

Model-Based Analysis of Combustion Characteristics for Future Split-Injection Hydrogen-Gasoline Engines

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Abstract Hydrogen enrichment represents one of the most promising approaches for improving the efficiency and environmental performance of spark-ignition engines while maintaining compatibility with existing combustion technologies. The present study investigates the influence of hydrogen addition on combustion characteristics and engine efficiency under lean-burn operating conditions using a combination of experimental measurements and numerical modelling. The analysis focuses on heat release rate, in-cylinder pressure evolution and brake thermal efficiency for various hydrogen-gasoline blends operating at different excess-air ratios. Experimental data were used to validate a simulation model capable of predicting combustion behaviour and identifying key parameters affecting engine performance. The results showed that increasing the hydrogen fraction accelerated the combustion process, shifted the peak heat release rate towards earlier crank angles and promoted earlier occurrence of maximum cylinder pressure. Furthermore, hydrogen enrichment enabled stable operation at leaner mixtures and increased brake thermal efficiency, with the highest values observed at $\lambda \approx 1.6$ for hydrogen-rich blends. The numerical model demonstrated good agreement with experimental measurements and successfully reproduced the observed combustion trends. Based on the obtained results, a conceptual framework for future split-injection control strategies is proposed, where model-based prediction of combustion characteristics can be used to optimize fuel delivery, ignition timing and air-fuel ratio management. The findings confirm that hydrogen-assisted combustion combined with advanced model-based control approaches offers significant potential for the development of next-generation low-emission spark-ignition engines.

Keywords hydrogen enrichment, spark-ignition engine, combustion modelling, engine control, lean-burn combustion

1. INTRODUCTION

The automotive industry is currently undergoing a significant transformation driven by increasingly stringent emission regulations, global decarbonization targets and the growing demand for sustainable transportation systems. Although battery-electric vehicles are expected to play a major role in future mobility, internal combustion engines remain an essential technology for many transportation sectors, including heavy-duty vehicles, hybrid powertrains and off-road machinery. Consequently, considerable research efforts are focused on improving engine efficiency and reducing environmental impacts through advanced combustion concepts and alternative fuels [1].

Hydrogen has emerged as one of the most promising alternative fuels due to its carbon-free combustion, high gravimetric energy density and favorable combustion characteristics. Compared with conventional gasoline, hydrogen exhibits a significantly higher laminar flame speed, lower ignition energy and wider flammability limits, allowing stable combustion even under very lean operating conditions [2,3]. These properties can contribute to improved thermal efficiency, lower fuel consumption and reduced greenhouse gas emissions while maintaining compatibility with existing internal combustion engine architectures.

Numerous studies have demonstrated that hydrogen enrichment accelerates flame propagation, shortens combustion duration and enhances combustion stability. Furthermore, hydrogen-assisted combustion can improve lean-burn capability and increase engine efficiency by enabling more favorable combustion phasing and reducing cycle-to-cycle variations [4,5]. However, the introduction of hydrogen into spark-ignition engines also alters heat release characteristics, pressure development and overall combustion dynamics, creating new challenges for engine calibration and control.

Modern engine development increasingly relies on numerical modelling techniques capable of predicting in-cylinder processes with high accuracy. Model-based approaches provide valuable insights into combustion phenomena, pressure evolution and thermal efficiency while reducing the need for extensive experimental testing. When properly validated against experimental measurements, simulation models can become an important component of advanced engine control systems and real-time combustion management strategies.

One of the promising concepts currently being investigated for future hydrogen-gasoline engines is split fuel injection. In such systems, the total fuel quantity is divided into multiple injection events to improve mixture preparation, combustion phasing and engine efficiency. The effectiveness of split-injection strategies strongly depends on a detailed understanding of combustion behaviour and accurate prediction of key combustion parameters, including heat release rate, maximum cylinder pressure and thermal efficiency. Therefore, the development of future model-based control algorithms requires comprehensive experimental and numerical analysis of combustion processes under various operating conditions.

The objective of this study is to perform a model-based analysis of combustion characteristics in a hydrogen-gasoline spark-ignition engine operating under lean-burn conditions. Experimental measurements and numerical simulations are used to evaluate heat release rate, in-cylinder pressure development and brake thermal efficiency for different hydrogen-gasoline blends. The obtained results are further discussed from the perspective of future split-injection control strategies and adaptive engine management systems for next-generation low-emission combustion engines.

2. MATERIALS AND METHODS

The experimental investigation was carried out on a spark-ignition engine operating with hydrogen-gasoline fuel blends under various lean-burn conditions. The objective of the measurements was to evaluate the influence of hydrogen enrichment on combustion development, heat release characteristics, in-cylinder pressure evolution and brake thermal efficiency. The engine was equipped with a combustion analysis system enabling crank-angle resolved pressure measurements, which served as the primary source of data for subsequent combustion analysis and numerical model validation. The tested operating conditions covered both stoichiometric and lean mixtures, with the excess-air ratio ranging from $\lambda = 1.0$ to $\lambda = 2.2$. Such a range was selected to investigate the combustion behaviour from conventional operation to ultra-lean conditions, where the beneficial effects of hydrogen become increasingly significant. Several hydrogen-gasoline blends with different hydrogen fractions were examined in order to evaluate the influence of fuel composition on combustion performance and engine efficiency.

To support the experimental investigation, a numerical combustion model was developed and calibrated using the measured engine data. The model was designed to reproduce the main thermodynamic processes occurring within the cylinder and to predict key combustion parameters, including heat release rate, in-cylinder pressure development and brake thermal efficiency. Particular attention was devoted to the prediction of combustion phasing and maximum cylinder pressure because these parameters represent important inputs for future model-based engine control systems. The accuracy of the model was assessed by comparing simulated and measured pressure traces under identical operating conditions.

The experimental pressure data were further used for heat release analysis in order to evaluate the rate and timing of energy release during combustion. The resulting combustion characteristics were subsequently correlated with brake thermal efficiency and analyzed with respect to varying hydrogen concentration and excess-air ratio. The obtained results provide valuable information regarding the relationship between fuel composition, combustion behaviour and engine efficiency. Furthermore, the validated model creates a foundation for the future development of adaptive control strategies and split-injection concepts, where accurate prediction of combustion processes is required for optimization of fuel delivery, ignition timing and overall engine operation.

3. RESULTS AND DISCUSSION

The combustion analysis revealed a significant influence of hydrogen concentration on the development of the combustion process and the associated thermodynamic parameters. Figure 1 presents the comparison of heat release rate profiles obtained for fuel blends containing different hydrogen fractions. The results indicate that increasing the hydrogen content substantially affects the timing of energy release during combustion. While both investigated fuel blends reached similar peak heat release rates of approximately 50 J/°CA, the hydrogen-rich mixture exhibited an earlier occurrence of the maximum heat release rate. The peak was shifted by approximately 5°CA towards top dead centre compared to the low-hydrogen blend, indicating a significantly faster combustion process.

The observed behaviour can be attributed to the favorable combustion properties of hydrogen, particularly its higher laminar flame speed and lower ignition energy. These characteristics promote faster flame propagation and shorten the combustion duration. As a consequence, a larger portion of the fuel energy is released closer to the optimum crank angle region, which contributes to improved thermodynamic efficiency. The results shown in Fig. 1 therefore confirm that hydrogen enrichment accelerates combustion development and alters combustion phasing, which must be considered in future engine control strategies and injection system design.

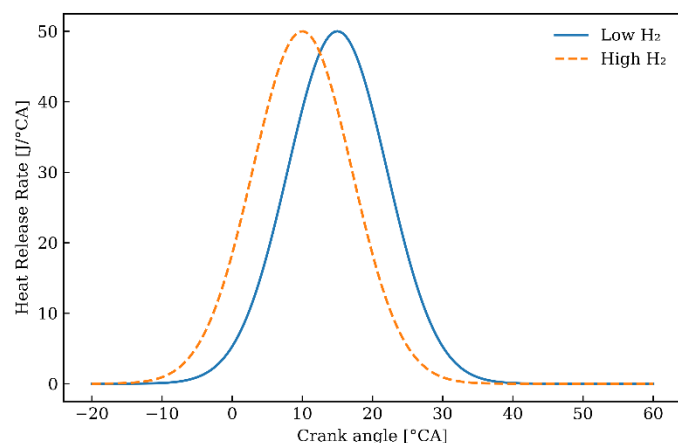


Figure 1 - Comparison of heat release rate profiles for low- and high-hydrogen fuel blends under lean-burn operating conditions

The influence of accelerated combustion is further reflected in the in-cylinder pressure development presented in Fig. 2. A comparison between experimental measurements and numerical simulations demonstrates a high level of agreement throughout the combustion cycle. The experimental pressure trace reached a maximum value of approximately 41 bar, whereas the simulation predicted a slightly higher peak pressure of approximately 43 bar. Furthermore, the simulated pressure maximum occurred approximately 2°CA earlier than the experimentally observed peak.

Despite these minor deviations, the numerical model successfully reproduced the overall pressure evolution, including the pressure rise during combustion, the maximum pressure region and the subsequent expansion phase. The relatively small difference between experimental and simulated results indicates that the model accurately captures the dominant physical processes governing combustion and energy conversion within the cylinder. Such agreement is particularly important for future model-based control applications, where reliable prediction of combustion behaviour is required for real-time optimization of engine operation.

The combined analysis of heat release rate and pressure development demonstrates a clear relationship between hydrogen concentration and combustion dynamics. Earlier heat release leads directly to an earlier pressure rise and higher peak pressure values, resulting in more favorable combustion phasing. From the perspective of future hydrogen-gasoline engines equipped with split-injection systems, these findings provide valuable information for determining optimal injection timing and fuel distribution strategies. Since hydrogen enrichment significantly modifies combustion speed and pressure development, future control algorithms will need to continuously adapt fuel injection parameters to maintain optimal combustion phasing and maximize engine efficiency.

The validation results presented in Fig. 2 also confirm that the developed numerical model can be used as a predictive tool for further investigations of advanced combustion concepts. Such model-based approaches are expected to play an increasingly important role in the development of adaptive engine management systems, where combustion parameters can be predicted and optimized before actual combustion occurs. Consequently, the presented model provides a suitable foundation for future research focused on split-injection hydrogen-gasoline combustion systems and advanced model-based control algorithms.

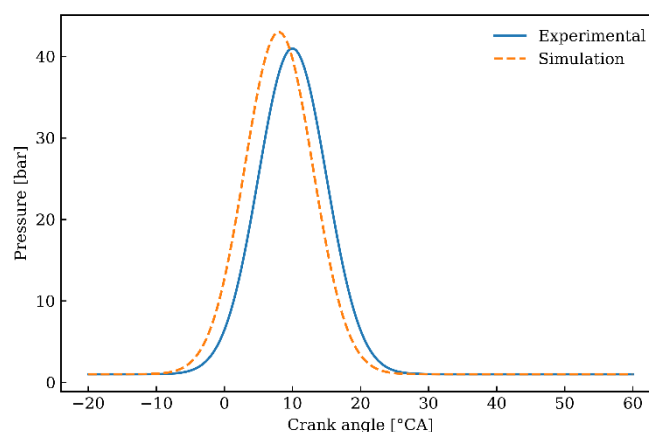


Figure 2 - Comparison of experimentally measured and simulated in-cylinder pressure traces used for numerical model validation

The influence of combustion characteristics on overall engine performance can be further evaluated through the brake thermal efficiency results presented in Fig. 3 and Fig. 4. The obtained data demonstrate that both hydrogen concentration and excess-air ratio significantly affect the efficiency of the combustion process. For all investigated fuel blends, brake thermal efficiency increased as the mixture became leaner, reaching an optimum operating point before gradually decreasing under ultra-lean conditions.

The behaviour observed in Fig. 3 indicates that low-hydrogen fuel blends achieved their highest brake thermal efficiency at approximately $\lambda = 1.4$. At stoichiometric operation, the efficiency remained close to 34 %, while progressive mixture leaning resulted in a noticeable improvement in thermal efficiency. The maximum values approached approximately 37 %, after which further increase in excess-air ratio caused a gradual decline. This reduction can be associated with decreasing combustion temperatures, slower flame propagation and reduced combustion stability under extremely lean conditions.

A different trend can be observed for the hydrogen-rich fuel blends shown in Fig. 4. In this case, the optimum operating point was shifted towards significantly leaner mixtures. The highest brake thermal efficiency was achieved at approximately $\lambda = 1.6$, where values close to 38 % were recorded. Compared to the low-hydrogen blends, the hydrogen-rich mixtures exhibited both higher maximum efficiency and an extended lean operating range. These results clearly demonstrate the beneficial effect of hydrogen on combustion stability and energy conversion efficiency.

The improved performance of hydrogen-enriched mixtures can be explained by the combustion characteristics discussed previously. As shown by the heat release analysis in Fig. 1, hydrogen promotes faster energy release and advances combustion phasing. The resulting pressure development, illustrated in Fig. 2, enables a greater proportion of the released energy to be converted into useful work during the expansion stroke. Consequently, the combination of accelerated combustion and improved combustion stability allows efficient operation even at higher excess-air ratios.

Another important observation is the excellent agreement between experimental measurements and numerical predictions presented in both Fig. 3 and Fig. 4. The simulation model successfully reproduced the efficiency trends over the entire investigated operating range, including the location of the efficiency maxima and the subsequent decrease under ultra-lean conditions. The relatively small deviations between measured and simulated values confirm the capability of the model to capture the dominant mechanisms

governing hydrogen-assisted combustion. Such predictive capability is particularly important for future model-based engine control systems, where combustion parameters must be estimated continuously under varying operating conditions.

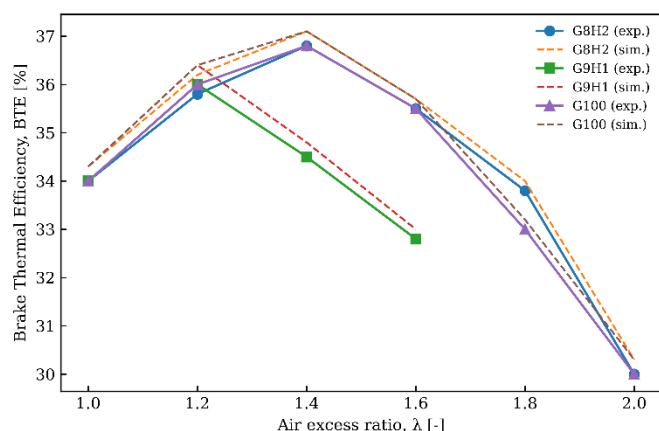


Figure 3 - Brake thermal efficiency as a function of excess-air ratio for low-hydrogen gasoline blends: comparison of experimental and simulation results.

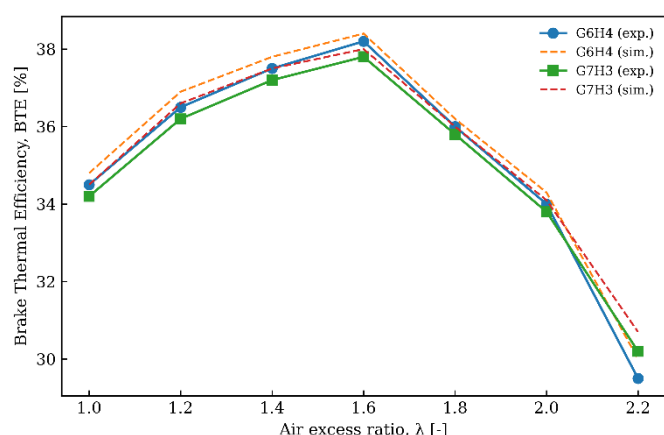


Figure 4 - Brake thermal efficiency as a function of excess-air ratio for hydrogen-rich gasoline blends: comparison of experimental and simulation results.

From the perspective of future split-injection hydrogen-gasoline engines, the obtained results provide valuable information regarding optimal combustion phasing and fuel delivery strategies. The shift of the efficiency optimum from $\lambda \approx 1.4$ to $\lambda \approx 1.6$ with increasing hydrogen concentration suggests that the fuel management system should dynamically adapt injection parameters according to both fuel composition and operating conditions. A split-injection strategy could utilize an initial pilot injection to improve mixture preparation followed by a main injection event responsible for achieving the desired combustion phasing. Such an approach would allow the engine control unit to compensate for the faster combustion behaviour associated with hydrogen enrichment while maintaining optimal efficiency and combustion stability.

The presented results therefore demonstrate that hydrogen concentration significantly influences not only combustion dynamics but also the location of the optimum operating point. These findings confirm the necessity of adaptive model-based control approaches capable of continuously adjusting injection timing, fuel distribution and ignition parameters. The validated simulation model developed in this study provides a suitable platform for future investigations focused on split-injection

strategies and advanced combustion control concepts for low-emission hydrogen-gasoline engines.

4. CONCLUSIONS

This study presented a model-based analysis of combustion characteristics in a hydrogen-gasoline spark-ignition engine operating under lean-burn conditions. The investigation combined experimental measurements and numerical simulations to evaluate the influence of hydrogen enrichment on heat release rate, in-cylinder pressure development and brake thermal efficiency. Particular attention was devoted to assessing the capability of the numerical model to reproduce the observed combustion behaviour and to identifying parameters relevant for future model-based engine control systems.

The results demonstrated that hydrogen addition significantly modifies combustion dynamics. The heat release rate analysis revealed that increasing the hydrogen fraction accelerates combustion and shifts the peak heat release rate towards earlier crank angles. Compared to low-hydrogen operation, the hydrogen-rich fuel blend exhibited a heat release peak occurring approximately 5°CA earlier, indicating faster flame propagation and shorter combustion duration. This behaviour was reflected in the pressure development, where earlier combustion phasing resulted in an earlier occurrence of maximum cylinder pressure.

The comparison between experimental and simulated pressure traces confirmed the validity of the developed numerical model. Although the simulation slightly overpredicted the maximum cylinder pressure, the overall agreement between measured and predicted pressure evolution was very good. The model successfully reproduced the main combustion characteristics and captured the influence of hydrogen concentration on pressure development throughout the engine cycle.

The brake thermal efficiency analysis showed that hydrogen enrichment not only improved combustion stability but also shifted the optimum operating point towards leaner mixtures. While the maximum efficiency for low-hydrogen blends was achieved at approximately $\lambda = 1.4$, hydrogen-rich mixtures reached their highest efficiency at approximately $\lambda = 1.6$. The highest brake thermal efficiency approached 38 %, confirming the potential of hydrogen-assisted combustion for improving engine performance under lean-burn conditions.

The obtained results indicate that future hydrogen-gasoline engines will require adaptive control strategies capable of responding to changing combustion characteristics and fuel composition. The validated numerical model developed in this work provides a suitable foundation for the future development of model-based combustion control systems and split-injection fuel delivery strategies. Future research will focus on integrating predictive combustion models into advanced engine control algorithms capable of optimizing injection timing, fuel distribution and ignition control under dynamically changing operating conditions.

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