Strategies for Operation of Controlled Auto Ignition Gasoline Engines

ABSTRACT

A tremendous opportunity exists for reducing fuel consumption and emissions in gasoline engines under part load operation, with the use of a Controlled Auto Ignition (CAI) system. The start of controlled auto ignition is achieved by reaching thermal ignition conditions at the end of compression. Chemical kinetics control the combustion process in a CAI system, which is dramatically different from the conventional premixed combustion process. Accordingly, the thermodynamic state determines the CAI combustion process, which can be either controlled by a high amount of residual gas and stratification of air or residual gas and fuel.

This study utilizes the combined approach of both fundamental and application relevant aspects. Determining the application strategy for CAI combustion requires knowledge of the auto-ignition process and its dependence on engine operating conditions. A complete understanding of the CAI process can be obtained through a detailed thermodynamic analysis of CAI combustion, optical diagnostics on a transparent engine and 3D-CFD analysis with reduced chemical kinetics. Determining stability and operating range extension measures requires that detailed fundamental information is shifted to a 1D-model, and then extended by a multi-zone approach that describes thermodynamic parameters and incorporates reduced reaction kinetics.

A single cylinder research engine, equipped with a fully variable valvetrain and direct injection, is used to develop the application strategies for CAI. Control over the CAI operating range can be completed through a stratification of the in-cylinder charge. Control of stratification is possible through valve timing and a strategy for direct injection.

The necessary variability of the valvetrain for realizing CAI operation in multi-cylinder engines can be identified, based on the thermodynamic requirements. This study uses a multi-cylinder engine with a mechanically variable valvetrain to realize the CAI combustion process.

INTRODUCTION

Increasing fuel economy is in the primary concern for current gasoline engine development. A significant increase in fuel economy has already been achieved by combining direct injection, reducing throttling losses with variable valvetrain systems and boosting. Controlled auto ignition or homogeneous lean combustion is a new combustion system that shows great potential for further reducing fuel consumption. Consideration for current as well as future emission legislation must be made when developing new combustion systems.

Controlled auto ignition combustion (CAI) is the primary subject of this study. CAI combustion results in very low NO_x emissions, which then avoids expensive exhaust aftertreatment systems that are required for lean concepts. In relation to conventional gasoline engines, CAI reduces throttling losses, which then leads to improved efficiency. Additionally, reducing the combustion duration adds another benefit, which allows the design to approach the thermodynamically ideal constant volume cycle. However, consideration must be given to the negative effect of rapid heat release on NVH characteristics during the combustion development.

The start of CAI combustion occurs with auto-ignition during the compression stroke near TDC. Auto-ignition of gasoline requires a specific temperature level, which is reached by internal exhaust gas recirculation. Achieving auto-ignition also requires a valve timing strategy and a controlled stratification of the in-cylinder mixture. It is not necessary to provide external heat for the intake air.

During previous studies, the operating range for stable CAI combustion has been determined through detailed thermodynamic engine testing [2]. A variety of EGR strategies have to be applied (see figure 1), to optimize the CAI operating range under the limitations that are provided.

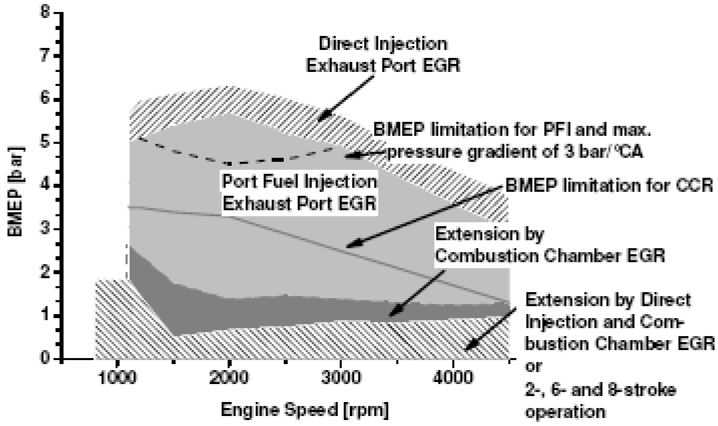

Figure 1: Operating Range of the CAI Strategies Including Direct Injection and Boosting

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.

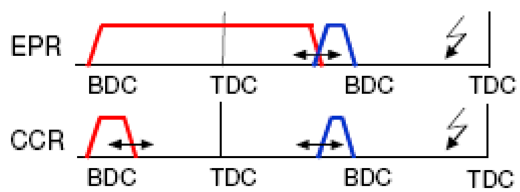

Figure 2: Exhaust Port Recirculation (EPR) and Combustion Chamber Recirculation (CCR)

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 dm^3
- Valvetrain: 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 Particle Image Velocimetry (PIV) or Laser-Induced Fluorescence (LIF).

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 modeling 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 discretization, 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.

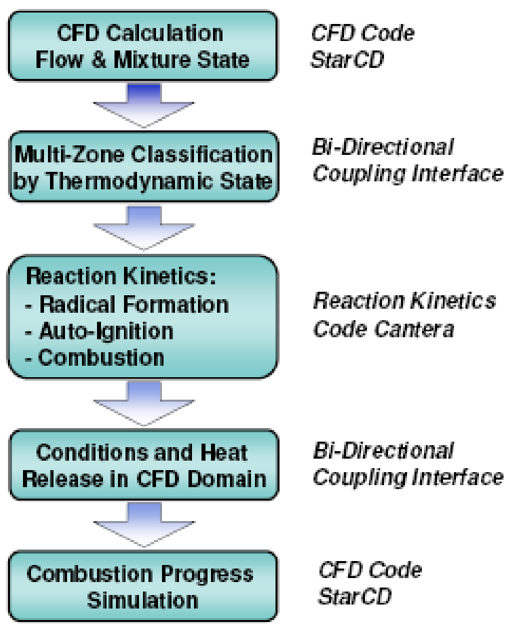

Figure 3: Coupling of 3D CFD Code and Reaction Kinetic Code

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.

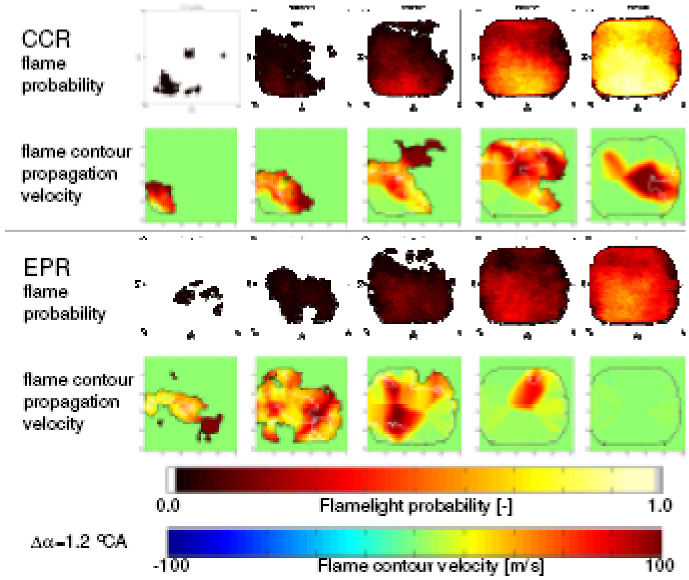

Figure 4: UV- flame Light Evaluation, Providing the Flame Probability and Flame Contour Normal Propagation Velocity

Figure 4 shows sequences of the flame probability and flame contour 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 values than EPR. It is worthwhile noting that flame contour propagation velocities reach values above 100 m/s, which is significantly higher than the flame propagation speed of turbulent pre-mixed combustion in SI operation under comparable load and speed conditions.

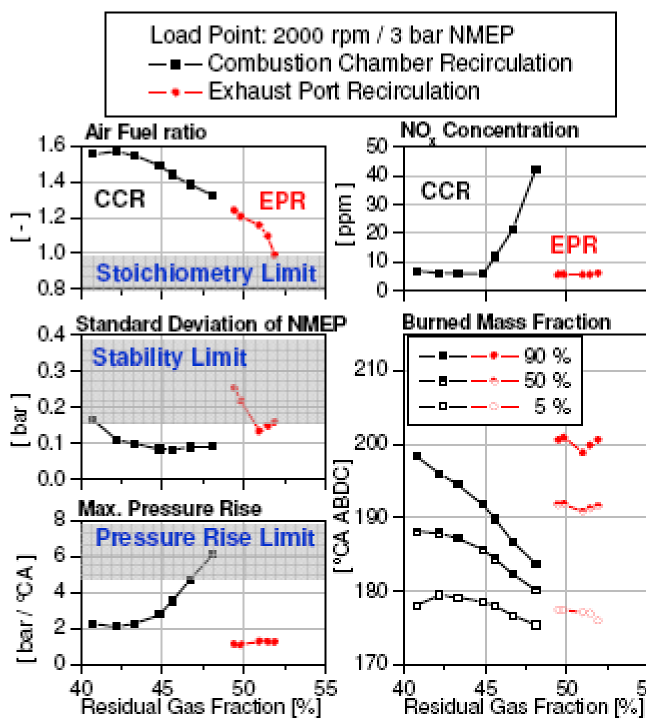

Figure 5: Combustion Characteristics at 2000 rpm and 3 bar NMEP

Figure 5 shows test results of a residual gas fraction (RGF) -variation comparing the two EGR-strategies for an engine speed of 2000 rpm and load of 3 bar NMEP. RGF is adjusted by changing the valve timing. The plots show the different limits for CAI operation.

For both EGR strategies, similar limitations for CAI operation apply, as there are NVH characteristics, represented by the maximum pressure rise limit, avoiding inefficient rich mixture, and most importantly the combustion stability limitation. A lower RGF leads to a lower compression end temperature and consequently a retarded combustion event. This is indicated by a longer burn delay and burn duration, which results in higher combustion instabilities, characterized by a higher standard deviation in NMEP.

The demand for good NVH characteristics restricts the acceptable maximum pressure gradient. Higher EGR rates result in higher compression end temperatures and therefore in an advanced combustion with higher pressure gradients. Also the NO_x emission increases, due to higher peak temperatures. Especially important to EPR is a limitation of the maximum RGF as the trapped air is limited and the rel. AFR should stay above stoichiometric for good fuel consumption and optimal emissions.

For operation in CCR mode the optimum residual gas fraction is found to be between 42 and 47 %. At RGF rates above 45 %, the NO_x-concentration as well as the maximum pressure gradient exceeds the defined limitation. Below 42 %, the combustion is retarded and instable, showing NMEP standard deviations higher than
0.1 bar.

The optimum RGF range for EPR operation at this operating point is much smaller compared to CCR, and is found between 49 and 52 %. The maximum pressure gradient is lower compared to the CCR strategy, due to a more retarded combustion. This also causes the more unstable combustion, with NMEP standard deviations higher than 0.1 bar. Stable combustion with higher RGF rates cannot be achieved as the mixture approaches stoichiometric state. As shown in figure 1, an NMEP of 3 bar is at the lower load limit of EPR, described by unacceptable combustion stability.

This comparison of CCR and EPR shows that EPR has a later and slower combustion, although it has a higher overall residual gas content. This gives an indication, that different stratification effects may play a role. To better understand the role of stratification, CFD analysis is used to quantify the degree of stratification in the combustion chamber. This approach allows a detailed sequentially and spatially resolved insight in the mixture states of air, of residual gas and fuel during intake and compression stroke and during the course of ignition reactions.

During the compression stroke at 90 °CA bTDC, the mass distribution of CCR shows a significantly broader range of RGF and mixture fraction compared to EPR. However, for CCR a large part of the total in-cylinder mass is observed in zones with relatively low RGF rates. EPR shows a broader maximum in high RGF rate zones.

Close to auto-ignition, at 10° CA bTDC, in-cylinder mixing causes a homogenization, which strongly changes the distribution of CCR, as it concentrates around a mixture fraction of 0.025 and an RGF rate of 0.5. In comparison, EPR shows lower homogenization, meaning a higher charge stratification.

The degree of stratification has an important effect on the auto-ignition, but even more on the subsequent combustion. The CCR strategy is shown in Figure 6, as an example.

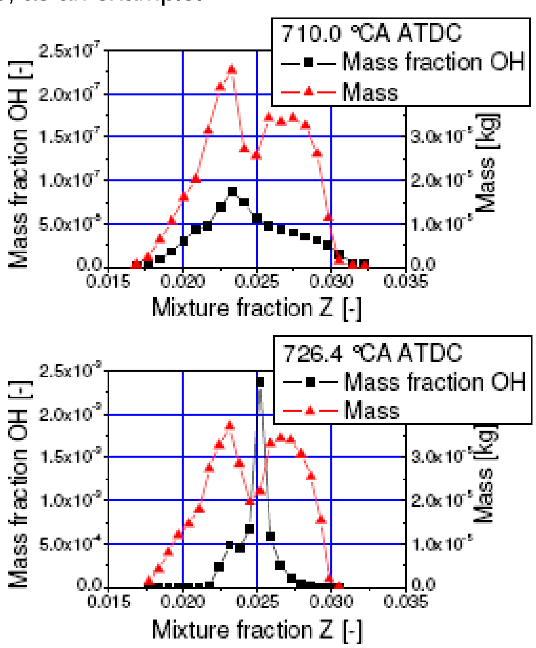

Figure 6: Instantaneous Mixture Fraction and Mass Fraction of OH Radicals at 10 °CA bTDC (ignition) and at 6.4 °CA aTDC (50 % Conversion Point) for CCR Operation

Figure 6 shows the instantaneous mass fraction of OH radicals at 10 °CA bTDC and at 6.4 °CA aTDC for CCR operation with an RGF of 46.9%. The shown values are simulated based on the coupled CFD and reaction kinetics. It can be seen that at the point of auto-ignition, at 10 °CA bTDC, the peak mass fraction coincides with the maximum in-cylinder mass at a mixture fraction Z of 0.023. This indicates that the auto-ignition conditions are reached in a zone which accumulates the highest in-cylinder mass. Hence, this leads to a high mixture conversion rate which in turn leads to a fast combustion. At 6.4 °CA aTDC, which corresponds to the point where 50% of the fresh charge is burned, a high OH mass fraction is found in the range of Z = 0.022 to 0.028. This range coincides with the major portion of the in-cylinder charge.

Lower combustion propagation is observed on the concave side of the main combustion region due to higher rel. AFR, and on the convex side due to leaner rel. AFR and a comparably smaller RGF, leading to reduced temperatures in this area.

In general, the results of the fundamental investigations show that stratification of the fuel and RGF has an important effect on auto-ignition and combustion. Hence, control of the degree of stratification enables one to adjust the auto-ignition and combustion characteristics in CAI operation. Direct measures to control the degree of stratification are valve timing and direct injection strategy.

Particularly for transient operating modes accurate control of the in-cylinder charge state with respect to temperature and RGF distribution is required. On the single cylinder research engine, transient operation can be realized by appropriate valve timing strategies, by making use of the high flexibility of the EMVT timing.

It is known that CAI combustion is affected by the temperature of the recirculated exhaust and is therefore influenced by the previous cycle. Immediately after the transition from SI to EPR strategy, the combustion of some cycles occurs very advanced, and is due to higher exhaust gas temperatures during the SI operation. After six combustion cycles the combustion phasing returns to the steady-state operation results.

CAI COMBUSTION SIMULATION

Detailed understanding of the auto ignition process is required for the layout of a control strategy for the development of a multi-cylinder CAI engine. Several approaches are used to model the engine. Reaction kinetics simulations are utilized to investigate the auto ignition of different mixture compositions and thermodynamic states. In the following, a reduced combustion model for fast simulation of the CAI combustion together with gas exchange simulations is presented.

CFD results of the gas exchange, injection and mixture formation are used to quantify the distribution of vaporized fuel and residual gas in the combustion chamber. The CFD calculations are performed for various RGF rates, injection timings and engine loads. The information about the distribution function is saved in lookup tables. This information is subsequently used for reaction kinetic calculations. Depending on the trade-off between calculation time and accuracy the number of zones can be chosen during the simulation. Typically the zones are initialized to be square in the two-dimensional phase space of mixture fraction and residual gas mass fraction. A multi-zone reaction kinetic model of the engine is utilized to simulate the high pressure cycle of the engine.

The early phase of heat release is underestimated while the end of combustion occurs a little too fast, and hence the maximum pressure and the maximum pressure rise are slightly overestimated. However, in general the simulation results agree well with the experiments, especially considering that the computational effort is noticeable reduced compared to detailed CFD models. The high pressure cycle can be calculated within 2 hours on a single 2 GHz CPU.

The developed procedure allows a useful prediction of CAI combustion behavior during engine development. However, the required computational time inhibits the direct use of the reaction kinetics simulation to predict transient operation, which is necessary e.g. for control algorithm development, where many cycles have to be simulated in a much shorter time.

Figure 7 shows the comparison of engine measurement and a GT-Power model using an adapted Vibe combustion model and a single zone reaction kinetics model. Due to the fast combustion without any delay in the burn rate, a single Vibe approach shows a good correlation to the measurement. Also cylinder pressure parameters such as peak pressure location, NMEP etc., which can potentially be used for closed-loop combustion control, can be simulated with a sufficient accuracy.

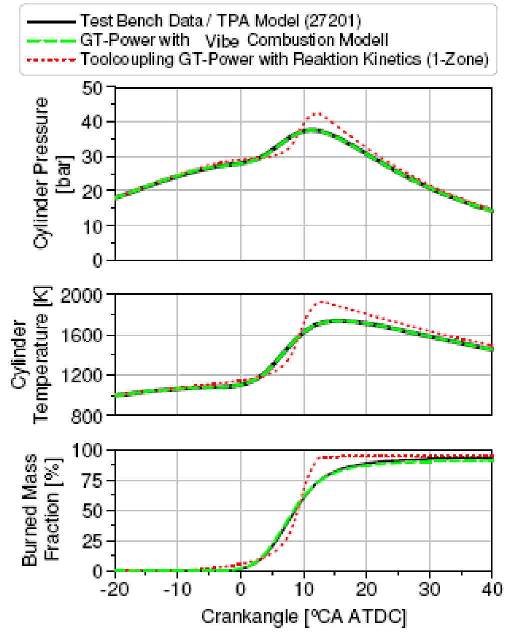

Figure 7: Comparison of Engine Testing Data with GTPower Results with Vibe and Reaction Kinetics Combustion Rate for CCR Mode at 2000 rpm and 3 bar NMEP

Additionally, a coupling of the GT-Power model with the reaction kinetics is possible. A single zone reaction kinetic simulation can be realized without knowledge of the degree of mixture stratification. The single zone results show a lower degree of correlation to the measurement results than the Vibe approach. Nonetheless, the peak pressure location and the NMEP can be predicted with acceptable accuracy at reasonable computational time. This coupling can also be used to predict the required valve timing flexibilities during the engine layout process. A simulation with more zones is currently being developed and shows a better correlation but requires significant higher computation times.

For investigation of the engine transient behavior, several load step tests have been performed. For these load steps all actuators are adjusted within one cycle from the previous to the next, with optimized steady-state settings. This use of fixed steady state control parameters is especially useful for validation of the modeling approach and the control algorithm layout. The measurement results show a noticeable transient behavior after the load steps with load increase. However, only 4-8 cycles are necessary to return to stable operation. The GTPower simulation with a Vibe combustion model implemented shows good correlation in steady state operation. As one can see, currently the increasing load step cannot be predicted accurately enough, which is due to the lower exhaust gas temperature in the previous lower load point. The ongoing investigation focuses on improving these transient conditions, using the presented strategies of CFD and reaction kinetics simulation combined with the engine testing.

CAI COMBUSTION SYSTEM DESIGN FOR MULTI-CYLINDER ENGINE

Based on above results a multi-cylinder engine has been designed and set up to run in CAI operating modes.

Figure 8 shows the cylinder head design with a variable valvetrain. The engine is based on FEV's 4-cylinder Spray Guided DI Turbo (SGT) engine with 1.8L displacement and a peak power of 160 kW. As shown, the realization of different EGR control modes is essential to enable CAI operation in a wide operational area. The turbo-charging allows extension to higher loads, as shown in figure 1.

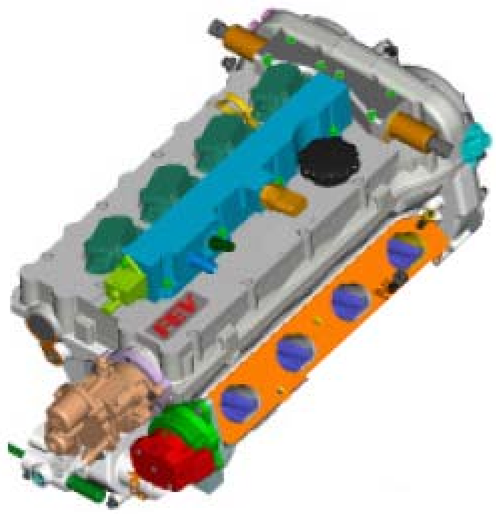

Figure 8: FEV SGT Cylinder Head Design

The EGR control is realized by a dual lift roller rocker arm and dual cam phasers. The developed valvetrain offers the capability to operate in CCR mode and also in two modes of EPR, with an early and a late exhaust gas recirculation. The requirements for the valvetrain layout in terms of maximum valve lift, event length and cam phasing speed, have been supported using the previously developed simulation tools, combining gas dynamic simulation with reaction kinetics.

CONCLUSION

While under part load conditions, CAI engines offer the potential to reduce fuel consumption and NO_x emissions. Control of the auto ignition process is completed through combustion chamber recirculation and early exhaust port recirculation. The combination of multi-dimensional simulation tools and optical investigations are used to provide a basic understanding of the CAI process. The operating limits are determined through experimentation. Meanwhile, the effect of the control parameters valve timing and injection timing are investigated simultaneously with combined CFD and reaction kinetic models.

The distribution and level of stratification of fuel, air and residual gas in the combustion chamber can be resolved in great detail through numerical analysis. The stratification state has a strong impact on the combustion rate, as shown by the reaction kinetic simulation, predicting auto ignition and the progress of combustion.

A key to the successful application of CAI combustion in future automotive applications can be found in extremely accurate control of transient modes and shifts between different operating modes. One crucial requirement is to improve the closed loop control of the combustion process [8]. This study utilized the approach of reduced modeling of the CAI process, which is used to generate data to better understand the behavior of the engine during load steps, which feeds into the control strategy. Currently, the design and setup of a multi-cylinder CAI engine is under development.

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