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Laser-Diagnostic Measurements and Modeling of Combustion in HCCI Engines

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In the last years, a new engine operation mode namely HCCI (Homogeneous Charge Compression Ignition) has been discussed frequently. This concept is based on a compression-induced autoignition process of a homogeneous air/fuel mixture. The main difference to conventional Spark Ignited (SI) engines is the absence of a conventional turbulent flame propagation. HCCI engines can run at high compression ratios and with very lean charges, enabling throttle-free engine operation with almost no NO_x (due to low gas temperatures) and no particle emissions (caused by the homogeneous mixture composition). Additional, due to the rapid combustion the HCCI process is similar to the ideal constant-volume combustion model and works therefore with an higher efficiency, i.e. lesser fuel consumption than SI engines.

The main problem with this concept is the correct timing and the control of auto-ignition in the engine cycle. The onset of auto-ignition during the compression stroke is controlled by the gas temperature and low-temperature kinetics in the endgas. Thus, for a better understanding and controlling of the HCCI operation mode, it is necessary to investigate in detail the chemical kinetic processes in the endgas.

In our work, we have combined optical investigations in four- and two-stroke HCCI engines with the results of numerical calculations to achieve a more detailed picture of the auto-ignition process and the mechanism of combustion.

Simultaneous measurements of two-dimensional laser–induced fluorescence (LIF) using acetone as a fuel-tracer and one-dimensional qualitative H_2CO-LIF [1] were carried out in an optical two-stroke engine shortly before autoignition occurs. Acetone was added in low concentrations to the fuel (iso-octane) and its LIF-signals represent the mixture distribution respective mixture homogeneity prior to ignition. In the subsequent combustion process the tracer was consumed completely. The one-dimensional LIF-traces of native formaldehyde (H_2CO) obtained in the endgas was used to visualize gas temperature fluctuations with high resolution in space. H_2CO is an important intermediate species and is produced in low-temperature regimes and consumed in the ignition step. Due to the fact that H_2CO is extremely sensitive to temperature, it can be used as a good marker for local temperature inhomogenities close before auto-ignition [1]. Using the fluctuations of the local H_2CO-LIF-signals and a calculated correlation of temperature and H_2CO-concentration, we are able to estimate the gas temperature fluctuations within the combustion chamber.

In order to validate the H_2CO-LIF approach for determining gas temperature fluctuations, we have performed additional measurements with shortly delayed acetone-LIF imaging. The aim is to visualize the onset of auto-ignition at locations with maximum gas temperature as indicated by the H_2CO-LIF signals. These "hot spots" are indicated by small "holes" in the uniform mixture distribution corresponding to acetone consumption during chemical reaction.

Numerical simulations using detailed chemical kinetics have been performed to exploit and complement the experimental results (Figure 1). The HCCI combustion process was simulated using a stochastic reactor model (ensemble of homogeneous reactors) (Maiwald et. al [2]). A temperature distribution within the air-fuel-mixture taken from typical experimental measurements was taken into account using a Presumed-Probability-Density-Function (PPDF). This method does not account for transport processes like diffusion or heat conduction, which have been shown to have a minor influence in this combustion regime. This has been confirmed by flamelet simulations with detailed chemical kinetics and detailed transport models.

Furthermore the influence and the role of shock waves on the HCCI combustion process initiated by autoignition centers was investigated. First we used a zero-dimensional model introduced by Lutz et. al [3]. This model combines energy and species equations with gas dynamic constraint for the expansion of an exploding center. The important dynamic effect of such a center is the production of a compression wave in the surrounding mixture. The criterion for the formation of such a shock wave is the excitation time. The excitation time has to be sufficiently short (t_e<10µs) in order to form a shock wave (Maas et. al [4]). For longer excitation times, the generated pressure rise is distributed uniformly in space. In

Addition to the zero-dimensional investigation, the influence of pressure wave on the HCCI combustion process was calculated using a one-dimensional model (Maas (1988) [5]), including detailed chemistry, multicomponent transport, and allowing spatial and temporal pressure fluctuations. This approach is able to take into account gas-dynamic effects.

Experimental findings show that auto-ignition does not occur simultaneously in the whole mixture, but starts at a few localised sites. Also, the presence of small temperature fluctuations is evident, while the mixture composition is spatially very homogeneous. Combined with numerical simulations of the auto-ignition process, these observations can be cast into the following picture: In the unburned end-gas, spatial temperature fluctuations in a quasi homogeneous air/fuel mixture are present. These fluctuations, despite small (some 10K), have a large influence on the local ignition delay time. Regions of slightly higher temperatures ignite significantly earlier than their cooler counterparts. This explains the occurrence of localised auto-igniting centers (Figure 2), an effect well known from investigations of knock phenomena [1].

The measured expansion speed of auto-igniting centers in our HCCI engine agrees well with the expansion speed obtained from one-dimensional calculations; this confirms the proposed mechanism of the HCCI process as a subsequent auto-ignition, governed by the local ignition delay time.

References:

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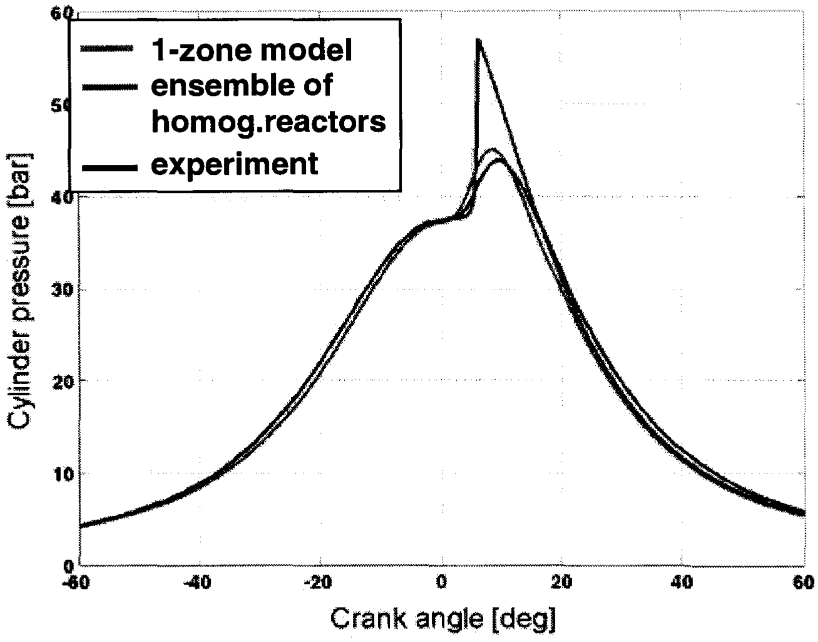

Figure 1: Comparison of measured and simulated pressure traces of a HCCI combustion process.

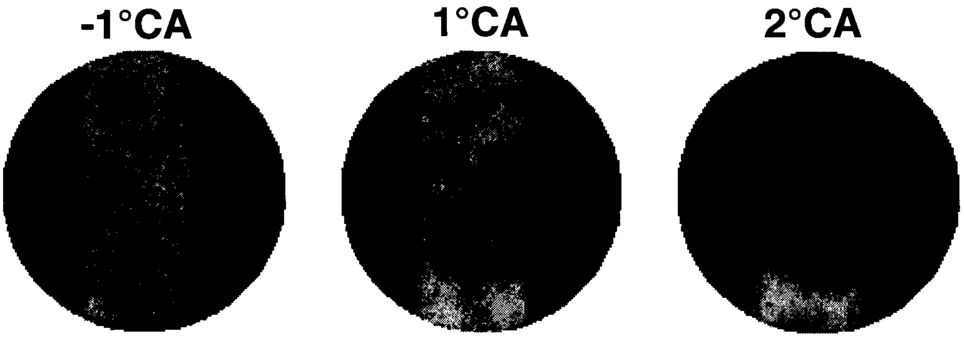

Figure 2: Localised auto-igniting centers in a quasi homogeneous air/fuel mixture visualized in an optical 4 stroke HCCI-engine using laser-induced fluorescence of the fuel-tracer acetone. Time base in units degrees of crank angle (0°CA corresponds to TDC).