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FUEL STRATIFICATION COMBUSTION CHAMBER ANALYSIS FOR FUTURE HYDROGEN COMBUSTION

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Abstract

Fuel stratification is one of the key technologies that helps to meet strict environmental standards as well as it increases efficiency of the internal combustion engines. Stratification of fuel is particularly useful at low and medium engine operational load where high engine power output is not required. To achieve long-term reliability in lean burn combustion, multiple technologies are currently under development. Creating fuel-rich zones inside the chamber, for example through fuel stratification, is the solution. As a result, a patented design, known as the "Combustion compartment with implementation of stratification and spark-controlled auto-ignition of the fuel mixture using compression", was created. The design was predicated on the idea that a stratified charge engine generates a leaner mixture in the combustion chamber as a whole and a richer mixture near the spark. A simulation analysis of the patented system verified its substantial contribution to reducing emissions. This technology is very important in development of hydrogen-powered combustion engines, where the goal is to optimize combustion process, to increase engine efficiency and to reduce engine emissions.

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Key Words: Fuel Stratification, Combustion Space, Piston, Simulation Analysis

1. INTRODUCTION

A new law prohibiting the sale of petrol and diesel vehicles from 2035 was approved by the European Parliament in 2023. This effectively means that, starting in 2035, no new conventional fossil fuel vehicles will be available for sale. In response to these changes, some nations are collaborating to resist and delay the implementation of the decision. For example, Germany and the European Commission have reached an agreement allowing Germany to continue selling vehicles powered by synthetic fuels that are carbon neutral. In addition to e-fuels, which do not contribute to climate change, hydrogen has emerged as a viable alternative for internal combustion engines. The direct combustion of hydrogen in internal combustion engines is anticipated to play a significant role, particularly in industries where battery-electric propulsion is not economically viable. The adoption of the climate-neutral fuel exemption represents a positive development for the future of the automotive industry in the EU. It offers a substantial alternative to battery-electric vehicles by enabling the continued use of internal combustion engines powered by hydrogen or e-fuels. When a stoichiometric mixture is burned conventionally, the flame propagates, converting the energy from combustion into heat and the mechanical work required to compress the piston [1]. However, when a lean mixture burns with a greater proportion of air relative to the same amount of fuel, diatomic molecules with high mobility, such as N_2 and O_2, are utilised more effectively. This approach enhances thermal efficiency due to an increased rate of pressure rise and a greater extraction of work from the same quantity of fuel. To achieve long-term reliability in lean-burn combustion, a range of technologies is being developed. One solution involves creating fuel-rich zones within the combustion chamber, for example, through fuel stratification [2].

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2. ADVANCED COMBUSTION TECHNOLOGY

The principle of combustion with a layered mixture, as employed in modern petrol engines, can be understood as an advanced form of stratified charge compression ignition [3]. The combustion process can be initiated either by a spark plug or via auto-ignition. Typically, fuel is directly injected into the cylinder, where the interaction between the fuel-rich zone and the surrounding air ensures complete combustion [4]. Compared to conventional internal combustion engines, the stratified charge system allows for the use of moderately higher compression ratios without abnormal combustion, while also enabling the combustion of a leaner fuel mixture [5, 6].

In a homogeneous charge system, the air-fuel ratio (*AFR*) is maintained very close to stoichiometric, meaning it contains precisely the required amount of air to achieve complete combustion of the fuel [7]. Attempts to improve fuel economy by operating with a much leaner mixture in homogeneous charge systems result in slower combustion and increased engine temperatures. This can negatively impact energy efficiency and emissions, particularly through higher nitrogen oxide (NO_x) production [8]. While leaner mixtures help stabilise combustion, they impose an upper limit on engine efficiency. Fuel stratification can be implemented in various ways, with the primary differentiation being how the injection sequences are managed:

- Partial Fuel Stratification (PFS): Closest to homogeneous charge compression ignition (HCCI).
- Moderate Fuel Stratification (MFS): Balances between lean and rich combustion zones.
- Heavy Fuel Stratification (HFS): Approaches conventional combustion characteristics.

Higher fuel stratification within the cylinder generally improves combustion stability; however, elevated temperatures in fuel-rich zones during combustion lead to increased emissions of NO_x and particulate matter (PM) [9].

Advantages of SCCI combustion:

- Requires only one injector and fuel (if primary injection is via direct injection, DI).
- Allows the same engine to operate using multiple combustion strategies.
- Operates across a relatively wide range of conditions.

Studies conducted by researchers have shown that while engine performance tends to be higher in traditional diffusion combustion modes, the SCCI mode provides significant benefits in terms of emissions reduction [10, 11].

Conventional combustion is defined as the chemical reaction of fuel with oxygen present in the air. The oxidation of fuel with air can be expressed as:

$$\mathrm{Fuel} + x\,(\mathrm{O_2} + 3.76\,\mathrm{N_2}) \rightarrow y\,\mathrm{CO_2} + z\,\mathrm{H_2O} \qquad (1)$$

where $(\mathrm{O_2} + 3.76\,\mathrm{N_2})$ represents air, which is composed of approximately 21 % oxygen and 79 % nitrogen. The coefficients *x*, *y*, and *z* depend on the specific fuel and the air/fuel equivalence ratio (*AFR*). The equivalence ratio is defined as:

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

where the denominator represents the stoichiometric air/fuel ratio, which is the ideal ratio of fuel to air required for complete combustion: $\o = 1$ indicates a stoichiometric mixture; $\o < 1$ represents a lean mixture (excess air); $\o > 1$ corresponds to a rich mixture (excess fuel).

Air/fuel equivalence ratio λ is the ratio of the actual *AFR* to the stoichiometric *AFR* for the specific mixture [12]. It is expressed as: $\lambda = 1.0$ indicates a stoichiometric mixture, $\lambda < 1.0$ represents a rich mixture, $\lambda > 1.0$ corresponds to a lean mixture.

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

The stoichiometric air/fuel ratio λ for various fuels is provided in Table I.

Table I: Stoichiometric air/fuel ratio for selected fuels.

Fuel	**Methane**	**Propane**	**Butane**	**Gasoline**	**Ethanol**	**Hydrogen**
AFR_{STOICH}	17.2	15.7	15.5	14.7	9.0	34

During conventional stoichiometric mixture combustion, the flame propagates, transforming the energy from combustion into the work required for piston compression [13, 1]. In lean mixture combustion, a significantly larger volume of air is present relative to the same quantity of fuel. This results in the increased utilisation of diatomic molecules such as N_2 and O_2, which move freely. The rate of pressure increase rises as a result of burning the same amount of fuel, and the amount of work extracted also increases, leading to improved thermal efficiency. The key effects of lean mixture combustion can be summarised as follows:

- Combustion of a lean mixture, characterised by a higher air-to-fuel ratio, results in an increased specific heat ratio.
- A reduction in combustion temperature decreases the temperature gradient between the gas and the wall, thereby lowering heat transfer and minimising cooling losses.
- Lean mixture combustion reduces throttle losses by permitting a greater intake of air at the same torque level compared to operation at $\lambda = 1.0$.

As the combustion temperature decreases, the specific heat ratio increases because higher temperatures require additional energy for molecular motion and decomposition. When a larger volume of air is introduced during combustion, the resulting lower temperature leads to a rise in the specific heat ratio [4].

3. FUEL STRATIFICATION COMBUSTION CHAMBER

The combustion of a lean fuel mixture is significantly influenced by its flow dynamics within the combustion chamber. To address this, the "Combustion Chamber with the Implementation of Stratification and Spark-Controlled Compression Ignition of the Mixture" was designed and patented. The design assumes that stratification creates regions of rich mixture concentrated around the spark plug, surrounded by leaner mixture areas throughout the combustion chamber. The rich mixture near the spark plug is easily ignited, subsequently initiating combustion in the lean mixture regions. This approach allows the engine to operate with a lean mixture, improving thermal efficiency while ensuring complete combustion [7].

Fig. 1 illustrates the intended stratification of the fuel mixture within the combustion chamber, determined by the shape of the stratification section of the piston and the angles of the injection points. The stratification bowl is specifically designed to guide the flow of injected fuel beneath the spark plug. High injection pressure is assumed to prevent fuel from adhering to the piston surface and to ensure a rich mixture is directed towards the spark plug area. The stratification of the fuel mixture is engineered to create regions with varying excess air coefficients (λ). As previously mentioned, the flow of the mixture within the combustion chamber is critical to achieving effective stratification. The bowl design of the piston demonstrates superior performance in directing the mixture, as shown in Fig. 2, which highlights the velocity and subsequent swirl within the combustion chamber. This design effectively channels the mixture towards the centre of the chamber volume, subsequently guiding it beneath the spark plug [14, 15].

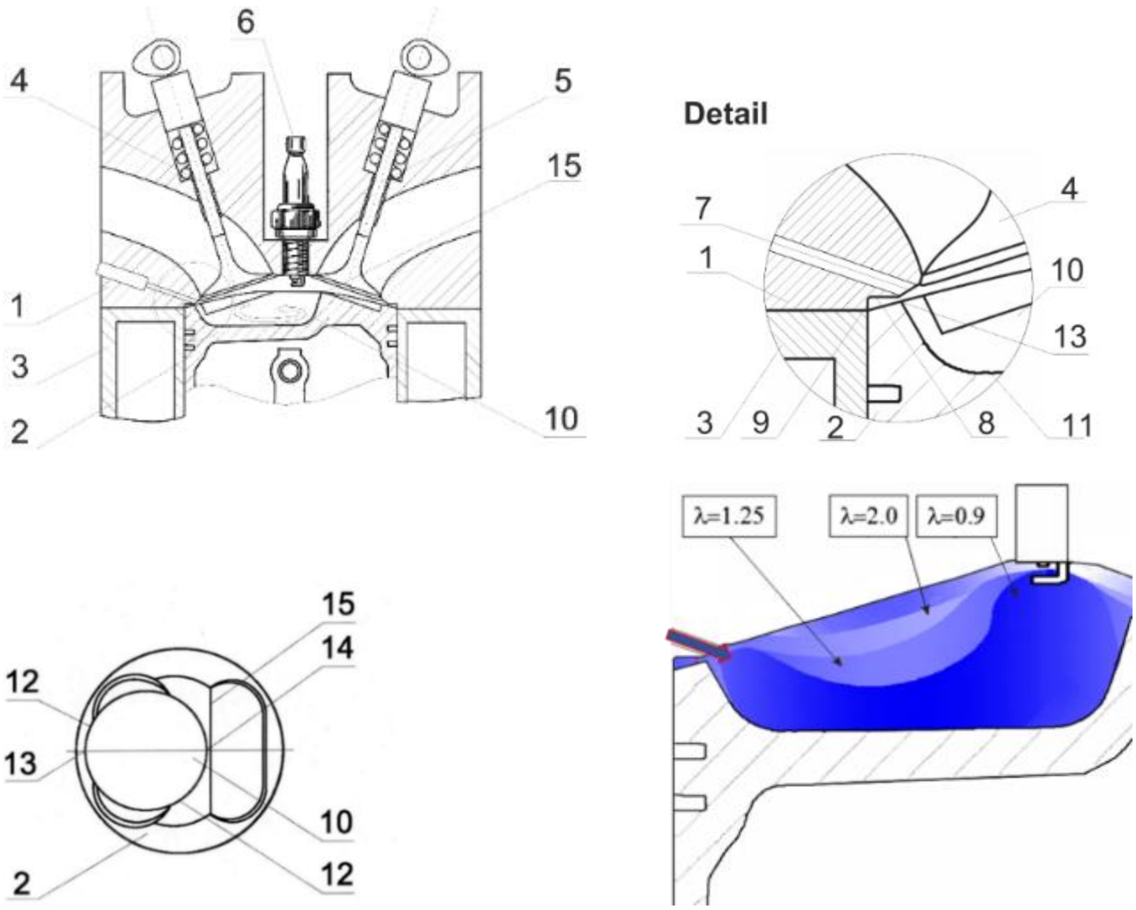

Figure 1: Combustion chamber with the implementation of stratification and a spark plug for controlled ignition of the fuel mixture using compression: 1 – cylinder head; 2 – piston; 3 – cylinder; 4 – intake valves; 5 – exhaust valves; 6 – spark plug; 7 – a curve delimiting in the plane part of the combustion space in the shape of a spherical canopy; 8, 9 – line segments delimiting the annular part of the combustion space in the plane; 10 – stratification part of the piston; 11, 12, 13, 14 – curves delimiting the stratification part of the piston; 15 – piston edge.

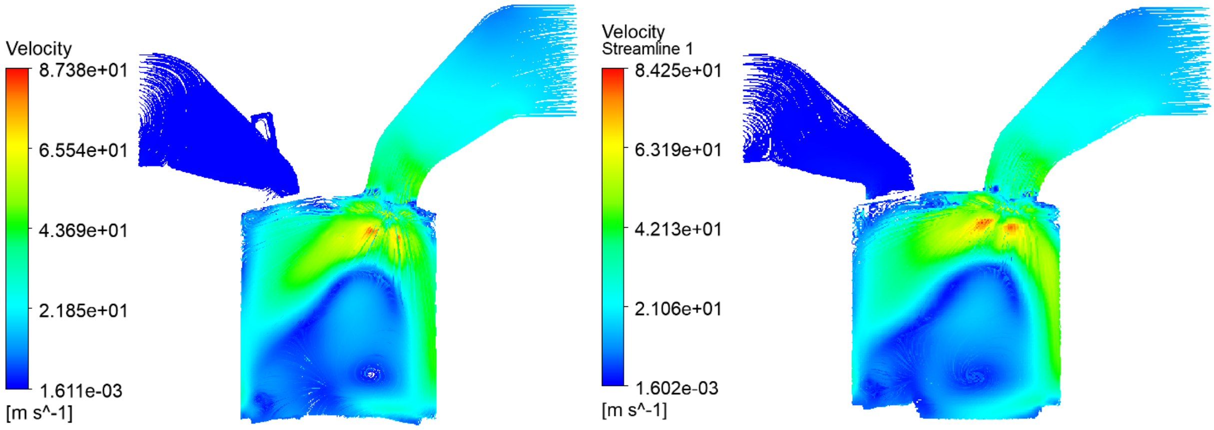

Figure 2: Velocity during intake stroke (flat and bowl-shaped piston).

4. ENGINE SPECIFICATIONS AND OPERATING CONDITIONS

The simulation was conducted on a four-cylinder engine with a compression ratio of 10.56 : 1, a bore of 73.5 mm, and a stroke of 90 mm. Direct fuel injection was employed, with the injector mounted laterally on the side of the cylinder. The injector featured eight injection points, each with a 0.3 mm diameter and a 14° cone angle. The injected fuel mass was 27 mg per cycle at 2000 rpm. Fuel injection commenced at 420° crank angle (*CA*) and lasted for 18.4° *CA*. The spark plug was centrally mounted in a pent-roof cylinder head, with the electrode extending into the combustion chamber. Ignition occurred at 705° *CA* and lasted for 10° *CA*. Detailed engine specifications are provided in Table II. Two piston designs were evaluated during the simulation. The first design featured a standard flat piston head with recesses for intake and exhaust valves. The second design utilised a bowl-shaped piston to enhance the mixing of the air-fuel mixture. Fig. 3 illustrates the piston geometries used in the simulation. Piston A features a flat head with recesses for the intake and exhaust valves, while Piston B incorporates recesses for the valves alongside a large bowl to improve air-fuel mixing.


Shape A
Shape B

Figure 3: Piston shape comparison (shape A – flat-shaped piston; shape B – bowl-shaped piston).

Table I: Engine specification (compression ratio for bowl-shaped piston).

Direct-injection gasoline engine	
Cylinder bore [mm]	73.5
Cylinder stroke [mm]	90.0
Compression ratio	10.56:1
Displacement [cm^3]	1522.79
Connecting rod length [mm]	14.43
Injection type	Direct injection
Number of nozzle openings	8
Diameter od nozzle openings [mm]	0.3
***CA* for intake valve open** [°]	308
***CA* for intake valve close** [°]	578
***CA* for exhaust valve open** [°]	144
***CA* for exhaust valve close** [°]	418
***RPM* (Engine speed)**	2000
Boost pressure [bar]	0.8
Intake temperature [K]	313
Injected fuel mass [mg]	27
Injected fuel	IC8H18
***CA* for fuel injection duration** [°]	18.4
***CA* for start of fuel injection** [°]	300 before top dead centre
***CA* for start of combustion** [°]	15 before top dead centre

5. SIMULATION RESULTS

The designed shape of the combustion chamber was evaluated using the 3D simulation software ANSYS CFX (Fig. 4) [16, 17]. The given software is determined for simulation of energy flows within the various components. This software tool can simulate flowing defined by the Navier-Stokes equations as well as it is able to simulate the turbulent flowing models. The calculation procedure also considers variability of the network shape during movement of the engine piston. The applied network is assembled of the $1.38 \cdot 10^6$ elements and $1.27 \cdot 10^6$ nodal points. It is possible to state that the majority of individual elements serves for simulation of the engine cylinder because it is the main part of the simulation process. There was applied the SST (Shear Stress Transport) model for simulation of the gas turbulent flowing. The SST model is especially suitable for simulation of supersonic streaming, which is characterised by the significant pressure gradients as it is the case of exhaust gas streaming [18, 19].

The standard flat-shaped piston and the bowl-shaped piston were tested under identical conditions to achieve the lowest possible combustion temperature, with the aim of igniting the air/fuel mixture throughout the entire combustion chamber. However, under the specified conditions, combustion was initiated but did not propagate through the entire combustion chamber. Nevertheless, the bowl-shaped piston increased the area of the combusted mixture, among other benefits [20, 21].

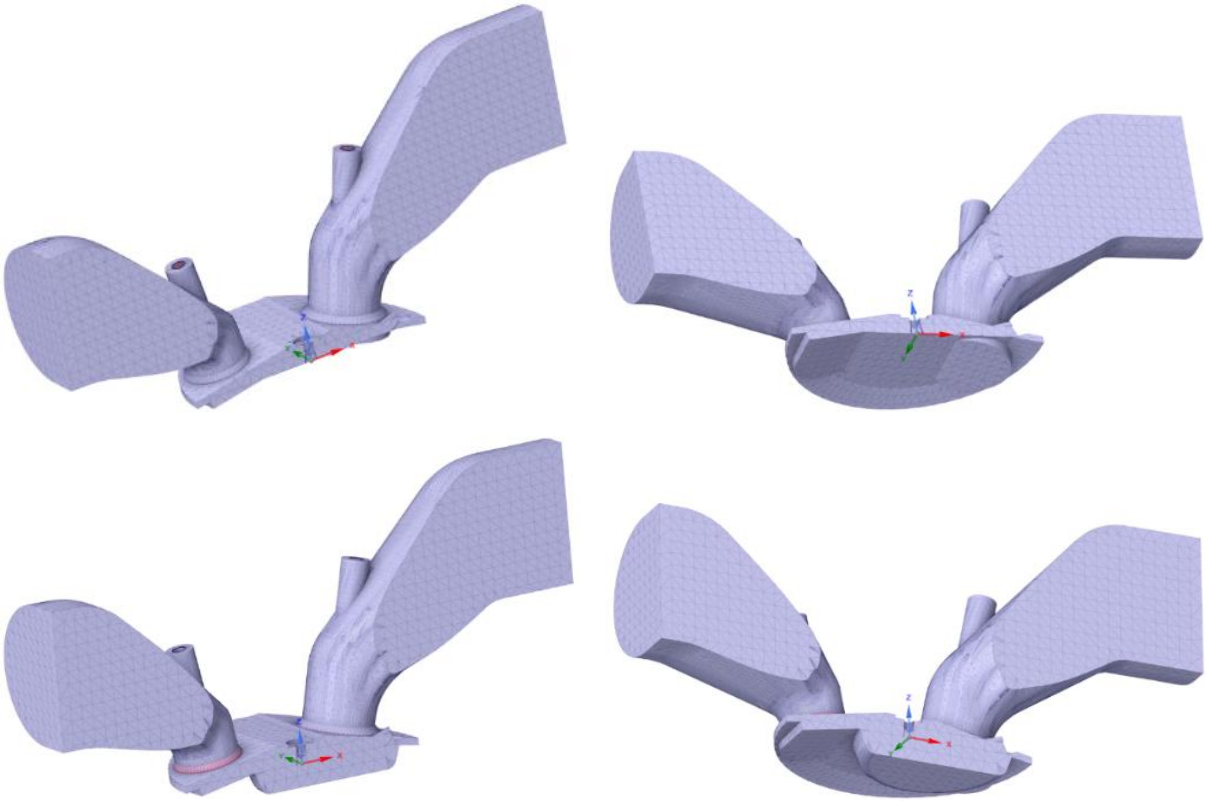

Figure 4: Standard and modified combustion space volumes mesh comparison.

Figs. 5 and 6 illustrate the progression of volume temperature during combustion for two different piston designs. The operating conditions were identical in both cases; however, the bowl-shaped piston demonstrates improved flame propagation, likely due to enhanced mixing of the fuel and air.

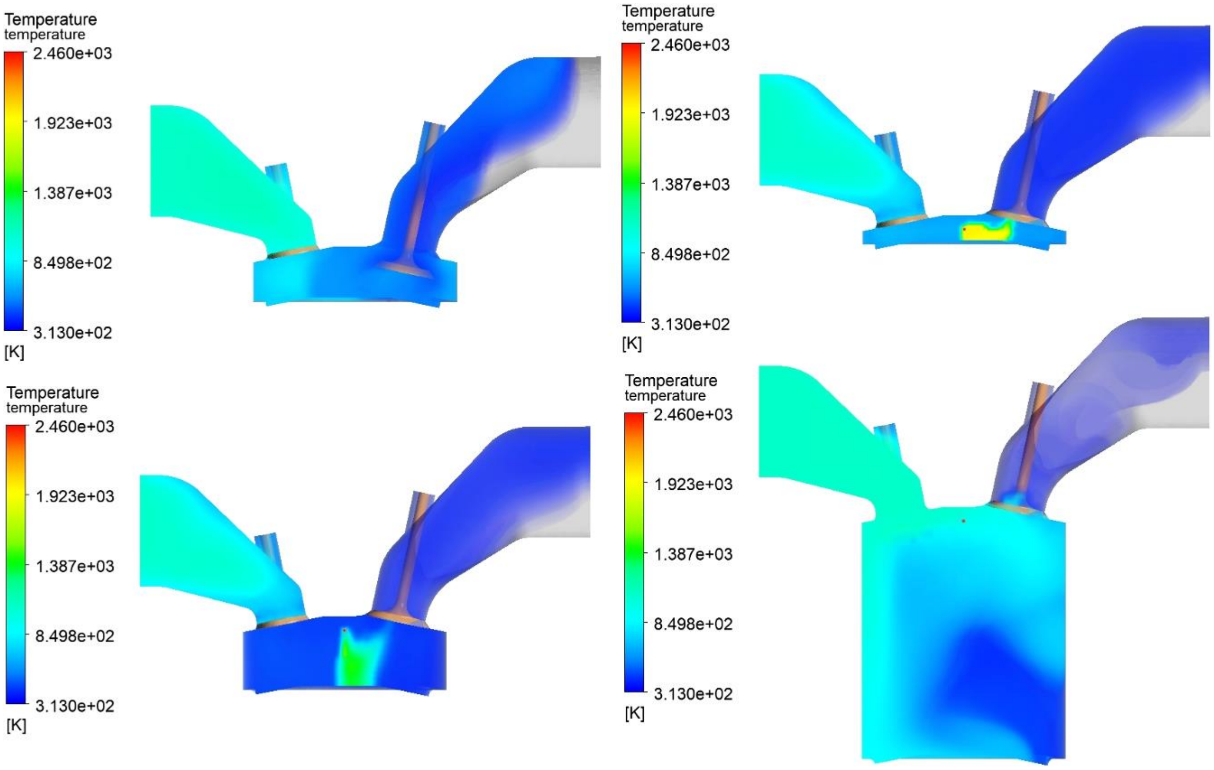

Figure 5: Combustion temperature analysis for flat-shaped piston.

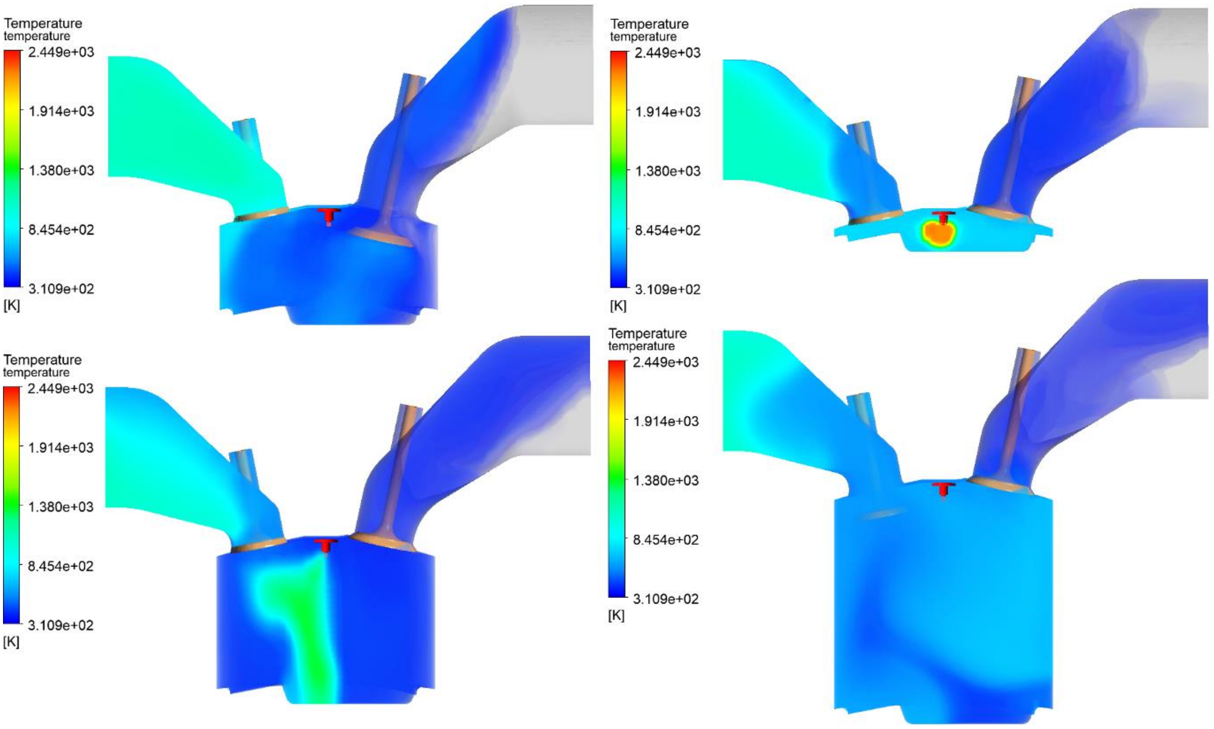

Figure 6: Combustion temperature analysis for bowl-shaped piston.

The analysis of two piston designs with different shapes indicates that the volume temperature meets the requirements for SCCI (Spark-Controlled Compression Ignition) applications, characterised by energy derived from a low-temperature combustion process. The low temperature, combined with the bowl-shaped piston design, impacts NO_x emissions, as confirmed by the simulation results (Figs. 7 and 8).

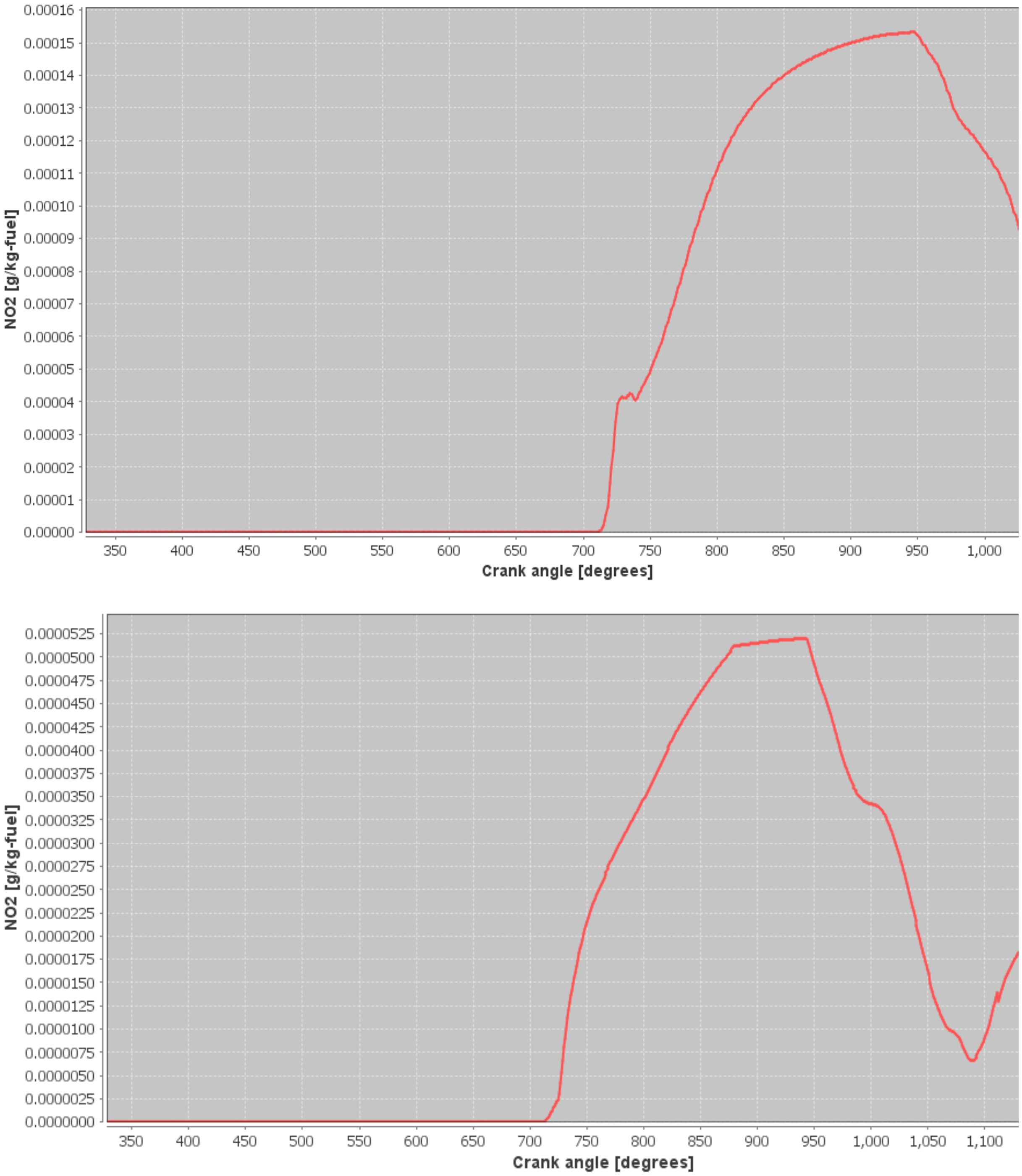

Figure 7: NO_2 and *CA* chart (upper chart: flat-shaped piston, lower chart: bowl-shaped piston).

The bowl-shaped piston demonstrated promising results in simulations, and with optimised operating conditions, further improvements could be achieved. These findings could form the basis for future testing, particularly with hydrogen as a fuel.

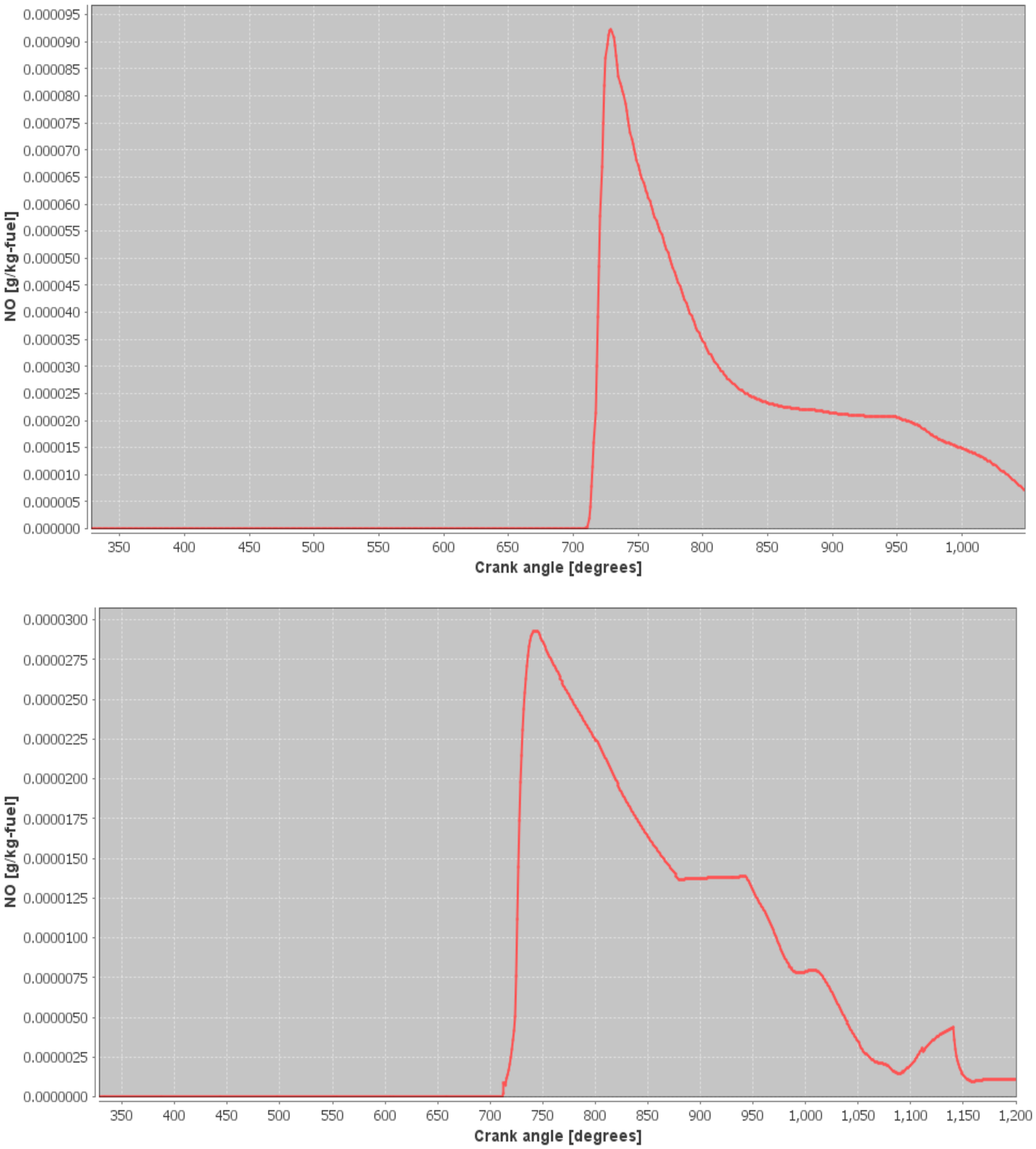

Figure 8: NO and *CA* chart (upper chart: flat-shaped piston, lower chart: bowl-shaped piston).

6. CONCLUSION

The principle of the stratified charge engine, which has been known for a considerable time, offers a potential avenue for improving the performance of spark-ignition engines to levels comparable with compression-ignition engines. One key advantage of this engine type is lower maintenance costs due to its cleaner operation. However, a significant challenge lies in combustion stability, as the reduced air/fuel ratio slows combustion speed and flame propagation. It is therefore crucial to develop solutions for combustion stabilisation to strike a balance between fuel efficiency and combustion stability. The proposed and patented design demonstrates positive results in reducing the environmental impact of power units. During the research and development of the experimental engine, additional optimisation opportunities were identified, which could further enhance performance characteristics. Due to time constraints, these alternatives could not be implemented but will be the focus of future research. Operational conditions for this type of combustion must be carefully adjusted to ensure effective layering of the fuel mixture around the spark plug and throughout the combustion chamber. This approach will serve as the starting point for testing the designed piston shape with hydrogen combustion, as hydrogen holds significant promise as a fuel for future internal combustion engines.

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