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EMISSION ANALYSIS OF A COMBUSTION CHAMBER WITH DUAL INJECTION FOR HYDROGEN INTERNAL COMBUSTION ENGINES

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Abstract: This study investigates the impact of hydrogen enrichment on emissions from a spark-ignition internal combustion engine. A thermodynamic model was used to simulate engine performance with pure gasoline and a gasoline-hydrogen blend under various load conditions. The results show that hydrogen addition leads to a significant reduction in carbon monoxide and hydrocarbon emissions, particularly at low and medium loads. Despite a slight increase in combustion temperature, nitrogen oxide emissions were also reduced compared to pure gasoline operation. These improvements are attributed to hydrogen's high reactivity, faster flame propagation, and better fuel-air mixture homogeneity. The proposed dual-injection combustion chamber further supports efficient hydrogen combustion and offers a promising solution for reducing emissions during the transition to low-carbon mobility.

KEYWORDS: hydrogen fuel, internal combustion engine, emissions reduction

1 Introduction

The current state of the European Union's industrial policy is characterized by a strong commitment to achieving carbon neutrality, as laid out in strategic documents such as the European Green Deal and the Fit for 55 packages. The transport sector, in particular, is under substantial pressure to significantly reduce emissions, as evidenced by the continuously tightening emission standards (e.g., Euro 7) and the proposed ban on internal combustion engine (ICE) passenger cars from 2035 [1]. This regulatory shift emphasizes the need for innovative propulsion systems and the decarbonization of fuels.

Despite this pressure, the transition to alternative propulsion systems must be implemented gradually, taking into account the complexity of the automotive industry and its extensive supply chain network [2]. According to recent projections by the International Energy Agency and the European Automobile Manufacturers' Association, internal combustion engines will continue to play a key role in hard-to-electrify sectors such as aviation, maritime transport, and long-distance road freight at least until 2030, and likely beyond [3]. In these areas, full electrification remains technologically and economically challenging, thus reinforcing the importance of clean fuel alternatives and hybrid systems.

In the automotive sector, current trends are primarily focused on hybrid powertrains, where the internal combustion engine remains a major component of the propulsion system. Plug-in hybrid electric vehicles (PHEVs) and full hybrids are expected to serve as a transitional technology that balances emission reductions with consumer acceptance and infrastructure readiness [4]. As a result, manufacturers continue to invest in increasing the thermal and overall efficiency of ICEs through advanced combustion strategies (e.g., Miller and Atkinson cycles), variable compression ratio systems, and the integration of waste heat recovery technologies [5].

One promising avenue for achieving lower carbon emissions from ICEs is the application of low-carbon and carbon-neutral fuels. Among them, hydrogen stands out as a key alternative.

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The main role of the National Hydrogen Strategy (NHS) of the Slovak Republic is to increase the competitiveness of the Slovak economy and, at the same time, to support the transition to a carbon-neutral society in accordance with the Paris Agreement, to which Slovakia is a signatory. The strategy sets out specific goals to support education, research, development, and innovation in the use of hydrogen across key sectors, including transport [6].

Hydrogen's carbon-free nature makes it a viable fuel for future automotive systems. Its favorable combustion characteristics—including high burning velocity, a wide range of flammability, and low ignition energy—make it suitable for both internal combustion engines and fuel cell applications [7]. Moreover, hydrogen internal combustion engines (H2ICEs) are gaining renewed interest due to their compatibility with existing engine architectures and rapid refueling times [8]. Recent studies confirm that, with proper control of combustion and emissions (especially NOx), H2ICEs can achieve high thermal efficiencies while producing near-zero CO_2 emissions [9].

In the Slovak context, the development of hydrogen technologies is further supported by national research initiatives and EU-funded projects aimed at establishing pilot hydrogen mobility systems and infrastructure. Such efforts are critical to ensuring that Slovakia remains aligned with broader European climate goals and industrial competitiveness.

2 Methodology and conditions

The strategy of fuel mixture preparing has an important influence on the overall combustion process of hydrogen. The LTC technology offers two basic fuel strategies: either the dual-fuel strategy or the single-fuel strategy. The dual-fuel strategy requires installation of two fuel tanks in the vehicle to store two kinds of fuel with different reactivity. One of the main technological challenges is the efficient combustion of hydrogen fuel, which holds significant potential for application in the next generation of internal combustion engines. However, a critical issue remains the control of the hydrogen combustion process, which is highly sensitive to operating conditions [10,11].

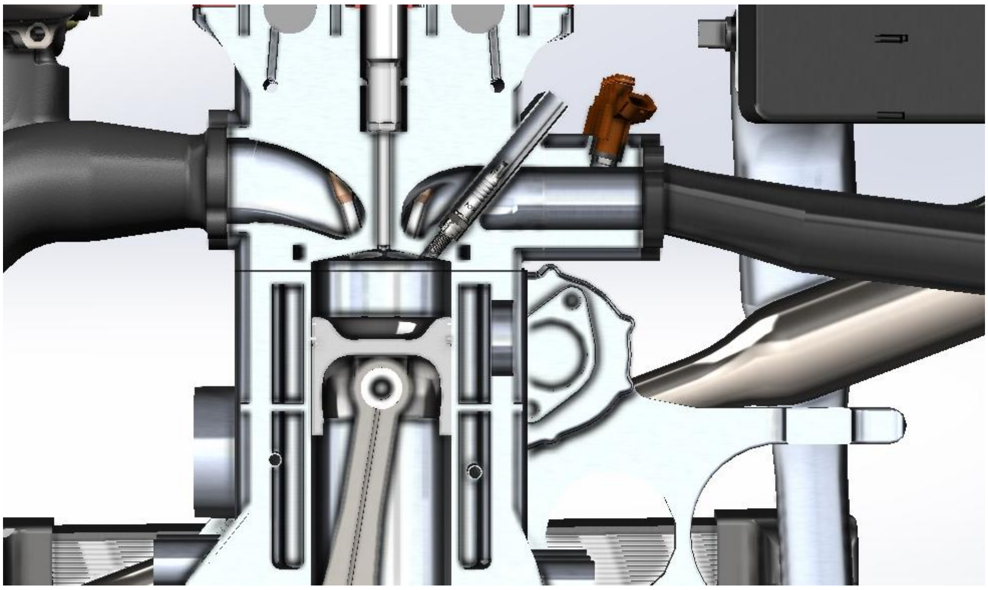

Fig. 1 Combustion chamber system

The proposed combustion chamber for hydrogen internal combustion engines with dual injection represents a technical solution aimed at improving the reliability and efficiency of hydrogen-powered combustion systems [2]. From a structural perspective, the combustion chamber consists of a cylinder head housing intake and exhaust valves, a high-pressure injector, and a spark plug. The cylinder head is firmly connected to the cylinder in which the piston moves, and the system also includes a low-pressure injector (fig.1).

The piston incorporates a specially shaped compression space formed by a series of concentric rings – intake, expansion, ejector, and compression (fig.2). A suitable fuel–air mixture swirl ratio is also crucial for ensuring proper combustion processes and for minimizing the formation of harmful emissions.

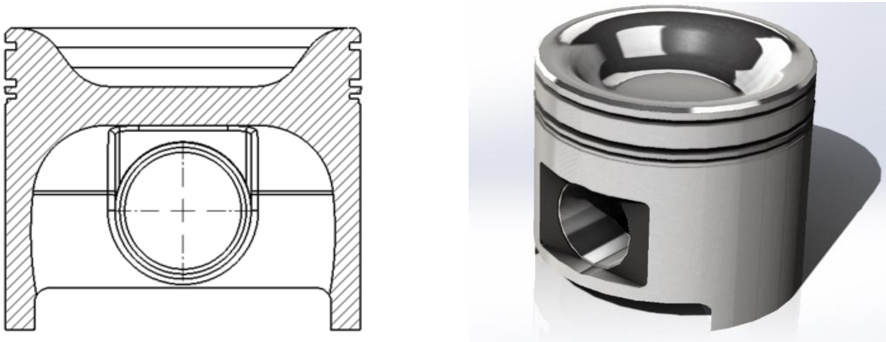

Fig. 2 Piston with specially shaped compression space

The main advantage of this configuration lies in its ability to effectively manage the hydrogen combustion process, which is one of the key barriers to implementing this technology in mass-produced engines [7]. The system's operation is based on dual injection of the same fuel type via two independent injection systems – a high-pressure and a low-pressure injector. Both systems allow for single or multiple fuel dosing depending on the operating mode [2]. The proposed solution is compatible with standard internal combustion engine architectures and enables operation across a wide load range while significantly reducing emissions [1, 3]. The combustion chamber for hydrogen internal combustion engines with dual injection offers a promising solution that may substantially contribute to meeting emission targets in the transport sector while also enabling the efficient use of sustainable fuels [9].

3 Emission analysis

For the purpose of verifying the proposed solution and analyzing exhaust gas emissions under various fuel mixtures, a thermodynamic model of a combustion engine was developed using simulation software. The model represents a four-stroke spark-ignition engine with fuel injection, and the calculations were carried out under steady-state operating conditions at 2000 revolutions per minute (RPM) and different load levels, defined by the brake mean effective pressure (BMEP). The engine was described as a system comprising the intake and exhaust tracts, combustion chamber, valve mechanism, and a combustion model. Detailed geometric parameters of the engine (stroke, cylinder bore, compression ratio) and valve timing were incorporated into the computational model. Thermal and mechanical losses were modeled using standard correlations available in the software. Within the simulation framework, two fuel variants were defined: pure gasoline (represented by the iso-octane component) and a gasoline-hydrogen blend, with hydrogen accounting for 30% of the fuel's energy content.

The combustion process was simulated using the Wiebe combustion model, which enables the adjustment of the heat release rate based on empirical parameters and ignition timing. The model also included a simplified emissions sub-model, in which CO, HC, and NO_x emissions are calculated based on local temperatures, oxygen concentration, and the residence time of combustion gases.

During the combustion of pure gasoline, hydrocarbon (HC) emissions were observed to be higher, particularly under low and medium load conditions. This trend is typical for conventional spark-ignition engines without specialized strategies for HC control. The addition of hydrogen to gasoline had a significantly positive effect on reducing HC emissions, as hydrogen enhances the combustion speed and enables the use of leaner fuel mixtures. It also helps to reduce the amount of unburned fuel in the peripheral zones of the cylinder (Fig. 3).

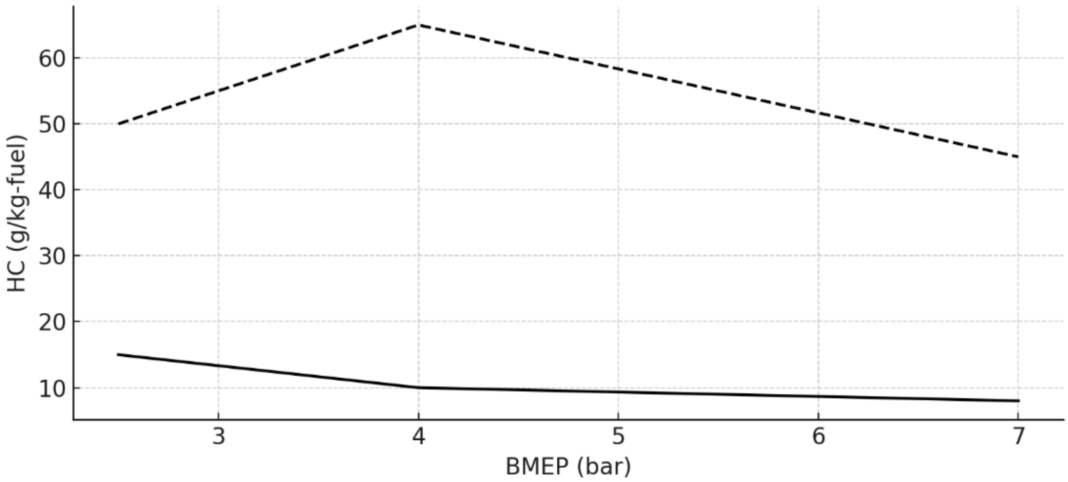

Fig. 3 Comparison of HC emissions for pure gasoline (dashed line) and gasoline with hydrogen (solid line) as a function of engine load (BMEP)

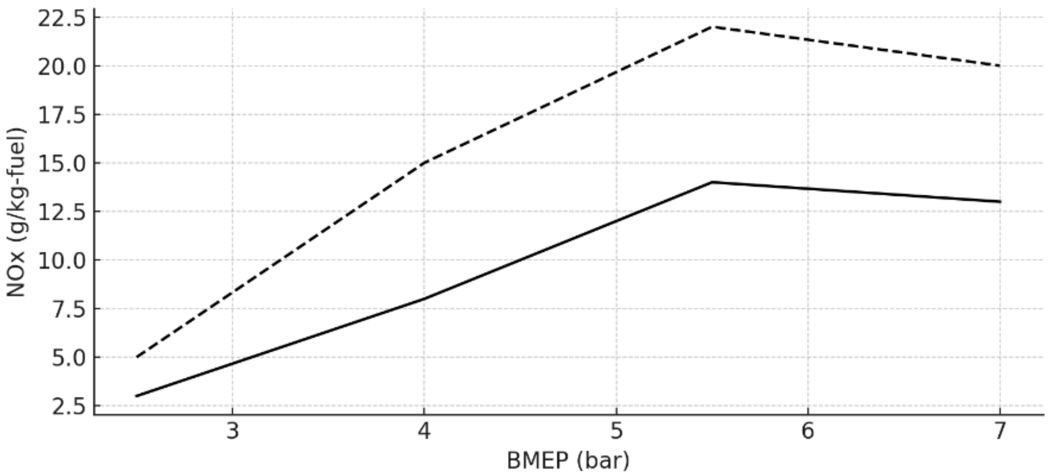

Fig. 4 Comparison of NO_x emissions for pure gasoline (dashed line) and gasoline with hydrogen (solid line) as a function of engine load (BMEP)

Nitrogen oxides (NO_x), particularly nitric oxide (NO) and nitrogen dioxide (NO_2), are among the most significant pollutants produced by combustion engines. During the combustion of pure gasoline, higher concentrations of NO_x are formed, especially under increased load conditions (BMEP). When using a gasoline-hydrogen blend, a slight increase in combustion temperature is observed, which could potentially promote NO_x formation. However, in practice, the total amount of NO_x emissions with this blend is found to be lower compared to pure gasoline combustion (Fig. 4).

Carbon monoxide (CO) is a product of incomplete fuel combustion, primarily formed during the combustion of rich mixtures (low excess air) or in cases of inadequate mixing of fuel and air. In combustion engines, CO represents a significant pollutant, with its concentration depending on the mixture composition, combustion temperature, as well as the geometry and control of the combustion process.

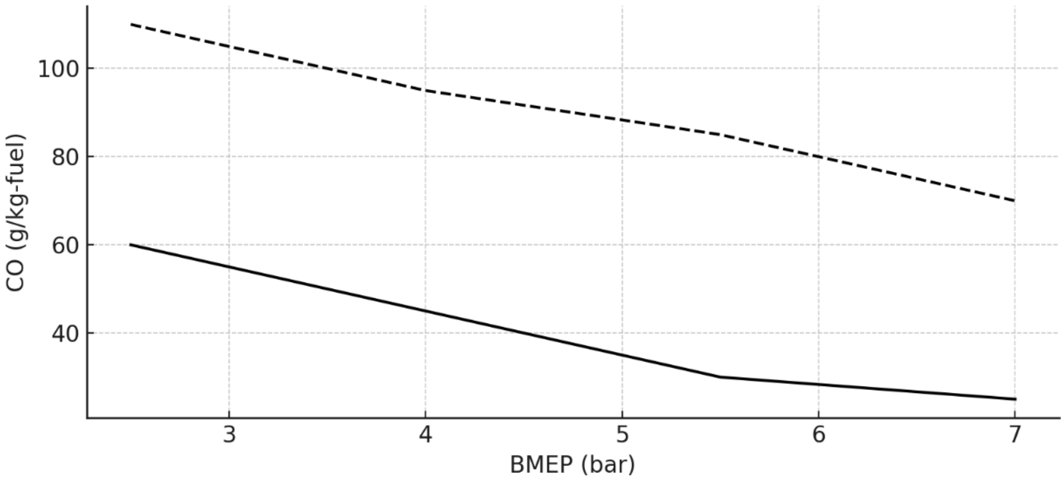

Fig. 5 Comparison of CO emissions for pure gasoline (dashed line) and gasoline with hydrogen (solid line) as a function of engine load (BMEP)

The addition of hydrogen to gasoline results in a significant reduction in CO emissions our analysis shows a decrease of more than 50% compared to pure gasoline combustion (Fig. 5). This effect is attributed to the higher reactivity of hydrogen, which increases flame propagation speed. Combustion is also more efficient due to improved mixture homogeneity within the combustion chamber. Furthermore, hydrogen as an additive enables the use of leaner mixtures without negatively affecting combustion stability, which naturally reduces CO formation.

CONCLUSION

The European Union's industrial and transport policies, as outlined in the European Green Deal and Fit for 55, are accelerating the transition toward carbon neutrality, placing increasing pressure on internal combustion engine (ICE) technologies. Hydrogen presents a promising low-carbon fuel alternative due to its favorable combustion properties, compatibility with existing ICE architecture, and support through national strategies such as Slovakia's National Hydrogen Strategy. Thermodynamic simulation results confirm that blending hydrogen with gasoline significantly reduces harmful exhaust emissions:

- HC emissions are notably lower, especially at low and medium loads, due to enhanced combustion speed and reduced quenching.
- NO_x emissions, although potentially promoted by higher temperatures, were in practice lower with the hydrogen blend, likely due to leaner mixture operation and improved combustion control.
- CO emissions were reduced by more than 50%, attributed to better mixture homogeneity and the ability to operate with excess air without compromising stability.

These findings support the strategic role of hydrogen-enriched fuels and advanced ICE designs in achieving intermediate emission targets, particularly during the transitional phase toward fully electrified transport.

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