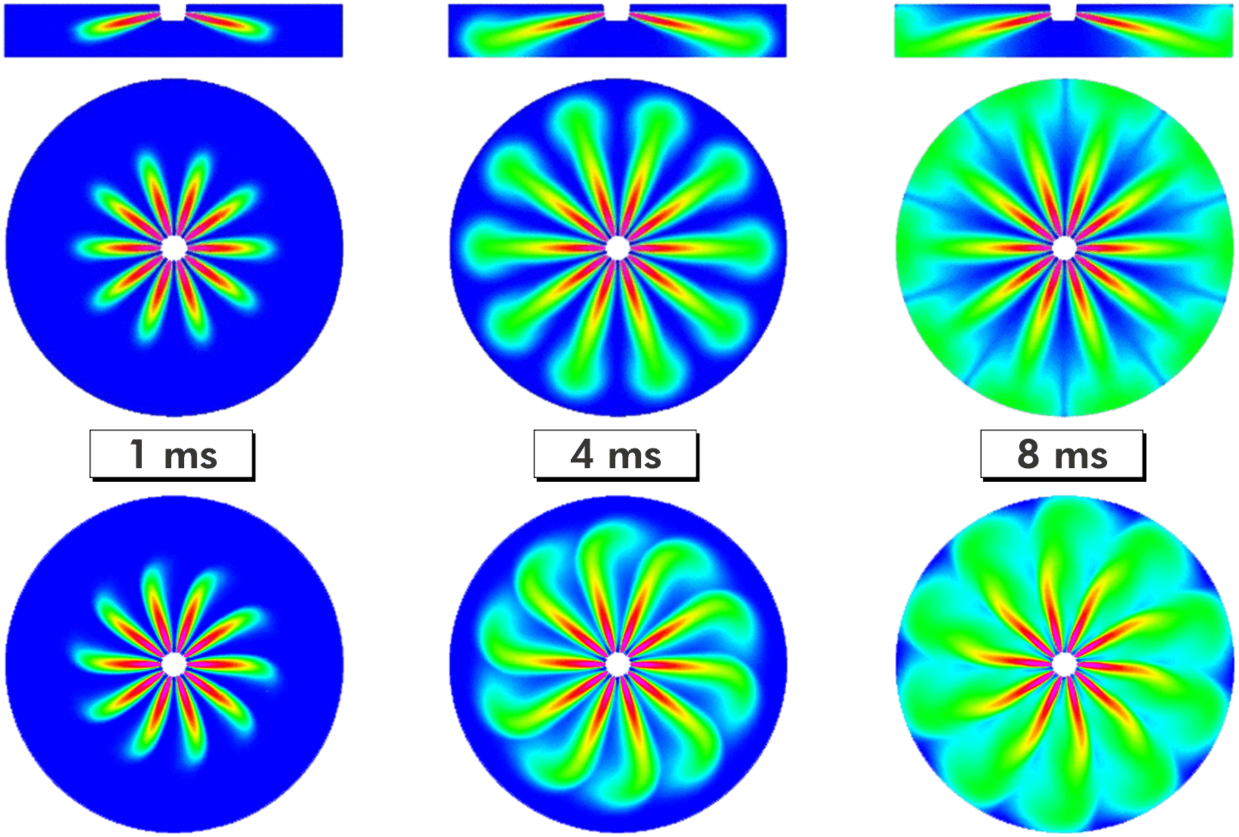

FIGURE 7. • CALCULATION OF THE IGNITION DELAY WITH TASCFLOW 3D AND 0-D REACTION-KINETIC CODE

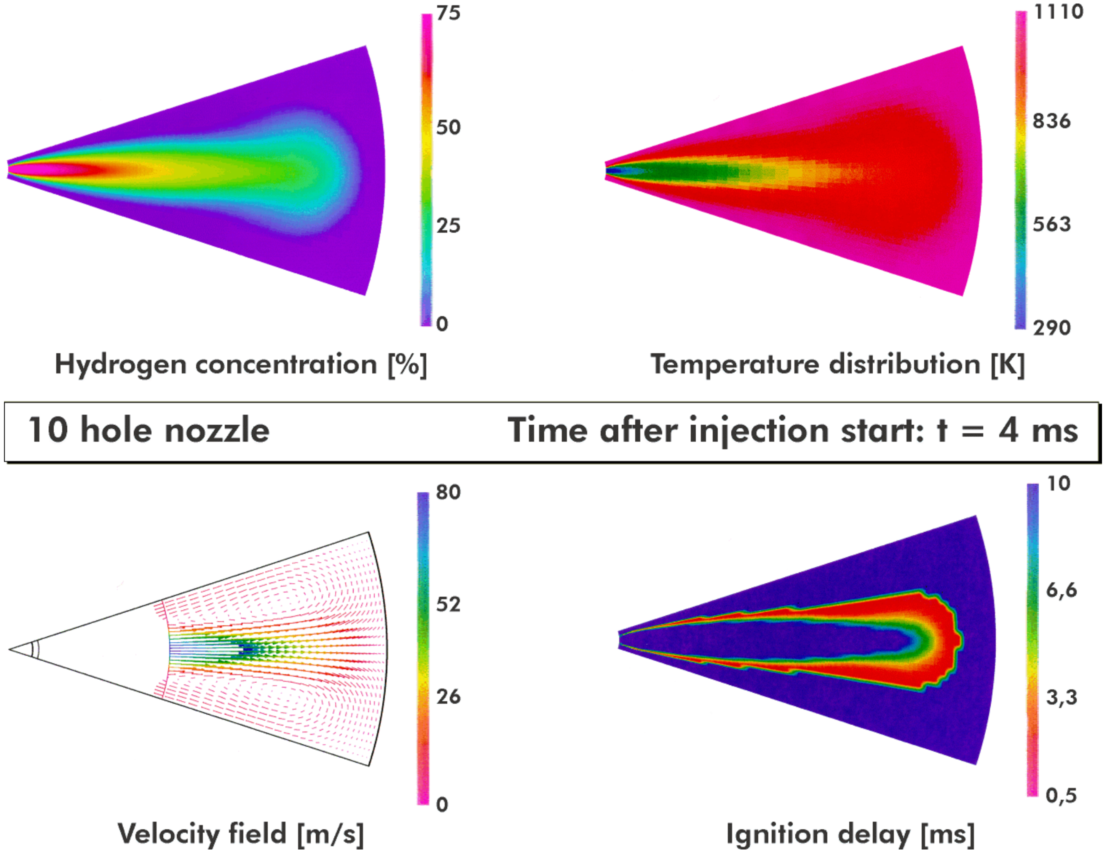

FIGURE 8. • CALCULATED IGNITION DELAY VERSUS AIR TEMPERATURE BY VARIATION OF THE AIR-FUEL RATION (LAMBDA)

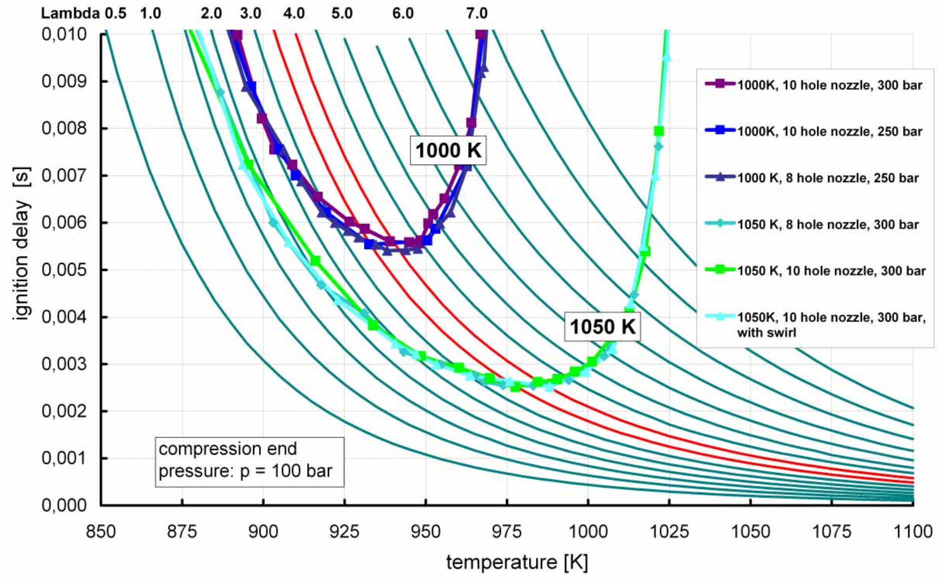

FIGURE 9. • COMPARISON OF THE HYDROGEN PENETRATION BETWEEN THE NUMERICAL SIMULATION AND THE EXPERIMENTS