ADVANCED COMBUSTION CHAMBER FOR HCCI TECHNOLOGY APPLICATION

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ABSTRACT

Engines using HCCI technology are potentially significantly more efficient compared to classic spark-ignition engines. Improved thermal efficiency is the result of several factors such as elimination of gas throttling losses, shorter burning time, higher compression ratios and lower heat transfer losses. The upper limit of the compression ratio is the occurrence of detonations. As part of the development of lean combustion, there are several technologies that are being developed to achieve long-term reliability. The solution is to create fuel-rich zones inside the chamber, e.g., using fuel stratification. Therefore, a "Combustion chamber with the implementation of homogenization and controlled self-ignition of the fuel mixture using compression" was designed, for which a patent was granted. The design was based on the assumption that a stratified charge engine creates a richer fuel mixture near the spark and a leaner mixture throughout the rest of the combustion chamber. The patent system was subjected to a simulation analysis, which confirmed a significant yield for emission reduction.

KEYWORDS

Advanced combustion chamber, emission, HCCI technology

1 INTRODUCTION

The automotive industry has recently been undergoing a significant transformation, largely influenced by the industrial policies of European Union member countries. This transformation is geared towards achieving a sustainable, renewable, and low-carbon economy. The aim is to decrease transportation-related emissions and enhance the contribution of industrial production to the EU's economy. This transition poses several challenges, including digitalization, the shift to electric vehicles, the introduction of new propulsion technologies, and the adoption of alternative energy sources [Brestovic 2014, Krenicky 2018].

Facing stringent emission standards, car manufacturers often find it challenging to comply. This challenge compels them to invest heavily in new engine designs and emission reduction strategies, despite uncertain outcomes. Therefore, the focus of current research and development is on technologies that optimize the efficiency of combustion engines while significantly reducing nitrogen oxide emissions. An example of such technology is SPCCI, which utilizes spark-controlled homogeneous combustion. This method combines compression and spark to achieve a uniform combustion of the fuel mixture throughout the cylinder's combustion chamber, leading to more efficient fuel use, enhanced combustion quality, and ultimately, cleaner emissions [Brennan 2008, Barbouchi 2009].

2 ARCHITECTURAL CONFIGURATION OF AN INTERNAL COMBUSTION ENGINE INCORPORATING SPCCI TECHNOLOGY

There are various methods being explored to control the timing of Homogeneous Charge Compression Ignition (HCCI) combustion [Jennischen 2003, Isik 2023]. One approach is adjusting the temperature of the mixture to influence combustion timing. This can be achieved through several means, such as altering valve timing, capturing residual exhaust gases, varying the compression ratio, using variable Exhaust Gas Recirculation (EGR) methods, setting fixed in-cylinder injection timings, modulating intake temperatures, implementing water injection, or adjusting coolant temperatures. Another approach to control ignition timing is by modifying the reactivity of the mixture, which can also be done in various ways, including through fuel modulation, fuel stratification, adding fuel additives, and applying specific control mechanisms [Homisin 2016, Malakova 2020].

To tackle these challenges, a range of solutions has been proposed. One such solution is starting the engine in a conventional mode and then transitioning to SPCCI mode after a brief warm-up period. Other solutions include using different types of fuels or fuel additives and increasing the engine's compression ratio.

The development of SPCCI technology has garnered investments from several automotive companies, emphasizing the importance of this direction in light of the challenges faced by current combustion engines. When integrated with cutting-edge technologies like direct injection, electronic camshaft timing, variable valve lift, and cylinder pressure measurement, SPCCI is anticipated to provide substantial fuel efficiency while adhering to future emission norms. SPCCI aims to combine the high-efficiency combustion of diesel engines with the high-performance characteristics of gasoline engines [Olsson 2001, Puskar 2022].

In classical combustion, the reaction of fuel with the oxygen in the air can be represented as:

$$Fuel + x(O_2 + 3{,}76N_2) \rightarrow yCO_2 + zH_2O \qquad (1)$$

Here, $(O_2 + 3{,}76N_2)$ denotes air, which is composed of about 21% oxygen and 79% nitrogen. The coefficients x, y, and z vary depending on the specific fuel and the fuel/air equivalence ratio in the reaction. The equivalence ratio (∅) is defined as:

$$\emptyset = \frac{{}^{m_{fuel}}/_{m_{air}}}{\left({}^{m_{fuel}}/_{m_{air}}\right)_{STECH}} = \frac{1}{\lambda} \qquad (2)$$

In this equation, the denominator represents the stoichiometric ratio of fuel and air required for complete combustion of all fuel and oxygen molecules. An equivalence ratio (∅) of 1 indicates a stoichiometric mixture, less than 1 indicates a lean mixture (excess air), and greater than 1 indicates a rich mixture (excess fuel). The air-fuel equivalence ratio (λ) is the ratio of the actual air-fuel ratio (AFR) to the stoichiometric value for a given mixture. λ = 1.0 signifies a stoichiometric mixture, λ < 1.0 a rich mixture, and λ > 1.0 a lean mixture.

$$\lambda = \frac{AFR}{AFR_{STECH}} \qquad (3)$$

Table 1 provides the stoichiometric air-fuel ratio, denoted as λ, for various commonly used fuels.

Table 1. Stoichiometric ratios of air to fuel for various common fuels.

Fuel	AFR
Methane	17.2
Propane	15.7
Butane	15.5
Gasoline	14.5
Ethanol	9.0

In the standard combustion process using a stoichiometric mix, the spreading flame converts combustion energy into heat and work to move the piston [Rodriguez 2022 and 2023]. In lean combustion, there's a considerably higher air-to-fuel ratio, which means diatomic molecules such as N_2 and O_2, that are more agile, are utilized in greater proportions. As a result, burning the same volume of fuel leads to a faster increase in pressure, enabling more work to be extracted, thereby elevating the thermal efficiency of this approach [Puskar 2017].

Lean combustion has several notable effects:

1. It increases the specific heat ratio due to a higher air-to-fuel ratio.
2. A decrease in combustion temperature reduces the temperature disparity between the gas and the wall, thereby lowering heat transfer and cooling losses.
3. Lean combustion reduces throttle losses compared to λ=1 operation by allowing more intake air for the same torque output, thus enhancing thermal efficiency significantly.

A specialized "Combustion chamber with implementation of homogenization and controlled self-ignition of the fuel mixture using compression" has been designed to address these aspects, earning a patent. This design is based on the principle that a stratified charge engine generates a richer fuel mixture near the spark plug and a leaner mixture in the rest of the combustion chamber [Toman 2017, Puskar 2021]. The rich mixture ignites first, which then ignites the leaner mixture, enabling the engine to efficiently use a leaner mixture while ensuring complete combustion.

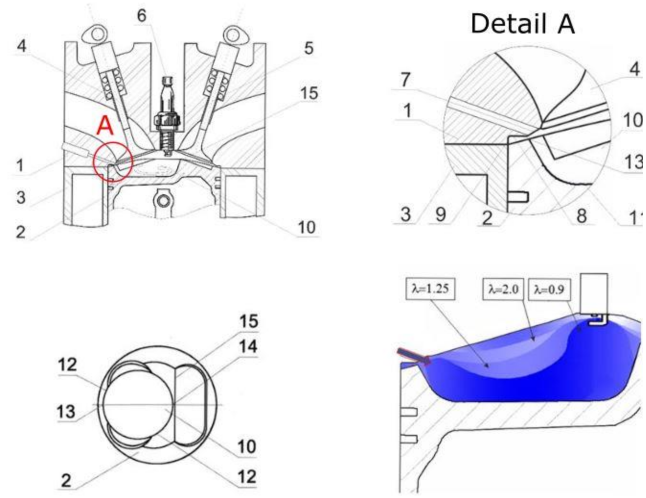
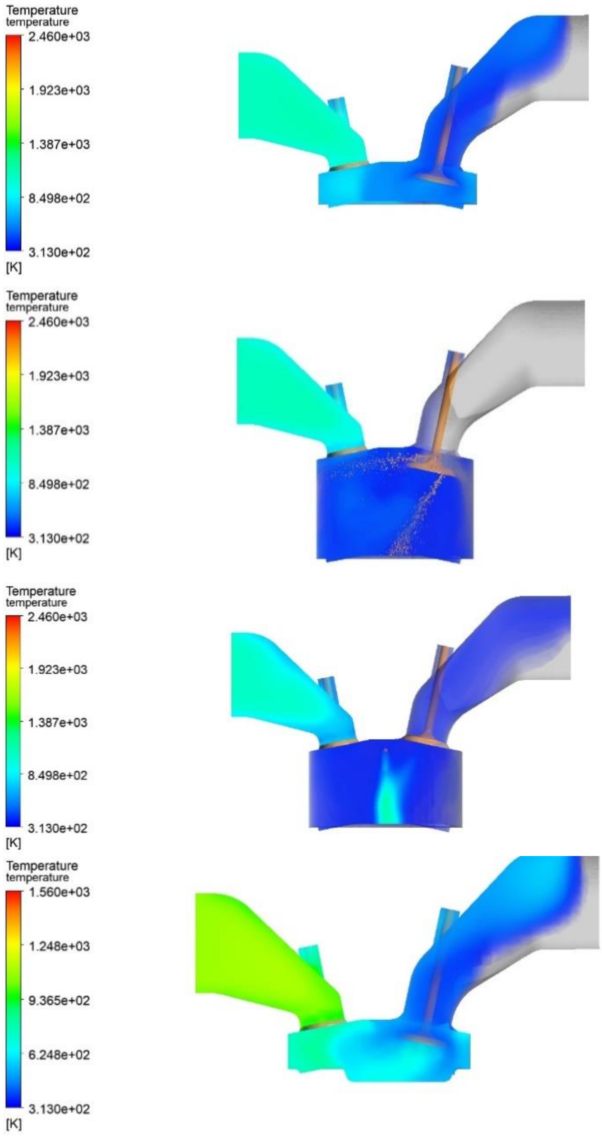


Figure 1. Combustion chamber incorporating homogenization and controlled compression-based self-ignition of the fuel mixture.

Fig. 1 illustrates this combustion chamber design, showcasing the method of mixture stratification during lean combustion based on the shape of the homogenizing part of the piston and the injection angle. The homogenizing part functions as a chamber near the inlet channel, and its design ensures that injected fuel landing on the piston's homogenizing curve flows under the spark plug, preventing fuel film formation on the piston bottom and ensuring a rich fuel supply under the spark plug [Kuznetsov 2020]. This stratification creates multiple zones with varying excess air coefficients λ.

3 RESULTS

The suggested approach was executed and assessed using 3D simulation software, concurrently with a simulation of the conventional method [Thomas 2022, Zhou 2022]. The outcomes of both simulations were juxtaposed, particularly in terms of work characteristics and emission improvements. The process analysis within the combustion chamber focused on temperature. Fig. 2 displays this temperature analysis in the combustion chamber, featuring the system developed for homogenization and controlled self-ignition of the fuel mixture through compression, as well as a typical piston used in standard engines.



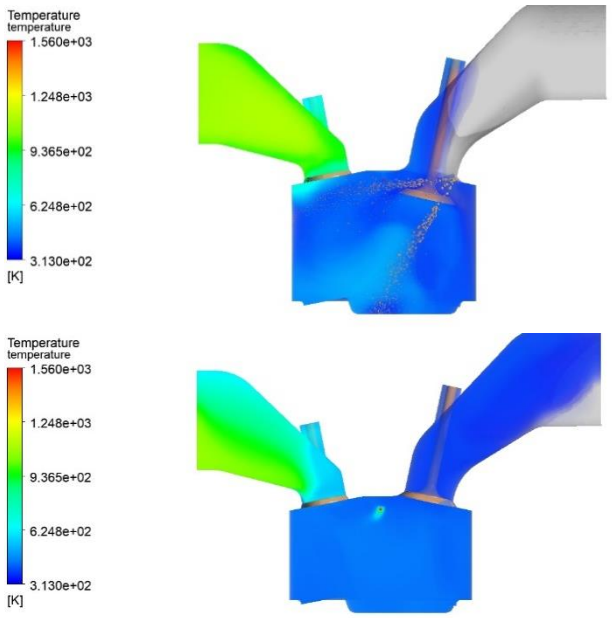


Figure 2. Examination of the working temperature in a combustion chamber with a standard piston (left); Investigation of the working temperature in a combustion chamber equipped with homogenization and controlled self-ignition of the fuel mixture using compression and a sparkplug (right)

Fig. 3 shows the variation of working temperature within the combustion chamber relative to the crankshaft position, where upper curve represents the standard solution and lower curve indicates the specially designed combustion chamber.

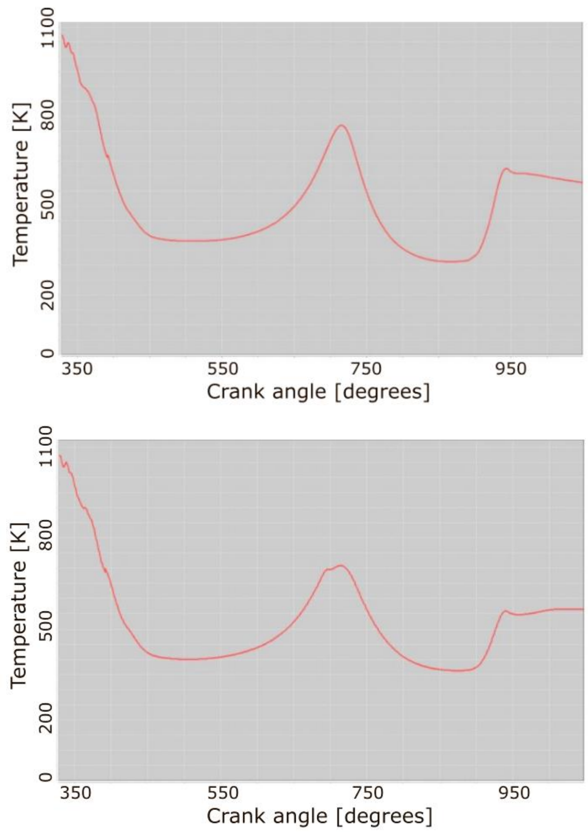


Figure 3. The variation of working temperature within the combustion chamber relative to the crankshaft position (upper curve represents the standard solution, lower curve indicates the specially designed combustion chamber).

Results of the nitrogen oxide emissions examination in relation to the crankshaft position are presented on Fig. 4, where upper curve represents the standard solution and lower curve represents the newly designed combustion chamber. The evaluation of carbon monoxide (CO) emissions based on the crankshaft position is shown on Fig. 5, where upper curve corresponds to the standard solution and lower curve pertains to the newly designed combustion chamber.

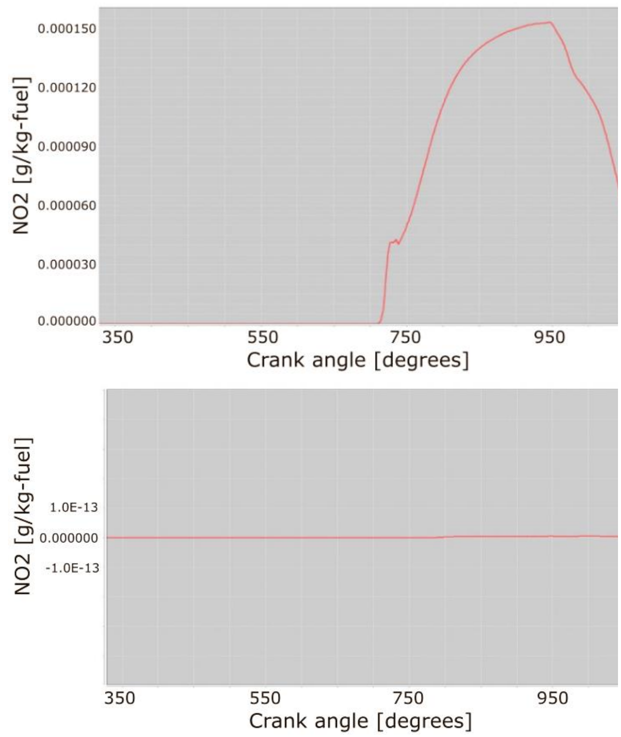


Figure 4. Examination of nitrogen oxide emissions in relation to the crankshaft position (upper curve for the standard solution, lower curve for the designed combustion chamber)

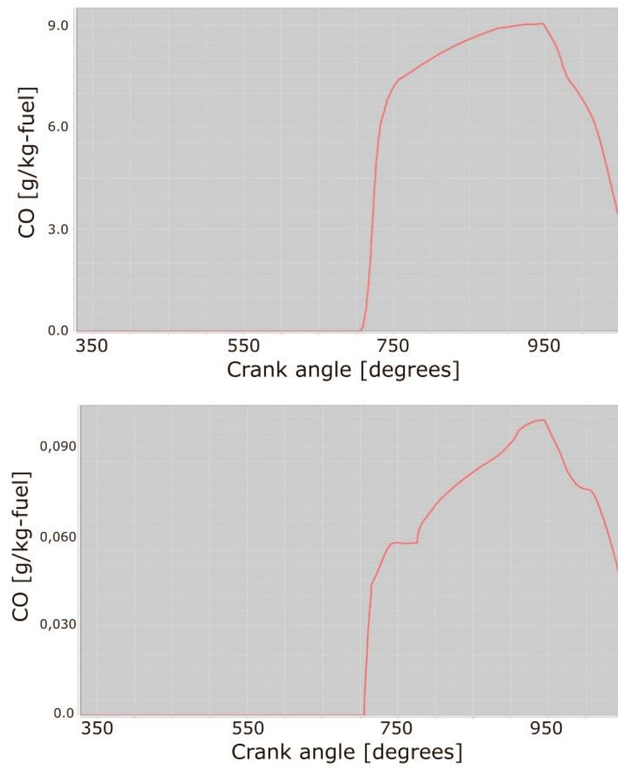


Figure 5. Evaluation of carbon monoxide (CO) emissions based on the crankshaft position (upper curve corresponds to the standard solution, lower curve pertains to the designed combustion chamber)

This analysis revealed a substantial reduction in the working temperature inside the combustion chamber, an essential aspect for implementing SPCCI technology. This technology is distinguished by generating energy via a low-temperature process. The considerable decrease in temperature is critically important for minimizing NO_X emissions, which, as the simulation results suggest, should be almost non-existent.

4 CONCLUSION

Even with the rapid growth of electric mobility, vehicles powered by internal combustion engines remain the most popular among consumers. Hence, research and development in new engine technologies remain crucial from an environmental perspective. Additionally, internal combustion engines play a vital role in hybrid drivetrains, and diesel engines in particular offer significant advantages in terms of performance parameters. While SPCCI technology requires further testing, initial results suggest its potential as a promising and viable option for motor vehicle combustion.

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