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Study on SI Engine Operation Stability at Lean Condition—The Effect of a Small Amount of Hydrogen Addition

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Abstract: The lean-burn mode is a solution that reduces the fuel consumption of spark-ignition internal combustion engines and keeps the low exhaust emission, but the stability of the lean-burn combustion process, especially at low loads, needs to be addressed. Enhancing gasoline with hybrid hydrogen oxygen (HHO) gas—a mixture of hydrogen and oxygen gases—is proposed to improve combustion of the lean-gasoline mixture. A three-cylinder, spark-ignition, naturally aspirated, MPI engine with HHO gas produced with an alkaline water electrolyzer and introduced as a gasoline enhancement was tested. The amount of hydrogen added to the lean-gasoline mixture ($\lambda = 1.4$) was in the range from 0.15 to 1.5%, and the results were compared to the stoichiometric ($\lambda = 1$) and pure lean mode ($\lambda = 1.4$) gasoline operation. The other authors' results show that a minimum 3% of the mass fraction of hydrogen is necessary to affect the gasoline combustion process. This paper proved that even a small hydrogen enhancement of gasoline in the amount of 0.3% of the mass fraction improves the combustion stability.

Keywords: internal combustion engine; combustion stability; HHO gas; hydrogen

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1. Introduction

Hydrogen has the potential to be a clean and environmentally friendly fuel for spark-ignition (SI) internal combustion engines (ICE) and fuel cells (FC). However, solving the problem of storing hydrogen onboard a vehicle for a driving range over 500 km on a single fill with the constraints of safety, weight, volume, efficiency and cost [1] is essential for the development of its automotive applications. As there is still no satisfactory solution, the idea of enhancement of gasoline combustion by a small hydrogen gas additive appears to be noteworthy. In that case, the amount of hydrogen should be low enough to be able to be produced onboard without a large tank but, on the other hand, high enough to assure the engine's stability at lean-burn operation without charge stratification.

Gasoline engines can operate in different modes, depending on the air–fuel composition characterized by an excess air coefficient λ or air–fuel ratio (AFR) as shown in Figure 1. However, only at lean-burn mode when $\lambda > 1.4$ is it possible to reduce both fuel consumption and engine out emission. The majority of small and medium size automotive multi-point port-injection (MPI) gasoline engines are characterized by stable operation at lean-burn condition up to an excess air coefficient λ of approximately 1.3 [2]. Beyond that value, the combustion begins to be unstable, misfires are observed, and hydrocarbon (HC) emission increases.

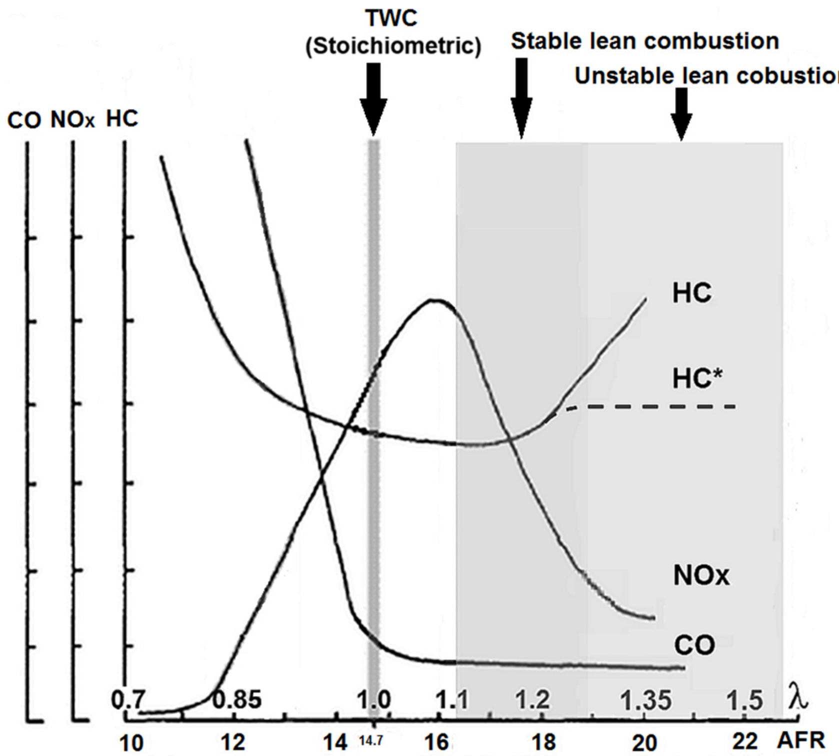

Figure 1. Gasoline engine's operating modes for different compositions of the air–fuel mixture (inspired by [3]).

Instability in combustion leads to cyclic variation. The intensity of the phenomenon rises when a combustion process tends to slow down, e.g., under the lean-burn mode or low-load operation. Cycle-to-cycle stability can be evaluated with the coefficient of variation (COV) in the indicated mean effective pressure (IMEP) [4,5]. It is a commonly used measure of combustion stability in a spark-ignited engine. It is assumed that a coefficient of variation in the IMEP (COV_{IMEP}) of less than 3% is required for most driving conditions [6], while a COV_{IMEP} greater than 10% results in vehicle drivability problems [3,7]. Currently, only stratified charge, gasoline direct-injection engines operate stable at lean-burn conditions at $\lambda > 1.4$ and keep the HC emission at an acceptable level—marked with a dotted line (HC*) in Figure 1.

To be able to stably run an MPI port-injection engine at $\lambda = 1.4$ and above, a hydrogen addition should be effective [2,8]. Due to its properties, even a small hydrogen gasoline enrichment reduces the number of misfires and extends the lean limit or dilution tolerance [9]. The data presented in Table 1 show that the flammability limits of pure hydrogen given by λ exceed the limits for gasoline by approximately three times for a rich mixture and over seven times for a lean one. Furthermore, the approximately ten times lower minimum-ignition energy and higher laminar burning velocity of hydrogen make the initialization of flame easier. At the same time, it should be pointed out that hydrogen does not fit well into the standard interpretation of octane number. Despite a very high RON value, it has low MON, and the knock resistance of hydrogen is in practice low due to low ignition energy.

Table 1. Combustion properties of hydrogen and gasoline.

Property		Hydrogen	Gasoline (Unleaded)	Ref.
Lower heating value (LHV)	MJ/kg	142–120	43–44	[10,11]
Higher heating value (HHV)	MJ/kg	141.8	47.3	[10,11]
Air–fuel ratio (AFR)	kg/kg	34.5 ($2.82\ m^3/m^3$)	14.7	[10]
Heating value of the air–fuel mixture (port injection)	MJ/m^3	~3.0	~3.5	
Flammability limits in air at 101.3 kPa	%Vol	74–4	7.1 (7.6)–1.2 (1.0)	[11,12]
AFR	kg/kg	5.0–344.4	3.5 (3.3)–22.3 (26.8)	
λ	-	0.14–9.98	0.24 (0.22)–1.52 (1.8)	
Minimum ignition energy in air:				
At stoichiometric mixture (λ = 1)	mJ	0.02	0.24	[11]
At lower flammability limit	mJ	10	n.a.	[11]
Maximum laminar burning velocity	m/s	2.65–3.25	0.37–0.43	[11]
Octane number (RON)	-	>130	95–98	[9,10]

The influence of hydrogen addition on the combustion process in gasoline spark-ignited engines has been considered in many research works.

Wang et al. [2] investigated the performance of hydrogen port-injection gasoline engines at wide open throttle (WOT) conditions under the stoichiometric and lean-burn modes. The experimental outcomes revealed raised thermal efficiency and shortened flame development and propagation durations. Hydrogen addition in the amount of 3% led to improved combustion stability and higher break mean effective pressure (BMEP) under the lean-burn mode; however, under the stoichiometric mode, the BMEP was lower in comparison to pure gasoline.

Sun et al. [8] analyzed the effects of hydrogen direct injection on engine stability in port-injected gasoline engines. It was found that a 10% hydrogen addition shortened the combustion duration and lowered the coefficient of variation in IMEP compared to pure gasoline, resulting in significant engine stability improvement. The brake thermal efficiency under the lean burn was increased.

The effect of spark timing on the performance of a hydrogen–gasoline engine at lean conditions was studied by Ji et al. [13]. The research was performed for two excess air ratios of 1.2 and 1.4 and hydrogen volume fractions between 0% and 3% under varying spark timing. The authors reported that, under hydrogen enhancement conditions, a decrease in spark advance in order to obtain max IMEP resulted in shortening of the flame development and prolongation of the flame propagation periods. At the same time, the coefficient of variation in the IMEP reached its minimum value.

Fennel et al. [14] investigated the impact of the hydrogen and carbon monoxide mixture from exhaust gas fuel reforming on gasoline engine efficiency. In that study, the EGR stream was enhanced by hydrogen in concentrations of 3.75% and 7.5%. The results demonstrated that the presence of hydrogen in the EGR stream influenced combustion by increasing the burn rate and resulted in an improvement of combustion efficiency. Based on the obtained value of the COV of IMEP below 5%, the proper combustion stability effect was also confirmed.

Karagöz et al. [15] investigated the effect of hydrogen enrichment on cyclic variations, emissions and performance of the SI gasoline engine under idle operating conditions. The hydrogen–oxygen gas mixture was used as an additional gasoline enhancer. Several hydrogen energy fractions (0%, 5%, 8%, 10% and 15%) were tested. They found that operation parameters could be improved by increasing the amount of hydrogen.

Quetz de Almeida et al. [16] conducted experiments on a flex-fuel engine fueled with a gasoline–ethanol blend (E22) and hydrous ethanol (E100). They investigated the effect of hydrogen enrichment on engine fuel consumption and pollutant emissions under stoichiometric and lean conditions at idle speed and 1400 rpm. The results demonstrated that engine operation stability under lean conditions can be improved by small amounts of hydrogen.

Another study on the effect of hydrogen addition on combustion and emissions performance was conducted by Ji and Wang [17]. In the study, the performance of the SI gasoline engine at low operating conditions (800 rpm) and lean-burn mode was explored. Hydrogen addition fractions in the total intake of 0%, 3%, 5% and 8% and excess air ratios between 1.0 and 1.7 were examined. The results showed that the wider flammability of the hydrogen–gasoline mixture decreased cycle-to-cycle variation and reduced misfire events at lean conditions.

Summarizing, the above-mentioned studies have proven hydrogen addition in the amount of at least 3–5% of the mass fraction to be effective for considerable modification of the engine operation parameters. However, it limits the automotive application, since the hydrogen tank is relatively big. Table 2 presents the volumes of such a tank calculated for 0.5–5% of hydrogen in regard to 60 dm^3 of gasoline with a density of 740–760 kg/m^3.

Table 2. Hydrogen tank volume at 298 K.

Hydrogen				
		p_{H2} **(Ambient)**	p_{H2} **(30 MPa)**	p_{H2} **(70 MPa)**
%	kg	dm^3	dm^3	dm^3
5	2.220–2.280	27,300–28,037	90.7–93.1	38.9–40.0
4	1.776–1.824	21,840–22,430	72.6–74.5	31.2–32.0
3	1.332–1.368	16,380–16,822	54.4–55.9	23.4–24.0
2	0.888–0.912	10,920–11,215	36.3–37.3	15.6–16.0
1	0.444–0.456	5460–5607	18.1–18.6	7.8–8.0
0.5	0.222–0.228	2730–2804	9.1–9.3	3.9–4.0

Certainly, in a passenger car, the storage of even 0.5% of hydrogen at ambient pressure is not feasible. There is no room for an additional tank of approximately 2800 dm^3. Hydrogen compressed up to 70 MPa needs a tank of 24 and 40 dm^3 for 3 and 5%, respectively. Finding such a space is difficult without a serious intervention in the car's architecture. By reducing the amount of hydrogen to 1% or 0.5%, the tank volume would drop below 20 or even 10 dm^3 at 30 MPa. It would be enough to use hydrogen enrichment of gasoline in medium or small passenger cars and, in the medium- or long-term, even produce hydrogen on-board with on-demand systems.

There are some methods of hydrogen or hydrogen rich gas generation [17], but not all of them are suitable for on-board automotive systems. Steam methane reforming is an example of a cost-effective and energy-efficient large-scale industrial method, but it is unsuitable for automotive application. On-board solutions need small-scale devices, which are easy to start and effective in a wide range of load. Therefore, solutions like water electrolyzers [15,16,18–21]; gasoline [14], ethanol [22] or ammonia [23] exhaust gases thermal reformers; or plasma and catalysis integrated technology [24] could be taken into account.

Considering this, the objective of this study is to define the smallest amount of hydrogen addition that improves MPI SI engine operation stability at lean condition. The stability of the engine's run and in-cylinder pressure graphs was used to assess the influence of hydrogen addition on the combustion process. If $\leq$0.5% of hydrogen affects lean combustion satisfyingly, then the idea of hydrogen gasoline enhancement will have a development potential for future automotive applications.

2. Experimental Setup and Procedures

2.1. Engine

The Stellantis 1.2 EB2 EURO 5 naturally aspirated gasoline engine was used for this study. It was a 1.2 dm^3, three in-line cylinder, MPI port-injection-type engine with centrally located spark plugs. The engine used a homogeneous, stoichiometric λ = 1 combustion strategy and a three-way catalyst (TWC) as the only aftertreatment device. Further specifications are listed in Table 3.

Table 3. The EB2 gasoline engine specifications.

Compression ratio	11:1
Bore × Stroke	75 × 90.5 mm
Rated power	60 kW at 5750 rpm
Rated torque	118 N*m at 2750 rpm
Valve train	4 valves per cylinder Variable intake and exhaust timing

2.2. Hydrogen Rich Gas Generator Development

The hydrogen used for fuel enhancement during the study was produced with an electrolytic hybrid hydrogen oxygen (HHO) gas (Brown gas) generator. Since a 12 V DC and ambient pressure alkaline water electrolyzer is relatively easy to be adapted for on-board automotive use, such a device was designed for this study.

The water electrolysis could be an exothermic, a thermo-neutral or an endothermic process. It depends on the applied voltage, as shown in Figure 2. In the exothermic process, additional heat is generated that must be removed from the cell for isothermal operation. In the thermo-neutral process, all energy is utilized for H_2O conversion, and in the endothermic process, additional heat must be delivered and consumed by the cell.

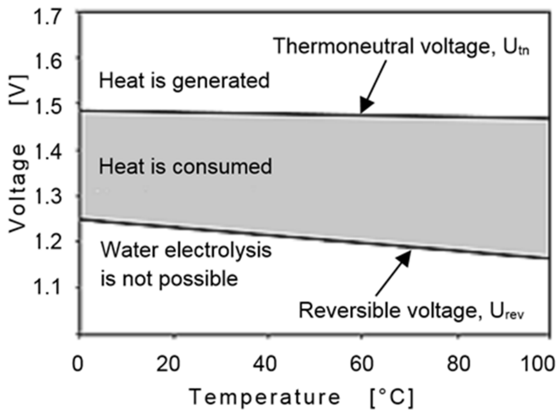

Figure 2. Reversible and thermoneutral voltage for water electrolysis at a pressure of 101.3 kPa (reprinted with permission from [18]).

The automotive electrolytic HHO generator consists of anode, cathode and neutral electrodes. Usually, the passenger car's electric installation voltage supply U_s is between 12 and 14.3 V and the number of neutral electrodes k ensures that the generator is divided into a series of electrolytic cells with a voltage drop U_{Cell} proportional to U_s and k:

$$U_{Cell} \cong \frac{U_S}{k+1} \tag{1}$$

In engineering practice, the generator productivity is characterized by the indicator liters per minute (LPM), and the efficiency is characterized by the indicator milliliters per minute per watt (MMW). The relation between the indicators is given by Equation (2), where the U_{Cell} and I_{Cell} are the cell voltage and current:

$$MMW = 1000\frac{LPM}{U_{Cell}I_{Cell}} \tag{2}$$

Since keeping U_{Cell} close to reversible U_{rev} = 1.23 V or thermo-neutral U_{tn} = 1.48 V voltage is important for the efficiency of the electrolytic process, it was necessary in the design process to consider the number of neutral electrodes and temperature of the electrolyte. The proposed design study assumed alkaline water electrolysis type with potassium hydroxide (KOH) in the amount of 7 g of KOH per 1 liter of H_2O used as the electrolyte. The tests with 3, 4, 5 and 6 neutral electrodes showed that the highest MMW value can be obtained for 5 electrodes, and this number of neutral electrodes was set into the HHO gas generator.

The ready-to-use HHO gas generator with 58 cm × 33 cm stainless electrode plates and polycarbonate transparent housing is presented in Figure 3. To separate the HHO gas from the H_2O + KOH mixture, the bubbler tank is used (above the generator in Figure 3).

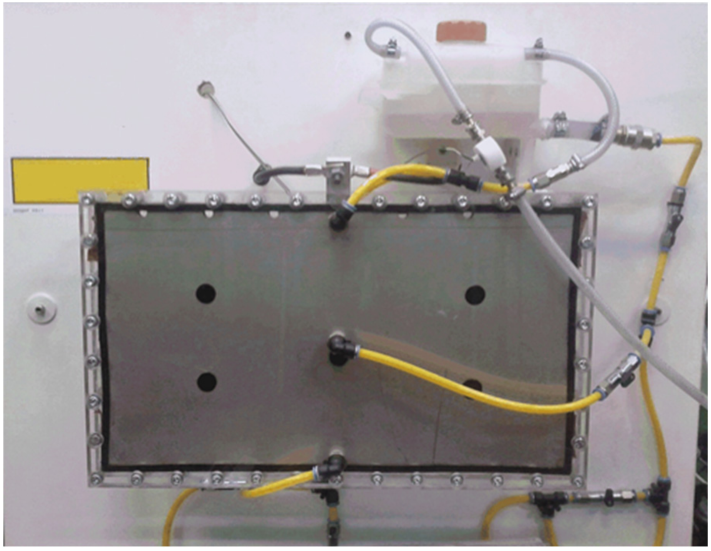

Figure 3. General view of the electrolytic HHO gas generator.

For an external DC voltage supply U_s = 12–14.3 V and maximum current I_{Cell} limited to 80 A, the generator that is divided into 6 electrolytic cells with voltage drop U_{Cell} = 2–2.4 V achieves an MMW value that varies from 5.2 to 5.9, which corresponds to an LPM = 6–6.7. This means that the power consumed by the electrolyzer should not exceed 960–1120 W.

The product of electrolysis is not pure hydrogen but a hydrogen rich HHO gas, which contains 11.1% of the mass fraction of H_2. It is worth mentioning that the HHO solution used as the gasoline enhancement does not affect the composition of the air–gasoline mixture, and in this way, the control of the engine is more convenient than in the case of supplying pure hydrogen from a gas cylinder. Setting the gasoline injection time is the only step necessary to maintain the proper value of λ when HHO gas is added.

2.3. Mesaurement System with HHO Gas Installation

The study of the influence of hydrogen gasoline enhancement on the engine's stability was performed on the dynamometer test bench. A schematic view of the entire HHO installation and measurement equipment is presented in Figure 4. In addition to the HHO gas generator and HHO gas separator tank, there is a heat exchanger to warm up the electrolyte to 60–80 °C and a small peristaltic pump (356 mL/min) that enables the circulation of the electrolyte. The gas from the bubbler tank is delivered to the engine's inlet system just before the throttle valve.

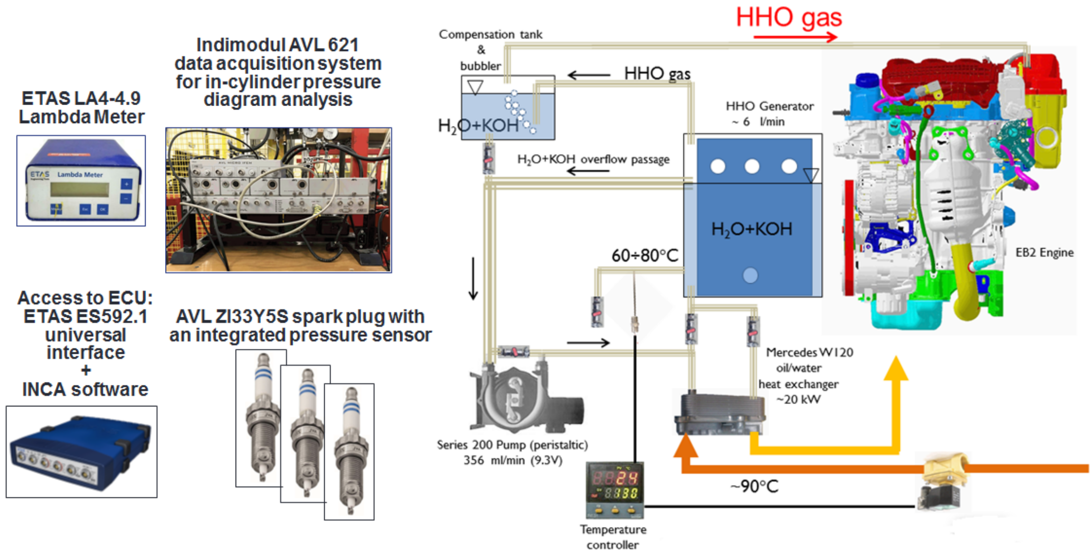

Figure 4. Schematic view of the measurement system with the HHO gas generator connected to the engine.

The generator was calibrated with the use of a gas flowmeter, and the rate of HHO gas flow in relation to the current I_{Cell} applied up to 80 A was established. The characteristic of HHO gas flow (given in Figure 5) was almost linear; the maximum gas flow rate of approximately 4 L/min was obtained. Thus, during the tests, the HHO gas flow rate was precisely controlled by the current value of the pulse width modulation (PWM) controller of the electrolytic generator. Since the controller had an external DC power supply, the consumption of electricity in the energy balance of the engine was not considered.

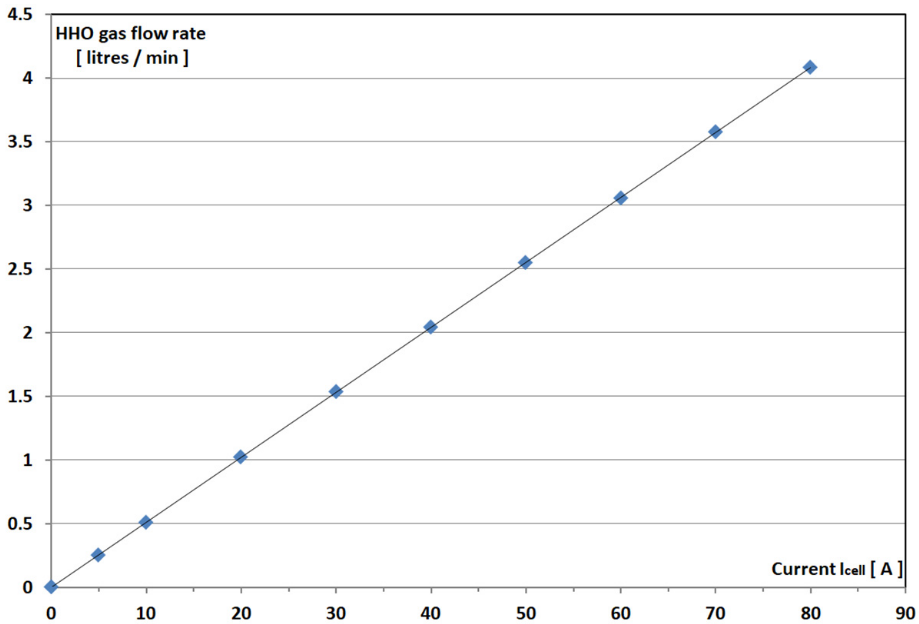

Figure 5. Relationship between HHO gas flow rate and current applied.

In order to adjust the engine parameters—injection timing, throttle position and spark advance—a programmable engine control unit (ECU) connected with the ETAS ES592.1 universal interface module and the ETAS INCA ver. 7.1 software was implemented. The ETAS LA4-4.9E lambda meter allows for the observation of the oxygen sensor signal. The engine test bench was equipped with the Schenck W130 eddy current dynamometer to load the engine.

The in-cylinder pressure signals were measured at each of the three cylinders by means of the AVL, indicating spark plugs ZI31 Y5S with a crank angle related resolution of 0.1 °CA provided by the AVL 365C crankshaft angle encoder. The signal conditioning and data acquisition system consisting of data acquisition unit AVL Indimodul 621 and indicating software IndiCom ver. 1.2 were applied to manage the measurement process with simultaneously real-time evaluation of the results. The specifications of the measuring equipment are presented in Table 4.

Table 4. Specification of the measuring equipment.

Device	Measurement Range	Accuracy
Gas flowmeter	0–10 L/min	<0.5% FSO
In-cylinder pressure transducer	0–20 MPa	<±0.5% FSO
Piezo amplifier	144–14,400 pC	±0.3%
Crankshaft angle encoder	20–20,000 rpm	±0.1 °CA
Lambda meter	0.645–15.999	0.001
Wide band oxygen sensor	0.650–∞	±1.5%

3. Results and Discussion

In order to determine the combustion stability under the lean-burn mode, the analysis based on the in-cylinder pressure fluctuations was conducted. Both kinds of instability—cycle-to-cycle and cylinder-to-cylinder cycle fluctuations—were taken into consideration.

For the *i*th cylinder, the cycle-to-cycle stability is expressed with the coefficient of variation in the indicated mean effective pressure $\mathrm{COV_{IMEP}}$, which is defined as the ratio of the standard deviation σ_i and mean value of the indicated mean effective pressure $\overline{\mathrm{IMEP_i}}$:

$$\mathrm{COV_{IMEP}} = \frac{\sigma_i}{\overline{\mathrm{IMEP_i}}} \quad (3)$$

Since cylinder-to-cylinder cycle fluctuations ($\mathrm{COV_i}$ values) are different for each cylinder, the following CS coefficient is introduced as one representative value of combustion stability for all three cylinders of the engine:

$$\mathrm{CS} = \frac{\sigma_1 + \sigma_2 + \sigma_3}{\overline{\mathrm{IMEP_1}} + \overline{\mathrm{IMEP_2}} + \overline{\mathrm{IMEP_3}}}\ 100\% \quad (4)$$

The $\overline{\mathrm{IMEP_i}}$ and σ_i were determined for j = 100 consecutive cycles:

$$\overline{\mathrm{IMEP_i}} = \frac{1}{100}\sum_{j=1}^{100} \mathrm{IMEP_i} \quad (5)$$

$$\sigma_i = \sqrt{\frac{\sum_{j=1}^{100}\left(\mathrm{IMEP_i} - \overline{\mathrm{IMEP_i}}\right)^2}{100}} \quad (6)$$

The results of the analysis—the average value of the indicated mean effective pressure for the 1st cylinder, its standard deviation and the combustion stability coefficient—for the lowest and highest load conditions are presented in Table 5. The standard deviation of the IMEP based on 100 cycles indicates that the variability of measurement values was in the range of approximately 0.04–0.35 bar and below the accuracy of the in-cylinder pressure sensor.

Table 5. Combustion stability for the lowest and the highest load conditions.

Case		1000 rpm/BMEP = 2 Bar				3000 rpm/BMEP = 5 Bar			
λ	-	1.0	1.4	1.4	1.4	1.0	1.4	1.4	1.4
H_2	(%)	0.0	0.30	0.15	0.0	0.0	0.30	0.15	0.0
$\overline{IMEP_1}$	(bar)	1.587	3.384	3.154	3.202	6.452	6.934	6.717	6.440
σ_1	(bar)	0.042	0.138	0.324	0.200	0.063	0.067	0.067	0.085
CS	(%)	2.35	3.34	10.32	10.87	0.84	1.08	0.98	1.20

Figure 6 presents all the results of the combustion stability analysis. The data are given for engine speeds between 1000 and 3000 rpm with 500 rpm increments and engine loads of 2, 3, 4 and 5 bar of BMEP, except pure lean mode (λ = 1.4 and 0.0% H_2) when the number of engine speeds is reduced to 1000, 2000 and 3000 rpm due to the very high instability in the engine operation—CS over 10% for BMEP = 2 bar and 1000 rpm. It means that the investigation of engine stability was narrowed down to approximately half of the highest load, BMEP = 11 bar, and half of the rated power speed, 5750 rpm.

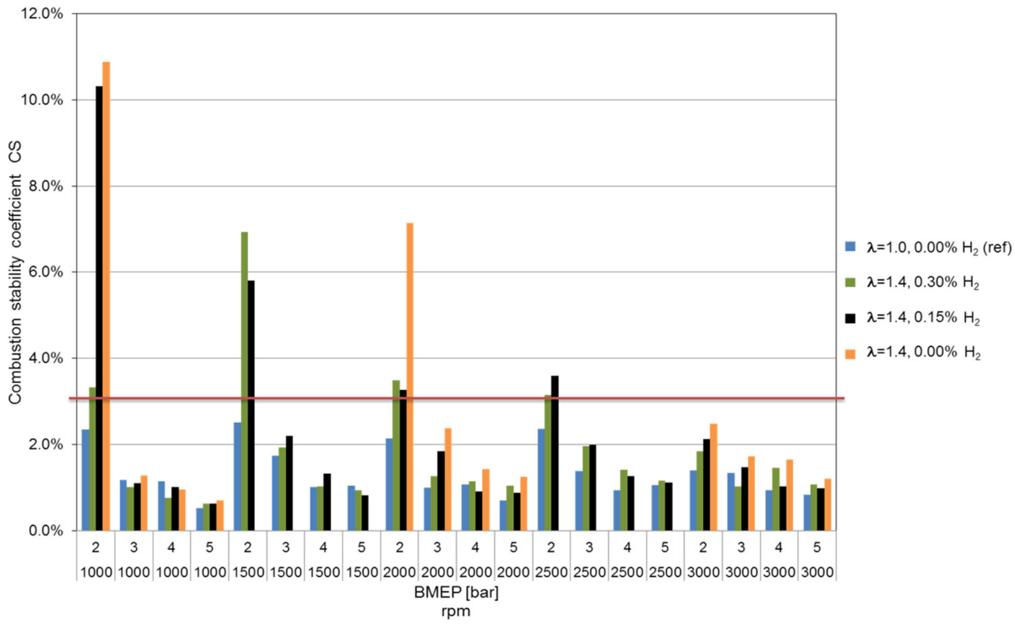

Figure 6. The combustion stability coefficient CS.

The horizontal line is for CS = 3%, which is the highest assumed CS value that ensures the smooth run of the engine. The data bars for 1000–2500 rpm and 2, 3, 4 and 5 bar of BMEP suggest that even such a small amount of hydrogen as 0.15–0.3% improves the stability of the lean-burn process at low load and low speed below 3000 rpm conditions. The highest impact of hydrogen addition is observed at the lowest load (BMEP = 2 bar) for each engine speed when the instability in combustion at pure gasoline lean condition is the highest. Further improvement could be possibly obtained for different ignition advance angles, as reported in [25]; however, in that case, the analyzed object was a direct-injection hydrogen engine.

Interestingly, for 1500 rpm and 2 bars, the CS was lower for the addition of 0.15% hydrogen in comparison to 0.3%; however, the results may not be reliable and may be unrepeatable due to unstable engine operation. With the increase in load and at higher speed, the impact of HHO gas enrichment becomes lower. However, CS does not exceed 3% even for pure lean-burn mode λ = 1.4 without any hydrogen enrichment. This may suggest that, when the throttle valve is less open, the density of the lean-gasoline mixture may not be high enough to ensure the ignition and sufficient burning velocity. The hydrogen with its wide flammability limits, low ignition energy and high burning velocity supports lean-burn distinctly. This fact suggests that the boundary line set at CS = 3% is almost reached for 0.3% of H_2 enrichment even at 1000 rpm and BMEP = 2 bar.

Figure 7 illustrates the impact of hydrogen enrichment on the in-cylinder pressure p_c and its derivative $dp_c/d\phi$. It gives a representative cycle graph—an average of 100 consecutive cycles—recorded for the first cylinder of the engine at 2000 rpm, which is the same ignition advance and throttle position equivalent to BMEP = 3 bar. At the lean-burn operation (λ = 1.4), gasoline was enriched with 0.3, 0.5, 1 and 1.5% of hydrogen. As a reference, pure gasoline stoichiometric (λ = 1.0) and lean-burn (λ = 1.4) lines are added.

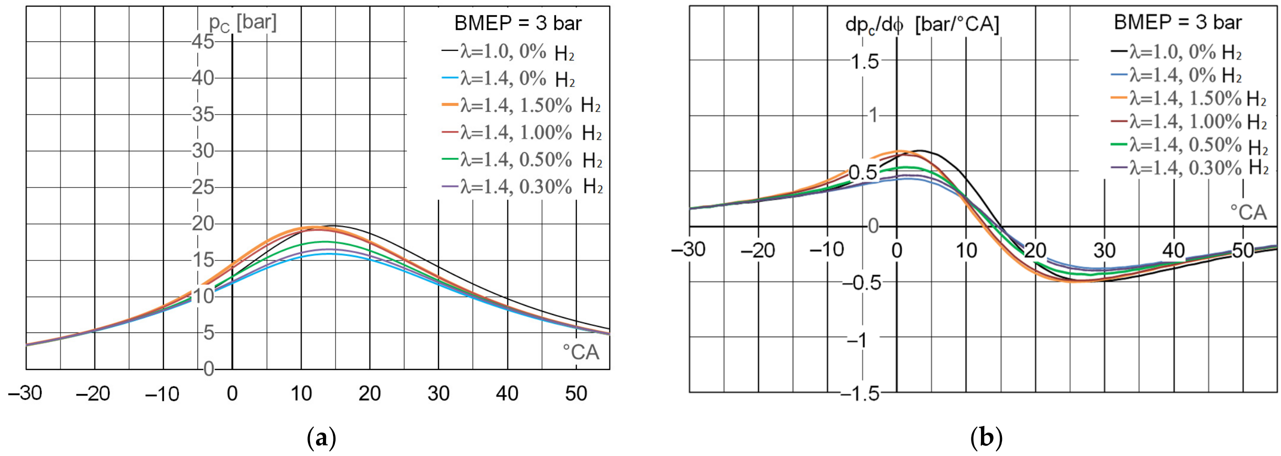

Figure 7. The impact of hydrogen enhancement on (**a**) in-cylinder pressure p_c; (**b**) derivative of in-cylinder pressure $dp_c/d\phi$ at 2000 rpm, BMEP = 3 bar for stoichiometric λ = 1, pure lean λ = 1.4 and lean λ = 1.4 combustion with 0.3, 0.5, 1.0 and 1.5% of hydrogen gasoline enrichment.

The HHO enrichment corresponding to 0.3% of the mass fraction of pure hydrogen (H_2) affects the lean-burn process very little, and the in-cylinder pressure line is only just above the lean-burn of the gasoline mixture during the combustion phase. The position of the maximum of the in-cylinder pressure is the same for both the pure-lean mode and 0.3% hydrogen-enriched mixture. This means that such a small amount of hydrogen is not enough to enhance the burning properties and change the character of the cycle. Although the maximum of p_c moves a little left in the TDC (°CR) direction for 0.5% of H_2, the cycle modification becomes evident when at least 1.0% of hydrogen is added. The pressure derivative $dp_c/d\phi$ shows that, for 1.0 and 1.5% H_2 enrichment, the in-cylinder pressure rises even steeper than for the stoichiometric mixture λ = 1.0. For this reason, the p_c lines for 1.0 and 1.5% H_2 enrichment are ahead of the λ = 1.0 conditions.

Figure 8 presents how the maximum values of the in-cylinder pressure $(p_c)_{MAX}$ and maximum of the pressure derivative $(dp_c/d\phi)_{MAX}$ depend on the amount of hydrogen added to the gasoline. At BMEP = 3 bar pressure, $(p_c)_{MAX}$, the maximum in-cylinder pressure, rises with the hydrogen fraction and becomes close to the reference λ = 1.0 stoichiometric mode (dotted line in Figure 8) for 1.5% of H_2 addition. For the maximum of the pressure derivative $(dp_c/d\phi)_{MAX}$, the same tendency is observed.

At 2000 rpm, the HHO gas generator enables the supply of up to 1.5% hydrogen by BMEP = 3 bar. Yet at a higher load, BMEP = 4 bar and BMEP = 5 bar, its productivity is reduced by up to 0.3% of hydrogen added to the gasoline.

The impact of such a small hydrogen enrichment on the p_c and $dp_c/d\phi$ for BMEP equal to 4 and 5 is shown in Figures 9 and 10, respectively.

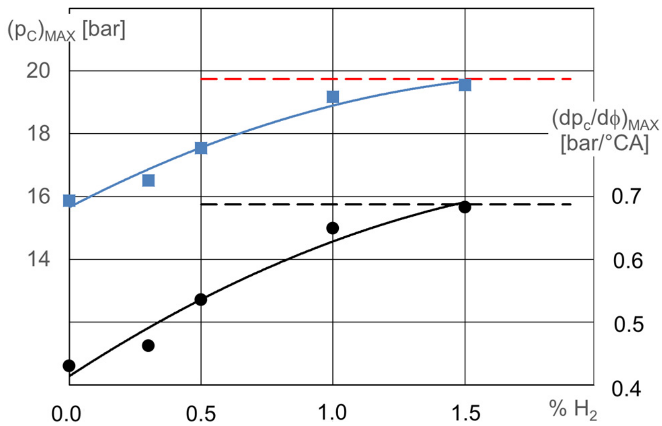

Figure 8. Relationship between maximum in-cylinder pressure $(p_c)_{MAX}$, maximum of its derivative $(dp_c/d\phi)_{MAX}$ and hydrogen gasoline enrichment $\%H_2$ at 2000 rpm, BMEP = 3 bar and lean λ = 1.4 combustion conditions.

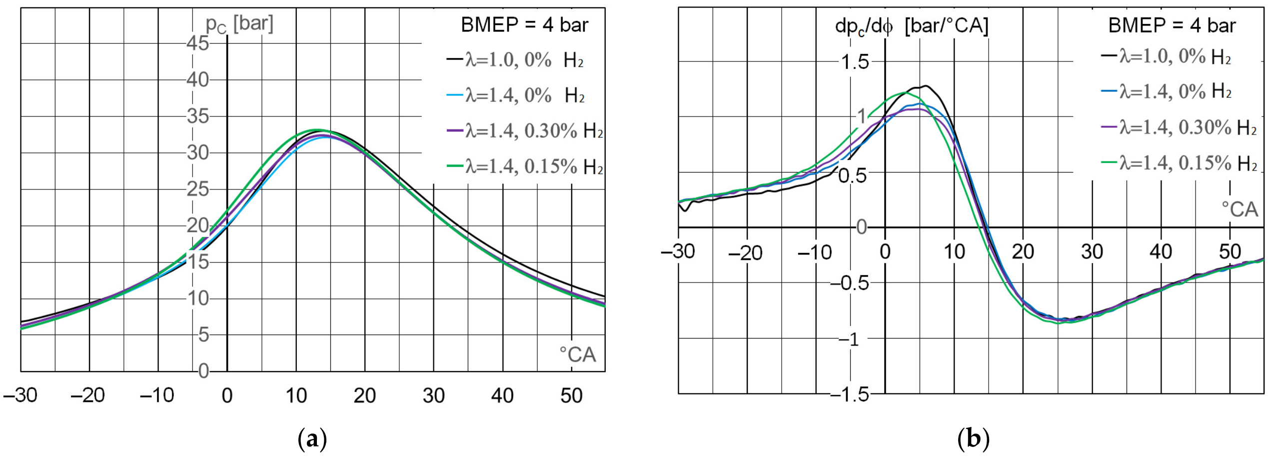

Figure 9. The impact of hydrogen enhancement on (**a**) in-cylinder pressure p_c; (**b**) derivative of in-cylinder pressure $dp_c/d\phi$ at 2000 rpm, BMEP = 4 bar for stoichiometric λ = 1, pure lean λ = 1.4 combustion and lean λ = 1.4 combustion with 0.15 and 0.3% of H_2 gasoline enrichment.

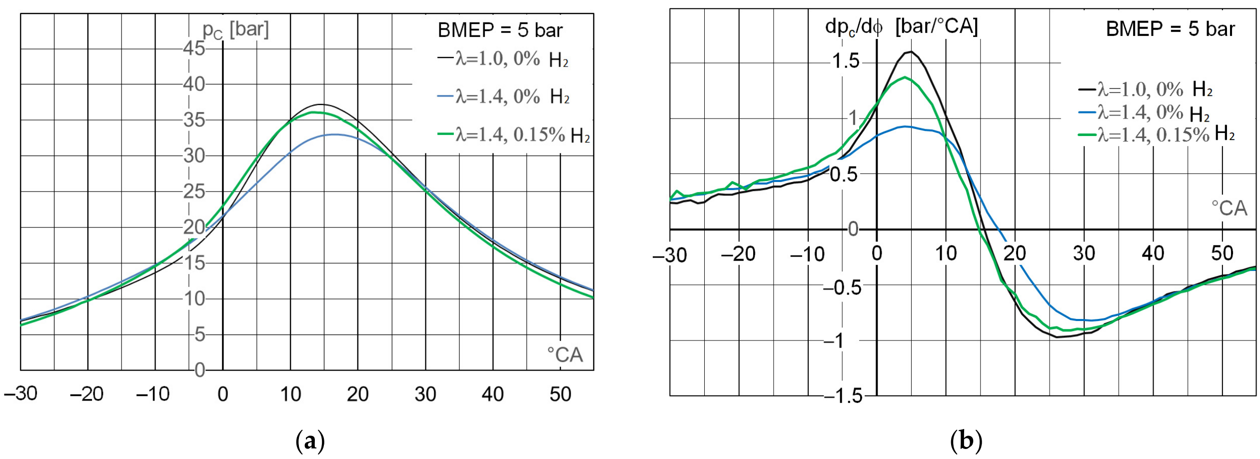

Figure 10. The impact of hydrogen enhancement on (**a**) in-cylinder pressure p_c; (**b**) derivative of in-cylinder pressure $dp_c/d\phi$ at 2000 rpm, BMEP = 5 bar for stoichiometric λ = 1, pure lean λ = 1.4 combustion and lean λ = 1.4 combustion with 0.15% of H_2 gasoline enrichment.

At higher load, namely BMEP = 4 bar and BMEP = 5 bar when the density of the cylinder charge raises and p_c is higher, the engine runs more stable even at lean-burn mode, and the p_c's are closer to each other in comparison to a lower load, BMEP = 3 bar. Therefore, a hydrogen enrichment as low as 0.3% affects the combustion process only in a minor way, but the impact on the derivate $dp_c/d\phi$ can still be observed.

The authors are aware of the fact that, in some paragraphs, the analysis of the results resemble a report; however, the literature lacks papers discussing in-cylinder pressure and operation stability of the SI engine at lean conditions when supplied with hydrogen in such small quantities. Therefore, there is no reference to compare. To our knowledge, the presented paper is the first in this field.

4. Conclusions

This study aimed to investigate the influence of a small amount of hydrogen addition on the combustion stability in SI gasoline-fueled engines. For this purpose, the HHO gas electrolytic generator was designed and implemented as a source of hydrogen. The following conclusions can be drawn:

1. The results of the laboratory tests show that the HHO gas fuel enhancement enables the improvement of the lean mode combustion stability.
2. It should be noted that the addition of pure hydrogen in an amount of at least 1% of the mass fraction is necessary to affect the in-cylinder pressure, but even such a small amount as 0.15–0.3% improves the stability of the lean-burn process. It should be emphasized that, usually, it is not possible to run the modern gasoline engine in unstratified lean-burn mode because of combustion instability and exhaust aftertreatment problems.
3. The results of the in-cylinder pressure analysis show that hydrogen enhancement of gasoline in an amount of less than 0.5% of the mass fraction at lean condition has a minor effect on the value of the in-cylinder pressure. However, the impact on the value of the maximum of the pressure derivative due to the shortened flame development and propagation durations is evident.
4. The highest impact of a small hydrogen addition on CS is observed at the lowest loads when the instability in combustion at the pure-lean condition is the highest. At a higher load and higher speed when the engine operates more stably, the effect of the enrichment becomes lower.
5. A hydrogen enrichment of less than 1% supplied from a small 10–15 dm^3 gas cylinder placed onboard a medium or small passenger vehicle may solve the problem of instability at lean conditions in MPI engines at idle or low-load operation. This can be the subject of future research.

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Abbreviations

AFR	Air Fuel Ratio;
BMEP	brake mean effective pressure;
CAD/°CA	crank angle degree;
COV/COV_i/COV_{IMEP}	coefficient of variation/COV for the *i*th cylinder/COV of IMEP;
CS	combustion stability coefficient;
DC	Direct current;
ECU	electronic control unit;
EGR	Exhaust Gas Recirculation;
FC	fuel cell;
FSO	Full scale output;
HC	Hydrocarbons;
HHO	Hybrid Hydrogen Oxygen;
HHV	higher heating value;
I_{Cell}	Current per generator cell;
ICE	Internal combustion engine;
IMEP/$IMEP_i$	indicated mean effective pressure/IMEP for the *i*th cylinder;
KOH	potassium hydroxide;
LHV	lower heating value;
LPM	Liters per Minute indicator;
MMW	Milliliters per Minute per Watt indicator;
MON	Motor Octane Number;
MPI	Multi Point Injection;
PWM	Pulse width modulation;
RON	Research Octane Number;
SI	Spark ignition;
TDC	Top dead center;
TWC	Three-way catalyst;
U_{Cell}	Voltage per generator cell;
U_{rev}	Reversible voltage;
U_S	Voltage supply;
U_{tn}	Thermoneutral voltage;
WOT	Wide open throttle;
k	Number of neutral electrodes of generator;
p_{H2}	Hydrogen pressure;
λ	Excess air coefficient;
σ_i	Standard deviation for the *i*th cylinder.

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