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THE SAFETY ISSUES OF HYDROGEN-GASOLINE DUAL-FUEL INJECTION IN NATURAL ASPIRATED INTERNAL COMBUSTION ENGINES

Attila Kiss[1], Bálint Szabó[2], Zoltán Weltsch[3]

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RESEARCH ARTICLE

ABSTRACT: Hydrogen-gasoline dual-fuelled internal combustion engines (ICEs) have emerged as a viable alternative to conventional gasoline engines, promising reduced emissions and improved fuel efficiency. The integration of hydrogen as a supplementary fuel in naturally aspirated engines, however, introduces a critical challenge that affects engine performance. Nevertheless, it also introduces significant security challenges, notably the increased risk of backfire within the intake manifold. This study investigates the security issues associated with hydrogen-gasoline dual-fuel engines, with a particular focus on the propensity for intake manifold backfire due to the presence of hydrogen. Through experimental analysis and simulations, the study explores various techniques to eliminate or reduce the occurrence of backfire. These techniques include optimized fuel injection timing and camshaft modification. The results of the simulation show how the modifications affect the basic characteristics of the natural aspirated internal combustion engine.

KEY WORDS: *hydrogen, dual-fuel, hybrid mixture formation*

[1] *Attila Kiss, John von Neumann University, 6000 Kecskemét Izsáki Street 10, Hungary, kiss.attila@nje.hu, -*(Corresponding author)*
[2] *Bálint Szabó, BDN Automotive Kft., 9025 Győr, Kereszt Street 3-5, Hungary, balint.szabo@bdn-automotive.com, -*
[3] *Dr. Zoltán Weltsch, Széchenyi Istvan University, 9026 Győr Egyetem Square 1, Hungary, weltsch.zoltan@sze.hu, -*

PITANJA SIGURNOSTI UBRIZGAVANJA DUALNOG GORIVA VODONIK-BENZIN GORIVA U ATMOSFERSKE MOTORE

REZIME: Motori sa unutrašnjim sagorevanj em (ICE) sa dualnim gorivom vodonik-benzin su se pojavili kao održiva alternativa konvencionalnim benzinskim motorima, obećavajući smanjene emisije i poboljšanu efikasnost sagorevanja. Međutim, integracija vodonika kao dodatnog goriva u atmosferskim motorima predstavlja kritičan izazov koji utiče na performanse motora. Ipak, on takođe uvodi značajne bezbednosne izazove, posebno povećan rizik od povratnog udara unutar usisne grane. Ova studija istražuje bezbednosna pitanja povezana sa vodonik-benzinskim motorima sa dualnim gorivom, sa posebnim fokusom na sklonost povratnom udaru usisne grane usled prisustva vodonika. Kroz eksperimentalnu analizu i simulacije, studija istražuje različite tehnike za eliminisanje ili smanjenje pojave povratnog udara. Ove tehnike uključuju optimizovano vreme ubrizgavanja goriva i modifikaciju bregastog vratila. Rezultati simulacije pokazuju kako modifikacije utiču na osnovne karakteristike atmosferskog motora sa unutrašnjim sagorevanjem.

KLJUČNE REČI: *vodonik, dualno gorivo, formiranje hibridne mešavine*

THE SAFETY ISSUES OF HYDROGEN-GASOLINE DUAL-FUEL INJECTION IN NATURAL ASPIRATED INTERNAL COMBUSTION ENGINES

Attila Kiss, Bálint Szabó, Zoltán Weltsch

INTRODUCTION

The growing concerns over environmental pollution and the depletion of fossil fuels have accelerated the search for cleaner and more efficient energy sources. Hydrogen has emerged as a promising alternative due to its high energy density and zero carbon emissions when combusted. Its potential as a sustainable fuel has been extensively reviewed, highlighting the challenges associated with its production, storage, and transportation Abdalla et al. [1]. One of the most viable applications of hydrogen is its use in internal combustion engines (ICEs), either as a standalone fuel or in combination with conventional fuels such as gasoline.

Hydrogen-gasoline dual-fuel engines offer a practical solution for reducing emissions while maintaining the operational flexibility of traditional ICEs. This approach leverages the existing infrastructure and engine technologies, making it a transitional strategy towards cleaner automotive solutions. However, integrating hydrogen into ICEs presents several challenges, such as backfire, pre-ignition, and knock, due to hydrogen's high reactivity and low ignition energy Aghahasani et al. [2]. Furthermore, the precise control of the air-fuel mixture and combustion timing is crucial to ensure stable engine operation and to optimize performance and emissions.

Recent studies have explored various strategies to enhance the performance and emissions characteristics of hydrogen-gasoline dual-fuel engines. For instance, Aghahasani et al. [2] conducted a numerical study on hydrogen-gasoline dual-fuel spark ignition engines, demonstrating that the addition of hydrogen can significantly improve thermal efficiency and reduce CO_2 emissions. However, this improvement often comes at the cost of increased nitrogen oxide (NOx) emissions due to higher in-cylinder temperatures. Similarly, Akal et al. [3] emphasized the need for advanced engine control techniques, such as water injection and multi-objective optimization, to balance performance and emissions in dual-fuel configurations.

The addition of hydrogen to gasoline engines has been shown to enhance flame speed and combustion stability, leading to improved engine efficiency D'Andrea et al. [4]. However, optimizing hydrogen use in ICE's requires careful management of fuel injection timing and mixture formation. Salek et al. [5] demonstrated the benefits of port water injection in reducing NOx emissions in a hydrogen-gasoline dual-fuel engine, highlighting the potential of advanced control strategies to mitigate the adverse effects of hydrogen combustion.

This study builds on the existing body of research by investigating a novel approach to optimize the performance and emissions of a hydrogen-gasoline dual-fuel engine. We propose a modification to the camshaft profile that delays the intake valve closure, reducing the risk of backfire and improving combustion stability. This modification is designed to limit the intake of hydrogen during critical phases of the intake stroke, thereby preventing premature ignition and enhancing engine reliability.

The remainder of this paper presents the experimental setup and methodology used to evaluate the impact of the camshaft modification on engine performance and emissions. The results are compared with existing studies, providing insights into the trade-offs between power output, fuel efficiency, and emissions. By addressing the challenges associated with hydrogen integration in ICE's, this research contributes to the development of more efficient and environmentally friendly automotive technologies, enhancing overall engine stability. While similar approaches have been explored in recent studies, our work offers a more refined camshaft design tailored for dual-fuel applications.

Despite the benefits in backfire prevention and emissions reduction, the delayed intake valve closure introduces some trade-offs. The modification leads to a reduction in engine power output and torque, as the shortened intake phase limits the air-fuel mixture entering the cylinder. Nonetheless, the environmental advantages, such as reduced nitrogen oxides (NO_x) emissions and improved combustion stability, outweigh the performance drawbacks, making this approach viable for eco-friendly applications.

1 MATERIALS AND METHODS

1.1 Engine

For the test series, we used a gasoline-powered M42B18 internal combustion engine produced by BMW, which was completely renovated before the research. The basic parameters of the engine are listed in ***Table 1***.

Table 1 Engine parameters [7]

Engine code	M43B18
Stroke	Four strokes
Layout	Inline-4
Fuel type	Gasoline
Displacement	1796 [cm^3]
Fuel system	Manifold injection
Firing order	1-3-4-2
Compression ration	9.7:1
Cylinder bore	84 [mm]
Piston stroke	81 [mm]
Valve arrangement	SOHC
Valves number	8, 2 valves per cylinder
Camshaft Total duration (intake)	244°
Camshaft total duration (exhaust)	244°
Intake valves maximum lift	10 [mm]
Exhaust valves masimum lift	10 [mm]
Valves overlap	35°

In order to avoid backburn, the profile of the original camshaft was modified in such a way that no valve lock occurs, and in fact, 9 degrees pass without any of the valves being open. Thanks to this, it cannot happen that the hot exhaust gas ignites the mixture of hydrogen, gasoline and air left in the intake pipe. ***Table 2*** contains the data of the modified camshaft.

Table 2 Modified camshaft parameters

Camshaft Total duration (intake)	200°
Camshaft total duration (exhaust)	200°
Intake valves maximum lift	8,5 [mm]
Exhaust valves masimum lift	8,5 [mm]
Valves overlap	-9°

1.2 Simulation

1.2.1 Structure of the simulation

A 1D simulation model of the engine was developed using AVL Cruise-M to simulate gas exchange, performance, and emissions. The software enables the construction of a complex engine model by utilizing built-in modules such as cylinders, pipes, junctions, throttles, and injectors. As a result, the intake and exhaust systems of the engine must be modelled with high accuracy, including the valve lift curves and the flow coefficients of the cylinder head ports and valves. The basic geometric parameters of the engine, as previously described, were used in this model. In our previous research, we validated the purely gasoline-powered simulation in a brake bench environment. This measurement took place as follows. The validation measurements were conducted across a range of engine speeds from 1000 to 4500 rpm, starting at 500 rpm, using gasoline as the fuel. To optimize engine efficiency, power, and emissions, lambda was maintained at 1, ensuring a stoichiometric air-fuel mixture. Additionally, the maximum possible spark timing was set just below the knock threshold before top dead centre (TDC), with the throttle body fully open. These conditions were chosen to achieve the highest performance at each measurement point by minimizing losses through the throttle valve, allowing for future comparisons of power output and emissions that are solely influenced by changes in fuel type.

Friction calculations were performed using the built-in Patton, Nitschke, Heywood model [6], while the heat release was defined using the Vibe 2-zone model to align with the combustion parameters measured on the actual engine. The following section presents the combustion parameters:

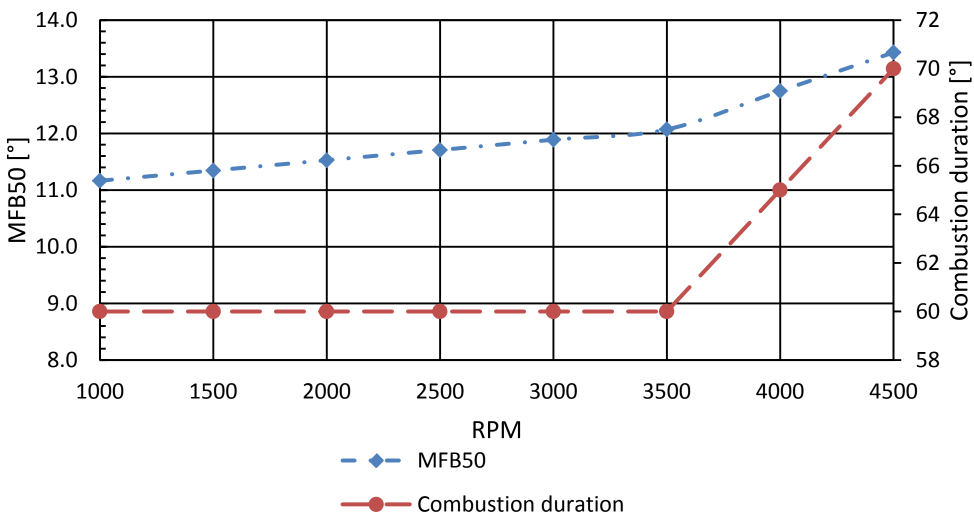

Figure 1. Combustion parameters

The parameters “m” and “a” were set to 6.9 and 1.9, respectively, for all engine speeds. The engine is connected to ambient boundaries on both the intake and exhaust sides, with temperature and pressure maintained at steady-state ambient values.

The valve lift curves were measured directly on the actual cylinder head with a crank angle resolution of 4° for both the intake and exhaust sides.

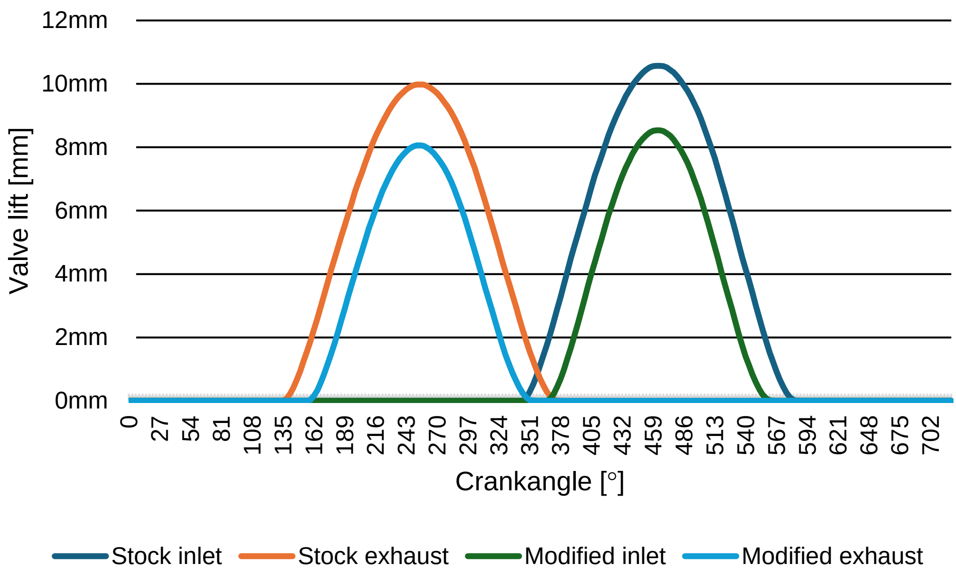

Figure 2. Valve lift curve (original and modified)

The valve lift curves of both the original and modified camshaft designs are illustrated in the Figure 2. The comparison between the two profiles reveals significant differences in valve operation characteristics. For the original camshaft, the typical valve lift pattern shows a standard opening and closing sequence, allowing for optimal airflow into and out of the cylinder during the intake and exhaust strokes. This configuration is designed to maximize the engine's volumetric efficiency and ensure effective combustion by facilitating adequate air and fuel mixture formation.

In contrast, the modified camshaft profile exhibits a distinct change in valve timing behaviour. As depicted in the figure, the valve opening phase is entirely absent in the modified camshaft configuration. This modification was intentionally designed to prevent the intake valve from opening during critical phases of the intake stroke. By eliminating the valve opening at specific crankshaft angles, the modified camshaft aims to reduce the risk of backfire and premature combustion, particularly when operating in a hydrogen-gasoline dual-fuel mode.

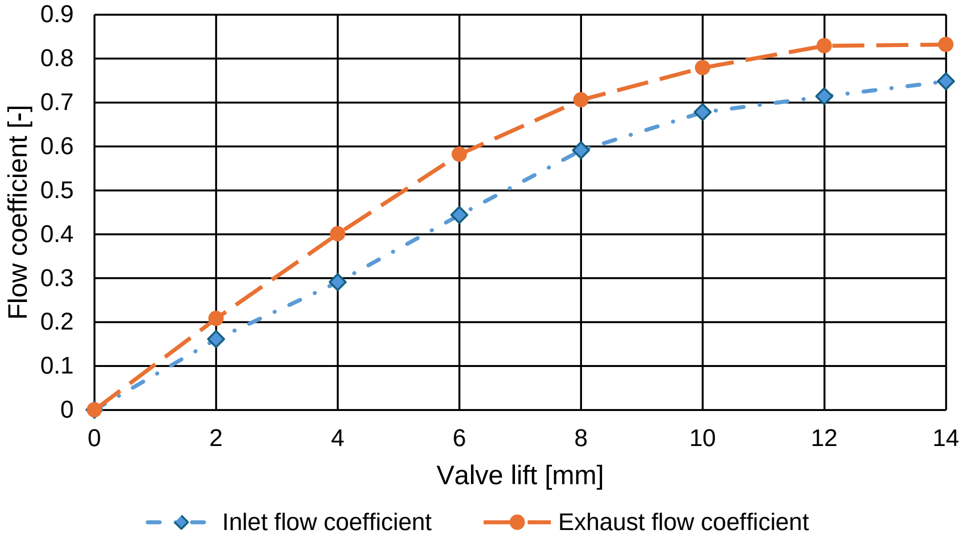

Figure 3. Valve lift coefficients

The flow coefficients of the ports were determined using a steady-state flow bench at a pressure difference of 6230 Pa (equivalent to 25 inches of H_2O). The calculations were based on the theoretical (isentropic) compressible mass flow for the given diameter, with the valve flow coefficients specifically calculated for the minimum valve seat diameter, dvdv

1.2.2 Simulation validation

In our previous research, we successfully validated the pure gasoline simulation within a standard AVL testbed environment. This validation process involved meticulous comparison between the measured values and those predicted by the simulation for key performance parameters, such as power, torque, and emissions. The results demonstrated a remarkable alignment, with deviations remaining under 3%, confirming the accuracy and reliability of the simulation model.

Building on this foundation, we advanced to the next phase of our research by developing a hydrogen-gasoline dual-fuel simulation. This phase aimed to explore the potential benefits and challenges associated with using hydrogen as a supplementary fuel in conventional gasoline engines. The dual-fuel simulation was meticulously configured to optimize the blend ratios, combustion timing, and fuel injection parameters, ensuring a balanced integration of both fuel types.

In the subsequent stage, we introduced a novel variable camshaft design specifically tailored for dual-fuel operation. This unique camshaft configuration was designed to optimize valve timing and lift profiles for eliminate the backfire problems and optimising the power and torque parameters at low RPM when operating on a hydrogen-gasoline mix. The modified simulation incorporated these advanced camshaft dynamics, allowing us to investigate the impact on engine performance and emissions under various load and speed conditions.

The experimental setup depicted in Figure 3 was instrumental in achieving these research objectives. This setup featured a highly controlled test environment equipped with precision sensors and data acquisition systems to monitor engine parameters in real-time.

This setup not only provided a robust framework for validating the dual-fuel simulation models but also facilitated the evaluation of the gasoline engine's performance and emissions characteristics under different configurations. The insights gained from these experiments will guide future developments in dual-fuel engine technology, with the potential to enhance fuel efficiency and reduce the environmental impact of internal combustion engines.

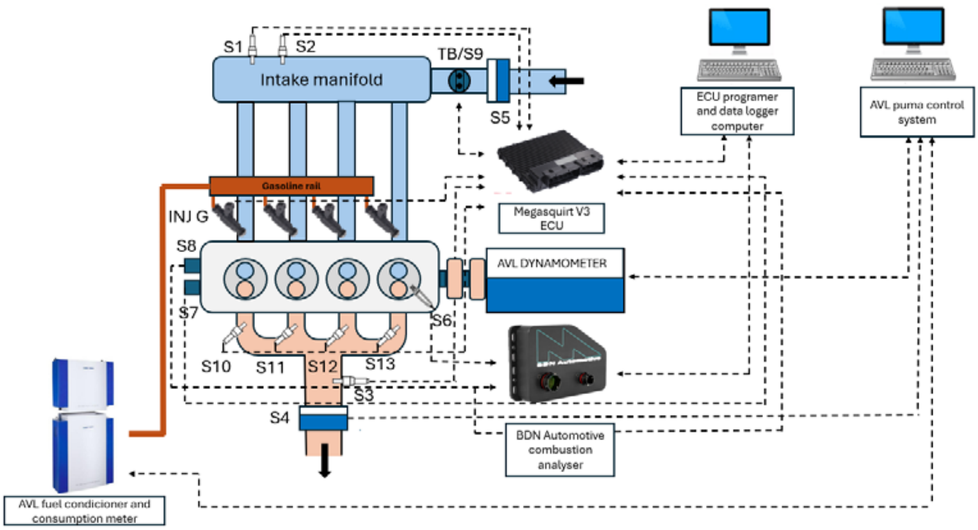

Figure 3. Testbed experimental setup

The unnamed elements of the block diagram are listed in Table 3.

Table 3 Modified camshaft parameters

S1	Intake air temperature sensor
S2	Intake manifold pressure sensor
S3	O_2 sensor
S4	AVL sesam i60 FTSII
S5	AVL flowsonix
S6	AVL indicator spark-plug and amplifier
S7	Camshaft position sensor
S8	Crankshaft position sensor
S9	Throttle position sensor
S10-S13	Exhaust teperature senores
TB	Throttle body

1.2.3 Fuel and air delivery system

Fuel was supplied to the engine using an advanced AVL fuel delivery system, which includes several key components for accurate measurement and control. The AVL fuel mass flow meter (735S) was utilized to measure the mass flow rate of the gasoline, ensuring precise fuel delivery throughout the testing process. The AVL flowsonix air flow meter was employed to monitor the intake air flow rat. To maintain consistent fuel properties, the AVL fuel temperature conditioner (752C) regulated the temperature of the gasoline to a stable 20[°C], minimizing variations that could affect combustion characteristics. The AVL fuel module (7531.21) managed the fuel supply at a constant pressure of 3,5 [bar], ensuring a steady and reliable fuel flow to the engine under all operating conditions. Under the measurement the air temperature was 20[°C] and the air pressure was 1022 [hPa]

1.2.4 Exhaust Emissions Analysis

The engine's exhaust emissions were analysed using the AVL sesam i60 FTSII exhaust gas analysis system. This state-of-the-art equipment enabled the continuous measurement of critical exhaust gas components, including carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NO_x), and unburned hydrocarbons (HC). By providing real-time emissions data, this system allowed for a detailed assessment of the engine's environmental impact under various operating conditions and fuel compositions.

1.2.5 Performance Measurements

Engine performance, including torque and power output, was measured using the AVL Dyno Road 200 dynamometer. This equipment is capable of precise torque and rotational speed measurements, providing accurate power output data across a wide range of engine speeds and loads. The dynamometer was crucial in evaluating the effects of different fuel blends and engine configurations on overall performance, helping to identify optimal operating parameters for the dual-fuel system.

1.2.6 Combustion Analysis System

To achieve maximum performance just below the knock limit and to facilitate the construction of an accurate simulation model, detailed combustion tests were conducted using a specialized combustion test system developed by BDN Automotive. This system was equipped with a CA-6 six-channel combustion analyser, which is capable of high-resolution data acquisition across multiple channels. An AVL indication spark plug and an AVL indicom charge amplifier were used to capture and amplify the combustion signals within the cylinder. The combustion analyser recorded data from all channels at a sampling rate of 1 MHz, allowing for the precise calculation of crank-angle-based combustion parameters, such as pressure, rate of heat release, and combustion duration.

The combustion test system utilized the signal from the original 60-2 pattern crank trigger wheel for accurate synchronization with the engine's operating cycle. This ensured that the combustion events were precisely correlated with the crank angle, enabling detailed analysis of the combustion process at various engine speeds and loads. The high sampling rate and multi-channel capability of the CA-6 analyser provided comprehensive insights into the in-cylinder phenomena, which were essential for refining the simulation model and improving the engine's performance and emissions characteristics.

1.2.7 Data Integration and Analysis

The data collected from the fuel delivery, exhaust emissions, and combustion analysis systems were integrated to provide a holistic view of the engine's behaviour. This comprehensive dataset was used to validate the simulation model, ensuring that the model accurately represented the real-world performance of the dual-fuel engine. By correlating the experimental data with the simulation results, we were able to identify key areas for optimization in both the engine hardware and the simulation model, leading to improved predictions and performance outcomes for the dual-fuel hydrogen-gasoline engine configuration.

Overall, the experimental setup and testing methodology provided a robust platform for investigating the complex interactions between hydrogen and gasoline in a dual-fuel engine. The insights gained from this research will contribute to the development of more efficient and environmentally friendly internal combustion engine technologies, supporting the transition towards sustainable mobility solutions.

2 SIMULATION RESULTS

The simulations confirmed that the custom camshaft design achieved a favourable balance between reducing backfire risk and maintaining engine performance, making it a promising solution for dual-fuel hydrogen-gasoline engines. Consistently illustrating the results of the simulation, we used a green line for petrol, a blue line for 20% hydrogen 80% petrol dual-fuel and an orange line for 20% hydrogen 80% petrol dual-fuel + modified camshaft values. Figure 4 represents the torque prediction.

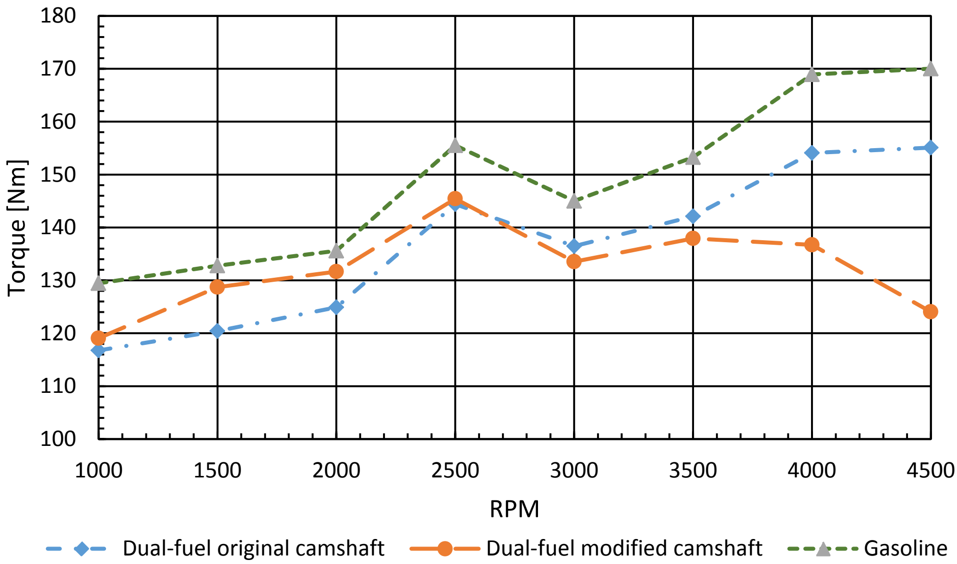

Figure 4. Torque prediction

It can be seen in the figure that using the new camshaft below 2500 rpm, we get higher torque values compared to the original camshaft in dual-fuel mode, but it still does not reach the torque level of gasoline mode. Between 2500 and 3500 rpm, we get slightly smaller torque values with the modified camshaft in dual-fuel mode, but above 3500 rpm, the torque curve drops drastically. Figure 5. represents the power prediction.

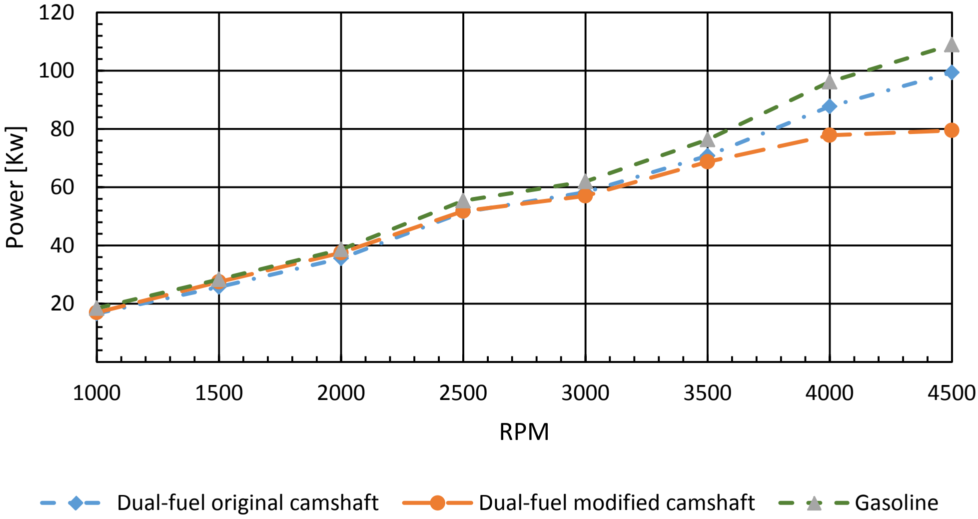

Figure 5. Power prediction

A significant difference between the performance curves can be observed above 3500 revolutions.

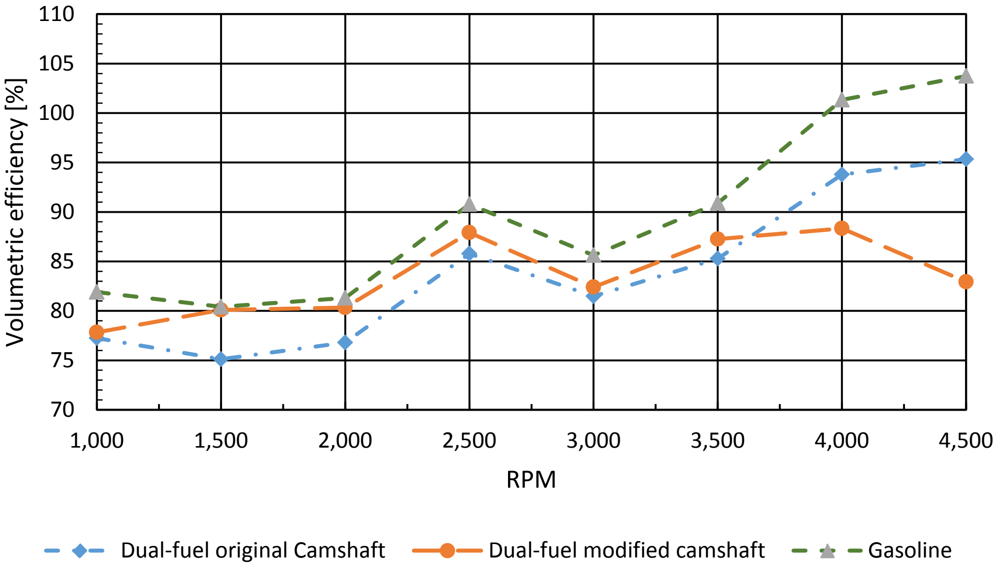

Figure 6. Volumetric efficiency prediction

The characteristics of the previously illustrated data and curves are explained by the change in the volumetric efficiency. At low revs, the volumetric efficiency with the modified camshaft is almost identical to that of pure gasoline. This is significant because hydrogen gas takes up a huge volume in the intake pipe in dual-fuel mode. On the other hand, the disadvantage of the modified camshaft is that the volumetric efficiency drops significantly at high revolutions, which has a great impact on the power and torque levels.

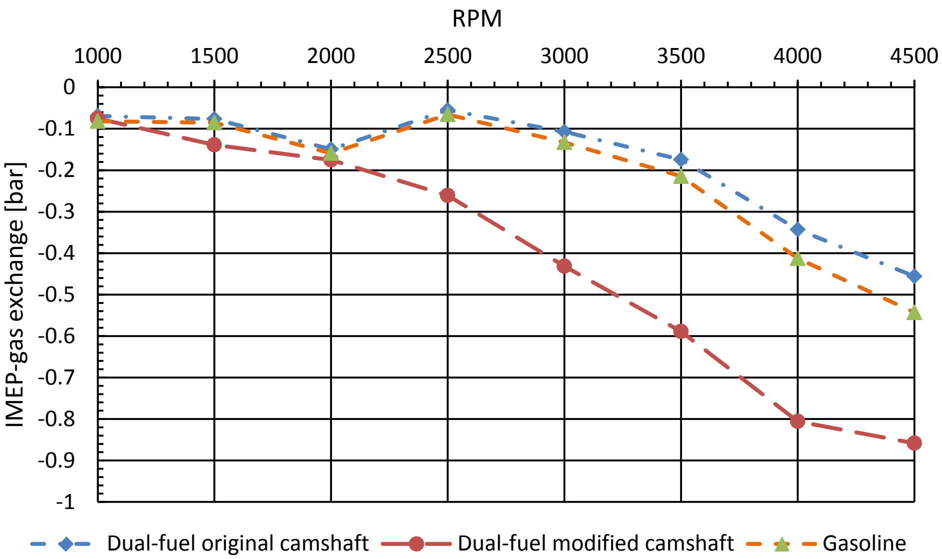

Figure 6. Indicated Mean Effective Pressure (IMEP)

In the modified camshaft configuration, the valve overlap is eliminated to prevent backfire and ensure more controlled combustion, especially when operating with hydrogen as a dual-fuel. However, this modification comes with a significant drawback: the absence of valve overlap at high engine speeds disrupts the natural flow of the intake and exhaust processes. Without valve overlap, the engine's ability to clear out residual exhaust gases is compromised, leading to increased reversion and decreased intake air charge. The modified camshaft design, with no valve overlap, significantly affects the engine's Indicated Mean Effective Pressure (IMEP) and overall performance, especially at high engine speeds.

3 CONCLUSIONS

This research investigated the effects of a custom camshaft design on the performance of a hydrogen-gasoline dual-fuel internal combustion engine using predictive simulations. The primary objective was to address the challenges associated with hydrogen integration, such as backfire, while optimizing overall engine performance. The proposed modification involved delaying the intake valve closure to reduce the likelihood of backfire and enhance combustion stability.

The simulation results demonstrated that the custom camshaft successfully minimized the risk of backfire and at lower engine speeds, improving combustion. However, the modification led to a noticeable decline in volumetric efficiency and IMEP gas exchange problems at higher revolutions, resulting in reduced power output and torque compared to the standard camshaft configuration. This trade-off highlights the inherent challenges in balancing performance and emissions in dual-fuel engines.

It is important to note that these findings are based on predictive simulations. In future work, we plan to validate these results by conducting experimental tests under real-world conditions using an AVL testbed. This will provide more comprehensive insights into the actual performance and emissions characteristics of the modified camshaft design in a practical setting, allowing for further refinement and optimization.

Despite the current limitations, the custom camshaft design showed promise in enhancing engine stability and emissions control under dual-fuel operation. The findings suggest that further optimization of camshaft timing and valve dynamics could field better performance outcomes without compromising the benefits of hydrogen addition. Future research should focus on refining camshaft profiles and exploring advanced control strategies to mitigate the limitations observed at higher engine speeds.

Overall, this study contributes valuable insights into the integration of hydrogen in ICE technology, supporting the development of more efficient and environmentally friendly automotive solutions. By addressing key challenges in dual-fuel engine design, the research paves the way for further innovations that could facilitate the widespread adoption of hydrogen as a sustainable energy source in the automotive sector.

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