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Hydrogen—An Alternative Fuel for Automotive Diesel Engines Used in Transportation

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Abstract: Considering the current environmental restrictions, particularly those imposed on fossil fuel exploitation, hydrogen stands out as a very promising alternative for the power and transportation sectors. This paper investigates the effects of the employment of hydrogen in a K9K automotive diesel engine. Experiments were conducted at a speed of 2000 min^{-1} with various engine load levels of 40%, 55%, 70%, and 85%; several quantities were monitored to evaluate the performance with hydrogen use in terms of brake-specific energetic consumption (BSEC), fuel economy, maximum pressure, and heat-release characteristics. It was found that at 55% engine load, the engine efficiency increased by 5.3% with hydrogen addition, achieving a diesel fuel economy of 1.32 kg/h. The rate of increase of the peak pressure and maximum pressure started to increase as a consequence of the higher fuel quantity that burned in the premixed combustion phase, while still remaining within reliable operational limits. The accelerated combustion and augmented heat release rate resulted in a combustion duration that was reduced by 3° CA (crank angle degree), achieving a mass fraction burned percentage of 10% to 90% earlier in the cycle, and the combustion variability was also influenced. Hydrogen use assured the decrease of CO_2, HC, NO_x, and smoke emission levels in comparison with classic fueling.

Keywords: combustion; diesel engine; hydrogen fuel; efficiency; heat-release rate; mass fraction burned; combustion variability

1. Introduction

1.1. Pollutant Emissions in Automotive Engines

The transportation sector causes a major part of the greenhouse gas emissions worldwide, but nowadays, sustainability and innovation in the automotive industry are based on new technologies [1], especially for internal combustion engines, which have an important place in the transportation field [2]. To mitigate the related environmental impact, restrictions are imposed to diminish these harmful emissions (which, in terms of greenhouse gas emissions, are estimated to add up to 20% for transportation) [3]. Specifically, severe limitations are set for unburned hydrocarbons (HC), carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NO_x), particles, and smoke [1–6]. As the root of the generation of these pollutants is the automotive engine, it is remarked that HC and CO result as a consequence of incomplete combustion, while NO_x (mainly nitrogen monoxide—NO and nitrogen dioxide—NO_2, known as NO_x emissions in the internal combustion engine (ICE) domain) is produced in the chemical reaction between nitrogen and oxygen unfolding in high-pressure conditions, such as the ones registered for in-cylinder combustion in engines [4]. Organic and inorganic components in the fuel supply (solid or liquid) are found in the exhaust gas as solid particles (PM). In more detail, they are formed based on a carbon-insoluble fraction (soot) and a soluble fraction that contains fuel and unburned oil. It is highlighted that the particles emitted by diesel engines have dimensions within the range from 0.01 to 1 µm, so they can easily enter the human lungs, therefore representing a major health threat. Smoke is composed of a suspension of liquid particles of unburned or partially burned fuel with diameters of up to 1 µm (white or blue smoke), or of carbon particles with diameters greater than 1 µm (black smoke) [4]. White and blue smoke appear under starting, idling, or low-load conditions when the engine thermal regime is reduced. Black smoke appears with increased loading operation, when the engine thermal regime is high.

For diesel engine operation, the largest share of the exhaust gases in terms of pollutant emissions belongs to nitrogen oxides, solid particles, and smoke [3–7]. As diesel engines are widespread in transportation, it is of crucial importance to significantly diminish the concentration of the pollutants and greenhouse gas emissions in the exhaust gas flows [8].

1.2. Overview of Hydrogen Utilization in Automotives

According to the Paris Agreement, signed by 200 countries at the United Nations Framework Convention on Climate Change in 2015, a series of proposals for the limitation of average global temperature increase and for pollutant emission concentration reduction have been introduced [7]. Furthermore, at the C40 Mayors Summit in Ciudad de Mexico held in 2016, a possible solution to the increased pollution in a few capitals (Paris, Athens, and Ciudad de Mexico) was considered to be the elimination of the automotive diesel engine by the year 2025 [8].

In this restrictive regulatory framework, the newest diesel engines must comply with the European Union standards regarding NO_x and microparticle emissions. The European Commission aims to reduce CO_2 emissions from transportation by 37.5% by 2030. Thus, clean diesel engines, which have a 15% lower CO_2 emission rate and a much lower specific fuel consumption compated to spark-ignition engines, represent a good solution. However, some innovative designs for improvement of the in-cylinder combustion process assume high costs and may be delayed in becoming profitable [5,6]. Moreover, the complexity of the engine increases. Therefore, employing alternative fuels emerges as a viable solution, enabling the replacement of fossil fuels and the reduction of pollutant emission concentrations [5,6].

Several studies have demonstrated that employing alternative fuels reduces environmental pollution, as presented in [9–11]. Among these solutions, the use of hydrogen as fuel for ICEs (replacing oil products) has been proven to reduce the diesel engine pollutant emission level [12,13], while also improving the energetic performance reached in operation [14,15]. An important factor supporting hydrogen use for such purposes is that it is naturally widespread. Taking into account that 70% of the planet's surface is covered by water and that hydrogen is one of its constituents, this may represent an inexhaustible source, considering that one cubic kilometer contains almost 113,100 tones of hydrogen [16–18]. It is remarked that hydrogen has good combustion properties, qualifying it as the cleanest fuel for ICEs and enabling high combustion efficiencies compared to other alternative fuels [19,20]. Hydrogen is an easily flammable gas, is inodorous, insipid, and colorless, and is found in nature as a diatomic molecule, H_2. Hydrogen is the lightest chemical element and is also the most prevalent element in the universe.

Regarding the storage of hydrogen, it can be in a liquid (in cryogenic reservoirs) or gaseous state (in pressurized reservoirs) on-board an automotive. Liquid-state storage is difficult because hydrogen has a very low boiling point (−253 °C), resulting in multiple technical and safety requirements and constraints. Gas-state storage presents the disadvantage of needing a relatively large volume of reservoirs because of hydrogen's low density (for instance, to substitute the quantity of diesel fuel that is stored in a 70 L reservoir, 11,720 L of compressed hydrogen is necessary) [21].

Hydrogen requires a much lower quantity of vaporization heat, implying a lower heat self-consumption if the fuel is directly injected in liquid state. The solubility of hydrogen in liquids is very low, and some metals dissolve hydrogen at high temperatures, forming interstitial hydrides. Due to its molecular mass, hydrogen has higher specific mass heat and heat conductivity compared to other gases [22]. Instead, the dynamic viscosity of hydrogen is two times lower compared to that of air. The very high diffusion velocity showed by hydrogen ensures good homogeneity mixtures in blends with other gases [23,24]. However, increased diffusion of hydrogen in thin holes or porous walls leads to negative effects on metal structures (according to some researches, the hydrogen diffusion velocity is 7.8 times higher comparative to gasoline [21]), and special storing conditions are required. High octane number makes hydrogen an ideal fuel for spark ignition engines with high compression ratios, but the raised autoignition temperature and lower cetane number define hydrogen as a fuel with inferior autoignition properties, and specific methods for hydrogen fueling must be applied for diesel engines. Hydrogen has wide flammability limits in air ($4.1\%_v$ inferior limit $-75.6\%_v$ superior limit) [15]. An important advantage of hydrogen use is the possibility of ultralean engine operation; in other words, the air-fuel ratio can be very high (over $\lambda = 10.8$), enabling an appreciable engine cycle efficiency improvement, i.e., around 38% [18]. Because the flame temperature in hydrogen combustion is much higher and ultralean mixtures are fed to the engine, nitrogen oxides levels augment, requiring treatment of the exhaust gases.

Experimental investigations carried out on hydrogen fueled ICEs have highlighted certain specific effects of its combustion versus diesel fuel [14,25]. Specifically, by increasing the hydrogen quantity, the peak pressure slightly increases in reduced loading conditions, while it rapidly increases at higher loads. This is a consequence of a smaller delay in diesel fuel autoignition, correlating with the higher combustion rate of hydrogen compared to that of diesel fuel [26,27]. The same trend applies to the maximum pressure rise rate [27,28]. Both parameters can be used for hydrogen addition optimization in order to limit mechanical stress on the engine [18,29].

Regarding the engine thermal efficiency, it has been observed that it increases with an increase in the hydrogen quantity in the diesel fuel blend, due to the improvement of the combustion process [30,31]. For greater engine loads (60–80%), the thermal efficiency sharply decreases because of the incomplete combustion of a rich mixture [32–34]. Furthermore, the maximum heat release rate increases by incrementing the hydrogen share in diesel fuel blends due to the higher combustion velocity of such mixtures (hydrogen has a nine times larger combustion velocity compared to diesel) [35–37]. For small hydrogen quantities, improved combustion ensures a decrease of CO and HC emissions levels, but further hydrogen addition leads to incomplete combustion, producing an increase in such emissions [35,36]. Some researchers have even demonstrated that the HC emissions increase regardless of the hydrogen amount, with a proportional O_2 intake reduction [31].

In reference to smoke emissions, it is noteworthy that the use of hydrogen in diesel engines achieves marked reductions due to improvements in the combustion process and a decrease in the grade of carbon concentrations from the cyclic fuel dose [38].

Compared to exclusive diesel fueling, by using a hydrogen–diesel blend with small to medium engine loads, the NO_x emissions depend on the hydrogen share, decreasing with small amounts of hydrogen and increasing with higher ratios (because of higher temperatures during combustion) [39].

According to the aforementioned observations, it has been demonstrated in the literature that hydrogen may be suitable as partial substitute of diesel fuel in CIEs, enabling also a reduction in exhaust gas emissions [40,41].

Different researchers have used hydrogen as fuel for different internal combustion engines in order to improve engine performance and reduce pollution. For example, Shin [42] used hydrogen to fuel a two-liter diesel engine with an operating regime of 1500 rev/min speed and a 2.5 kg/h diesel fuel rate. Through the addition of hydrogen, NO_x emission levels decreased, and combustion duration and the maximum pressure increased.

Das [43] defines hydrogen as a clean alternative fuel whose use leads to improved thermal efficiency and reductions in NO_x emissions without abnormal combustion phenomena in lean mixture operation.

Dell [44] promotes the use of hydrogen as an alternative fuel which is economically and environmentally feasible in automotive and truck engines. Moreover, affirms that the hydrogen combustion in internal-combustion engines is totally different to that of classic fuels, and requires special design modifications, because hydrogen's low ignition energy and rapid flame speed lead to phenomena like preignition, backfire and knock.

Sorensen [45] confirmed that the thermal engine efficiency increase with the use of hydrogen in diesel and spark ignition engines is due to hydrogen's higher combustion speed. Sorensen [26] observed the rate of consumption of injected hydrogen. If hydrogen is fed into the cylinder from a specific side, a zone of "unused" oxygen appears in the combustion chamber, i.e., the oxygen distribution inside the combustion chamber is affected. The author proposes the use of catalytic converters to reduce NO_x emission levels [45].

Verhelst [46] presented an overview of hydrogen internal combustion engines and highlighted the increase of engine efficiency and the reduction of pollutant emissions.

Mansor [47] used hydrogen and methane to fuel a diesel engine and observed that if the diesel fuel cyclic quantity is raised, then the in-cylinder maximum pressure decreases and the ignition delay is reduced. With an increase of hydrogen quantity, the maximum pressure increases significantly and the autoignition delay starts to decrease. This higher maximum pressure corresponds to higher hydrogen contents [47]. Also, for higher hydrogen ratios, the combustion temperature and the NO emission levels are higher. Finally, Mansor proposes the use of small hydrogen quantities in order to achieve lower combustion temperatures, thereby improving the thermal efficiency, i.e., with reduced thermal losses [47].

Sandalci [48] used hydrogen addition to fuel a diesel engine with an operating regime of 5.1 kW and 1300 rev/min. The hydrogen is injected into the intake manifold, and the air–hydrogen mixture is ignited by a diesel fuel pilot. Regarding the use of hydrogen, Sandalci observed a reduction in smoke emissions, an acceleration of premixed combustion and an increase in maximum pressure proportional to the ratio of hydrogen in the fuel [48]. However, for large hydrogen contents, the NO_x emission levels increased, the thermal efficiency decreased and fuel consumption increased [48].

Dhole [49] used hydrogen as a secondary fuel for a diesel engine, with good results in terms of thermal efficiency (i.e., a 6 to 10% increase, depending engine load and hydrogen content) and NO_x emission level reductions (i.e., a 63% decrease with small engine loads and 32% decrease with large loads) [49].

Karagöz [50] used hydrogen as an additive fuel in a CFR diesel engine with a full load regime and different speeds; a decrease of smoke and CO_2 emissions levels, a significant increase in NO_x emission level and a slight increase in HC were observed. The maximum vales of in-cylinder pressure and heat release increased with the addition of hydrogen [50]. Kavtaradze [51] noted that in-cylinder processes are fundamentally different with hydrogen diesel compared to classic diesel fuel, with influences on combustion parameters and pollution performance. In this regard, Kavtaradze [51] conceded that hydrogen diesel engines are a new field of investigation, and that this topic has not yet being sufficiently investigated. Therefore, Kavtaradze [51] used hydrogen to fuel a single cylinder MAN diesel engine; a 920 ppm of NO, an nine-bar mean effective pressure and a 0.48 efficiency indicator were achieved. Based on these experiments, Kavtaradze [51] confirmed that hydrogen is a suitable fuel for diesel engines and could be successfully used to reduce pollution emissions.

Ghazal [52] investigated the effect of the use of a hydrogen/diesel fuel and water injection in engine ports on the operation of a diesel engine. Ghazal's simulation showed that an increase of hydrogen flow, in correlation with water flow, led to increased combustion temperature, NO emission levels, engine power and brake specific fuel consumption, as well as of thermal efficiency, at high engine speeds [52]. With a decrease of injection timing, engine efficiency was affected and the emission of NO also increased, while CO emission levels decreased [52]. At a specific engine speed, i.e., 3000 rev/min, and at higher injection timing, the CO emissions decreased, but higher in-cylinder pressure, pressure rates and temperatures led increased fuel consumption, NO emission levels and operating vibrations [52]. Even with a constant flowrate of hydrogen, in-cylinder pressure, temperatures and emissions level started to increase [52]. Ghazal [52] decreased the injection timing in order to reduce NO and CO emissions levels to an acceptable level.

Monemian [53] defines hydrogen as a “long-term fuel solution” for diesel engines, and used it to partially substitute traditional fuel in a single cylinder HD diesel engine. At higher hydrogen doses, Monemian [53] observed increased engine efficiency, with a corresponding decrease in CO_2 emission levels of 32%up to 58%, depending on engine load [53]. At small loads, CO and soot emissions were shown to decrease with hydrogen use [53]. With a constant injection moment, the NO_x emission levels increased by 26% under an average engine load, and by 56% under a higher load because of the increased combustion temperature [53]. Lešnik [54] identified hydrogen as a viable solution to improve the technology level of modern internal combustion engines. In his study, he espouses the benefits of hydrogen use, especially in heavy-duty, commercial automotive, or passenger car diesel engines, in terms of reductions of pollutant emissions [54]. Lešnik further affirms that, in the future, internal combustion engines will continue to play an important role in road transportation [54]. Yip [55] studied the use of hydrogen in internal combustion engines, focusing in part on diesel engines and analyzing different types of fueling solutions. It was observed that the use of a diesel fuel pilot in order to ignite the air–hydrogen mixture as an operating mode of dual fueled diesel engines (hydrogen and diesel fuel) eliminated issues of hydrogen use in spark ignition engines and yielded reduced pollutant emissions compared to traditional diesel engines [55]. Yip [55] states that a fueling system that ignites a hydrogen–air mixture using a diesel fuel pilot may be viable in the future. Regarding hydrogen use, Yip [55] observed the possibility of decreasing CO and smoke emissions by up to 50%, depending on the hydrogen dose. The NO_x emission levels may increase, but this is dependent on the hydrogen fueling method, and further reductions can be achieved [55]. Saroj [56] noted that hydrogen is a nonpolluting energy source which may be used to fuel diesel engines in a dual fuel formula with biogas. Saroj [56] observed that dual fueling led to an increase of brake specific fuel consumption by 36%, compared to traditional engines. For dual fuel mode operation, the maximum pressure increase was 23% and the heat release rate increased by 30% [56]. Compared to the use of traditional fuels, the NO_x emission and smoke emission levels were reduced by 20% and 60%, respectively, but CO emission levels increased by 30%, according to Saroj [56]. Finally, Saroj concluded that hydrogen supply can improve the performance of diesel engines fueled by biogas [56].

1.3. Aim of Research

The accelerated depletion of oil reserves highlights the necessity of alternative fuels, especially from durable and renewable resources, such as hydrogen, which may be produced from plants [1,2,5,6,9]. While this paper presents some challenges, its main objective is to study the increase in the energetic performance of automotive diesel engines through the addition of hydrogen to diesel fuel. On one hand, hydrogen has a lower energy density compared to diesel, so an adequate design of fueling systems must be developed, in order to keep the engine power constant. On the other hand, the inferior autoignition properties of hydrogen necessitate the application of methods which are specific to hydrogen fueling. So our main objective, i.e., measuring the increase in the energetic performance of automotive diesel engines by the addition of hydrogen to the fuel, requires the use of a fueling method which is easy to apply and suitable for all diesel engines. The diesel–gas method, which is considered easy to apply to old or new diesel engine designs, was used as the fueling method. This paper presents some experimental results of hydrogen use in a diesel engine. The authors studied the influence of the hydrogen cyclic dose on the energetic and combustion performance of the engine.

The novelty aspect of this research is its determination of the optimal correlation among engine operating regime, fuel cyclic dose, combustion parameters and pollutant emissions, in order to apply these data to a modern diesel engine. The hydrogen–diesel fueling system designed by authors is electronic controlled and actuated by a Dastek Unichip Program via on open ECU Unichip unit, which adjusts the cyclic doses of the fuels (hydrogen and diesel fuel) in order to maintain the engine power according to a reference engine. Thus, the fueling system developed by the authors can be used with modern automotive diesel engines equipped with electronic control, for operation under variable load and speed regimes. In terms of the added hydrogen, if the quantities are small, the novelty is reflected in the possibility of the use of an on-board hydrogen generator. The fueling system is designed to be versatile, i.e., switching to classic fueling is possible anytime. Additionally, it does not require modifications to be made to the engine. The optimal correlation of the aforementioned variables makes it possible to control the NO_x emission levels without exceeding the levels resulting from the use of traditional fuels, as well as to continuously decrease HC.

To accomplish this objective, experimental investigations were carried out at 40%, 55%, 70% and 85% engine loads, and at 5%, 10%, 15% and 20% ratios of diesel fuel to hydrogen. Beside the advantage of reduced dependence on traditional fuels, hydrogen offers the advantages of reduced diesel fuel consumption and improved combustion. The reduction in diesel fuel consumption, with 1.32 kg/h less diesel fuel consumed at 55% engine load, appears to be due to improved engine efficiency and to the combustion process, in terms of an accelerated heat release rate, more rapid mass fraction burned per cycle, and higher values of maximum pressure and rate of maximum pressure increase under normal engine operation conditions. This last aspect was evaluated by an analysis of engine response to combustion variability with hydrogen use—with the coefficients of variability for IMEP and maximum pressure in the normal range—using a normal engine running on dual fueling.

2. Experimental Investigations Design

This paper investigates the effects of a hydrogen mixture with diesel in a supercharged K9K diesel engine. To this end, the engine was fueled with diesel fuel and hydrogen at different proportions. Additionally, the engine loading was varied from 40%, 55%, 70% and 85% for a constant operational speed of 2000 min^{-1}. The combustion characteristics and engine performance were assessed, as described below.

The test bench designed to evaluate the performance of the hydrogen diesel engine is shown in Figure 1. The fueling system was equipped with an open-type ECU which was connected to a fueling system and controlled by a computer running the Dastek Unichip software. To maintain the engine power with an increase of hydrogen cyclic quantity, the diesel fuel was reduced. The fuel quantities were electronic managed by controlling the duration of open injectors. The durations of the injections were established in concordance with engine regime/combustion parameters and pollutant emissions.

Table 1 presents the main characteristics of the equipment.

Table 1. Main characteristics of test bed equipment.

Measured Parameter	Measurement Device	Unit	Uncertainties
Engine speed	Horiba Schenck E90	rev/min	±1 rev/min
Engine torque	Horiba Schenck E90	Nm	±0.2%
Diesel flow rate	Optimass 3050 C	kg/h	±0.1%
Hydrogen flow rate	Alicat Scientific MCR	kg/h	±0.4%
Inlet air flow rate	Krohne H 250	m3/h	±0.35%
In-cylinder pressure	AVL GU 12 P	bar	±0.05%
Crank angle degree	AVL 365 CC	° CA	±0.1%
Temperatures	Thermocouple Cromel–Alumel TTC	°C	±1 °C
	Thermoresistence Pt100 TTR	°C	±2 °C
	Shimaden SR93 indicators	°C	±0.3%

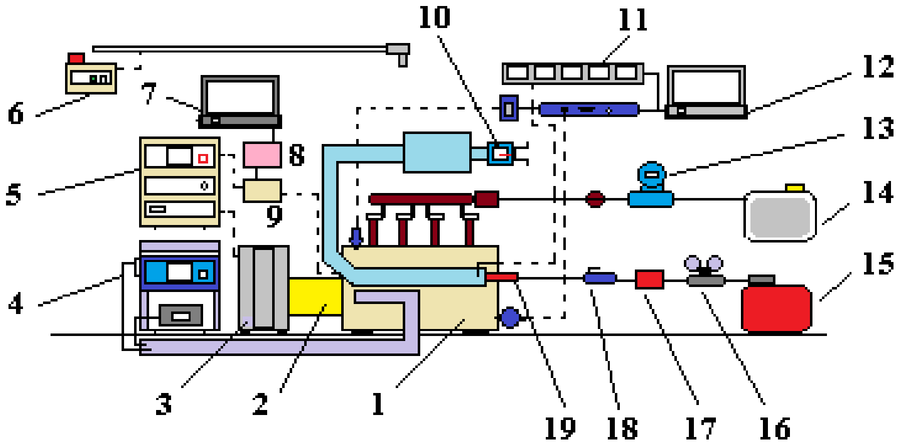

Figure 1. The hydrogen-diesel engine test bench, comprising the following parts: 1—supercharged four cylinder K9K diesel engine; 2—Voith coupling shaft; 3—Horiba Schench eddy current dyno; 4—AVL DiCom 4000 gas analyzer and opacimeter; 5—dyno control cabinet; 6—test cell safety sensor for hydrogen detection; 7—Dastek Unichip computer; 8—Unichip Q; 9—ECU of K9K engine; 10—Krohne air flowmeter; 11—Shimaden supercharging pressure and temperature indicators; 12—AVL data acquisition system (AVL Indimodul Card C1 acquisition board, AVL Indimodul 621, AVL-3067A01 charge amplifier, AVL-GU12P pressure transducer and AVL-365CC angle encoder); 13—Optimass diesel fuel flowmeter; 14—diesel fuel reservoir; 15—hydrogen reservoir; 16—hydrogen pressure regulator; 17—Alicat Scientific MCR hydrogen flowmeter; 18—flame arrestors; 19—hydrogen injector.

At the beginning of the experimental procedure, all the experimental instruments and the equipment were calibrated. The diesel engine was designed by the authors [26,28] and included a hydrogen fueling system with an embedded hydrogen injector connected to the inlet manifold, a flame arrestor, a pressure regulator and a hydrogen reservoir. In order to monitor the hydrogen flow, a dedicated flowmeter was installed on the fuel line. The hydrogen injector was set in motion from a computer running the Dastek Unichip software (an Unichip electronic unit connected with the ECU of the K9K engine). The Unichip unit controlled the opening durations of the diesel fuel inlet and hydrogen injectors, thereby reducing the diesel fuel cyclic amount with an increase of hydrogen flow in order to keep the output brake power constant at the level of standard fueling. In this way, different hydrogen flows were set, so the energetic substitute ratio was modified. Thus, it was possible to ensure the best correlation between engine running regime, fuel cyclic quantities, in-cylinder peak pressure, pollutant emissions levels and exhaust gas temperature for high engine efficiency when using hydrogen. This represents a novel aspect introduced by this research. For each engine operating regime, the diesel fuel and hydrogen flows, emissions levels, supercharging pressure, temperatures of the exhaust gases, inlet air, oil and cooling liquid and number of 250 pressure diagrams were monitored.

3. Results and Discussions

The variation ratio (VC) is defined according to Equation (1) [41]:

$$\mathrm{VC} = \frac{\sqrt{\frac{1}{n}\cdot\sum_{i=1}^{n}\left(x_i - \frac{\sum_{i=1}^{n} x_i}{n}\right)^2}}{\frac{\sum_{i=1}^{n} x_i}{n}} \tag{1}$$

A set of three measurements were recorded for each engine load regime. The VC was used to evaluate the measurement error for the results. Due to the stability of the operating regimes, the VC values calculated for all measures (engine brake torque, engine speed, brake fuels consumptions, gas temperature) did not exceed 1%. Thus, the data spread was narrow, the measurement sample was uniform and the VC value was below the limit of convergence for each measured dataset.

Figure 2 presents the Brake Specific Energetic Consumption (BSEC) variation versus xc substitute ratios at different engine loads. For each engine load, the specific energy consumption decreased with an increase of xc due to an improved mixing process of hydrogen and air, and to improved combustion. At partial loads of 40% and 55%, for maximum xc, the BSEC decreased by 8.16% and 4.16%, respectively. For high loads (85%) the BSEC slowly increased because the inlet air quantity decreased.

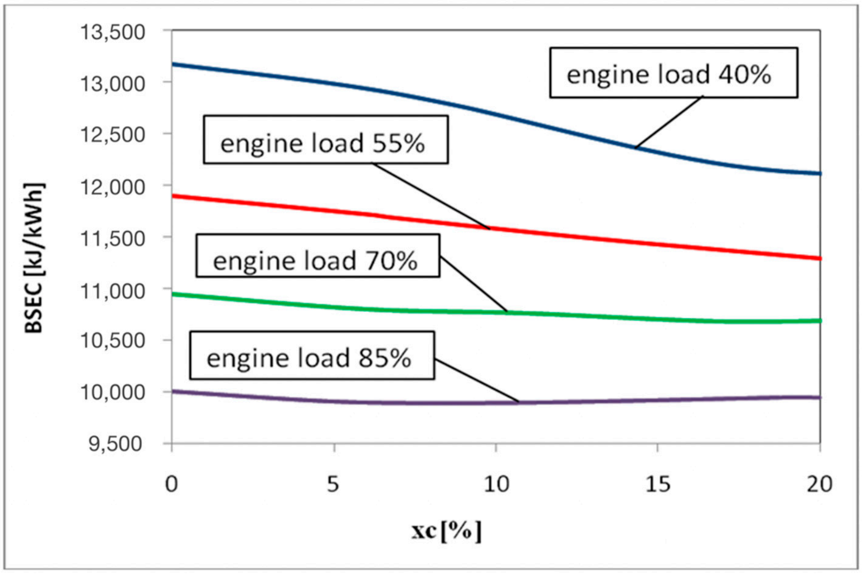

Figure 2. Break Specific Energetic Consumption versus substitute ratio at different engine loads and 2000 min^{-1} speed.

Figure 3 presents the variation of the BSEC versus engine load for 2000 min^{-1} speed and different xc substitute ratios. As shown in Figures 3–5, hydrogen fueling with flows ensuring maintained engine power at the same load and speed, in terms of diesel fuel consumption, yielded a significant economy of diesel fuel and a lower energetic specific consumption.

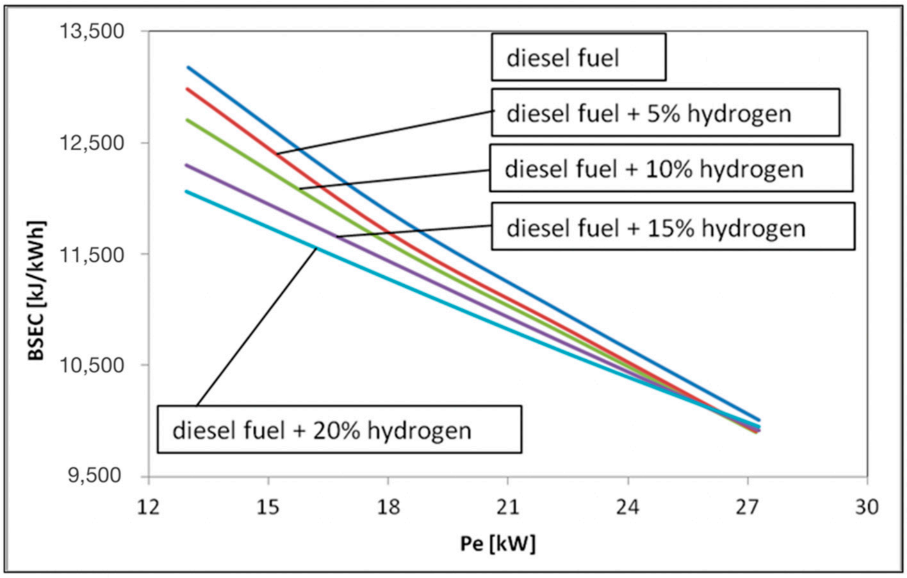

Figure 3. Brake Specific Energetic Consumption versus engine load at 2000 min^{-1} speed and different substitute ratios.

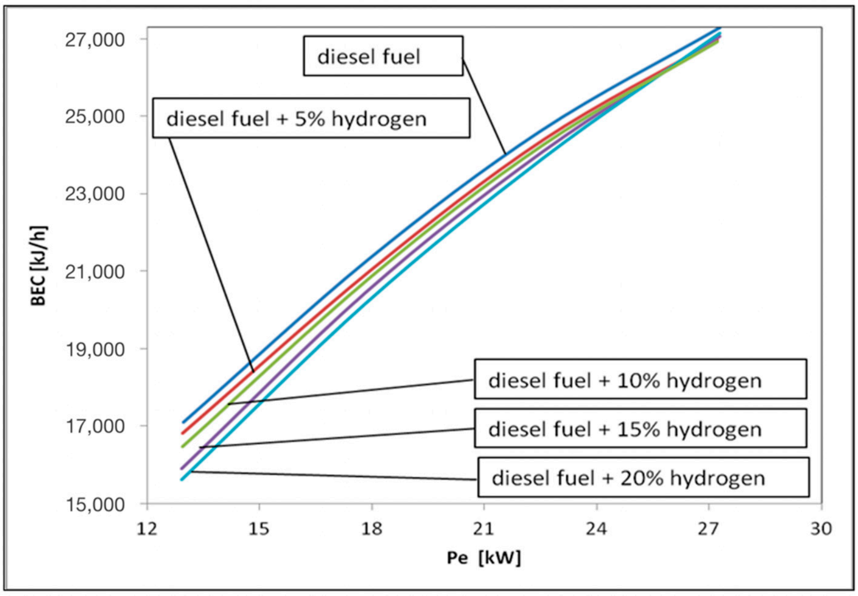

Figure 4. Brake Energy Consumption versus engine load at a speed of 2000 min^{-1} and different substitute ratios.

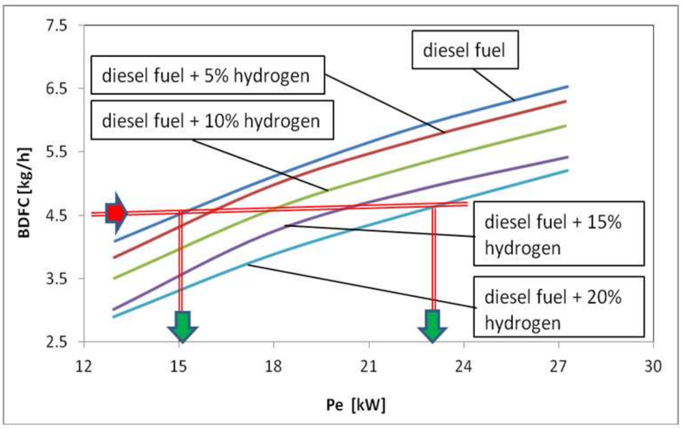

Figure 5. Brake Diesel Fuel Consumption versus engine load at a speed of speed 2000 min^{-1} and different substitute ratios.

Figures 4 and 5 present the variation of the Break Energy Consumption (BEC) and the Brake Diesel Fuel Consumption (BDFC), respectively, versus engine load at 2000 min^{-1} and using different substitute ratios.

For example, at 55% engine load (P_e = 18 kW), the economy of diesel fuel was 1.32 kg/h and the diesel engine efficiency η was increased by 5.3%; see Figure 6. For hydrogen and diesel fueling, with the same diesel fuel consumption, the engine operating load range increased and the engine power increased from 15 kW to 22.5 kW; see Figure 5.

Figure 7 presents averaged pressure diagrams p-α for classic fueling (xc = 0) and for hydrogen addition (xc = 6.76%, xc = 13.39% and xc = 20.97%), at 55% engine load and a speed of 2000 min^{-1}. The combustion intensification and the reduction of droplet combustion duration in the presence of an air–hydrogen mixture are in correlation with the increasing tendency observed during our experiments regarding the peak pressure and maximum pressure rise rate; see Figures 7–9.

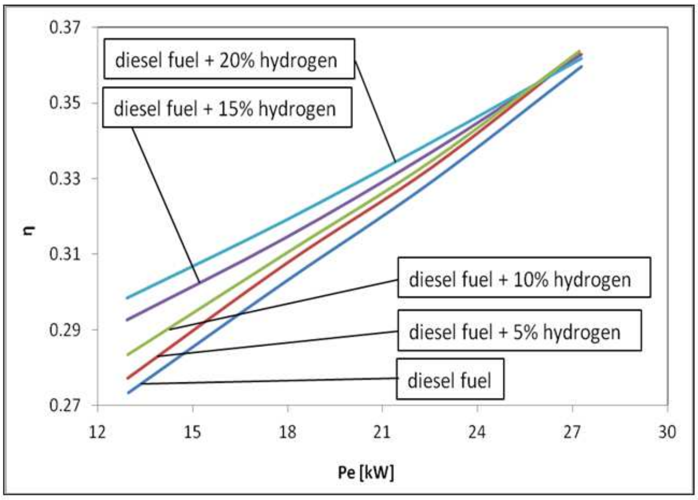

Figure 6. Brake Efficiency versus engine load at a speed of 2000 min^{-1} and different substitute ratios.

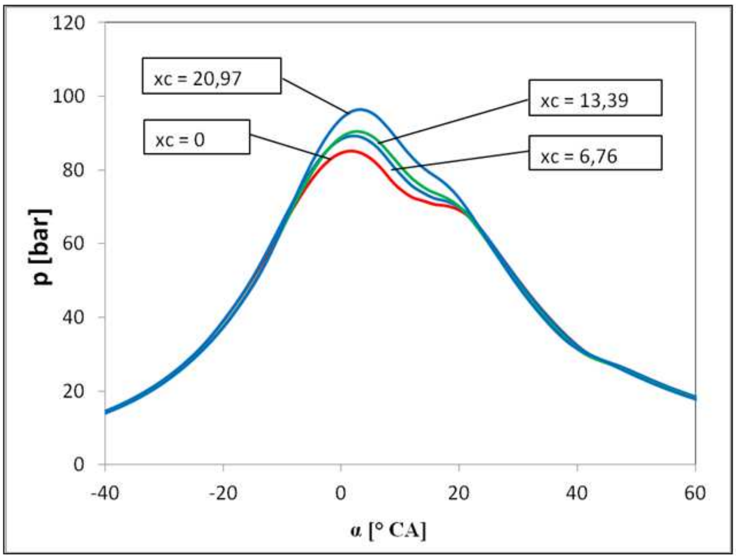

Figure 7. Pressure diagrams at 55% engine load and a speed of 2000 min^{-1} for different substitute ratios.

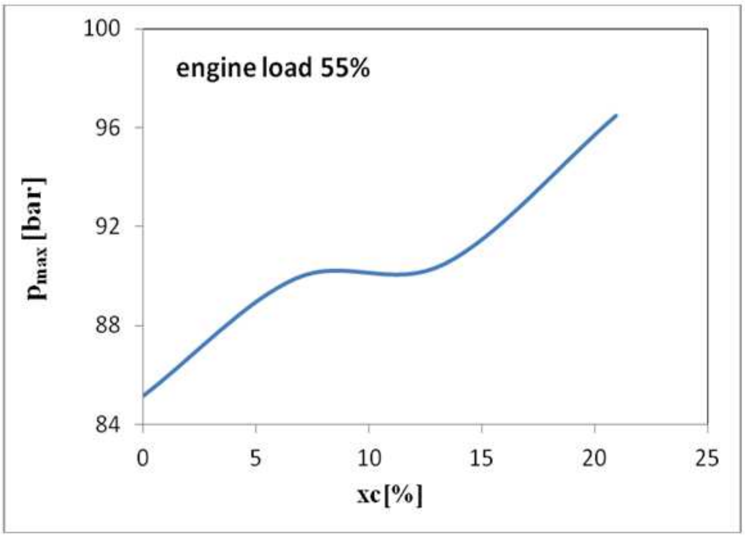

Figure 8. Peak pressure versus substitute ratio at 55% engine load and a speed of 2000 min^{-1}.

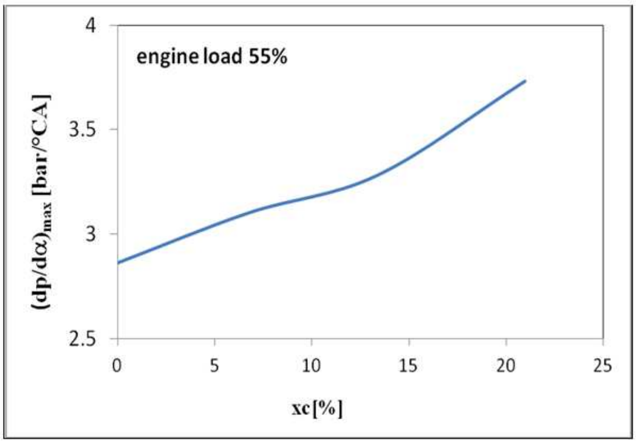

Figure 9. Maximum pressure rise rate versus substitute ratio at 55% engine load and a speed of 2000 min^{-1}.

The peak pressure p_{max} and the maximum pressure rise rate $(dp/d\alpha)_{max}$ began to rise with the addition of hydrogen (see Figures 8 and 9) due to the increase in the fuel being burned in the premixed stage. The higher combustion speed and calorific value of hydrogen ensured the increase of heat release during the early stages of combustion (see Figure 10) in correlation with the increase in the values of in-cylinder peak pressure and maximum rate of pressure rise (see Figures 7–9). Thus, compared to diesel, the addition of hydrogen led to an increase of peak pressure by 6% for xc = 6.76 and 13.39, and by 13% at xc = 20.97.

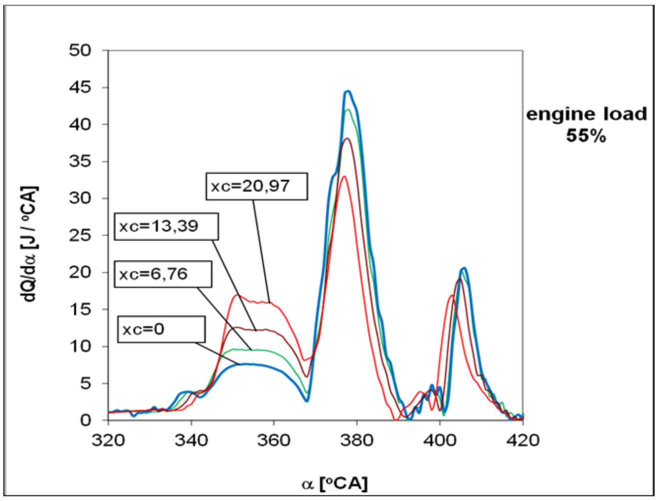

Figure 10. Heat release rate for different substitute ratios at 55% engine load and a speed of 2000 min^{-1}.

The maximum value of pressure rise rate started to increase from 7.6% to 14% for xc = 6.76 to 13.39, and by 29% at xc = 20.97. The reached values did not affect engine reliability, as the usual range of values was not exceeded; however, the tendency of these values to increase may be considered as a limitation regarding the portion of hydrogen to be used. Similar results of maximum pressure increase with the use of hydrogen were also recorded in experiments presented elsewhere [42,47,48,50,52].

With diesel–hydrogen fueling, due to the increase of fuel quantity which combusted in the rapid stage, in correlation with the higher heating value and combustion rate of hydrogen, the rate of heat released (dQ/dα) into the combustion premixed stage increased; see Figure 10. The higher combustion speed of hydrogen accelerated the release of heat, appearing sooner per cycle, with 3 crank angle degrees for xc = 20.97. Due to the increased calorific value of the hydrogen fuel, the peak of heat release rate during the first stage of combustion started to rise, reaching 28.6% at xc = 6.76, 68% at xc = 6.76, and 126% at xc = 20.97; this tendency correlated with the increased variation of maximum pressure and rate of pressure rise. The acceleration of the premixed mixture combustion was consistent results reported elsewhere [42,47,48,52,56].

Regarding TDC, the heat release reached 95% at maximum hydrogen dose use, with increases being 23% to 52% for xc = 6.76 to 13.39, which is comparative to classic fuel. The maxima in heat release tended to appear five crank angle degrees sooner per cycle, in correlation with the acceleration of heat release during the early stages of combustion when using hydrogen. These aspects are connected with the decrease of angle values related to the conventional Mass Fractions Burned (MFB), which were achieved sooner per cycle, i.e., closer to TDC, which correlates with the acceleration of the combustion process when using hydrogen; see Figure 11.

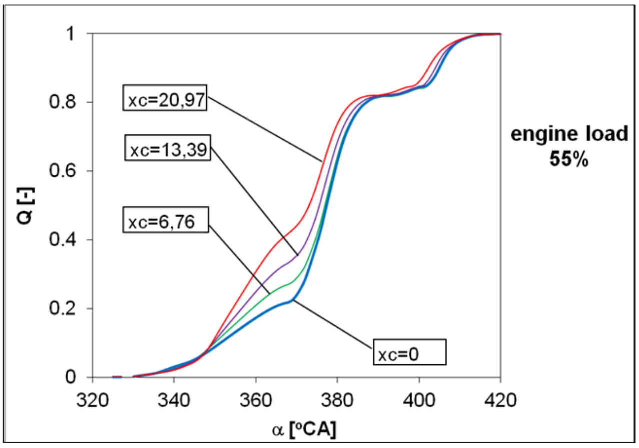

Figure 11. Heat release characteristics for different substitute ratios at 55% engine load and a speed of 2000 min^{-1}.

Thus, for hydrogen use, the Mass Fraction Burned (MFB) during the rapid phase of combustion occurred sooner per cycle, with 4° CA, (50%-MFB = 377° CA at xc = 0 versus 50%-MFB = 373° CA at xc = 20.97). Additionally, the total combustion duration decreased by 3° CA (90%-MFB = 405° CA at xc = 0 versus 90%-MFB = 402° CA at xc = 20.97); see Figure 12. With the hydrogen addition, the $\Delta\alpha_{1\text{-}90\%}$ combustion duration started to decrease and became comparable to that of to diesel fueling, with 3° CA for xc = 20.97 (from $\Delta\alpha_{1\text{-}90\%}$ = 70° CA with diesel fueling to $\Delta\alpha_{1\text{-}90\%}$ = 69° CA at xc = 13.39 or $\Delta\alpha_{1\text{-}90\%}$ = 67° CA at xc = 20.97). The tendency of decreasing combustion duration was related to the increase of peak pressure, the rate of maximum pressure rise and the rate of heat release, as noted previously under the same operating regime.

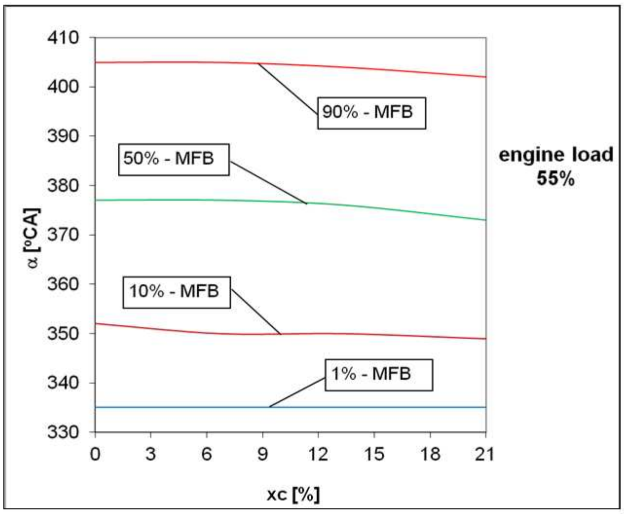

Figure 12. Angles of MFB versus substitute ratio at 55% engine load and a speed of 2000 min^{-1}.

In order to evaluate the combustion variability with hydrogen, the coefficients of variability (COV) of maximum pressure and indicated mean effective pressure (IMEP) were studied. In order to evaluate the fluctuation of the energy generated during combustion, which influences the rate of combustion in relation to the variance of the indicated mean effective pressure, which, in turn, affects torque and performance, the COV of IMEP was deemed to be suitable. Generally, the COV of maximum pressure is used to define the cycle variability of in-cylinder combustion for running regimes in the MBT injection timing range (Maximum Brake Torque). If the values of these coefficients do not surpass a limit of 10%, then the engine is running properly [41].

For a measurement sample, the COV shows the relationship of the standard deviation, S_x, to the arithmetic average of the measurement sample values, x_{average}, for a sample of 250 cycles, as the following relation shows [41]:

$$COV_X[\%] = \frac{S_X}{X_{average}} \cdot 100 \tag{2}$$

where "x" represents the $p_{\max}$, IMEP and $(dp/d\alpha)_{\max}$.

At 2000 min^{-1} and 55% engine load, the increase of the substitute ratio led to an increase in COV for peak pressure from 0.32 to 0.7 at maximum xc.

With hydrogen use, the maximum value of COV for peak pressure did not exceed 3% and the limitation of xc was not necessary from this point of view; however, the increasing tendency should be taken into consideration; see Figure 13. The increasing tendency was much more obvious for xc >10%.

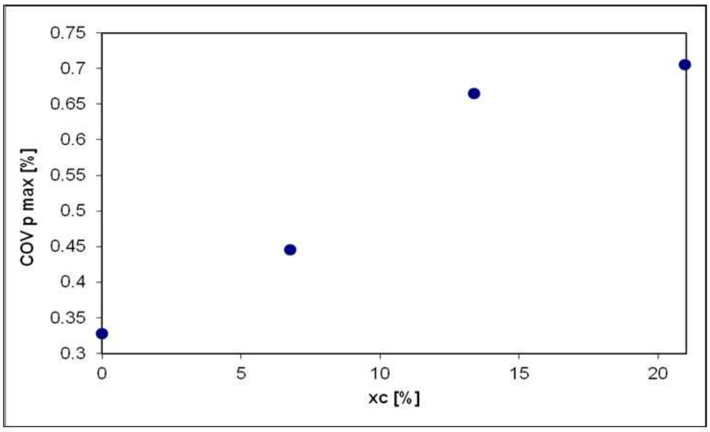

Figure 13. COV of peak pressure versus substitute ratio at 55% engine load and a speed of 2000 min^{-1}.

With hydrogen addition in the inlet air, the IMEP increased by ~2.6% at maximum xc, but the dispersion between the values reached in combustion consecutive cycles started to increase. Thus, the COV of IMEP (see Figure 14) reached a value that was 1.2 times higher for maximum xc compared to that of a traditional fuel. Also, the increasing tendency meant that the COV values increased slightly, i.e., by 0.55% for xc = 6.7 to 20.9.

Even the COV of IMEP increased at maximum xc in some combustion cycles when the maximum pressure did not exceed $p_{\max}$ = 100 bar and the maximum pressure rise rate did not surpass $(dp/d\alpha)_{\max}$ = 4.3 bar/°CA. The increase of combustion variability with the use of hydrogen was related to the ultralean air-hydrogen mixtures established inside the cylinder before combustion started.

Greater homogeneity of the air–hydrogen mixture, which burned very rapidly during the rapid phase, led to an increase in peak pressure and the maximum pressure rise rate, and to a decrease in the COV for the maximum pressure rise rate; see Figure 15. With hydrogen fueling, the COV of $(dp/d\alpha)_{\max}$ was 1.3 times lower at maximum xc compared to traditional fueling.

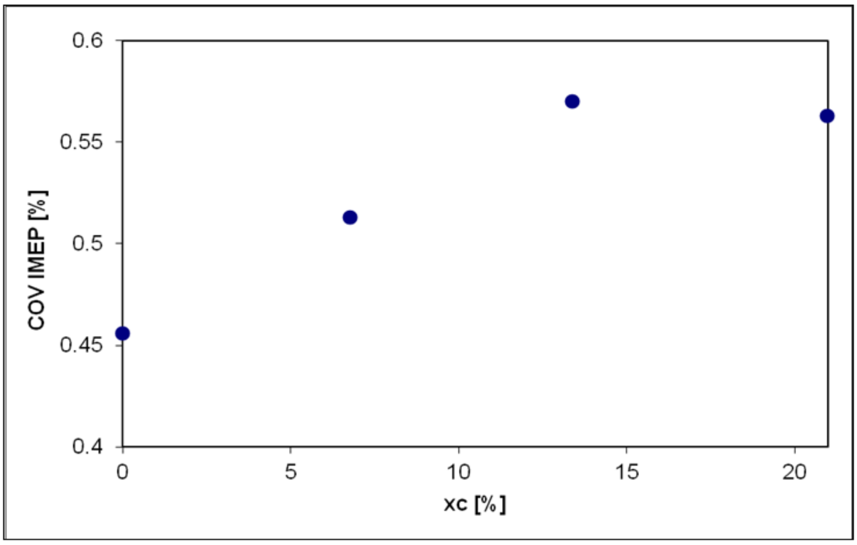

Figure 14. COV of IMEP versus substitute ratio at 55% engine load and a speed of 2000 min^{-1}.

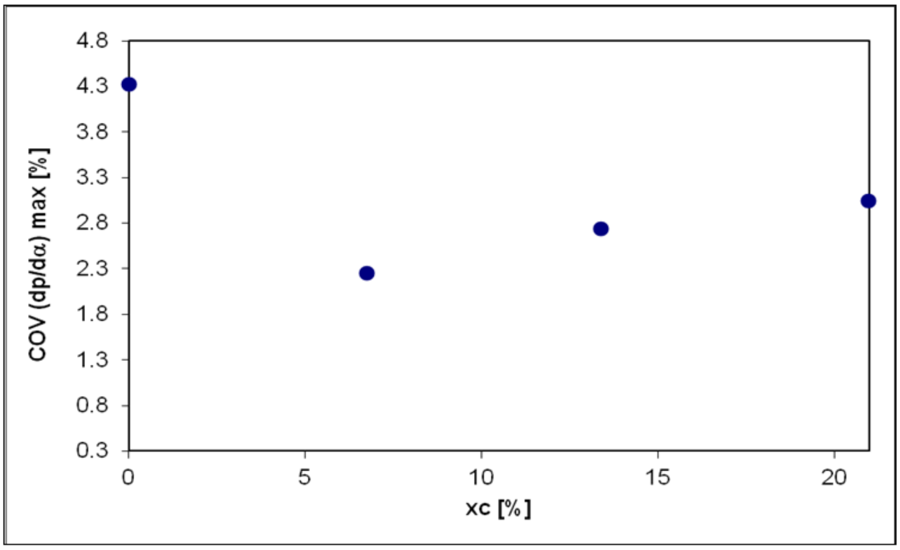

Figure 15. COV of $(dp/d\alpha)_{max}$ versus substitute ratio at 55% engine load and a speed of 2000 min^{-1}.

Regarding combustion variability, the applied substitute ratio values ensured the normal operation of the diesel engine with dual fueling.

With hydrogen addition, due to improved combustion, the CO_2 emission level started to decrease with increasing the cyclic dose of hydrogen; see Figure 16. The level of CO_2 emission decreased by 4% at xc = 6.67, by 8.3% for xc = 13.39 and by 14% at xc = 20.97. The continuous reduction of the BSEC with the increase of hydrogen cyclic quantity, i.e., by 5% at maximum xc (see Figure 2) was reflected in the decrease of the CO_2 emission level.

The acceleration of the combustion process may be explained by the increase of the heat release rate. Meanwhile, the reduction of hydrocarbon fuel type with the increase of hydrogen quantity led to 14% and 28.5% decreases in unburned HC emission level for xc = 6.76 and xc = 13.39 to 20.97, respectively; see Figure 17.

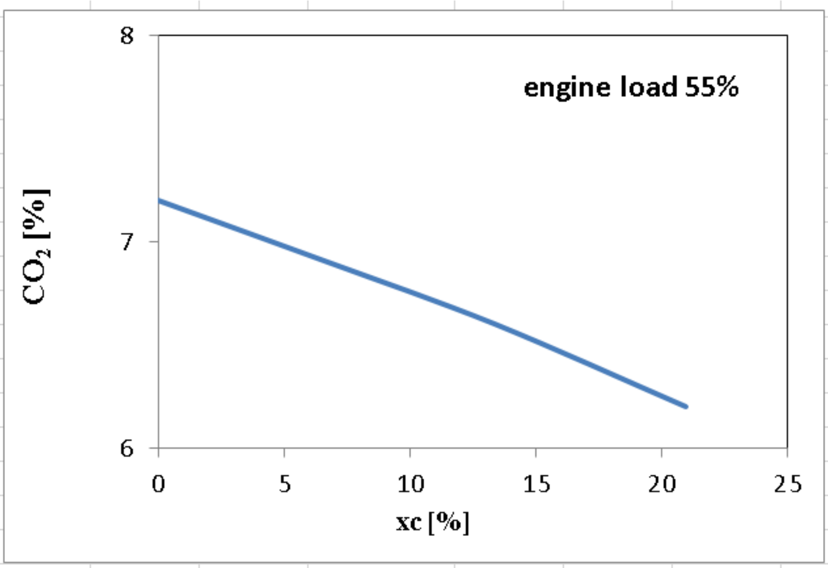

Figure 16. The CO_2 emission level versus substitute ratio at 55% engine load and a speed of 2000 min^{-1}.

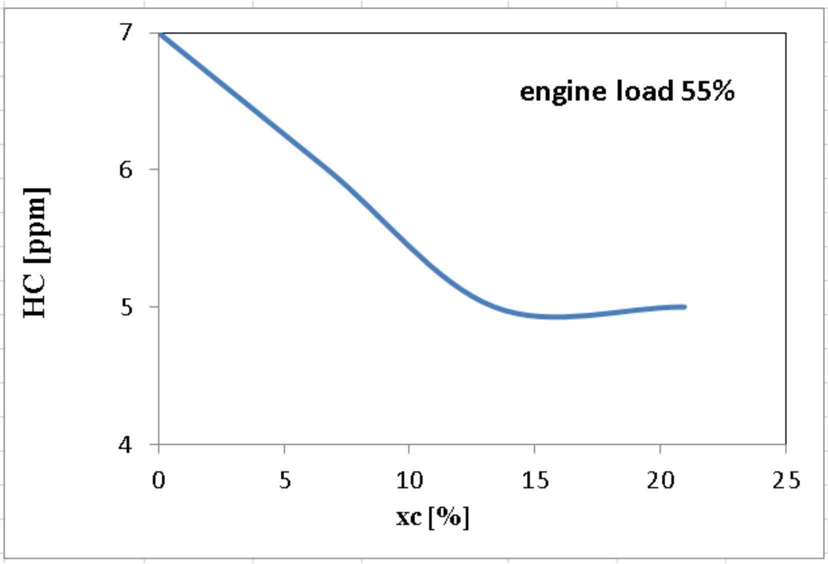

Figure 17. The HC emission level versus substitute ratio at 55% engine load and a speed of 2000 min^{-1}.

With a 55% load and a speed of 2000 rev/min, the increase of heat release at maximum xc led to an increase in NO_x emissions at large hydrogen doses; however, the obtained value was 6.8%, i.e., under the value of traditional fuels; see Figure 18. For xc = 6.76 and 13.39, the NO_x emission level decreased by 20% and 16.7%, respectively. The local richer mixture and the increase of water vapor molar fraction in the combustion products, with an influence on burned gas temperatures, may explain the decrease of NO_x emissions. A similar phenomenon regarding NO_x emissions was reported previously [23,24,28–30], showing that, in general, the NO_x level starts to decrease when hydrogen is used, but that increasing the hydrogen quantity may increase the NO_x emission level. This is in accordance with the increases in combustion temperature and thermal losses [28]; consequently, the emission level is influenced by the quantity of hydrogen [30], and small hydrogen quantities are recommended [28–30].

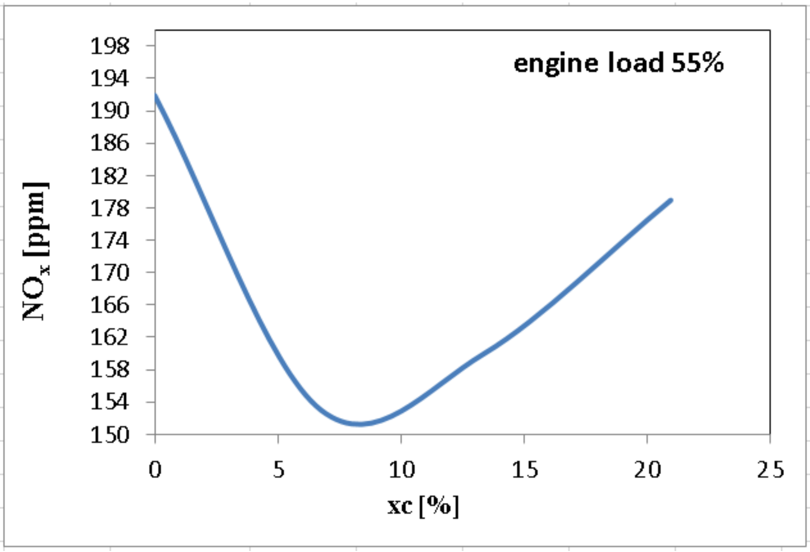

Figure 18. The NO_x emission level versus substitute ratio at 55% engine load and a speed of 2000 min^{-1}.

The smoke emission was evaluated by K smoke number. Its variation relative to the substitute ratio of diesel fuel for hydrogen is presented in Figure 19. The carbon content in the final mixture started to decrease with an increase of hydrogen cyclic quantity, with the smoke emission level decreasing by 24% for xc = 6.76, by 19% for 13.39% and by 14% at xc = 20.97. The decrease in the combustion rate of diffusive formed mixtures up to 26% with hydrogen fuel was in correlation with the reduction of the smoke emission level; see Figure 10.

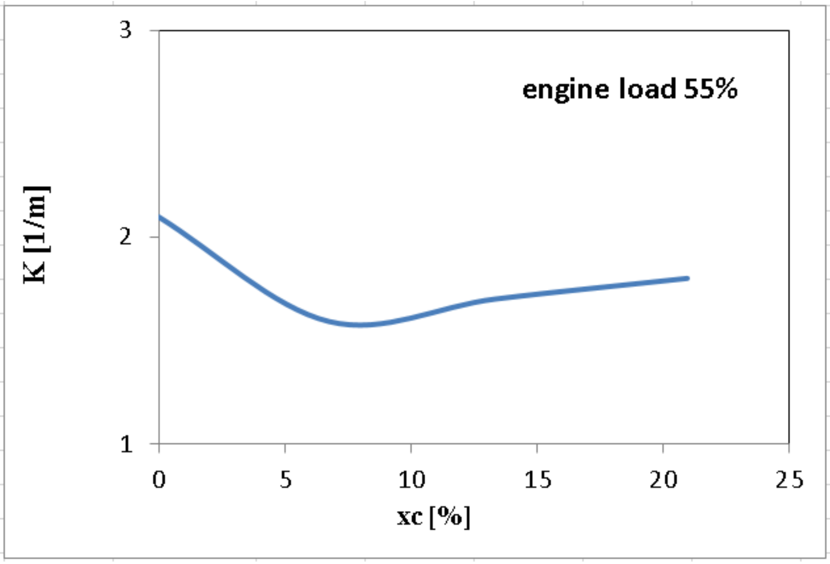

Figure 19. The K number versus substitute ratio at 55% engine load and a speed of 2000 min^{-1}.

Similar tendencies regarding the reduction of pollutant emissions levels have been reported in papers describing the effects of hydrogen use in ICE [23,24,27–30,52,53,55,56].

4. Conclusions

The contribution of the present paper to studies of ICE lies in measuring the optimal correlations among engine operating regime, diesel fuel and hydrogen cyclic quantities, supercharging pressure, combustion peak pressure, pollutant emissions levels and exhaust gas temperatures, measured during an experimental investigation into achieving maximum engine efficiency using hydrogen as an additional fuel. Another novelty aspect of the research is the observed correlation between diesel fuel consumption and engine load spread, which reflects a broadening of the conditions under which engine load quality adjustments can be made. With the same diesel fuel consumption, engine operation at higher power becomes possible, with the wideness of load used increasing by 7.5 kW. Thus, using hydrogen as a fuel and tuning the transmission system to ensure the interlacing of qualitative and quantitative load adjustment, it becomes possible to adjust the engine load over a larger range. The use of hydrogen as a fuel for K9K automotive diesel engines ensures a reduction of the Break Specific Energetic Consumption for each engine load due to an improved combustion process compared to that obtained using a homogeneous air–hydrogen mixture. Thus, compared to traditional fueling, it is possible to achieve a significant economy of diesel fuel and lower energetic specific consumption while achieving similar engine power and increased engine brake efficiency under all load regimes. Because the fuel quantity which burns in the rapid phase increases with the addition of hydrogen, the peak pressure and maximum pressure rise rate start to increase for 55% load and 2000 min^{-1}, but the peak values reached do not exceed the normal values. Hydrogen ensures an acceleration of the combustion process and an increase of the cyclic quantity and rate of heat release, with the amount of heat being released in the premixed phase being much larger and the variability of the maximum pressure rise rate being reduced in correlation with the higher combustion velocity of hydrogen. The acceleration of combustion is related to a decrease in the combustion duration, with 10%-MFB being achieved earlier in the cycle, nearer to TDC, in correlation with the increase of peak pressure, maximum pressure rise rate and amount of heat released into premixed phase of combustion.

Compared to classic fueling, with hydrogen fueling, an ultralean mixture, established in the cylinder before combustion starts, leads to a slight increase in combustion variability, with COV values for peak pressure and IMEP being increased 2.1 and 1.2 times, respectively.

Generally, hydrogen use offers reduced greenhouse gas and pollutant emissions, but the decrement degree depends on the hydrogen cyclic dose. Hydrogen use at an operating regime of 55% load and a speed of 2000 rev/min led to a 14% reduction of CO_2 emissions levels due to an improved combustion process. When using hydrogen, the unburned HC emission levels decreased by 28.5%, correlating with a reduction in the combustion rate of diffusive mixtures and in diesel fuel consumption. The addition of hydrogen led to an increase in the molar fraction of water vapors in the combustion products, influencing the combustion temperature and decreasing the NO_x emission levels by 20%. The reduction of the carbon content in the final mixture when hydrogen replaced diesel fuel led to a 24% decrease in the smoke emission.

Hydrogen is a viable alternative fuel for automotive diesel engines; its use offers an increase of thermal efficiency without requiring significant changes to the engine design.

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Abbreviations

AVL	Anstalt für Verbrennungskraftmaschinen List automotive research institute which fabricates the test bed equipment
BDFC	brake diesel fuel consumption
BEC	brake energy consumption
BSEC	brake specific energetic consumption
°C	Celsius degree
° CA	crank angle degree
CFR	Cooperative Fuel Research
CIE	compression ignition engine
CO	carbon monoxide
CO_2	carbon dioxide
COV	coefficient of variability
$(dp/d\alpha)_{max}$	maximum pressure rise rate
$dQ/d\alpha$	heat release rate
ECU	engine electronic control unit
HC	unburned hydrocarbons
H_2	hydrogen
ICE	internal combustion engine
IMEP	indicated mean effective pressure
K	smoke number
MAN	Maschinenfabrik Augsburg-Nürnberg AG
MBT	maximum brake torque
MFB	mass fraction burned
N	nitrogen
NO	nitrous monoxide
NO_x	nitrous oxides
NO_2	nitrous dioxide
O_2	oxygen
p	in-cylinder pressure
P_e	engine effective power
p_{max}	in-cylinder peak pressure
PM	particle
ppm	parts per million
Q	heat release characteristic
TDC	top dead center
VC	variation ratio
xc	diesel fuel substitute ratio with hydrogen, % energetic
α	crankshaft angular position
η	engine brake efficiency
λ	air fuel ratio

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