

Operation Strategies for Controlled Auto Ignition Gasoline Engines

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ABSTRACT

Controlled Auto Ignition combustion systems have a high potential for fuel consumption and emissions reduction for gasoline engines in part load operation. Controlled auto ignition is initiated by reaching thermal ignition conditions at the end of compression. Combustion of the CAI process is controlled essentially by chemical kinetics, and thus differs significantly from conventional premixed combustion. Consequently, the CAI combustion process is determined by the thermodynamic state, and can be controlled by a high amount of residual gas and stratification of air, residual gas and fuel.

In this paper both fundamental and application relevant aspects are investigated in a combined approach. Fundamental knowledge about the auto-ignition process and its dependency on engine operating conditions are required to efficiently develop an application strategy for CAI combustion. To develop a comprehensive understanding of the CAI process detailed thermodynamic analysis of CAI combustion, optical diagnostics on a transparent engine and 3D-CFD analysis with reduced chemical kinetics is used. In order to deduce measures for stability and operating range extension, the detailed fundamental information is transferred to a 1D-model, extended by a multi-zone

approach describing thermodynamic parameters and incorporating reduced reaction kinetics.

Application strategies for CAI are developed on a single cylinder research engine with a fully variable valve train and direct injection. It is found that control of the CAI operating range can be achieved by realizing stratification of the in-cylinder charge. Stratification control is possible via valve timing and the strategy for direct injection.

Based on the thermodynamic requirements, the necessary variability of the valve train for realization of CAI operation in multi-cylinder engines can be identified. A multi-cylinder engine with a mechanically variable valve train to realize the CAI combustion process is presented.

INTRODUCTION

Fuel consumption reduction is in the main focus of gasoline engine development. By combining technologies, such as direct injection, reducing throttling losses by variable valve train systems and boosting, a significant reduction of fuel consumption has already been achieved. New combustion systems, such as controlled auto ignition or homogeneous lean combustion show potential for further fuel consumption

reduction. For all new combustion systems, current as well as future emission legislations have to be considered.

This paper focuses on controlled auto ignition combustion (CAI), which produces very low NO_x -emissions, and can therefore avoid expensive exhaust aftertreatment as required for lean concepts. Compared to conventional gasoline engines, reduced throttling losses lead to improved efficiency. In addition to this, the combustion duration is shorter, which approaches the thermodynamically ideal constant volume cycle. However, the negative effect of rapid heat release on NVH characteristics must be considered during the combustion development.

CAI combustion is initiated by auto-ignition in the compression stroke near TDC. The temperature level required for auto-ignition of gasoline is achieved by internal exhaust gas recirculation. For its realization the valve timing strategy plays a decisive role, alongside controlled stratification of the in-cylinder mixture. Additional external heating of the intake air is not necessary.

In previous investigations the operating range for stable CAI combustion has been determined by thorough thermodynamic engine testing [2]. To maximize the CAI operating range under given limitations, different EGR strategies have to be applied (see figure 1).

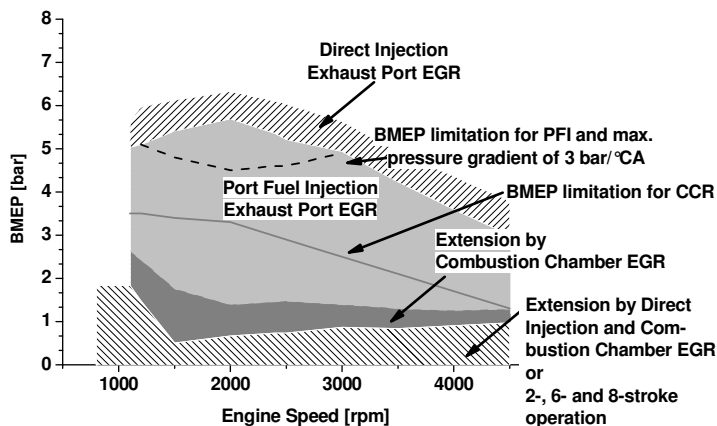


Figure 1: Operating range of the CAI strategies including direct injection and boosting

FUNDAMENTAL INVESTIGATION METHODS

SINGLE CYLINDER EMVT CAI ENGINE

Fundamental experimental investigations of CAI combustion are done on a single cylinder research engine, equipped with an electromechanical valvetrain (EMVT). The engine can be operated with port fuel injection (PFI) or direct injection (DI). The DI injector is in

the central position. The EMVT system gives the required flexibility of valve timing as well as fast switching times. It enables investigations of different exhaust gas recirculation strategies, exhaust port recirculation (EPR) and combustion chamber recirculation (CCR). These strategies are schematically shown in figure 2. For EPR, the exhaust valve open duration is significantly longer, so exhaust gas is drawn back from the exhaust port during the intake stroke. For the CCR strategy the exhaust gas is kept in the combustion chamber due to a highly negative valve overlap.

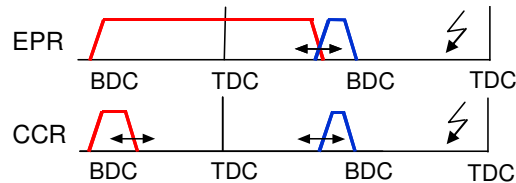


Figure 2: exhaust port recirculation, EPR and combustion chamber recirculation, CCR

Main characteristics of the CAI single cylinder research engine:

- Single Cylinder Engine: FEV system engine
- Bore x stroke: 84 mm x 90 mm
- Displacement: 0.499 dm³
- Valve train: EMVT (4 valves)
- Valve lift (In / Ex): 8 mm / 8 mm
- Compression ratio: 12
- DI injector position: central

The investigations have been performed using commercial RON 95 grade fuel.

For the optical investigations, the engine is equipped with a transparent liner and a piston window in an elongated piston, which provides the space for a mirror to view through the transparent piston window. The optical arrangement enables one to visualize the combustion process with an intensified high-speed camera, providing cycle resolved information on the UV-flame luminosity, caused by OH and CH radicals. Furthermore the application of laser optical diagnostics is possible, such as PIV (particle image velocimetry) or LIF (laser-induced fluorescence).

NUMERICAL CFD ANALYSIS

The simulation of in-cylinder flow has - during the past years - become an efficient and useful tool for the development and investigation of new combustion systems. To understand the nature of the flow and mixture formation, gas exchange and fuel injection have to be computed.

Meshing of the intake ports, the combustion chamber, including the piston as well as the valve motion is done

using the tool es-ice. The CFD calculation is performed using the code StarCD.

The final step in CFD simulation is modelling of the combustion. Understanding when and where the auto-ignition takes place is essential to develop combustion control strategies. Valve timing and injection are known parameters to be used for controlling the CAI process.

For describing the auto-ignition process, a kinetic model has been developed and implemented into the CFD code [4]. Due to high computational times it is not feasible to directly implement the kinetic mechanism into the CFD domain with its high spatial discretisation, especially when simulating engine parameter variations. Hence, the reaction kinetics are calculated in a discretization of the thermodynamic states instead of a spatial discretization. The discretization is performed via a two dimensional classification in the two state variables mass fraction of residual gas, Y_{RGF} , and mixture fraction, Z . The effect of temperature is neglected in the chosen classification scheme. This has been justified in a previous investigation, showing the existence of a strong correlation between temperature and mass fraction of residual gas [5].

The reaction kinetic model used is that of iso-octane as a reference fuel, and is based on a reduced kinetic mechanism by Golovitchev with 84 species and 412 reactions [3].

The coupling between the CFD code StarCD and the reaction kinetic code Cantera for a single time step is schematically described in figure 3.

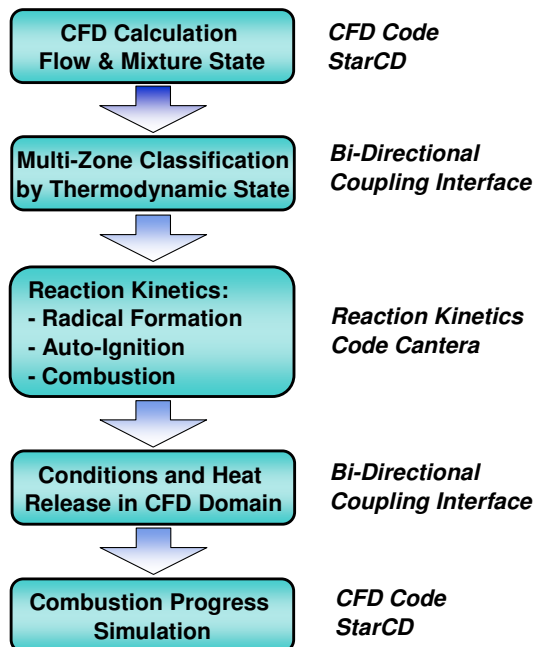


Figure 3: Coupling of 3D CFD code and reaction kinetic code

Based on the outcome of the 3D gas exchange, injection and mixture formation simulation, the cylinder charge is classified into multiple zones by Y_{BGF} and Z . All identified zones are transferred into a reaction kinetic model. The result of this step is the thermodynamic state and the radical composition in each specific class, and if auto-ignition occurs. The calculated heat release of each class is mapped back into the 3D CFD. Finally, the progress of combustion can be determined by integration of the heat release.

RESULTS OF FUNDAMENTAL INVESTIGATIONS

In the following, the fundamental processes, the interaction of charge motion, burned gas fraction, fuel stratification and reaction kinetics are investigated for the engine operating point, NMEP = 3 bar at 2000 rpm engine speed. This operating point has been chosen because it can be operated by both valve timing strategies, CCR and EPR. As can be seen in figure 2, this operating point is close to the upper operating limit of CCR and close to the lower operating limit of EPR mode. By comparing both EGR strategies, the influence of in-cylinder stratification on the auto-ignition and combustion process can be analyzed.

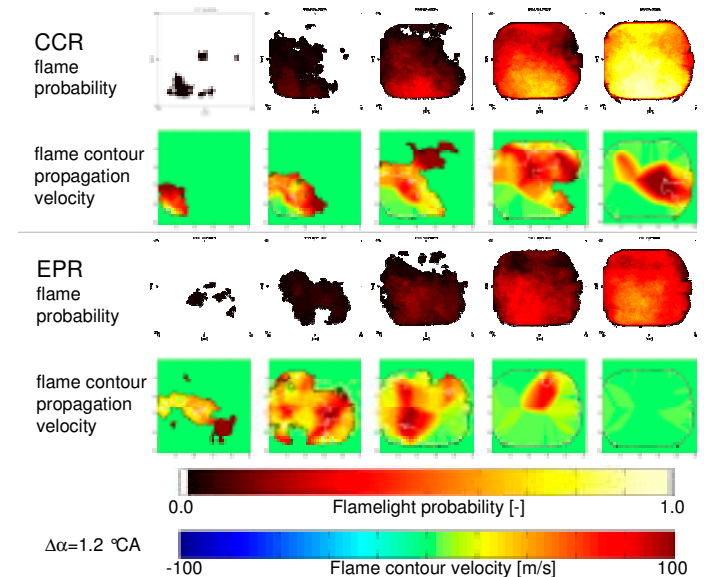


Figure 4: UV- flame light evaluation, providing the flame probability and flame contour normal propagation velocity

Figure 4 shows sequences of the flame probability and flame contour UV propagation velocity, based on the measured UV flame light emission in CCR and EPR operation mode at 2000 rpm, 3 bar NMEP. It can be seen that for CCR the flame probability increases over the combustion image sequence from 0 to local maxima of 0.9, which is higher than for EPR, which reaches a local maximum of approx. 0.7. A similar observation is made for the flame contour propagation velocities normal to the contour surface, where CCR reaches higher