

Development of an Innovative Combustion Process: Spark-Assisted Compression Ignition

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ABSTRACT

In the competition for the powertrain of the future the internal combustion engine faces tough challenges. Reduced environmental impact, higher mileage, lower cost and new technologies are required in order to maintain its global position both in public and private mobility.

For a long time, researchers have been investigating the so called Homogeneous Charge Compression Ignition (HCCI) that promises a higher efficiency due to a rapid combustion - i.e. closer to the ideal thermodynamic Otto cycle - and therefore more work and lower exhaust gas temperatures. Consequently, a rich mixture to cool down the turbocharger under high load may no longer be needed. As the combustion does not have a distinguished flame front it is able to burn very lean mixtures, with the potential of reducing HC and CO emissions. However, until recently, HCCI was considered to be reasonably applicable only at part load operating conditions.

The 3D-CFD engine development tool QuickSim, which has been developed at the FKFS in cooperation with the IVK/University of Stuttgart, is able to simulate the entire flow path of the engine, including both flame propagation and HCCI combustion. In a recent project with the German Aerospace Center (DLR) it was possible to calibrate the parameters of the auto-ignition HCCI model using a highly variable free piston linear generator.

This paper addresses the potential of virtual engine development in the creation of a new combustion process for series engines. The described process is called Spark-Assisted Compression Ignition (SACI). It utilizes a pre-chamber spark plug to initialize and control the following auto-ignition. This prevents accidental combustion and also ensures an auto-ignition that is less dependent on the environment and transient conditions, while maintaining the efficiency and emission advantages of a conventional HCCI combustion (auto-ignition of the air-fuel mixture merely regulated by local thermodynamic variables in the combustion chamber).

CITATION: Chiodi, M., Kaechele, A., Bargende, M., Wichelhaus, D. et al., "Development of an Innovative Combustion Process: Spark-Assisted Compression Ignition," *SAE Int. J. Engines* 10(5):2017, doi:10.4271/2017-24-0147.

INTRODUCTION

In the pursuit of an efficient combustion a lot of effort was put into the research of Homogenous Charge Compression Ignition (HCCI). The first investigations date back to the 1930s when Nikolai Semenov established his chain theory of ignition, utilizing chemical reaction kinetics in contrast to SI or CI combustion processes which are driven by physical properties. Together with Gussak *et al.* he published a combustion process called LAG (Avalanche Activated Combustion) [1]. The first systematic investigation of the phenomena is commonly recognized in the work of Onishi *et al.* [2] and Nogutchi *et al.* [3]. The research published in 1979 focused on 2-stroke engines promising lower fuel consumption and HC-emissions. Both papers refer to chemical intermediate products as the dominant effect during

the combustion, called ATAC (Active Thermo-Atmosphere Combustion) or respectively TS (Toyota-Soken). In 1983 Najt and Foster [4] introduced a semi-empirical model, which predicts the heat release rate, stating that through an appropriate choice of temperature and species concentration CIHC (compression-ignited homogeneous charge) is also possible in a 4-stroke engine. Based on this publication Thring [5] investigated the effect of residual gas and lambda (defined as $\lambda = 1/\phi$), introducing the name Homogeneous Charge Compression-Ignition (HCCI) which is today's most commonly used term for this type of auto-ignition combustion. He explained the concept of using HCCI in idle and part-load conditions and switching to a flame based combustion for higher loads.

Stockinger *et al.* [6] presented a four cylinder engine that was able to run within a limited engine map using high compression ratio and heated intake air.

A lot of effort was put into the widening of the engine map using HCCI. Independently, several research groups discovered that a key to this can be valve timing, either by early closure of the exhaust valve or negative valve overlap [7, 8, 9]. This can be realized using a variable valvetrain or, even more cost effective, via a modified conventional camshaft. At that time it was believed that by setting the conditions of the cylinder filling, HCCI is controllable over a sufficient range of engine speeds. For this operation concept an additional term has been introduced: Controlled Auto-Ignition (CAI). In this paper, however, the term CAI is not used, to avoid any confusion, as time has shown that by regulating temperature and pressure the combustion cannot be controlled sufficiently to be used in passenger cars. Instead the authors refer in this paper to the term HCCI or the more general term “auto-ignition” to describe a combustion process based on self-ignition volume reactions.

HCCI describes a desired auto-ignition of a gasoline fuel during the compression stroke. The charge is homogenous and therefore has very similar properties in the entire combustion chamber enabling a volume reaction. It is mainly utilized as a part load strategy aiming to combine a rapid combustion and therefore high indicated efficiency with a de-throttling of the engine via an extensive exhaust gas recirculation (EGR) [5]. Consequently, this results in a high peak pressure, increasing work output and lower exhaust gas temperatures which can in turn be beneficial to wall heat transfer and NO_x formation.

These benefits are generally accompanied by a number of drawbacks which have prevented HCCI from becoming a widely spread combustion strategy in series production cars. The hardest to overcome is the lack of control. Despite the intensive research, conventional HCCI is very difficult to be implemented, since it is highly sensitive to the local thermodynamic variables of the mixture in the combustion chamber. These variables are strongly affected by the engine operating conditions in particular during transients. E.g. during startup, when the engine is cold and no hot exhaust gas is available, the engine has to be operated with a flame propagation combustion to heat up and to guarantee a stable operating point. With the requirement of a high EGR rate, a strong coupling between the consecutive working cycles exists. Usually this prohibits a smooth transition from a flame propagation combustion to HCCI and requires a switch over strategy. As already introduced, in transient conditions, conventional HCCI reaches its more evident limits as the changes between two working cycles cannot be controlled properly anymore. The common control values cannot be adjusted fast enough to compensate for the change in the operating conditions. For this reason it is very difficult to design an engine that delivers an equally broad map range as well as drivability as a spark ignited flame propagation combustion even under part load conditions. Under high loads, the operation becomes even more difficult, as the charge contains more energy, causing increasing peak pressure and mechanical stress for the engine. In case of an undesired early auto-ignition (peak pressure too close to top dead center) the additional mechanical stress would likely lead to engine failure. It

can be concluded that conventional HCCI yields a lot of benefits but its application is clearly limited due to the insufficient controllability of the system.

The main obstacles of conventional HCCI can be overcome by using an HCCI-like combustion that is started by an external trigger. In comparison to conventional HCCI combustion, where the timing of auto-ignition is a result of the cylinder conditions, the use of a trigger signal can delay or even prevent the combustion process. This can extend the operating conditions under which a volume reaction is safely usable, including transient operation conditions.

Traditionally the trigger mechanisms may be realized via different strategies, e.g. variable compression ratio, change in residual gas content or intake pressure. For different engine designs some of the stated approaches can be more promising than others. As outlined in [10,11] a free piston linear generator with variable piston trajectories is able to change the compression ratio from one working cycle to the next without any extra effort. In case of a crankshaft based engine a more substantial effort has to be made in order to realize a mechanism able to control HCCI combustion. In all cases the switch mechanism requires a very fast shifting so that a safe and stable transition from flame propagation combustion operation and HCCI can be ensured, even under transient conditions.

The aim of this work is to present a combustion strategy, that mainly utilizes the spark timing to trigger the auto-ignition process, so that the combustion process can be easily controlled like a regular gasoline engine, but with higher efficiency and comparable power output. For this target a pre-chamber spark plug has been implemented and intensively investigated in order to understand the behavior and the corresponding parameters of this concept as a potential way to control auto-ignition.

The extensive engine development, reported here, has been performed on a single cylinder engine, which has been investigated both virtually (virtual development by 3D-CFD-simulations) and experimentally on a test bench. In the first part of the paper, the concept and the behavior of the pre-chamber spark plug are presented. In the second half, spark assisted compression ignition is compared to the flame propagation combustion in terms of pressure traces and performance characteristics. The final part of this work reports the validation of one simulated operating point with test bench measurements.

METHODS AND COMBUSTION STRATEGY TOWARDS AN EFFECTIVE SPARK ASSISTED COMPRESSION IGNITION

The Spark Assisted Compression Ignition (SACI) is a strategy that employs the spark plug as an actuator to start a favorable auto-ignition combustion. In comparison to standard spark-ignited engines the spark process, as trigger for the combustion start, is amplified to create enough potential to safely and effectively control the auto-ignition process. This can be done by a number of different approaches which have in common that they utilize two generated volumes within the

combustion chamber. One is the main combustion chamber, i.e. the largest portion of the total volume, while the other one is a smaller sub-volume (usually $< 2\%$ of the piston clearance/total volume). Ignition by a spark plug always occurs in the smaller sub-volume followed by a regular flame propagation that releases part of the contained energy and mass (radicals) to the main combustion chamber finally causing a very rapid HCCI-like combustion.

The principle how to perform a SACI combustion is schematically shown in Figure 1. Here a continuous line reports a motored operation (no combustion) that is always below a critical auto-ignition threshold with a distance being a safety margin. This means that the engine never faces an auto-ignition of the mixture without sparking, i.e. the safety margin has to cover, among other things, cycle-to-cycle variations and all the influences of a transient operating conditions. The threshold to auto-ignition is mainly characterized by temperature, pressure and fluid composition (including radicals). By adding a certain amount of energy and radicals, much higher than possibly provided by a simple spark plug, the charge can be forced into a volume reaction (dashed line). In order to ensure this, an amplifier of the spark plug effects is required.

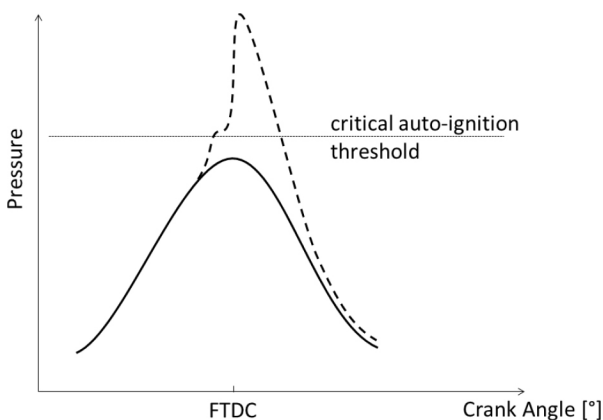


Figure 1. Schematic visualization of the auto-ignition potential.

The amplifier volume can be shaped very differently. One possibility is the use of a pre-chamber spark plug. This design is known from large gas engines. A cover with holes/orifices is directly attached to the spark plug tip creating an assembly that can be mounted in a conventional cylinder head. Without adjustment of the piston shape this approach is limited in terms of volume as well as energy and radical release. Another critical point with this design is represented by the exceptionally high thermal load and the corresponding material requirements of the cover. As the two volumes are only connected via several small holes/orifices, attention in the design of the pre-chamber has to be paid, in order to ensure a proper scavenging towards an ignitable charge at the spark plug for the desired ignition point.

A second approach is the use of a piston cavity as sub-volume, shaped to encapsulate the spark plug while in Top Dead Center (TDC). The spark ignites the encapsulated volume forcing the partially burned charge through the gap between piston and combustion chamber roof.

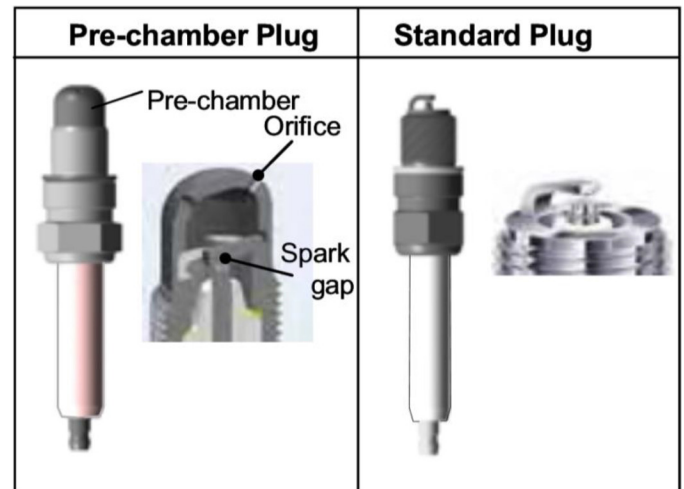


Figure 2. Pre-chamber spark plug for a gas engine [12]



Figure 3. Piston of a Mazda skyactive engine with central cavity. [13]

Benefits of this approach are the larger volume of the piston recess and the less restrained shape compared to the pre-chamber version. Mazda already uses a piston cavity in their skyactive Gen 2 engines with the aim of creating a stratified mixture with favorable conditions at the spark plug (Figure 3). A similar system may be used to divide the cylinder volume during ignition.

The third approach that can potentially be used has been developed by Mahle as Turbulent Jet Ignition (TJI) concept [14], also called Jet Ignition®. Mahle promotes the system as an accelerator of the flame propagation combustion, but a similar system may be used as a trigger mechanism for SACI combustion (very similar to the pre-chamber spark plug concept).

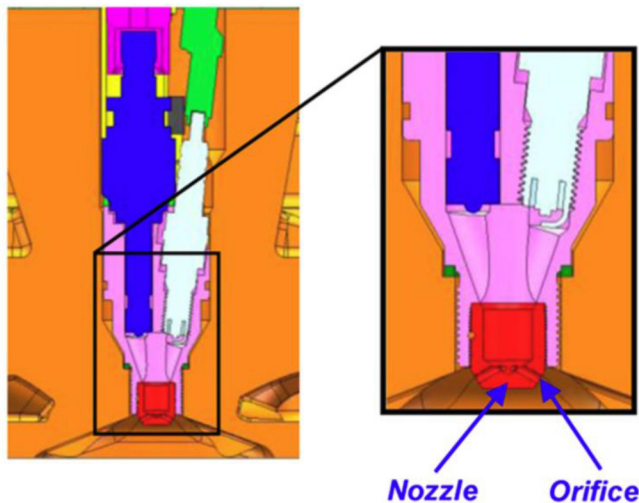


Figure 4. Cut through the cylinderhead with Mahle TJI [15]

The Mahle-concept uses a combination of an additional injector (blue) and a spark plug (white) mounted in a separate assembly so that, in comparison to the pre-chamber spark plug approach also the composition of the fresh charge in the sub-volume can be effectively controlled. In particular, the engine can operate with a very lean mixture in the combustion chamber ignited by a stable and rich mixture in the sub-volume (more radicals in the jet ignitions). The dimension of the sub-volume of the Mahle-concept is higher than the pre-chamber spark plug, which, under particular operating conditions, should ensure an even more stable operation with SACI combustion. On the other hand, a relevant drawback of this concept is the demand for two injectors per cylinder, which increases cost and complexity. Additionally, the cylinder head has to be specifically designed to accommodate the described assembly.

For all the concepts introduced, after the ignition has been triggered, the volume reaction will burn rapidly enough to ensure a very efficient combustion with very short duration but not too fast as to provoke knocking. In addition, in order to limit the mechanical and thermal stresses of the engine, the energy content and heat release rate have to be controlled carefully. The most common approaches are the use of EGR (internal or external) or a very lean mixture as both of them decrease the mass specific energy content of the charge. EGR or air surplus act like a gas spring by damping the pressure peaks and gradients, therefore reducing mechanical stresses and noise. Using lean mixtures the engine can be de-throttled at part load with additional advantages in terms of efficiency. In any case, the SACI combustion cannot be ensured over the entire range of the engine map, as it requires certain thermodynamic conditions at the end of the compression strokes even when using spark plugs amplifiers. Therefore, e.g. at low loads and low engine speeds the engine, if necessary, may have to be operated with a regular flame propagation combustion strategy, which can be assured in any case.

ENGINE SPECIFICATIONS

The experimental investigations were performed on a single cylinder engine at the Technische Universität München with a displacement of 400cm³ equipped with high-pressure direct injection. The setup of a single cylinder research engine can contribute either as a pre-development tool or as additional investigation device. It offers the possibility to install additional measurement equipment, due to better accessibility with respect to a full engine. Endoscopes or other imaging devices can be installed for optical investigations inside the cylinder.

The numerical investigations were performed at the research institute FKFS in Stuttgart. To ensure a good correlation of both tools the existing test bench was modeled in the 3D-CFD engine development tool "QuickSim" prior to the measurements. Extensive numerical validations also in previous projects [16,17] have confirmed a very good correlation between experimental and numerical investigations.

Table 1. Data of the one cylinder engine used for the investigations of this paper.

Displaced volume	400 cm ³
Stroke	73.8
Bore	83 mm
Compression ratio	12.0:1
Number of valves	4
Max speed	8000 rpm
Injection	Direct with one multi-hole injector
Max boost pressure	4 bar
Max Power	> 75hp

During the analysis two pre-chamber spark plugs are used, both of them having eight holes with an identical pattern. The smaller one has a volume of 150 mm³ while the second one has 300 mm³.

3D-CFD ANALYSES

Analyses on test bench devices, regardless whether of a single cylinder or full engine, provide a huge amount of information about the actual engine behavior. However, the observation and evaluation of internal engine processes is very limited. Supplementary 3D-CFD simulations enable a more detailed investigation of spatially and temporally resolved phenomena within the engine. This allows for a better understanding of the processes involved, whereas the knowledge gained can be used for targeted optimization during the engine development.

Software

The numerical investigations within the presented project were carried out with the 3D-CFD tool QuickSim, which has been developed and constantly enhanced over the last years at the FKFS. Using the commercial software STAR-CD as solver, QuickSim is a fast response 3D-CFD tool which is particularly dedicated to the simulation of ICEs. By using ICE-adapted computational models, e.g.

for the wall heat transfer or the fuel caloric, coarser meshes compared to traditional approaches can be used. Hereby, the time expense for a simulation is highly minimized. This not only allows the extension of the simulation domain to a full engine, but also the calculation of several successive operating cycles in a reasonable time frame. As a result, a stable flow field can evolve and the influence of user-defined initial and boundary conditions can be reduced significantly. In detail, there are no limitations concerning:

- Engine layout:
Any cylinder number, combustion chamber geometry, intake and exhaust system geometry and any injection system (DI, SPI, MPI, etc.) with arbitrary injector geometry can be realized.
- Ignition type:
Spark Ignition, Compression Ignition, Homogeneous Charge Compression Ignition (HCCI) and SACI
- Fuel type:
Gasoline, Diesel, Compressed Natural Gas (CNG), Bio-Fuels.
- Valve and piston motion.

The clear and detailed evaluation of the simulation results includes the display of relevant engine parameters using tables, charts, images and animations.

Table 2. General simulation models

Simulation methodology	Multiphase RANS
Multi-phase flow	Euler/Lagrange
Turbulence	k- ϵ
Combustion – Flame Propagation	two-zone Weller-model adapted to GDI-combustion for spark ignition flame propagation.
Combustion - HCCI	Phenomenological HCCI volume reaction model based on local self-ignition induction time terms.
Time step Δt	Const = 0.5 °CA

Table 2 gives an overview of employed simulation models. For more information, especially on additionally implemented models, the reader may refer to [17].

3D-CFD SINGLE CYLINDER VIRTUAL TEST BENCH

The entire real engine at the test bench has been reproduced in a 3D-CFD model including intake and exhaust system. Figure 5 displays the test bench whereas Figure 6 shows the corresponding simulation model.

The extension of the 3D-CFD domain to both the air tank and the exhaust muffler, as introduced before, remarkably reduces the influence of the boundary conditions. Here, the pressure signals can be assumed as constants - e.g. boost pressure for the intake. On the other hand more simulation cycles (usually 6-8 cycles) must be

performed in order to reach convergence of the scavenging process which takes in any case, e.g. persistent cycle-to-cycle variations in the air consumption into account.

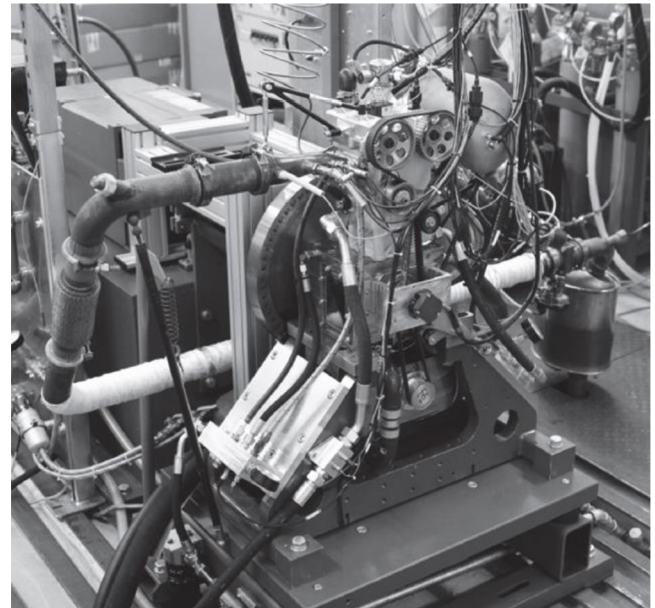


Figure 5. Research engine Z01 at the LVK, Technische Universität München [16].

Although the extended mesh contains approximately 240,000 cells, the simulation of one operating cycle takes no longer than 3 to 4 hours. By comparison, a full engine simulation takes about 9 hours using one CPU (Intel® Xeon® E3-1245 v3), which is more than twice as long. However, compared to conventional 3D-CFD simulations, this is still very fast.

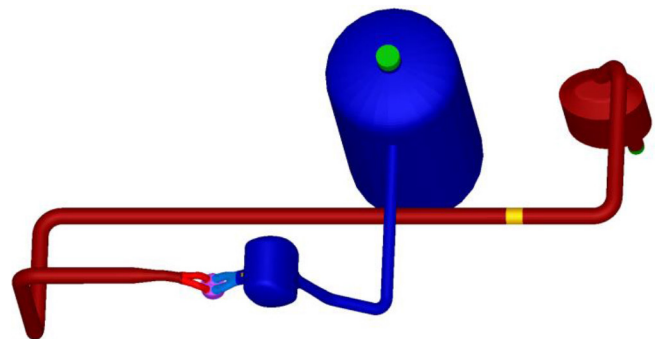


Figure 6. QuickSim modell of research engine Z01 with test bench environment.

PRE-CHAMBER ANALYSIS

This work focuses on the application of the pre-chamber spark plug as an amplifier for SACI because it is versatile and requires little effort as most parts can be sourced from conventional engines. The pre-chamber is described by a number of geometrical parameters, e.g. the volume, the number of holes and their diameter and orientation. It has been found that the parameters of the pre-chamber cannot be optimized independently but need to have the correct proportion to each other and to the combustion chamber geometry. The design goal, however, is a pre-chamber that can be used over a wide range of conditions as a reliable amplifier for the spark plug.