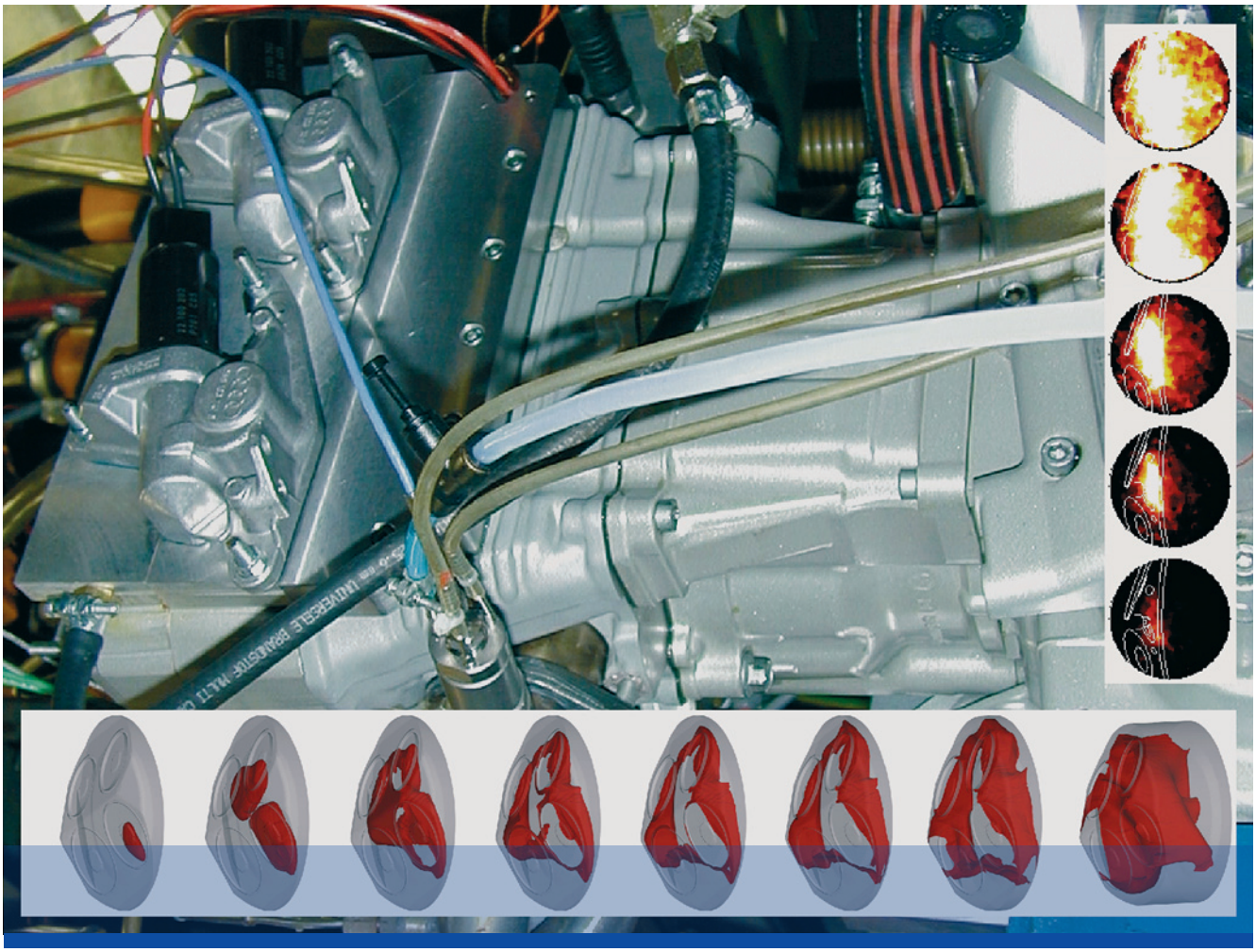

Effects of Mixture Quality on Controlled Auto-Ignition in Petrol Engines

Controlled auto-ignition in petrol engines is a promising concept for the reduction of exhaust emissions and fuel consumption. Experimental and numerical investigations have been carried out at the Institute for Reciprocating Engines (IFKM) and the Institute of Technical Thermodynamics (ITT) to investigate the implementation of this combustion process in passenger car engines.

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1 Introduction

The auto-ignition of petrol is achieved by compressing a hot air/fuel mixture until auto-ignition occurs. The high temperatures required for auto-ignition are obtained by trapping hot residual gas in the combustion chamber. In contrast, combustion in conventional petrol engines is induced by spark ignition, which leads to a propagating flame front and the subsequent combustion of the homogeneous air/fuel mixture. Since the conventional combustion of petrol/air mixtures with low cycle-to-cycle fluctuations leads to high temperatures in the flame front, high nitrogen oxide (NO_x) emissions cannot be avoided. In conventional diesel engines, non-premixed combustion leads to high soot and NO_x emissions. In Homogeneous Charge Compression Ignition (HCCI) combustion, fuel conversion without flame front propagation or non-premixed combustion is feasible. In this mode, it is possible to achieve combustion of very lean mixtures. Therefore, peak temperatures in the combustion chamber are reduced and NO_x formation due to high temperatures can be avoided 0. Thermodynamic and numerical analyses of engine operation in HCCI mode were performed based on experimental investigations with an optically accessible single-cylinder engine. The adaptation of a new three-dimensional visualisation system provided insight into the actual combustion process inside the engine. An efficient combustion chemistry model was developed and coupled with a commercial three-dimensional Computational Fluid Dynamics (CFD) code to describe the spatial progress of the reactions. These numerical simulations were used as an aid to interpret the experimental observations in terms of mixing and reaction progress.

2 Test Engine and Special Experimental Measurement Techniques

The engine used, **Table**, is a modified four-stroke motorcycle engine. Engine modifications include the addition of a vane-type cam phaser and direct fuel injection. Auto-ignition is achieved via symmetrical negative valve overlap 0. The three-dimensional visualisation system 0 consists of three fibre-optic endoscopes and three cameras, **Figure 1**. The camera system employed here is characterised by a high sensitivity for ultraviolet radiation and a high temporal resolution.

3 Chemical Kinetic Model to Describe the Auto-Ignition

The point of time at which auto-ignition occurs depends neither solely on the average temperature nor solely on the glo-

Table: Technical specifications of the test engine

Basic engine	BMW / Rotax F650
Engine Type	Single-cylinder, four-valve pentroof
Compression ratio	11.5
Displacement	652 cm^3
Bore x Stroke	100 mm x 84 mm
Engine Speed	2000 rpm
Mixture formation	Swirl injector (sideways located) Multi-hole-injector (centrally located)
Injection pressure	125 bar
Maximum lift, intake valves	2 mm
Maximum lift, exhaust valves	1.5 mm
Opening duration, intake valves	120 CAD
Opening duration, exhaust valves	110 CAD
Intake valve closing	182 CAD BTDC – 140 CAD BTDC
Exhaust valve closing	272 CAD ATDC – 324 CAD ATDC

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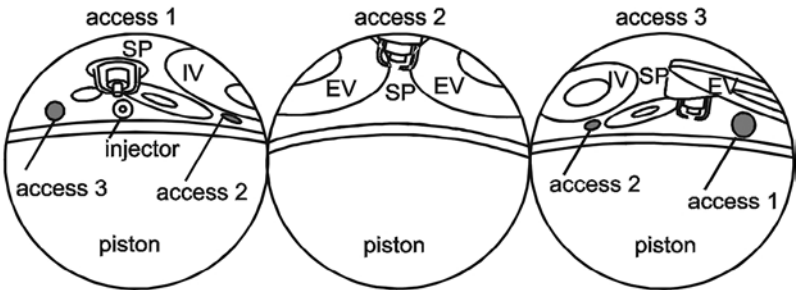

Figure 1: Images of the combustion chamber captured by endoscopes 1-3

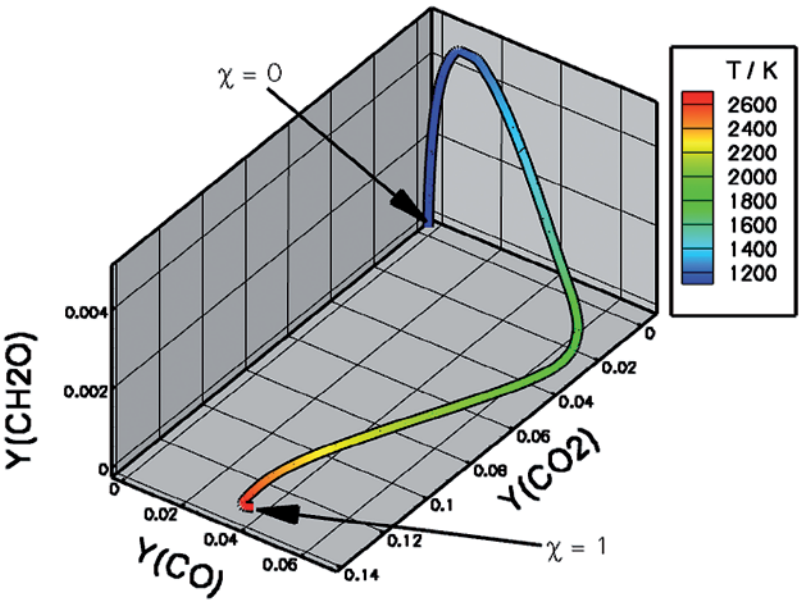

Figure 2: Reaction trajectory in the CO_2, CO and CH_2O mass fraction subspace

bal mixture composition, but is strongly influenced by the local thermodynamic conditions. Hence, zero-dimensional or one-dimensional tools cannot describe the processes and chemical reactions inside the combustion chamber of an HCCI engine with sufficient accuracy. Different approaches exist to realistically incorporate the auto-ignition and combustion processes into three-dimensional simulations. While simple models are computationally inexpensive, their accuracy is quite poor. Chemical source terms can be computed accurately using detailed reaction mechanisms, but this method is computationally prohibitive. An efficiently reduced method for modelling the chemical reactions in a CFD code was developed. The model is based on a detailed reaction mechanism 0. The link between the CFD code and the chemical kinetics model is made by defining a chemical progress variable whose source term is tabulated as a function of the local conditions. This chemical progress variable is defined and the rate of this variable is pre-calculated for a homogenous reactor and then tabulated, depending on the physical and chemical conditions, using detailed chemistry. The values of the progress variable range from zero (fresh mixture of fuel and air before the start of any reactions) and one (chemical equilibrium after combustion). The arc length of the reaction trajectory based on detailed kinetics in the state space was selected as the progress variable χ. **Figure 2** shows an example of such a reaction trajectory. The development of ignition and combustion are shown in the carbon dioxide (CO_2), carbon monoxide (CO) and formaldehyde (CH_2O) mass fraction subspace. At the start of the reaction, the mass fractions are zero for all three species. Shortly before the beginning of ignition, the CH_2O mass fraction reaches its maximum. CO is an intermediate species that is transformed into CO_2 as the process continues. The mass fraction of CO_2 increases during the combustion process. The colour of the reaction trajectory represents the temperature during the combustion process. The implementation of the chemistry model in the CFD code StarCD requires the solution of additional governing equations for the progress variable and for the mass fractions of various species (CO_2, CO, CH_2O, fuel). Given values of the pressure, air/fuel ratio, enthalpy of the gas mixture and chemical progress variable, the chemical rate of the progress variable and the chemical mixture are looked up in pre-calculated tables of the detailed chemistry and passed to the CFD code. A more detailed description of the combustion model can be found in 0.

4 Effect of Injection Timing

It was determined from the experimental investigations that the start of injection (SOI) has a major effect on the oper-

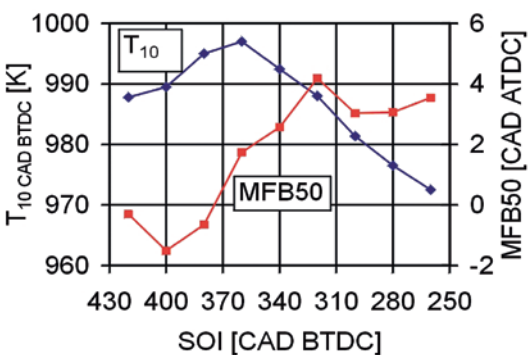

Figure 3: MFB50, calculated temperature 10 CAD BTDC (T10 CAD BTDC) as a function of SOI, IMEP=2 bar, 2000 rpm

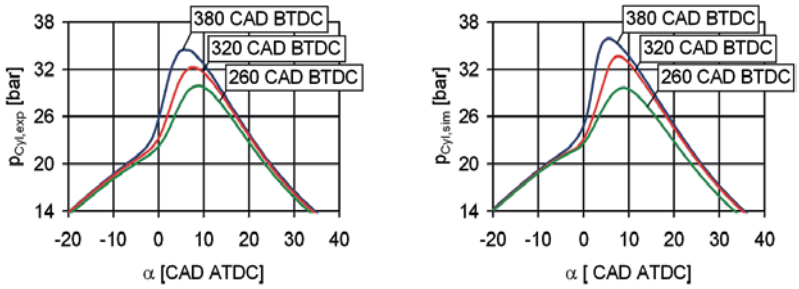

Figure 4: Comparison of the measured (pCyl,exp) and simulated (pCyl,sim) pressure curves

ating behaviour in HCCI mode, **Figure 3**. By varying SOI, the point of 50 % mass fraction burned (MFB50) can be changed. As a result of this investigation, it was discovered that the shifting of MFB50 is primarily related to the temperatures in the combustion chamber at the end of compression (T10CAD BTDC in Figure 3). Because of the charge cooling effect, a late injection leads to a higher amount of cool fresh air in the cylinder at intake valve closing. Hence, the mixture has lower temperatures that lead to later auto-ignition. For early SOI, the effects of negative valve overlap have to be considered. The required amount of hot residual gas is trapped in the cylinder by early exhaust valve closing and late intake valve opening (negative valve overlap). This leads to compression of the residual gas with maximum temperatures of approximately 1400 K and maximum pressures of approximately 15 bar in the cylinder. If an early SOI is chosen, the fuel is injected into the hot residual gas, which may lead to pre-reactions. By detecting the radiation emitted during the negative valve overlap, it has been shown that, in operating points with lean air/fuel ratios and early fuel injection, a small amount of fuel reacts during the compression after the exhaust valves close 0. On the other hand, later injection timings result in poorer mixture preparation. For very late SOIs, it was observed that the temperatures calculated for the end of compression no longer correlate with the start of combustion. To determine the influence of the mixture quality on the combustion progress, the spatial and temporal progress of the auto-ignition was analysed for three different SOIs (380, 320 and 260 computer-aided design before top dead centre, CAD BTDC) with the three-dimensional visualisation technique and the three-dimensional simulation. In all cases, the same air/fuel ratio (λ=1.15) was maintained. With early SOI at 380 CAD BTDC, the fuel was injected during the compression of the hot residual gas after the exhaust valves had closed. The middle injection was set to 320 CAD BTDC before intake valve opening and the late injection was set to 280 CAD BTDC during the intake stroke. **Figure 4** shows a comparison of the measured and simulated pressure curves. Comparable results are achieved by using the chemical kinetic model developed in this work. The images in **Figure 5**, which were taken with the three-dimensional visualisation system, show the ignition process for early, middle and late injection timings. The different starts of combustion for the three cases can be seen. For all three cases, an ignition spot in the centre of the combustion chamber can be identified. It can be clearly seen that the ignition of the air/fuel mixture does not occur simultaneously throughout the entire combustion chamber. Due to the local mixture and temperature distribution, auto-ignition occurs in some regions earlier and in other regions with a delay. By analysing the images captured by the visualisation system, the combustion process can be three-dimensionally reconstructed. The so-called "ignition sites" are not located close to the combustion chamber wall, but rather in the centre of the combustion chamber. Starting from these ignition sites, a sequential auto-ignition process can be seen. This process ceases in the outer regions of the combustion chamber under the valves. In **Figure 6**, the experimentally determined locations of ignition sites are shown. A variation of SOI leads to the displacement of these ignition sites. With an early SOI, the ignition sites are located on the opposite side

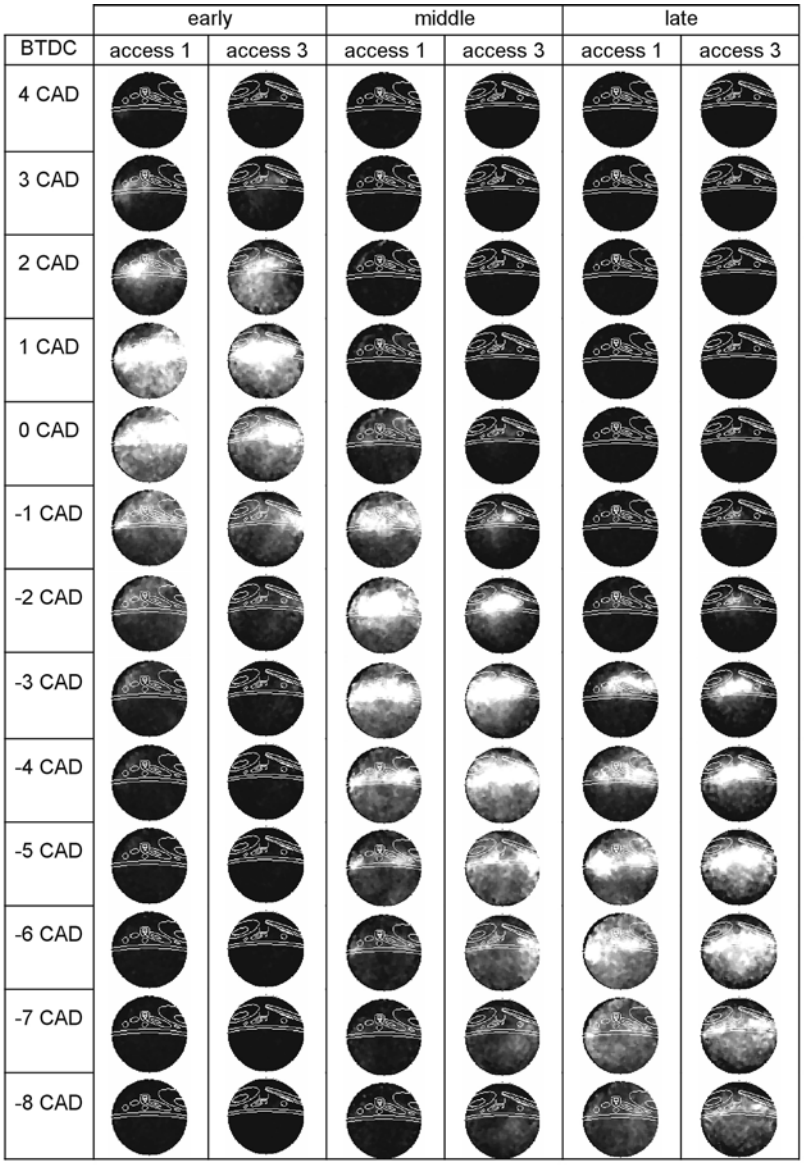

Figure 5: Selected single cycles for early, middle and late SOI

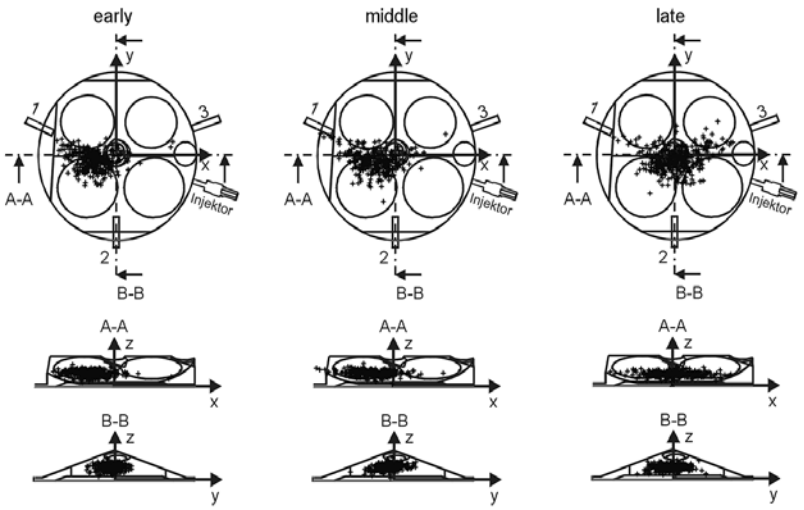

Figure 6: Experimentally determined locations of the ignition sites with early, middle and late SOI

of the injector. Retarding the SOI shifts the preferred ignition sites to the centre of the combustion chamber. Results from the three-dimensional simulation confirm this trend. The simulations of the different injection timings show that the differences regarding the residual gas distribution are negligible. Regarding the fuel distribution, the early and middle SOIs lead to more uniform fuel distributions than the late SOIs. A late SOI leads to a highly inhomogeneous local air/fuel ratio with very rich and very lean regions. The temperature distribution in the combustion chamber shows that the highest temperatures occur in regions with low mass fractions of fuel and high mass fractions of residual gas. Late SOI leads to the most inhomogeneous temperature distribution, in which the regions with high amounts of fuel have the lowest temperatures. For early SOI, the regions with high amounts of fuel and high mass fractions of residual gas overlap partially or are located side-by-side. Thus, a homogeneous temperature distribution is achieved. The comparison of the reaction progress in **Figure 7** for early, middle and late SOI shows that the homogeneous temperature and fuel distribution in the case of the early injection timing leads to very rapid combustion, whereas the inhomogeneous mixture in the case of late SOI leads to a slower reaction progress. In all cases, the ignition sites are located in the regions of highest temperature. With late injection timing, the combustion is retarded so drastically that, in lean regions, complete fuel conversion is not achieved. By simulating different injection timings, it was shown that the progress of the combustion is influenced by specific variations in the fuel distribution. As a result of fuel stratification, an increased ignition stability, shifted ignition timing and control of the combustion duration can be achieved.

5 Conclusion

The process of auto-ignition in an HCCI engine was investigated with a combination of engine experiments and CFD simulations. The development of a chemical kinetic model enabled an analysis of the engine behaviour with three-dimensional simulations. For the first time, ig-

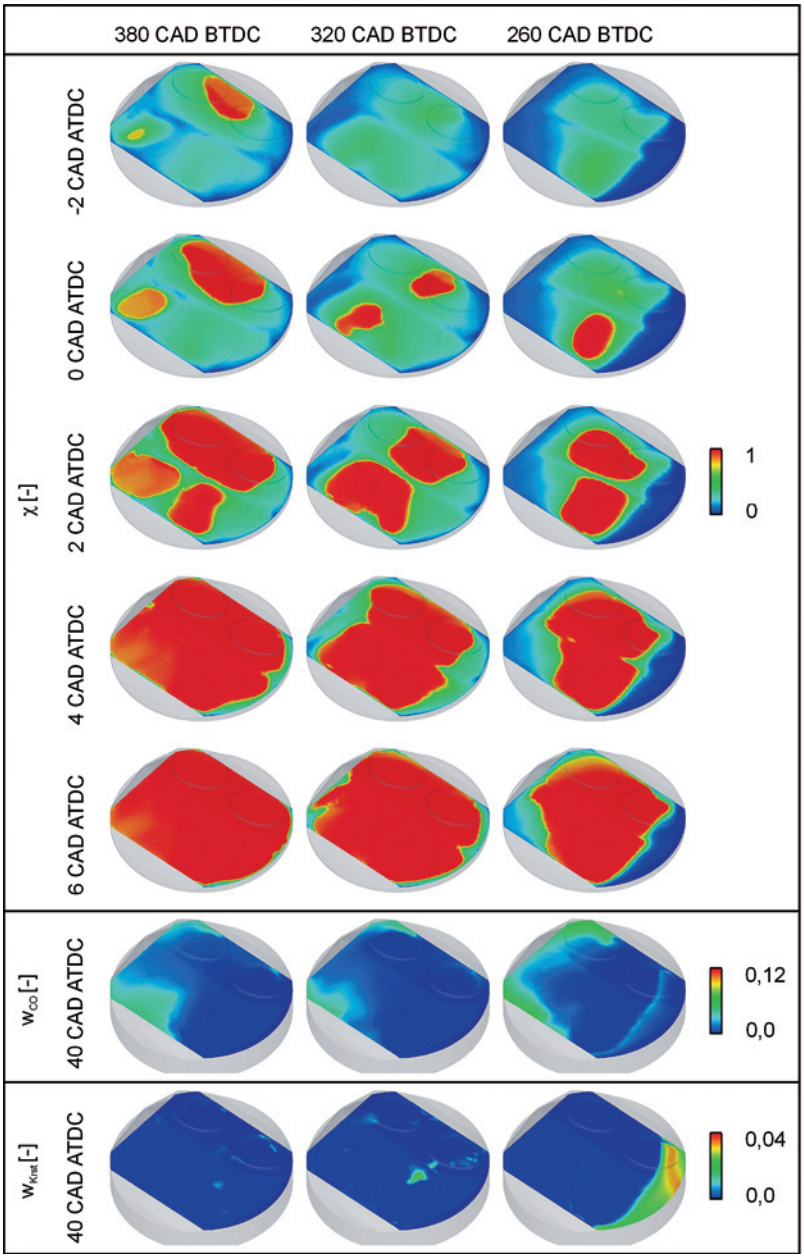

Figure 7: Reaction progression with early, middle and late SOI; CO mass fraction (wCO) and fuel concentration (wfuel) after combustion

nition sites have been located three-dimensionally by the application of an endoscopic fibre-optic visualisation system. Extensive investigations of the effect of SOI on the combustion were also analysed and injection timing was determined to be a feasible control parameter for the start of combustion.

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