6 Pre-chamber Ignition 1

6.1 Development of a Pre-chamber for Spark Ignition Engines in Vehicle Applications

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Abstract

Future gasoline engines in hybrid powertrains for passenger cars and light commercial vehicles will also continue to require further reductions in fuel consumption and emissions. A major step towards increasing efficiency is represented by lean operation. Here, pre-chamber jet ignition systems, which are already being used successfully in large gas engines, offer the potential of realizing lean burn coupled with lowest nitrogen oxide emissions.

As part of the EU funded EAGLE project, FEV together with the Institute for Internal Combustion Engines at the RWTH Aachen University and other partners, have developed a pre-chamber for an efficient ignition jet process. Based on the objective to present a high efficiency and low emission lean burn engine for use in electrified powertrains, the pre-chamber and the associated cylinder head environment have been developed, calculated, designed and tested on the single cylinder engine test bench. The tools used for the CAE-based design are derived from the standards, but were adapted and extended to the development of the pre-chamber.

The resulting lean engine burn process, with its drastically improved lean burn capability and with low raw emissions, offers excellent conditions for further improving the efficiency of electrified powertrains.

Kurzfassung

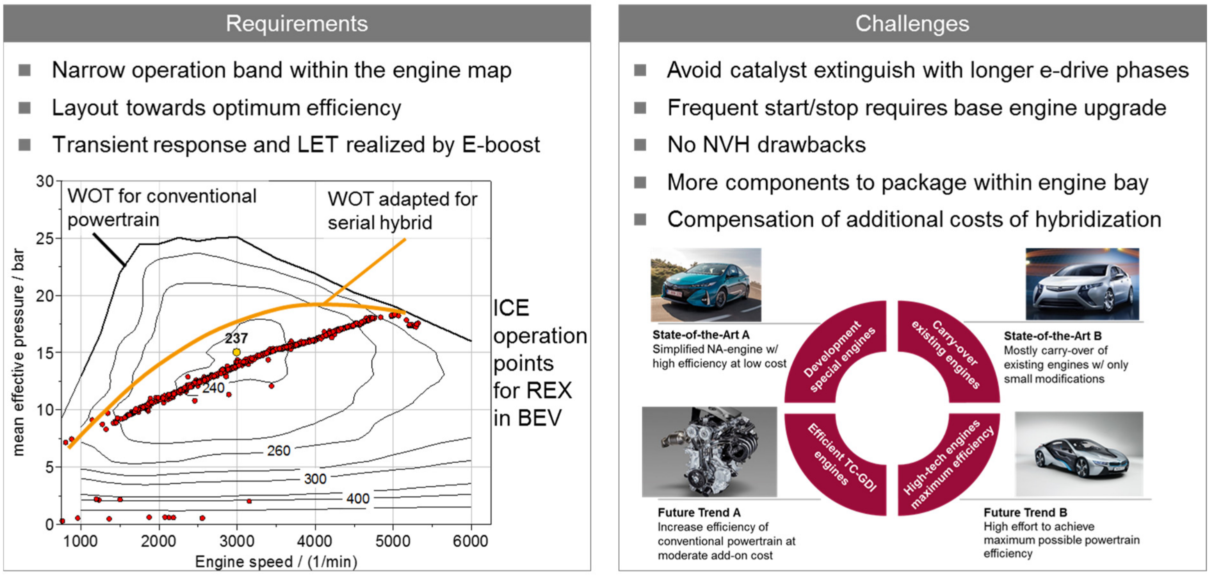
Auch bei zukünftigen Ottomotoren in hybridisierten Antrieben für PKW und leichte Nutzfahrzeuge wird die weitere Verbrauchs- und Emissionsabsenkung gefordert. Einen großen Schritt zur Wirkungsgradsteigerung repräsentiert der Magerbetrieb. Hier bieten Zündstrahlverfahren, wie sie bereits erfolgreich bei großen Gasmotoren eingesetzt werden, das Potenzial, Magerverbrennung gepaart mit niedrigsten Stickoxidemissionen zu realisieren.

FEV hat gemeinsam mit dem Lehrstuhl für Verbrennungskraftmaschinen an der RWTH Aachen und weiteren Partnern im Rahmen des von der EU Co-finanzierten EAGLE-Projekts eine Vorkammer für ein effizientes Zündstrahlverfahren entwickelt. Ausgehend von der Zielsetzung, einen Mager-Ottomotor mit hohem Wirkungsgrad und niedrigen Emissionen zur Anwendung in elektrifizierten Antriebsträngen darzustellen, wurden die Vorkammer und die zugehörige Zylinderkopfumgebung entwickelt, berechnet, konstruiert und am Einzylindermotor-Prüfstand untersucht. Die dabei benutzen Werkzeuge zur CAE-basierten Auslegung entstammen den Standards, wurden jedoch zur Entwicklung der Vorkammer angepasst und erweitert.

Das resultierende ottomotorische Magerbrennverfahren bietet durch seine drastisch verbesserte Magerlauffähigkeit, verbunden mit niedrigen Roh-Emissionen, eine hervorragende Voraussetzungen für die weitere Wirkungsgradverbesserung von elektrifizierten Antriebsträngen.

1 Introduction

Further fuel consumption and emission reduction of combustion engines for passenger cars and light duty vehicles will be required in future. This holds true even in highly electrified powertrains, even though the requirements may significantly differ from today´s conventional applications, see Figure 1. In hybridized powertrains, which e.g. incorporate internal combustion engines as range extenders (REX) in serial or dual-mode configuration, the peak propulsion power demand is generated by the e-machine(s), while the combustion engine provides the base load. In this case, the required engine map is narrowed, while simultaneously other requirements such as e.g. high efficiency are enforced, depending on the specific application.



Requirements

- Narrow operation band within the engine map
- Layout towards optimum efficiency
- Transient response and LET realized by E-boost

Challenges

- Avoid catalyst extinguish with longer e-drive phases
- Frequent start/stop requires base engine upgrade
- No NVH drawbacks
- More components to package within engine bay
- Compensation of additional costs of hybridization

State-of-the-Art A
Simplified NA-engine w/ high efficiency at low cost

State-of-the-Art B
Mostly carry-over of existing engines w/ only small modifications

Future Trend A
Increase efficiency of conventional powertrain at moderate add-on cost

Future Trend B
High effort to achieve maximum possible powertrain efficiency

Figure 1: Requirements and challenges for combustion engines in hybrid powertrains

In a previous project, FEV and TMG have jointly developed a spark-ignition (SI) engine for the future with the aim of high thermal efficiency and low emission [1]. In order to accomplish the high efficiency target, a homogeneous lean burn combustion process has been selected as the technology enabler. As shown, the lean burn limit can be shifted to a relative air fuel ratio of up to 1.9 with still reasonable cyclic variation levels with a significant effort in specific development for lean operation and with the application of a high energy ignition system.

However, to shift the limit further or apply homogeneous lean burn operation in an engine with a smaller bore, the capability of a conventional spark ignition is limited. To enable ultra-lean homogeneous operation with relative air fuel ratios above 2, an ignition system is required, which not only reduces cyclic variations, resulting from the burn delay, but also reduces the burn duration and thus improves the combustion stability.

As flame quenching can be one reason for a slow and unstable combustion, a space ignition system may help to enhance the lean burn capability. With point ignition, as realized by a conventional spark plug, the energy transfer is locally restricted and can only be increased by flow. Furthermore, the flame travel is long. With space ignition, the ignition system itself ignites a larger share of the combustible volume. The energy transfer is higher and the flame travel is reduced.

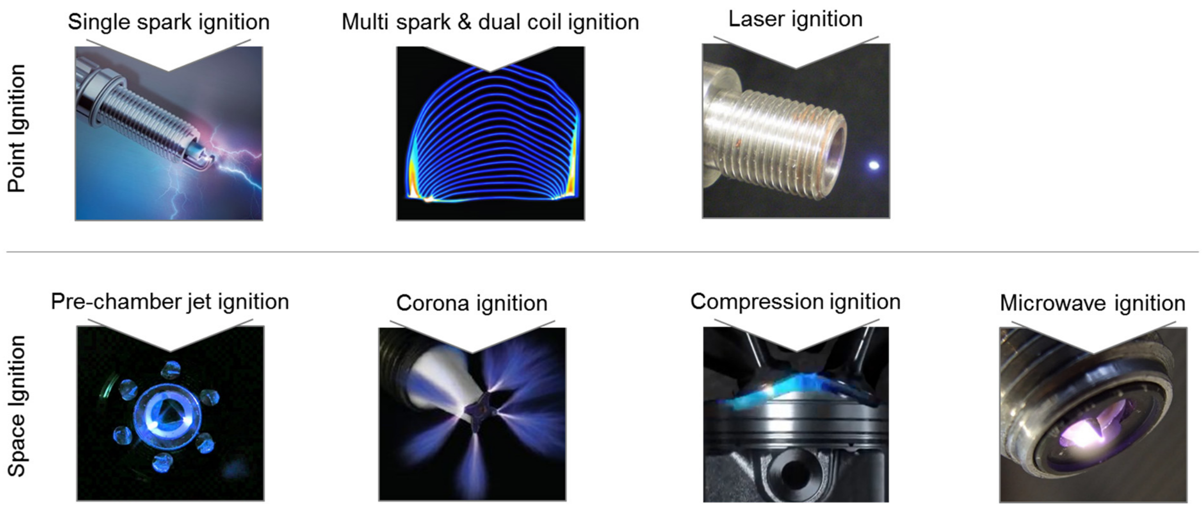


Figure 2: Multiple options to ignite large volumes (pictures by Beru, Federal Mogul, Delphi, Photonics)

As figure 2 indicates, there are various ignition systems for both categories, point and space ignition. Considering the previously discussed challenges of ultra-lean homogenous operation, in particular the pre-chamber ignition offers some important advantages. It supplies a large quantity of turbulent hot gas to the main combustion chamber to ignite the highly diluted mixture. Hence, it is one of the space-igniting techniques [2, 3, 4].

According to the classification shown in figure 3, the mixture in the pre-chamber, which is ignited by a spark, can be realized in two different ways: Whereas in so called passive pre-chambers, the air-fuel-mixture around the spark plug is mainly created during the compression stroke by the charge entering from main combustion chamber, active pre-chambers do have an additional external fuel feeding.

For ultra-lean conditions, the active pre-chamber operation is favored for external fuel enrichment allowing a stoichiometric or slightly rich mixture in the pre-chamber, without compromising the homogeneous lean mixture formation in the main combustion chamber. The dosing can be done either by a check valve, commonly used in commercial gas engines, or by a separate injector. Active pre-chambers can be supplied with either liquid or gaseous fuels.

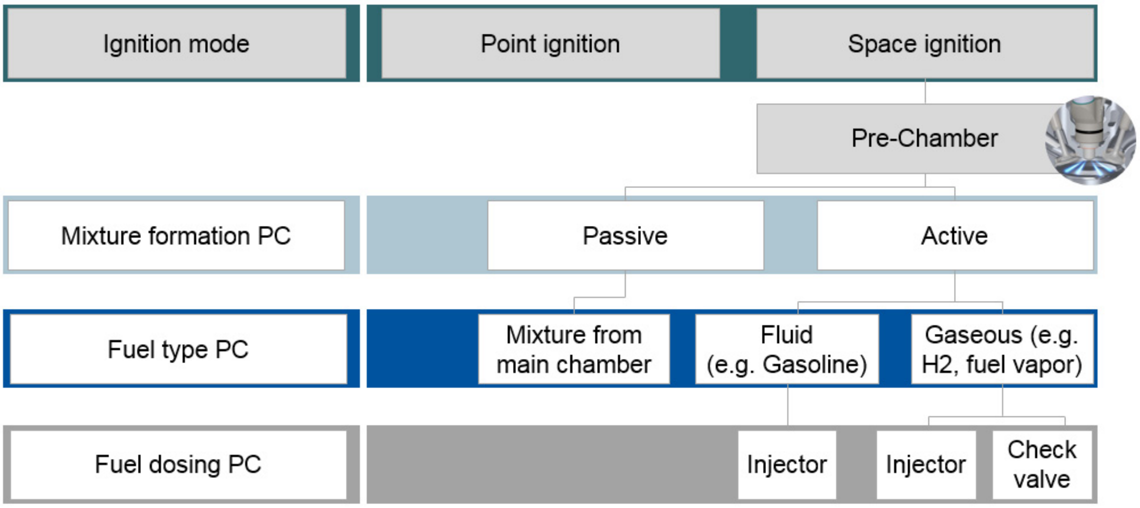


Figure 3: Classification of different pre-chamber configurations

Compressed Natural Gas (CNG) as a gaseous fuel is already being successfully used for both, passenger car gas engines as well as commercial gas engines. In comparison to liquid fuels, gaseous fuels have some advantages with regard to mixture formation. For the fuel supply to an active pre-chamber there are examples using fuel vapor [5], a pre-mixed fuel / air mixture [2, 4], methane [2] or hydrogen [6]. Bearing in mind that the powertrain should be installed in a vehicle, reasonable applications for passenger cars might differ from the ones for commercial engine applications. Fuel vapor could be generated onboard by a vaporizer or taken from canister purge. Hydrogen could be generated by fuel reforming, and CNG could be considered for BI-fuel or CNG operated engines.

However, considering the fuel supply infrastructure for passenger cars, liquid injection into the pre-chamber remains a very attractive option, although there are challenges for the mixture formation and risks with regard to particulate emissions to be considered.

2 Boundary Conditions

For the application in a hybrid powertrain, driving cycle simulations have indicated that BFSC at high load is most relevant for CO2-Emissions. Therefore, emphasis for the layout of the engine is placed on these operation points, while keeping in mind that also low load and idle operation conditions are to be considered.

In order to achieve low engine raw emissions as well as high efficiency, ultra-lean operation with a relative air-fuel-ratio of 2 and above is aimed for the entire engine operation map. As this should be achieved with a homogeneous mixture in the combustion chamber, enriching strategies in the pre-chamber by the spray target of the main chamber injector were not taken into account.

An active pre-chamber was chosen to be integrated in the all new cylinder head to achieve the above mentioned project targets. The active pre-chamber is supplied with either gasoline fuel or gaseous fuels. In any case, a separate injector is provided in the pre-chamber for this purpose. This allows a precise fuel metering as well as flexible adjustment of the injection timing.

All experimental investigations were carried out with a single cylinder engine (SCE) at the Institute for Combustion Engines (VKA) of the RWTH Aachen University. The main engine specifications are listed in table 1.

The cylinder head design allows realization of geometric compression ratios between 11 and 16.

Table 1: Single cylinder engine specification

Bore	75 mm
Stroke	90.5 mm
Stroke / Bore Ratio	1.206
Displacement	399 cm³
Peak pressure capability	170 bar
Geometrical Compression Ratio	11-16
Injection System	DI, 350 bar, lateral injector
Fuel	RON 98
Active pre-chamber enrichment with	Gasoline or gaseous fuel (CNG, H2)

The long stroke of 90.5 mm and the arrangement of the valves, combined with the intake port and the combustion chamber shape, generate a charge motion level, which is comparable to state-of-the-art turbo-charged engines.

For an optimum central position of the ignition system in the combustion chamber, a lateral DI injector position was chosen. To allow a fair comparison between the pre-chamber and the conventional ignition system, the engine can either be operated with a conventional ignition system or with the pre-chamber ignition system. The pre-chamber assembly in the new cylinder head is displayed in Figure 4.

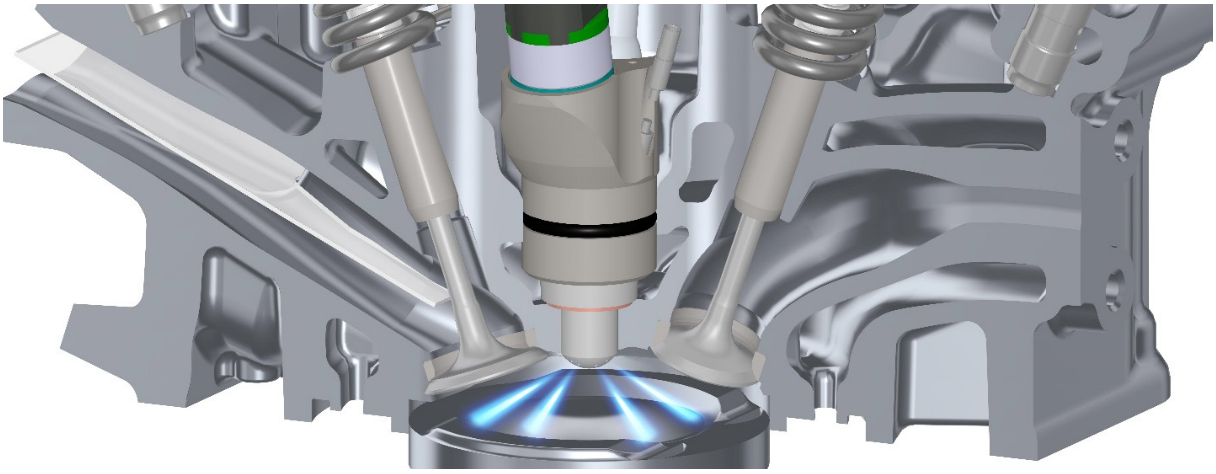
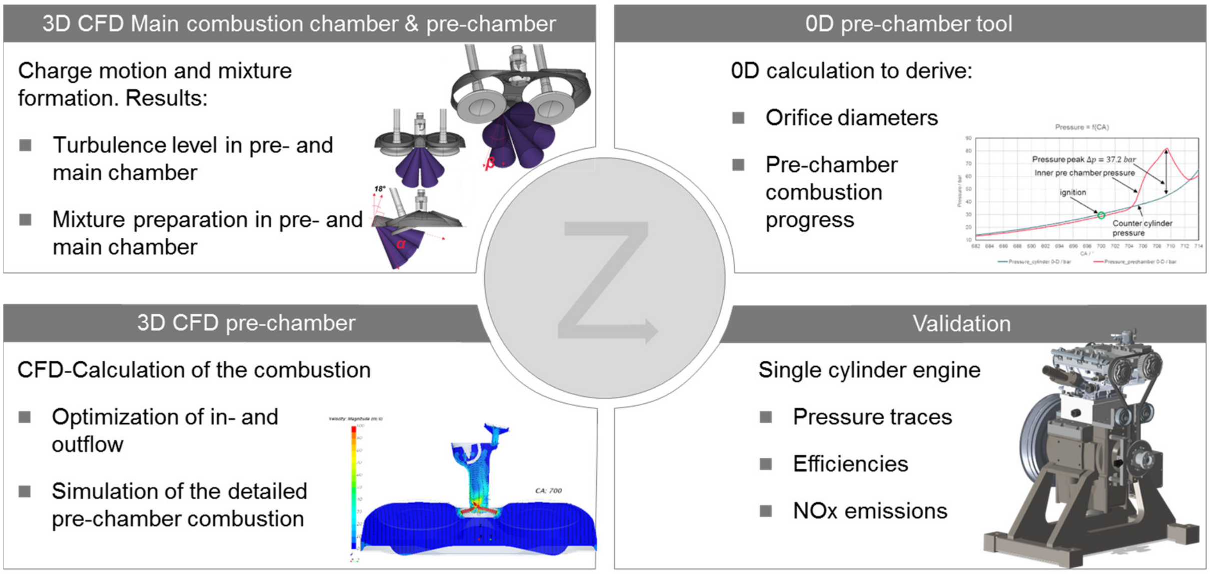


Figure 4: SCE cylinder head with pre-chamber

3 Layout Process

The pre-chamber design was performed with the help of various simulation tools, see figure 5. At first, 3D CFD simulations of the flow and mixture formation were carried out in order to obtain an initial estimate of the turbulence and mixing levels in the pre-chamber. These data serve as input for 0D simulations of the pre-chamber. Based on these simulations, basic parameters like hole size diameters, number of holes, chamber volume etc. can be pre-determined. Purposeful parameter sets are then selected and refined with CFD simulations including combustion modelling. The results are finally validated in the single cylinder engine test program.



3D CFD Main combustion chamber & pre-chamber

Charge motion and mixture formation. Results:

- Turbulence level in pre- and main chamber
- Mixture preparation in pre- and main chamber

0D pre-chamber tool

0D calculation to derive:

- Orifice diameters
- Pre-chamber combustion progress

3D CFD pre-chamber

CFD-Calculation of the combustion

- Optimization of in- and outflow
- Simulation of the detailed pre-chamber combustion

Validation

Single cylinder engine

- Pressure traces
- Efficiencies
- NOx emissions

Figure 5: Development of the pre-chamber using 0D and 3D simulation tools

The design optimum found for the location of the 4-hole pre-chamber has an offset in lateral direction and height, see Figure 6. This supports the rotation of the gas flows entering the pre-chamber and allows them to move along the longitudinal axis without significant dissipation losses. Compared to a conventional pre-chamber design, the turbulence level can be more than doubled by this which significantly improves the mixture formation in the pre-chamber. This results in a much faster combustion and finally in a larger penetrating power of the hot gas jets entering the main combustion chamber.

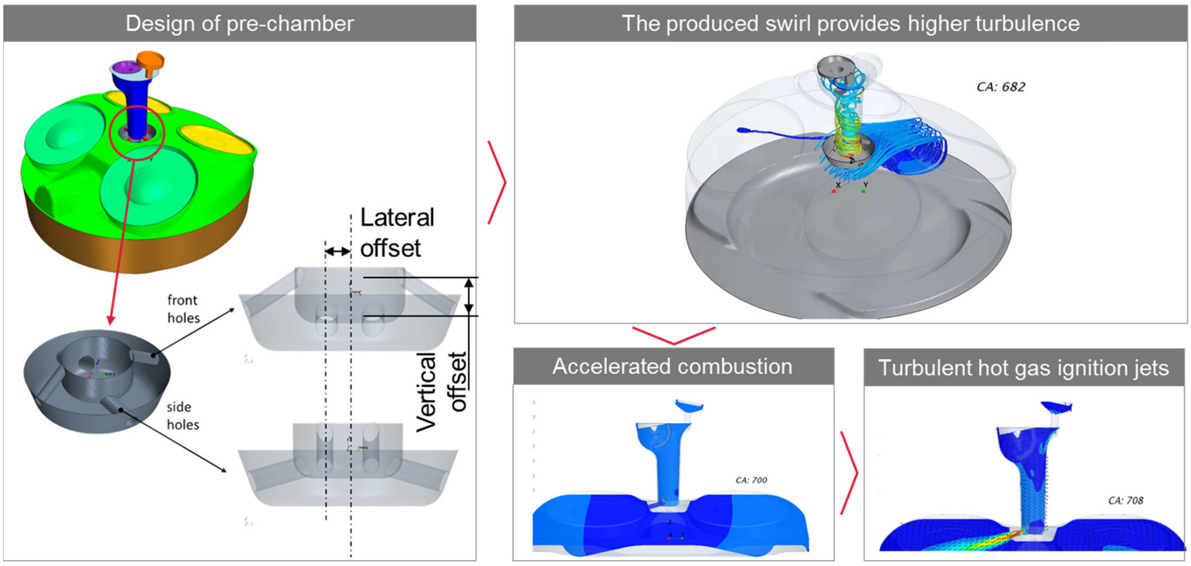


Figure 6: Optimized pre-chamber design

For the ultimate validation of the layout process described above, 3 pre-chamber designs were selected for manufacturing, see Figure 7. These pre-chambers have a different arrangement of the jet holes, but the same pre-chamber inner volume (~ 3 % of compression volume). Also, the overall jet hole cross section was kept constant for all variants. This means the ratio of the spray hole areas and the pre-chamber volume (A/V) remains constant (~0.03 cm^{-1}).

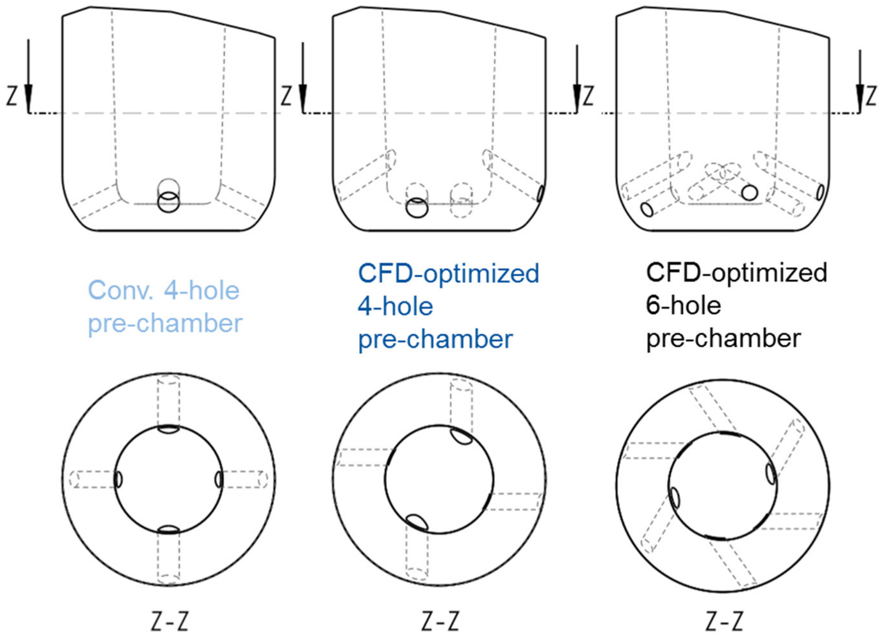


Figure 7: Tested pre-chamber jet hole designs

While the conventional pre-chamber layout only has 4 holes oriented perpendicular to outer round surface, the CFD optimized 4-hole pre-chamber has the same holes with a small side and a significant height offset to introduce a swirl in the pre-chamber. A similar approach was used for the CFD optimized 6-hole pre-chamber. For both 4-hole and the 6-hole pre-chambers, the orientation of the holes has been designed in such a way that the swirl is supporting the turbulent kinetic energy level at the spark plug during the charging phase of the pre-chamber, while during the discharging phase, the turbulent jets have a long free travel to ignite the mixture in the main combustion chamber as homogeneously as possible.

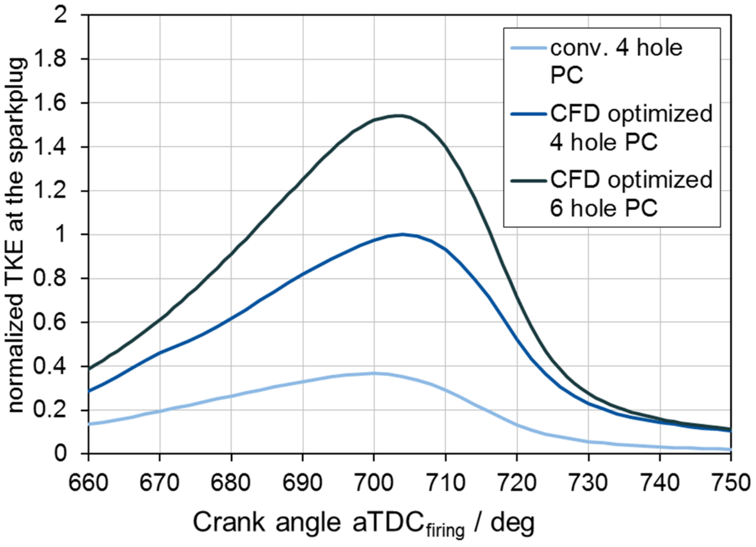


Figure 8: Normalized turbulent kinetic energy at the spark plug in the 3 selected pre-chambers

The turbulent kinetic energy in the pre-chamber at the spark plug is the smallest for the conventional pre-chamber, see Figure 8. The CFD-optimized 6-hole pre-chamber generates a peak turbulent kinetic energy level which is roughly 50% higher than the maximal value of the CFD-optimized 4-hole pre-chamber. It can be expected that this version should the most support the mixture formation in the pre-chamber and reduce the burn duration. This should maximize the potential for lean burn operation. However, the very turbulent charge motion complicates the inflammation in the pre-chamber and thus places higher demands on the ignition system.

4 Engine Test Results

The following results have been obtained on a single cylinder engine test bench. The operation points investigated are highlighted in green in Figure 9. The following analysis will focus on 3 operation points, which are most relevant for operation in hybrid powertrain applications:

- 2000 1/min, 12bar (IMEP)
- 2000 1/min, 15 bar (IMEP)
- 4000 1/min, 16 bar (IMEP)

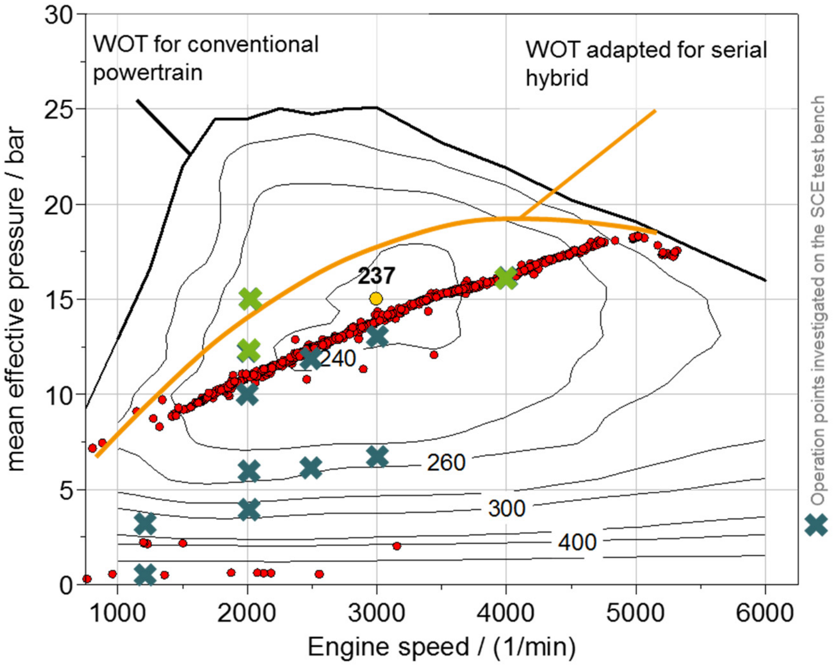


Figure 9: Operation points of pre-chamber ignition system on SCE test bench

For all results shown, the engine operated under similar boundary conditions. An MFB50% sweep has shown that the commonly used MFB50% timing at 7-8° CA aTDC is also the optimum for engine efficiency at ultra-lean operating conditions with the presented pre-chambers. Therefore, the spark advance was set to 7-8° CA aTDC for MFB50%, if there was no knocking limitation which required retarded ignition timing.
The valve timing of the conventional valve lift profiles was set to a small valve overlap. All results with pre-chamber operation were realized with a geometric compression ratio of 13.0. For conventional spark plug operation, the compression ratio was slightly

higher. The relative air fuel ratio was determined via exhaust gas measurement according to Spindt [7, 8]. It represents the global value as it considers main combustion chamber and pre-chamber fuel. For the determination of the engine efficiency results, also both fuel fractions were taken into account.

4.1 Comparison of different pre-chambers

With a small amount of gas injected into the pre-chamber, the lean burn capability of the engine can already be improved. Figure 10 compares the CFD-optimized 4-hole pre-chamber with a high turbulence level due to swirl introduced with a conventional four hole pre-chamber. At 2000 1/min, 15 bar (IMEP) the burn delay of the non-optimized pre-chamber is following the same trend as the spark ignited engine. As a result the lean burn limit can be shifted from a relative air-fuel-ratio of 1.6 to 1.8 only.
Dosing the same small amount of CNG into the optimized pre-chamber with 4 jet holes, while keeping all other boundaries constant, the lean burn limit can be extended to 2.2. Although the hydrocarbon emissions are increasing towards ultra-lean conditions, it is possible to still achieve the same level of hydrocarbon emissions with the pre-chamber at these ultra-lean conditions as with the spark ignited operation at stoichiometric conditions.
With all pre-chamber variants, the burn duration (5%-90%) can be reduced by about 5 ° crank angle in stoichiometric conditions. In lean condition, these advantages improve further. When spark plug operated, the burn duration increases with increasing mixture dilution, in the case of pre-chamber operation, an almost constant burn duration over the entire air-fuel-ratio range is maintained.

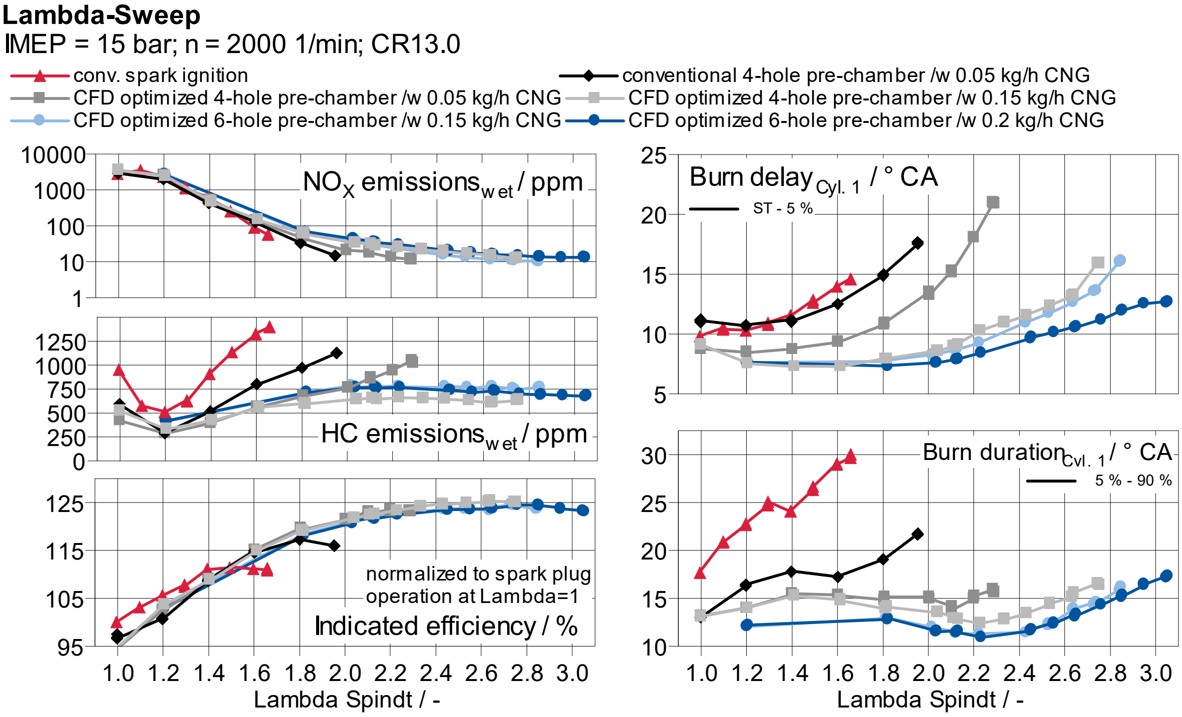


Figure 10: Emissions, efficiency, burn delay and duration for different configurations at 2000 1/min, 15 bar (IMEP)

Increasing the fuel amount injected into the pre-chamber from 0.05 kg/h (~0.83 mg/cycle) up to 0.15 kg/h (~2.5 mg/cycle), the lean burn limit can be shifted even further with the same CFD-optimized 4-hole pre-chamber. While the burn delay is significantly reduced, the burn duration is the same up to relative air-fuel-ratio 1.8 and only slightly reduced above it. However, still a remarkable lean global relative air-fuel-ratio of 2.7 can be achieved.

Increasing the fuel injection quantities into the CFD-optimized 4-hole pre-chamber to a mass flow of 0.2 kg/h (~3.3 mg/cycle), is not giving any benefit with regard to lean burn capability or stability, compared to operation with 0.15 kg/h CNG mass flow.

Further lean burn potential can be exploited with the CFD-optimized 6-hole pre-chamber. With the higher turbulent kinetic energy level at the spark plug (see figure 8), a better tolerance at high CNG mass flow is achieved. While the 6-hole pre-chamber achieves similar burn delay and lean burn capability as the 4-hole pre-chamber with a CNG mass flow of 0.15 kg/h, it provides a slightly reduced burn duration due to the increased ignited volume of the 6-hole pre-chamber, compared to 4-hole pre-chamber. The burn duration is almost the same, even if the pre-chamber is supplied with 0.2 kg/h. However, at higher relative air-fuel-ratios, the burn delay is reduced.

Considering high efficiency and low engine out emissions as a target for such an engine application, the recommended operating range should be set between relative air-fuel-ratios of 2.3 and 2.8. Within this range, the hydrocarbon (HC) emissions as well as the nitrogen oxide (NOx) emissions are on a constant low level. Whereas the HC-Emissions with 750 ppm are clearly below the HC emission of the spark plug operated engine at stoichiometric conditions, the NOx emissions are in a range of only 25 – 10 ppm.

The engine was knock limited with spark plug and pre-chamber ignition system at stoichiometric conditions, but also in lean conditions up to Lambda 2.2. Thus, the efficiency is drastically increased towards lean conditions. However, also beyond Lambda 2.2, the overall efficiency still raises slightly so that the sweet point is reached at a relative air fuel ratio of 2.5 for the 4-hole pre-chamber and at a relative air fuel ratio of 2.7 for the 6-hole pre-chamber. As the efficiency drop would be rather small, if the engine is not operated exactly at the sweet spot, the named range for operation seems to be reasonable.

Figure 11 shows ignition and burn stability for the variations discussed. The CFD-optimized 4-hole pre-chamber offers a good stability with comparable low CNG mass flow of 0.05 kg/h, until reaching a relative air-fuel-ratio of 2. With the 6-hole pre-chamber, at 0.2 kg/h CNG mass flow the standard deviation for MFB05, MFB50 and MFB90 can be kept on a very low level even for a relative air-fuel-ratio of 3. With regard to ignition and combustion stability, the pre-chamber ignition system provides a wide operating range.

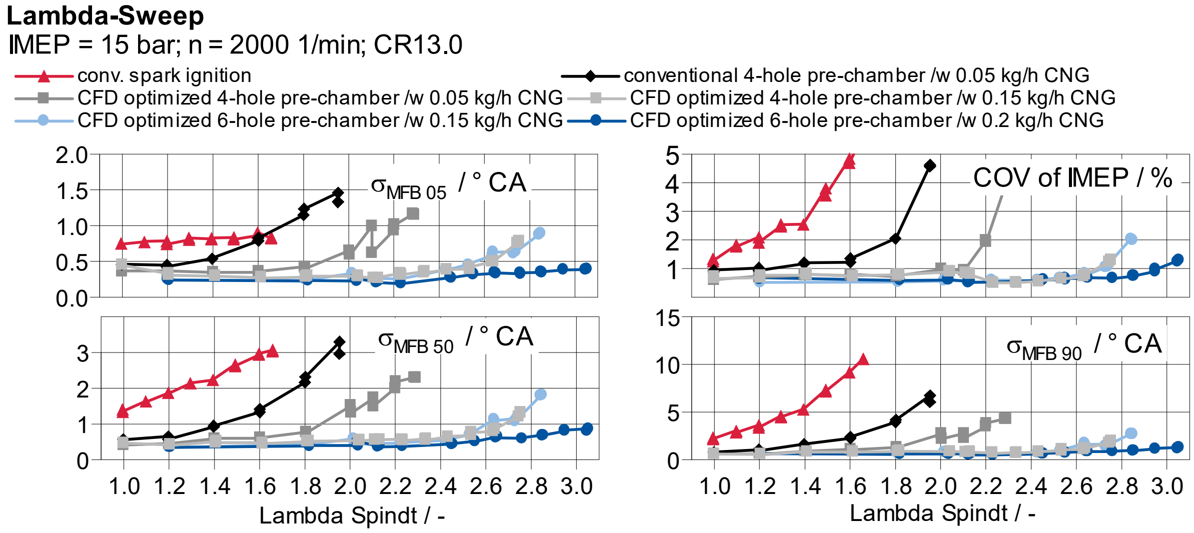


Figure 11: Ignition and burn stability for different configurations at 2000 1/min, 15 bar (IMEP))

To also cover higher power demands, the ultra-lean combustion should be capable of higher engine speeds and loads. Therefore, the operation point n = 4000 1/min and IMEP = 16 bar was investigated. Usually, combustion of highly diluted mixture becomes more critical at higher speeds, as the spark advance demand increases with the engine speed.

As shown in figure 12, the lean burn capability can be increased significantly by the application of a pre-chamber ignition system. In comparison to the conventional spark plug operated engine, the lean burn limit can be shifted from a relative air fuel ratio of 1.6 to 2.3 or 2.4 with a CNG mass flow of 0.2 kg/h (~1.67 mg/cycle). Following the same trend as for the 2000 1/min / IMEP = 15 bar operation point, the burn duration is shortest for the 6-hole pre-chamber. But also with the 4-hole versions, the burn duration can significantly be reduced, compared to the spark plug mode. The burn delay is, like for lower speeds, mainly defined by the amount of fuel with is injected into the pre-chamber.

Between a relative air-fuel-ratio of 2.0 and 2.4, an almost constant engine efficiency and constant HC emission concentration can be realized. Also the NOx emissions are on a low level between 60 and 25 ppm. Of course, higher relative air-fuel-ratios yield in a higher (emission) mass flow.

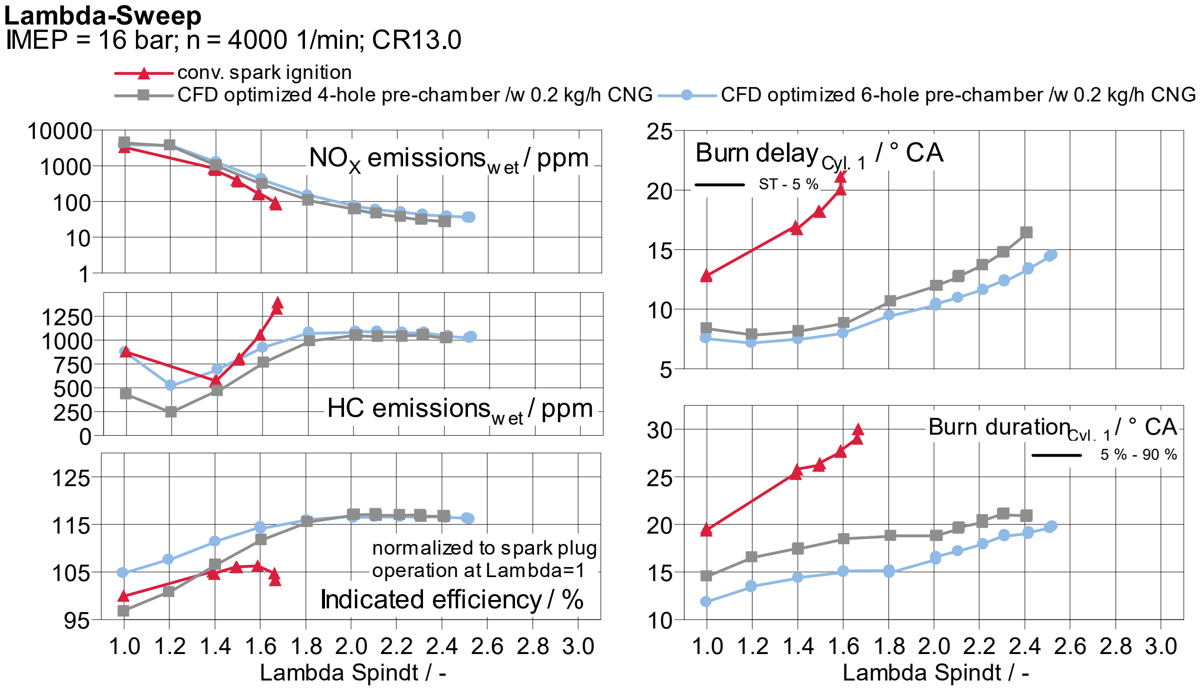


Figure 12: Emissions, efficiency, burn delay and duration for different configurations at 4000 1/min, 16 bar (IMEP)

4.2 The influence of different pre-chamber fuels

The results discussed so far have been created with CNG fuel supply for the pre-chamber ignition system. However, CNG might not always be the first choice for the pre-chamber fuel supply, as it requires a second fuel tank and a specific gas injection system in the vehicle.

From a fuel supply infrastructural point of view, direct injection of gasoline into the pre-chamber is the most obvious solution. This however involves some challenges, too: The spray target, the linked mixture formation as well as the dosing of the very small amount of liquid fuel into the pre-chamber provide very unusual boundary conditions for the layout of a direct fuel injection system.

To round off the picture, the injection of hydrogen has also been investigated. The results are shown in comparison to CNG and liquid gasoline injection in figure 13.

Compared to CNG, hydrogen and gasoline have a shorter burn duration in the pre-chamber. Thus, a higher pressure difference between pre-chamber and main combustion chamber is created. While the burn delay in lean operation conditions is noticeably affected by this fact, the burn duration shows no clear trend. The displayed differences are in the range of measurement and operation accuracy.

Overall, the lean burn capability is best, when gasoline is supplied to the pre-chamber system, although a long burn duration results at a relative air-fuel-ratio of 2.6. A stoichiometric operation of this pre-chamber is not possible with 0.075 kg/h gasoline fuel mass flow. For these operation points, even a passive operation of the pre-chamber is an alternative, as the pre-chamber fuel is not really required for the ignition and consequentially reduces engine efficiency.

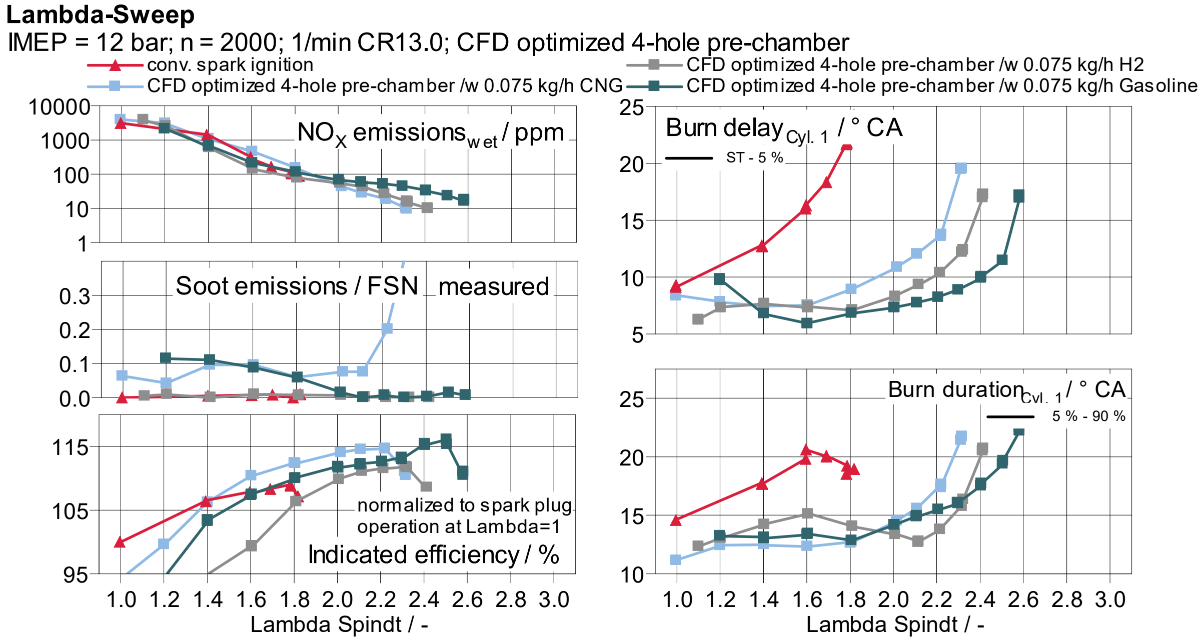


Figure 13: Emissions, efficiency, burn delay and duration for different pre-chamber fuels at 2000 1/min, 12 bar (IMEP)

Although the operation with hydrogen indicates similar advantages with regard to burn delay and burn duration, the overall efficiency is significantly lower. This is related to the higher calorific value of hydrogen. As most of the pre-chamber fuel energy is used for ignition of the mixture in the main chamber, and only a small share is contributing to the work performed onto the piston, the engine has a higher efficiency, when the same burn delay and burn duration are achieved at the same relative air fuel ratio with less energy consumed in the pre-chamber.

Nevertheless, the use of hydrogen has strong advantages with regard to particulate emissions. While CNG and gasoline fuel supply to the pre-chamber result in local areas with rich air fuel ratios, where some particulate emissions are being created, hydrogen supplied pre-chamber operation creates very low particulate emissions over the entire relative air-fuel-ratio range.

With gasoline fueling into the pre-chamber, the particulate emissions are significantly reduced for highly diluted mixtures, indicating that higher pressure and the highly diluted mixture are supporting mixture formation in the pre-chamber in leaner conditions.

5 Conclusion

Based on the objective of demonstrating a high efficiency and low emission ultra-lean burn engine for use in electrified powertrains, a suitable pre-chamber space ignition system with the associated cylinder head environment have been developed and investigated experimentally on a single cylinder engine test bench. Standard CAE-tools, which were used for the development, were adapted and expanded with regard to the specific requirements of the pre-chamber configuration.

It could be shown that smart use of CFD-tools allowed pre-optimization towards a high maturity level. It turned out that the jet hole configuration is of crucial significance. With the optimized configuration, a large air/fuel-ratio window of stable combustion can be realized, providing excellent pre-conditions for calibration. The fuel introduced into the pre-chamber (CNG, gasoline or hydrogen) has only a relative small influence on the overall operating behavior.

6 Outlook

The resulting engine lean burn process, with its drastically improved lean burn capability and low raw emissions, provides excellent preconditions for further improving the efficiency of electrified powertrains. Next steps should focus on:

- Further insight into the extreme lean combustion process
- Assessment of the emission behavior towards adapted requirements for the exhaust aftertreatment system
- Further definition of an ultra-lean combustion system for automotive application

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