Hindawi
Journal of Combustion
Volume 2022, Article ID 5526205, 10 pages
https://doi.org/10.1155/2022/5526205

Research Article

Effects of Gasoline and Hydrogen Blends on Exhaust Gas Emissions and Fuel Consumption from Gasoline Internal Combustion Engines

Merlin Zacharie Ayissi,[1,2] Ivan Aquigeh Newen,[1,2] Rhiad Alloune,[3] and Dieudonné Bitondo[1,2]

[1] *Ecole Nationale Supérieure Polytechnique de Douala, Douala, Cameroon*
[2] *Laboratory of Energy, Materials, Modelling and Methods (E3M), University of Douala, Douala, Cameroon*
[3] *Development of Renewable Energy Center, University M'hamed Bougara of Boumerdes, Boumerdès, Algeria*

Correspondence should be addressed to Ivan Aquigeh Newen; ivannewen@yahoo.com

Received 13 April 2022; Revised 19 July 2022; Accepted 16 August 2022; Published 14 September 2022

Academic Editor: Constantine D. Rakopoulos

Gasoline engines remain a potential source of atmospheric pollution. Dual fuel combustion was under investigation to cope with exposure to pollutants. Investigations on emission parameters and engine performance for a single-cylinder four-stroke petrol engine are carried out using multicriteria decision-making method (MCDM). Bar charts are constructed for three emission parameters in function of engine temperature and fuel consumption for different blends. Fuels were supplied at different engine running speeds. Parameters recorded during the experimental study were the concentrations of carbon monoxide (CO), hydrogen sulfide (H_2S), percentages of lower explosive limit (LEL), and combustion duration. The maximum concentration of CO was 339 ppm at 70°C and 4000 rpm. The maximum concentration of H_2S (3 ppm), was recorded at 94°C and 4000 rpm. The maximum percentage of LEL recorded was 3% at the majority of temperature and 4000 rpm. Consumption of 25 Cl of (gasoline + HHO) was recorded during the maximum time (50 min). The experiment showed high emissions of CO that can provoke respiratory disorders and explosive gases, factors of explosion at high speeds (4000 rpm), and low temperature (70°C). H_2S emissions are very low (0–3 ppm) independently of the engine speeds and temperature. Blending gasoline with HHO shows a reduction in fuel consumption.

1. Introduction

The use of gasoline in internal combustion engines participates in the production of harmful emissions responsible for atmospheric pollution, health hazards, and greenhouse emissions responsible for climate change [1, 2]. With dual combustion using hydrocarbon fuels, the exhaust gases still produce pollutants, some of which have been widely investigated and others still need to be investigated properly. The growing need for transportation energy and depleting reserves of petroleum are of great concern [3] for fuel-driven activities and fuel-driven sectors as well. Fortunately, hydrogen gas can be used in traditional ICE's provided certain modifications are made, such as the use of; (i) hardened valves and valve seats, (ii) stronger connecting rods, (iii) higher voltage ignition coils, (iv) injectors designed for gases, (v) stronger head gasket materials, and (vi) modified intake manifolds [3–5]. Stoichiometric combustion of hydrogen using thermochemical equations indicates that hydrogen is not very suitable for compression ignition (CI) engines because of its high self-ignition property but can be used directly in gasoline engines.

In fact, hydrogen-fueled internal combustion engines are still in the development stage. They are very liable to pre-ignition, backfiring, rapid pressure rises, knocking, low volumetric efficiency, and compression loss problems that limit the engine's achievable load and efficiency. This underlines the need for thorough research work on their use as fuel in internal combustion engines. Hydrogen (H_2) being a hazardous substance in all its molecular forms, systems, and equipments, safety features should be installed to automatically control the equipment required to reduce the hazards suggested by the triggering of caution and warning systems [6]. The drawbacks of using hydrogen as a fuel are (i) low energy content per unit volume, (ii) high tankage weights, (iii) the storage, transportation, and filling of gaseous or liquid hydrogen in vehicles, (iv) the large investment in the infrastructure that would be required to fuel vehicles, and (v) the inefficiency of production processes. However, gases filled with hydrogen are used successfully in Europe to carry out residential requirements, which shows that there is a high percentage of safe usage of hydrogen. Further large reductions of risk linked to the use of hydrogen include (i) appropriate design, (ii) training, (iii) competence, and (iv) respect of safety norms. The technology involved in the production and use of hydrogen in internal combustion engines still remains expensive and premature [7, 8]. Furthermore, fuel cell electric vehicles (FCEVs) still encounter the problem of space and load for tanks and storage batteries [9,10]. Hydrogen was perceived by many as a dangerous substance for being a highly flammable gas [11]. However, recent studies found that in a collision in open spaces, a hydrogen fuel cell (FC) car would be safer than either natural gas or petrol vehicles. In fact, hydrogen leak would be less dangerous than a leak of a conventional fuel [12] given its low explosive energy per unit of fuel. Therefore, research on the production and combustion of hydrogen as a standalone system is imperative, giving credit to the continuous work on the adaptation and use of hydrogen as a fuel. A remedy to the backfire phenomenon was attempted, good hydrogen operating range was 2600–3800 rpm, and hydrogen had a higher brake thermal efficiency [13].

Roadmaps and development (R&D) for the use of hydrogen as a fuel have been established by different standard bodies and researchers who classified fuel cell applications as portable, stationary, and transport [14]. Others focused on hydrogen storage for FC's, notably hydrogen absorption by carbon nanomaterials using different techniques [15]. More investigations have been conducted in the use of hydrogen tanks in the automobile to supply FC's. Due to the drawbacks presented by FCV's, recent research projects are investigating the use of hydrogen in internal combustion engines (ICE's) [16].

Hydrogen is a promising alternative to gasoline owing to its almost near-zero engine-out emissions and higher thermal efficiency, low fuel consumption, and higher torque compared to conventional petrol-fueled (spark ignition SI) engines at certain operating conditions [17, 18]. However, the use of hydrogen still presents a number of drawbacks as described above. A potential solution to circumventing or alleviating the above limitations is hydrogen direct injection and utilization of newly designed gas regulators [18, 19]. The low flammability limits and low energy required for ignition of hydrogen cause preignition and backfire when using hydrogen fuel [20]. Adding hydrogen in an internal combustion engine decreases HC, CO, CO_2, and smoke levels. This instigated the use of hydrogen in transportation engines [21]. Dual fuel engines, bivalent engines, homogeneous charge compression ignition (HCCI), and low temperature combustion (LTC) are amongst the recent combustion technologies [22]. However, the rise of the temperature in the combustion chamber brings an undesirable phenomenon; the rise of nitrogen oxide (NOx) particularly at high load conditions [23]. Internal combustion engines do not require pure hydrogen gas to achieve power generation like fuel cells do. HHO gas has been observed to increase the thermal efficiency of the engine, decrease unburned hydrocarbons in the exhaust gases, as well as reduce the specific fuel consumption [21]. The presence of HHO decreases the combustion chamber temperature and thus decreases the chances of engine detonation. The use of hydrogen/natural gas fuel blend penalizes the engine operation with 1.5 to 2.0% decrease in torque, but provides up to a 36% reduction in CO, 30% reduction in NO_X, and 5% increase in brake thermal efficiency (MBT) [24]. A paradigm shift towards the utilization of carbon-neutral and low-emission fuels in the internal combustion engine industry is necessary [17, 25]. NOx as a byproduct from hydrogen boilers and engines can be minimized through control of combustion conditions, but this can lead to reduced power output and performance. Zavadskas et al. [26] used the multicriteria decision-making method (MCDM) to evaluate the ecological and performance parameters of internal combustion engines. Evaluation of the environmental impact of H_2-ICE and fuel cell vehicles considering the impact of global warming, air quality depletion, and noise (Ecoscore) were made. Highest values were obtained for vehicles using hydrogen from electrolysis produced with 100% renewable energy. Ecoscore values varied from 0–100, with 100 representing a perfectly clean and totally silent vehicle [27].

Different blends of H_2 with natural gas were experimented in ICEs with an objective to obtain the optimal performance. Kumar and Rao [28] showed that it is very easy to integrate both the alternative fuels with the existing engines without requiring major hardware modifications. The use of hydrogen in gasoline engines resulted in high brake thermal efficiency and mechanical efficiency compared to gasoline fuel [29]. Baiju et al. [30] demonstrated that hydrogen gas combined with the standard air/fuel mixture minimizes the consumption of gasoline as well as increases the power of vehicle. Shadidi et al. [31] reviewed that with the application of hydrogen in the majority of internal combustion engines, hazardous exhaust pollutants are reduced, and engines' overall performance improves. Baiju et al. [30] and Dandrea et al. [32] showed that dual fuelling reduced fuel consumption by 30% but undergoes cycle-to-cycle variation depending on the percentage of hydrogen added, which in turn relies on the equivalent ratio. Sapate and Tikekar [33] reported that the application of direct in-cylinder fuel injection in two-stroke engines reduces exhaust emissions.

Almost all chemicals are hazardous and toxic when it enters the environment and the human body beyond the threshold level. Bhomick and Rao [34] described H_2S as harmful to humans. It attacks the nervous system, the liver, and the kidney. It is an irritant and asphyxiant, whose effects depend on the duration of exposure. CO, NO, and H_2S have the same toxicity. In ICEs, H_2S is formed when the engine runs rich, the exhaust contains unburned fuel, and the added hydrocarbons can combine with the accumulated sulphur to form smelly hydrogen sulfide. Rich air-fuel ratios occur normally when a cold engine is being warmed up, when a car is being accelerated, and when the engine is idle [35]. Wang et al. [36] indicated that the explosion of binary and multicomponent mixtures is more dangerous and destructive than that of methane alone in the air. Karelin et al. [37] reported that every gas has its own LEL, which is the most important property employed to assess the overall flammable and explosive hazard potential of a chemical. The LEL, which is usually expressed in percentage volume (vol.%) at 298°K, is the minimum concentration of a combustible substance that is capable of propagating a flame through a homogeneous mixture of combustible and air under the specified conditions of the test [38]. In gasoline vehicle engines, the main emissions generated are nitrogen oxides (NOx), carbon monoxide (CO), hydrocarbons (HC), and volatile organic compounds (VOC). These pollutants have significant adverse health effects and deteriorate environmental quality [39, 40].

Experiments reported were run to verify the effects of dual fuel combustion on pollution and fuel consumption in ICEs, following the phase of production of hydrogen using NaOH and stainless-steel electrodes in an alkaline electrolysis cell carried out by Aquigeh et al. [41]. In this paper, experimental observations on pollution exposure from a four-stroke single-cylinder gasoline engine were performed. Unlike previous pioneer studies, which considered mostly the emission of NOx, $CO_{2,}$ and HCs, the present work investigated the effects of dual combustion of gasoline-hydrogen and gasoline-hydrogen oxides on both fuel consumption and the emission of alternative pollutants such as CO, H_2S, and LEL from the exhaust gases. These pollutants have been, in most cases, studied with respect to equivalence ratios and engine speed. In this paper, it is done with respect to both engine temperature as well as engine speed. Furthermore, the combustion time of 25 cl of gasoline with and without a blender is investigated for different engine speeds.

2. Materials and Methods

Experiments involving pollution exposure and combustion duration were carried out separately, and each of the pollution exposure and combustion duration formed a single independent variable with three levels. The experiment on fuel consumption was comprised of two levels. A descriptive statistical approach was employed, with 10 repetitions per level and the mean values calculated. A four-stroke gasoline engine (Model: HK 150–8, OMEGA Co. Ltd. Nasimabad, Pakistan) equipped with a single-cylinder, naturally aspirated, and air-cooled was used. The cylinder capacity was 150 cm^3, and the maximum power was 1.491 KW. Gasoline was used as the major fuel blended with H_2 and HHO in a single cell electrolyser described by Aquigeh et al. [41]. The measuring tools were (i) a flow rate meter, (ii) a digital thermometer, (iii) an infrared thermometer, and (iv) a multiple gas detector. A hydrogen detector described by Aquigeh et al. [41] was used to detect leaks, a safety requirement. The working engine temperature of the experiment was comprised between 70°C and 112°C for safety reasons. It was also observed that within this interval there was some degree of reversibility (proportionate variation in temperature).

2.1. Experimental Setup. Various tests and measuring instruments were used in the experiment (Figure 1).

2.1.1. Constituents of the Experimental Setup. Safe measuring distance is about 0.5 m away from the tailpipe due to the fact that the gas detector should not be exposed to a heavily polluted atmosphere as indicated by the manufacturer. The baseline experiment for pollution exposure was run with gasoline at an engine speed of 3000 rpm, while the gas detector was aligned with the tail of the exhaust pipe at 0.5 m. Speeds varied from 1000 rpm to 4000 rpm to constitute the different engine operating conditions with and without hydrogen or HHO. In these cases, the gas detector was aligned with the tail of the exhaust pipe at 1 m. The electrolyser used in the various experiments consisted of 200 ml 60 w% sodium hydroxide (NaOH) electrolyte. Each electrode was made up of a 10 cm long, 4 mm diameter straight stainless-steel rod, and with a 3 cm length submerged in NaOH solution. The electrolyser was connected to a 12 V battery mounted on the engine's stand. The electrolyser produced H_2 and O_2 for the experiment involving H_2 only. The pipe for H_2 is connected to the engine's supply and for experiment involving HHO the pipes for H2 and O_2 are connected before supplying the engine. The gases were detected by a portable multigas detector (Model S318, Henan Zhongan electronic detection technology Co. Ltd, Zhengzhou, China).

During the testing, an infrared thermometer (Model AS530, Intel Smart Instrument, California, USA) was used to monitor the temperature of the engine. A flow meter (Model NKR32FC-VKB1V1N, Hubei Nankong Instrument Technology Co. Ltd, Guangzhou, China) helped measure the hydrogen flow rate and calculate the A/F ratio. The dashboard was composed mainly of a tachometer for the reading of the engine speed. In the gasoline consumption test, 25 Cl of gasoline were burned with or without H_2 or HHO, and the burning time was recorded.

The pipe pressure was determined from volumetric flow rate (Q_v):

$Q_v = V/t$; where V is the volume of fluid flow and t is the time.

$$P = \frac{128\mu Q_v l}{\pi D^4} \text{ (Hagen Poiseuille)}, \qquad (1)$$

where P is the pressure gradient, μ is the fluid viscosity, l is the length of the pipe, and D is the diameter of the pipe.

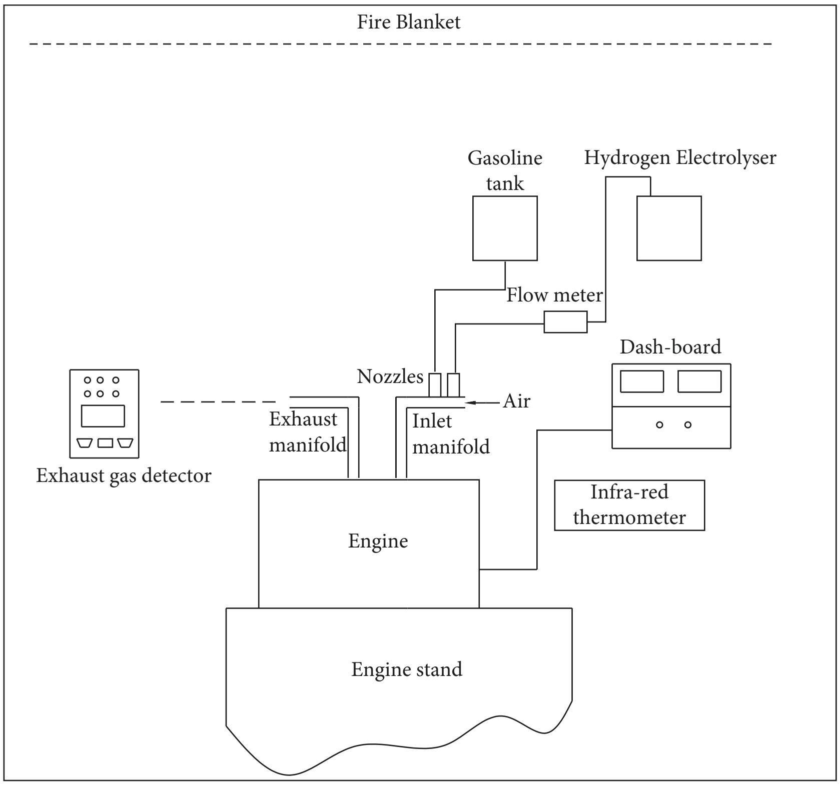

Figure 1: Elements of the experimental setup.

Combustion Stoichiometry was performed as described by Karaman [12].

Total volume of air injected into the cylinder = (mass flow rate *x* time of flow)/air density.

$$\frac{\text{Air}}{\text{fuel ratio}} = \frac{\dot{m}_a}{\dot{m}_f} = \frac{\text{air mass flow rate}}{\text{fuel mass flow rate}}. \quad (2)$$

Stoichiometric (theoretical) combustions of gasoline and hydrogen in air were summarized by the respective following reactions (reasonable approximations):

$$\begin{aligned} &C_{7.9}H_{14.8} + 11.6\,O_2 + 43.767\,N_2) \\ &\geq 7.9\,CO_2 + 7.4\,H_2O + 43.767\,N_2, \\ &H_2 + \frac{1}{2}O_2 + 1,887\,N_2 \geq H_2O + 1.887\,N_2. \end{aligned} \quad (3)$$

Stoichiometric A/F ratios: gasoline = $C_{7.9}H_{14.8}$ (A/F) $s = 14.6$. Hydrogen = H_2 (A/F)$s = 34.3$.

2.1.2. Characteristics of the Test Environment. The test environment was composed essentially of a 4.5 m × 4 m *x* 2.5 m room with openings for ventilation well above to control the wind effect during measurements. The main door (4 m large *x* 2 m high) was always kept closed during testing and opened wide after each test to enable sufficient air into the room. The operating parameters were set at standard temperature and pressure (STP). The engine was cooled down and pollutants were evacuated after each sequence of testing. A fan was installed in the test room to fasten the cooling of the engine and help evacuate pollutants from the test room. This ensured a similar environment for each test for measurement accuracy.

The measuring instruments were checked and reset before any sequence of measurements.

The major safety measures involved the presence of a fire blanket placed on the roof above the test bench for any eventuality, a cylinder of a fire extinguisher, and a hydrogen detector to make sure that no leakages were present and to ensure the presence of hydrogen at the carburetor's inlet during each experiment.

2.2. Test Procedures

2.2.1. Procedure for Baseline Parameters. To test the engine's emission with gasoline only as a fuel, start the engine with no load and run it at an idle speed of 1000 rpm. Allow the engine to reach a steady state operating condition (70°C). Set the engine speed at (3000 rpm). Place the gas detector (0.5 m) at the tail end of the exhaust pipe to record the data. For gasoline/hydrogen blended fuel, the procedure was similar to the preceding one with the exception of hydrogen addition.

2.2.2. Procedure for the Testing of Engine's Emissions with Gasoline plus H_2. Repeat the procedure in section 2.2.1 while setting the engine speed (1000, 2000, or 4000 rpm). Set the electrolyser to supply H_2 and record data at the specified engine temperatures. Hydrogen was supplied through a flexible pipe of length 0.5 m and diameter 0.005 m. The pressure at the outlet of the pipe was 1.8 bars and the temperature was slightly above room temperature.

2.2.3. Procedure for the Testing of Engine's Temperature Variation. Repeat the procedure in section 2.2.1. Set the engine speed (1000, 2000, or 4000 rpm) and the electrolyser to supply HHO, then record the time for each speed.

2.2.4. Procedure for Testing the Engine's Fuel Consumption (Combustion Duration). Replace the tank with a transparent tank containing 25 Cl of gasoline. Set the electrolyser to supply (H_2 or HHO). Set the engine speed to 2000 rpm for all tests, record start time, temperature, end time, and temperature corresponding to when 25 Cl of gasoline gets finished from the tank.

Repeat all tests at least two times to evaluate repeatability and to validate the data.

3. Results and Discussion

To investigate the consumption, pollution exposure, and benefits of blending gasoline with hydrogen of a four-stroke gasoline engine, experiments were designed and ran. Results were expressed in the form of bar charts. The charts present the exposure by plotting emission parameters versus engine temperature for different engine speeds.

3.1. Baseline Parameters

3.1.1. Carbon Monoxide in Function of Temperature. Data recorded as the engine's temperature increased from 70°C to 112°C at 3000 rpm, using gasoline only, showed that the CO concentration was constant with a value of 592 ppm. At 1 m from the exhaust pipe, the concentration was moderate because of diffusion in the atmosphere reduced the gases reaching the detector (Figure 2). The concentrations detected at the distance of 1 m for the combustion of gasoline only varied from 222 ppm at 85°C to 374 ppm at 70°C, while that of gasoline plus hydrogen varied from 171 ppm at 91°C to 311 ppm at 94°C. The production of CO with temperature tends to be almost constant since its production depends more on air-fuel ratio. On average, there was a 17.2% reduction of CO concentration with the addition of hydrogen. This can be explained by the fact that in dual combustion the quantity of gasoline for combustion is reduced and in turn carbon is reduced since hydrogen is carbon free. CO concentrations were presumably high. According to Nomiyama et al. [42] and Cauda [43] the occupational exposure limit of CO concentration is 50 ppm for time weighted average to 400 ppm for short-term exposure limit, meaning that at 0.5 m of gasoline only there is a high risk of health hazards and at 1 m with and without hydrogen, the concentration was above the limit for time weighted average and within limits for short-term exposure limit, with potential risks of breathing difficulties and other health issues.

3.1.2. Hydrogen Sulfide in Function of Temperature. Observations carried out as the engine's temperature increased from 70°C to 112°C at 3000 rpm, running on gasoline only, showed that at 0.5 m from the exhaust pipe, H_2S concentration varied from 1 ppm at 85°C and 112°C to 7 ppm at 70°C (Figure 3). At 1 m from the exhaust tailpipe, the concentration dropped, as a result of thermochemical reactions and diffusion to the atmosphere, reducing the gases reaching the detector at this distance. H_2S concentration detected at a distance of 1 m in the combustion of gasoline only varied from 0 ppm to 2 ppm when the temperature increased from 70°C to 112°C, while that of gasoline plus hydrogen combustion indicated 2 ppm at 70°C and dropped to 1 ppm in a few cases and 0 ppm for most of the temperatures. This can be due to the fact that, with the presence of H_2 new substances are formed by reacting with hydrogen sulfide. Water is formed during combustion and this water combines with the hydrogen ions in H_2S to form hydronium (H_3O) and the sulphur reacts to form sulfuric acid (H_2SO_4). At high temperatures the speed of the reactions increased, leading to lower production of H_2S. With the addition of hydrogen there were averagely of 46.2% reduction of H_2S. The highest H_2S concentration recorded was 7 ppm, and which confirmed the finding by Barne and Jack [35] that H_2S is formed when the engine runs rich, that is, usually when a cold engine is being warmed up, when a car is being accelerated and when the engine is at idle. Nomiyama et al. [42] reported that H_2S occupational exposure limit is 5 ppm, meaning that at 0.5 m with gasoline only, there is a slight risk of health hazards and at 1 m with and without hydrogen concentration, it is below the limit which makes it environmentally friendly.

3.1.3. LEL at Different Engine Temperatures. Experiments were carried out as the engine's temperature increased from 70°C to 112°C, at 3000 rpm. Using burning gasoline only, it was observed that LEL in the exhaust gases alternates between 6% and 7% within the measuring interval at 0.5 m distance from the exhaust tailpipe (Figure 4). LEL alternated between 1% and 3% in most cases at 1 m from the exhaust pipe, with the combustion of gasoline only, and recorded its highest value (4%) at 106°C. The blend of gasoline with hydrogen at 1 m distance presented almost similar behavior even though the majority alternated between 1% and 2% with a few cases of 3%. There was an average reduction of about 16.7% of LEL concentration with the addition of hydrogen. In its pure state, gasoline has a lower explosive limit (1.2%) by volume than hydrogen (4%) but the fact that when hydrogen is added, the quantity of pollutants in the exhaust gases is reduced, making it possible for the lower LEL. Cao et al. [38] defined LEL as the minimum concentration of a combustible substance that is capable of propagating a flame through a homogeneous mixture of combustible and air, meaning that at 0.5 m and 1 m from the exhaust tailpipe with and without hydrogen, there is a risk of flame propagation because of the presence of small volumes of explosive gases. Therefore, the atmosphere can be considered safe from explosion only if 0% LEL is detected in the exhaust gas.

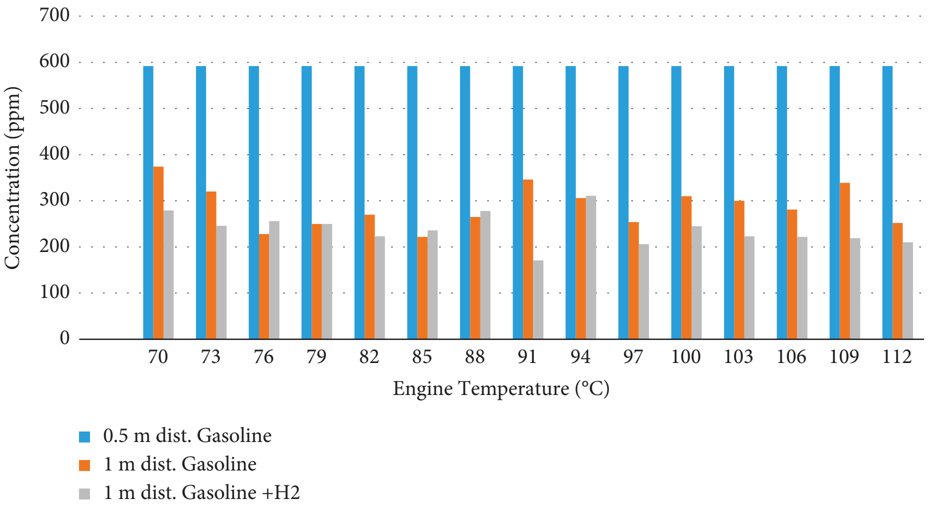

Figure 2: CO exposure at 0.5 m and 1 m distances at 3000 rpm engine speed.

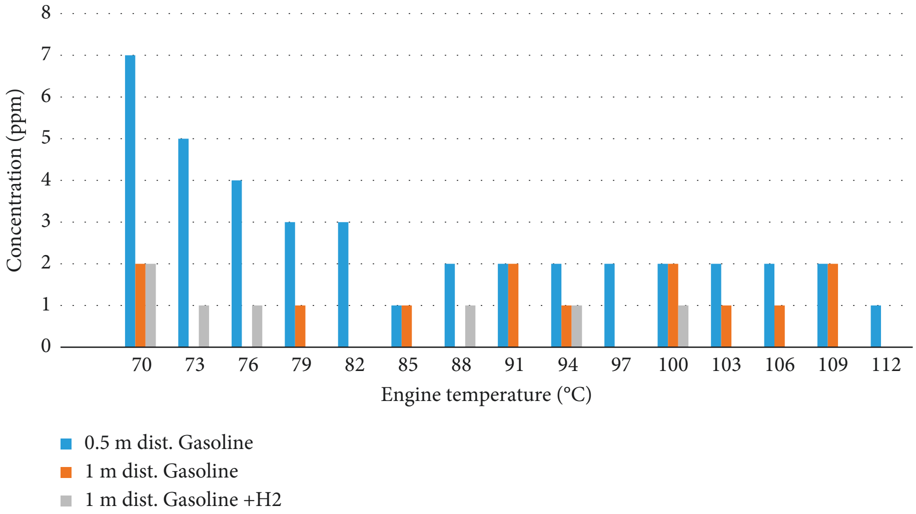

Figure 3: H_2S exposure at 0.5 m and 1 m distances at 3000 rpm engine speed.

3.2. CO Exposure, H_2S Exposure, and Lower Explosive Limit Exposure

3.2.1. CO Exposure for Different Engine Speeds. CO emission was high at low temperatures and high speeds. The maximum concentration (339 ppm) occurred at 70°C and at 4000 rpm. The lowest recorded at 4000 rpm was 191 ppm at 91°C. The second highest concentration (311 ppm) was obtained at 3000 rpm and 94°C. Emissions at 1000 rpm presented severe oscillations with a peak value (202 ppm) at 91°C and a minimum (43 ppm) at 70°C. At 2000 rpm, the emissions oscillated weakly with a maximum of 121 ppm at 79°C and a minimum of 71 ppm at 103°C (Figure 5). Sayana and Bagade [20] obtained the highest concentration of CO (4500 ppm) at 3700 rpm, even though they did not consider the effect of temperature. The result confirmed the fact that peak values for CO emission were recorded at high engine speeds. There is less exposure at low engine speeds and high exposure at high engine speeds. The feature could be explained by the fact that the air-fuel mixture is rich at low speed, low temperature, and high speeds, as noticed in oxygen levels versus engine speed by Sayana and Bagade [20]. Also, the fact that the percentage of hydrogen in the mixture reduces as speed increases (1000 rpm–65% H_2, 2000 rpm–30% H_2, 3000 rpm–20% H_2, and 4000 rpm–15% H_2) is also a factor of low exposure at low engine speeds and high exposure at high engine speeds.

3.2.2. H_2S Exposure for Different Engine Speeds. It was observed that the concentration alternated between 2 ppm at 70°C for 1000 rpm, 2000 rpm, and 3000 rpm and then dropped to 1 ppm in a number of cases and to 0 ppm for few of the temperatures. At 2000 rpm, the concentration dropped and fell to 0 ppm for temperatures above 79°C (Figure 6). The peak concentration was 3 ppm for 4000 rpm at 94°C. This could be explained by the same facts for CO above for engine speeds. Owing to the fact that H_2S have an

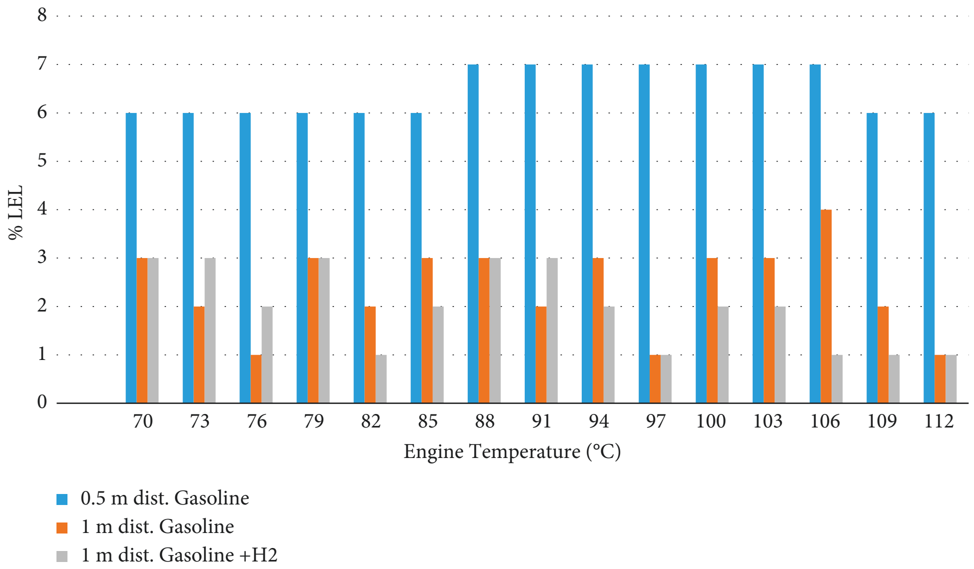

Figure 4: LEL exposure at 0.5 m and 1 m distances at 3000 rpm engine speed.

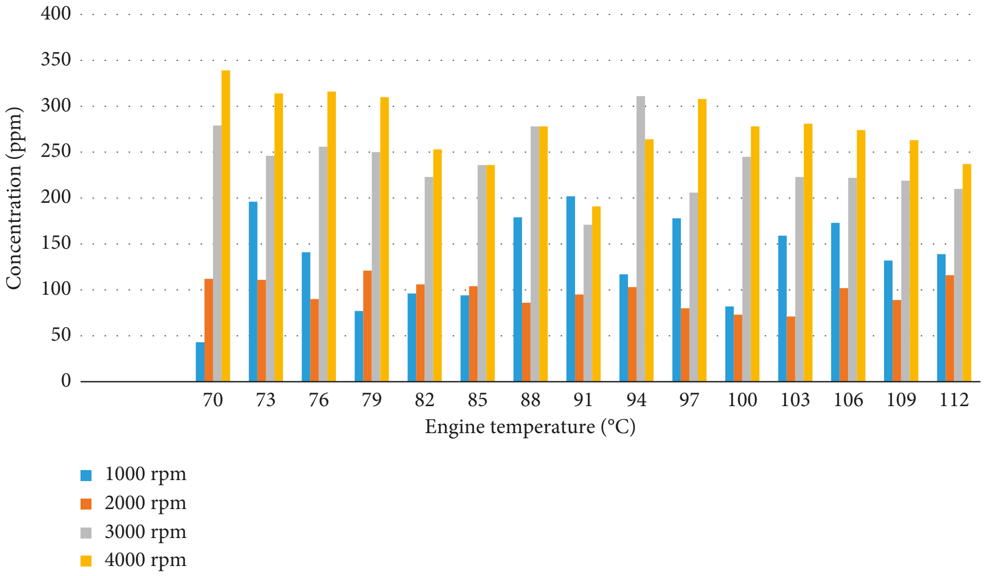

Figure 5: CO exposure at 1 m distance for different engine speeds for gasoline + H_2 blend.

occupational exposure limit of 5 ppm, Nomiyama et al. [42], implies that for all engine speeds used for the observations at 1 m from the exhaust tailpipe, there are little or no health risks since the peak value is less than the exposure limit.

3.2.3. Lower Explosive Limit Exposure for Different Engine Speeds. LEL alternated between 1% and 3% in most cases. At 4000 rpm, almost half of the observations had values of 3% and almost half gave 2% and 1% at 82°C. At 3000 rpm, 1/3 of the observations produced 3%, 1/3 produced 2%, and another 1/3 produced 1%. At 2000 rpm, LEL was 1% throughout, except at 79°C and 88°C where it was 3%. At 1000 rpm, it was observed that at the majority of engine temperatures, LEL was 2% and a few were 1% (Figure 7). LEL is almost constant at low speeds and alternates with higher values at high speeds. The later observation is proper to richer mixtures at the given engine working conditions that were already explained in Section 3.2.1. There is a risk of explosion in any environment once the LEL is different from zero, Cao et al. [38]. Therefore, there are risks of explosion at 1 m from the exhaust tailpipe for all engine speeds.

3.3. Estimates of Combustion Duration from 70°C to 112°C. Combustion of gasoline only at 3000 rpm took 9 min on average from 70°C to 112°C. Combustion of gasoline + HHO-rich air at 4000 rpm took 4 min, 6 min at 3000 rpm, 7 min at 2000 rpm, and 15 min at 1000 rpm. This implies pure gasoline takes a longer time from 70°C to 112°C compared to a blend of gasoline and HHO-rich air for the same engine speed. For gasoline and HHO-rich air blends at

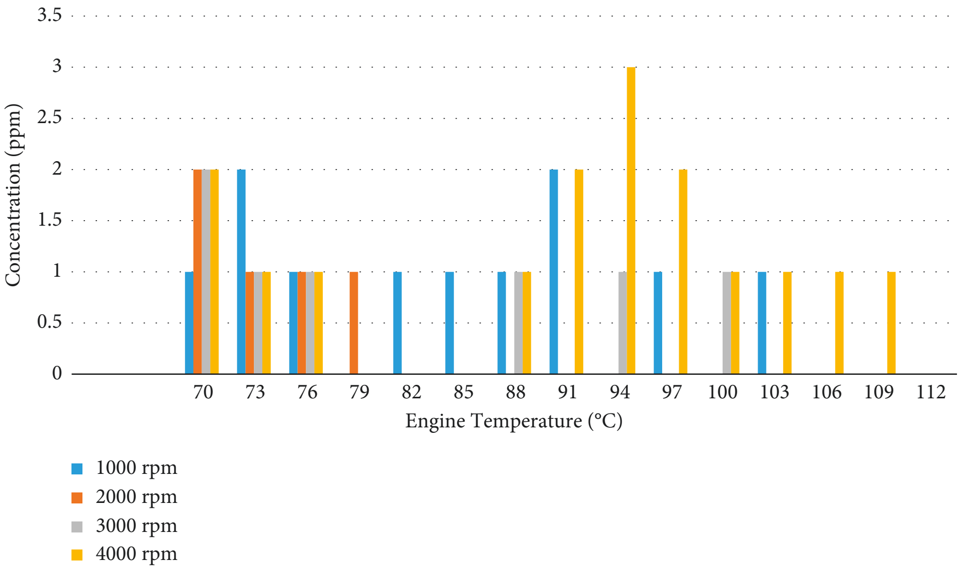

Figure 6: H_2S exposure at 1 m distance for different engine speeds for gasoline + H_2 blend.

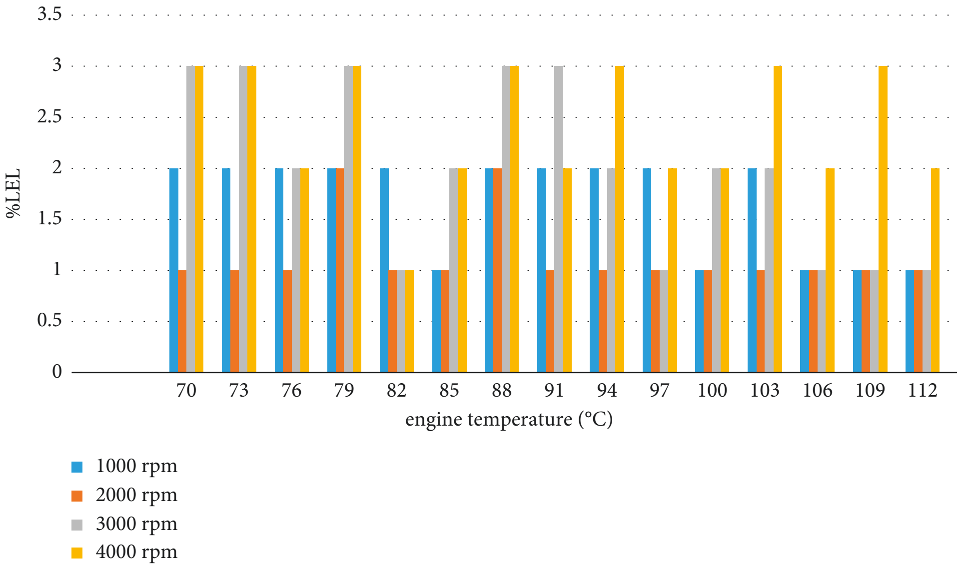

Figure 7: LEL exposure at 1 m distance for different engine speeds for gasoline + H_2 blend.

different engine speeds, it was found that the time taken from 70°C to 112°C is inversely proportional to speed. This is in response to Hosseini and Butler [21], who mentioned that HHO increases the thermal efficiency of the engine as well as reduces its specific fuel consumption.

3.4. Results of Fuel Consumption for Different Blends with the Combustion of 25 Cl of Gasoline at 2000 rpm. The combustion of 25 Cl of gasoline only took 45 min to be consumed, during which the temperature difference varied by 65°C. A blend of gasoline and HHO-rich air took 50 min with a temperature variation equal to 51°C. A blend with hydrogen-rich air took 48 min with a temperature variation estimated at 72°C. There are economic benefits when gasoline is blended with HHO and H_2. In fact, there was an 11.1% increase of the time to consume gasoline in HHO-rich air and a 6.6% increase for gasoline in an H_2-rich air. Hosseini and Butler [21] found that one of the effects of operating an engine with additive HHO gas is decreased fuel consumption (gasoline) from 0.57 kg/h to 0.49 kg/h, 14% decrease.

4. Conclusion

The study was aimed at determining the benefits of dual fuel combustion on pollutant exposure and fuel economy to recommend the use of hydrogen in internal combustion engines. Data on pollutant emissions and the time to burn 25 Cl of gasoline + hydrogen blends revealed that high speeds and low temperatures favoured high exposure to pollutants (CO, H_2S) and high risk of explosion based on the estimated LEL values. H_2S produced was below the exposure limit regardless of engine speed and temperature. Blending gasoline and HHO improved fuel economy and reduced temperature variations compared to blending gasoline with H_2. Dual combustion of gasoline plus H_2 or HHO could be recommended as suitable fuels for internal combustion engines. Other engine performance criteria like torque, power, and efficiency should be studied. Furthermore, the exposure to other pollutants (H_3O and H_2SO_4) should be observed for a safer implementation of hydrogen in internal combustion engines.

Abbreviations

MCDM:	Multicriteria decision-making method
CO:	Carbon monoxide
H_2:	Hydrogen
HC:	Hydrocarbons
CO_2:	Carbon dioxide
H_2S:	Hydrogen sulfide
LEL:	Lower explosive limit
PPM:	Part per million
HHO:	Oxyhydrogen
FC:	Fuel cell
FCEV:	Fuel cell electric vehicle
MBT:	Mean brake torque
R&D:	Roadmap and development
PEFC:	Polymer electrolyte fuel cell
ICE:	Internal combustion engine
C.I:	Compression ignition
S.I:	Spark ignition
LTC:	Low temperature combustion
HCCI:	Homogeneous charge compression ignition
NOx:	Nitrogen oxide
NaOH:	Sodium hydroxide
A/F:	Air-fuel
D.C:	Direct current.

Data Availability

The experimental data used to support the findings of this study are provided in supplementary materials.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

Test and measuring equipment were provided by the E3M laboratory, University of Douala, Cameroon. The authors are grateful to Dr. Claude Bakoumé for his constructive comments on the study and the manuscript.

Supplementary Materials

Supplementary materials are appended to this manuscript. (*Supplementary Materials*)

References

[1] W. Dalhuijsen, H. Bosma, M. Merts, and L. Buning, *Internal Combustion Engine Vehicle: Emissions and Performance Using Blends of Natural Gas and Hyrogen*, HAN University, Mobility Technology Research department, Arnhem, Netherlands, 2007.

[2] P. R. Chitragar, K. V. Shivaprasad, and G. N. Kumar, "Use of hydrogen in internal combustion engines: a comprehensive study," *Journal of Mechanical Engineering and Bomechanics*, vol. 1, no. 3, pp. 84–96, 2016.

[3] K. I. Hamada, M. M. Rahman, D. Ramasamy, M. M. Noor, and K. Kadirgama, "Numerical investigation of in cylinder flow characteristics of Hydrogen-fuelled internal combustion engine," *Journal of Mechanical Engineering and Sciences*, vol. 10, no. 1, pp. 1782–1802, 2016.

[4] S. K. Sharma, P. Goyal, and R. K. Tyagi, "Hydrogen-fuelled internal combustion engine: a review of technical feasibility," *International Journal of Performability Engineering*, vol. 11, no. 5, pp. 491–501, 2015.

[5] J. A. N. Kumar, N. Gowtham, and S. Senthil, "Design and fabrication of hydrogen powered I.C engine," *International Review of Applied Engineering Research*, vol. 4, no. 5, pp. 423–426, 2014.

[6] H. Beeson and S. Woods, "Guide for hydrogen hazards analysis on components and systems," 2003, https://ntrs.nasa.gov/api/citations/20040033949/downloads/20040033949.pdf.

[7] A. S. Tijani, N. A. B. Yusup, and A. A. Rahim, "Mathematical modelling and simulation analysis of advanced alkaline electrolyzer system for hydrogen production," *Procedia Technology*, vol. 15, pp. 798–806, 2014.

[8] E. Dugamin, L. Truche, and F. V. Donzé, "Natural hydrogen exploration guide," *ISRN GEONUM-NST*, vol. 01, p. 16, 2019.

[9] I. Abe, "Alkaline water electrolysis," *Journal of the Hydrogen Energy System Society*, vol. 1, 1998.

[10] L. F. B. Babo, "Simulation and optimization of a hydrogen internal combustion engine," Faculdade de Engenharia da Universidade do Porto, Porto, Portugal, Masters Theses, 2016.

[11] M. Ricci, G. Newsholme, P. Bellaby, and R. Flynn, "Hydrogen: too dangerous to base our future upon?" *Symposium Series NO*, vol. 151, 2006.

[12] M. T. Chaichan, "Safety using of hydrogen as vehicle fuel: a review," *International Journal of Computation and Applied Sciences*, vol. 4, no. 2, 2018.

[13] E. Kahraman, *Analysis of a Hydrogen Fuelled Internal Combustion Engine*, Masters Thesis, School of Engineering and Sciences of İzmir Instute of Technology, Urla, Turkey, 2005.

[14] J. Garche and L. Jörissen, "Applications of fuel cell technology: status and perspectives," *The Electrochemical Society Interface*, vol. 24, pp. 1–5, 2015.

[15] M. A. Sk, K. V. Rao, and J. V. R. Rao, "Hydrogen as fuel carrier in PEM fuel cell for automobile applications," *IOP Conference Series: Materials Science and Engineering*, vol. 73, no. 1, pp. 012139–12144, 2015.

[16] P. M. Chavan, "Hydrogen fuel cell vehicle," *International Journal of Latest Trends in Engineering and Technology*, vol. 7, no. 3, 2016.

[17] L. V. Plotnikov and N. V. Ulman, "Computational and analytical evaluation of the efficiency of using hydrogen as a fuel in an internal combustion engine," *IOP Conference Series: Earth and Environmental Science*, vol. 723, no. 5, Article ID 052018, 2021.

[18] J. A. Yamin and M. A. Hamdan, “The performance of hydrogen-powered 4-stroke SI engine using locally designed fuel regulator,” *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, vol. 32, no. 3, 2010.

[19] H. L. Yip, A. Srna, A. C. Y. Yuen et al., “A review of hydrogen direct injection for internal combustion engines: towards carbon-free combustion,” *Applied Sciences*, vol. 9, no. 22, p. 4842, 2019.

[20] G. Sayanna and C. M. Bagade, “Hydrogen internal combustion engine,” *International Journal of Technical Research and Applications*, vol. 6, no. 5, pp. 01–11, 2018.

[21] S. E. Hosseini and B. Butler, “An overview of development and challenges in hydrogen powered vehicles,” *International Journal of Green Energy*, vol. 17, no. 1, pp. 13–37, 2020.

[22] Y. Karagöz, “Effect of Hydrogen addition at different levels on emissions and performance of a diesel engine,” *Journal of Thermal Engineering*, vol. 4, no. 2, pp. 1780–1790, 2017.

[23] D. Gheorghe, D. Tutunea, M. Bica, A. Gruia, and M. Calbureanu, “Hydrogen a new fuel for internal combustion engines,” *IOP Conference Series: Materials Science and Engineering*, vol. 595, no. 1, Article ID 012032, 2019.

[24] K. S. Chapman and A. Patil, “Performance, efficiency, and emissions characterization of reciprocating internal combustion engines fueled with hydrogen/natural gas blends,” Technical report, Kansas state University, Manhattan, Kansas, 2008.

[25] A. C. Lewis, “Optimising air quality co-benefits in a hydrogen economy: a case for hydrogen-specific standards for NO_x emissions,” *Environmental Sciences: Atmosphere*, vol. 1, no. 5, 207 pages, 2021.

[26] E. K. Zavadskas, A. Cereska, J. Matijosius, A. Rimkus, and R. Bausys, “Internal combustion engine analysis of energy ecological parameters by neutrosophic Multimoora and Swara methods,” *Energies*, vol. 12, no. 8, p. 1415, 2019.

[27] N. Sergeant, F. Boureima, J. Matheys, J.-M. Timmermans, and J. V. Mierlo, “An environmental analysis of FCEV and H2-ICE vehicles using the Ecoscore methodology,” *World Electric Vehicle Journal*, vol. 3, pp. 635–646, 2009.

[28] G. A Kumar and G. V. Rao, “Performance characteristics of oxy hydrogen gas on two stroke petrol engine,” *International Journal of Engineering Trends and Technology*, vol. 6, no. 7, pp. 1–9, 2013.

[29] C. M. Samath and C. S. Aalam, “Analysis of hydrogen fuelled two stroke petrol engine,” *International Journal of Advanced Engineering, Management and Science*, vol. 1, no. 2, pp. 1–6, 2015.

[30] B. Baiju, S. Gokul, S. Schin, C. M. Ranjith, and U. Sathyamoorthy, “Hydrogen petrol mixture SI engine,” *International Journal of Engineering and Advanced Technology*, vol. 3, no. 6, pp. 1–6, 2014.

[31] B. Shadidi, G. Najafi, and T. Yusaf, “A review of hydrogen as a fuel in internal combustion engines,” *Energies*, vol. 14, no. 19, p. 6209, 2021.

[32] T. Dandrea, P. F. Henshawa, and D. S. K. Ting, “The addition of hydrogen to a gasoline-fuelled SI engine,” *International Journal of Hydrogen Energy*, vol. 29, no. 14, pp. 1541–1552, 2004.

[33] K. D. Sapate and A. N. Tikekar, “Pollution aspects of emissions from small two-stroke automobile engines,” *Nature Environment and Pollution Technology*, vol. 7, no. 1, pp. 33–38, 2008.

[34] P. C. Bhomick and K. S. Rao, “Sources and effects of hydrogen sulfide,” *Journal of Applicable Chemistry*, vol. 3, no. 3, pp. 914–918, 2014.

[35] G. J. Barnes and C. Jack, “Hydrogen sulfide formation over automotive oxidation catalysts,” *SAE International*, vol. 84, no. 1, pp. 477–484, 1975.

[36] H. Wang, S. Gu, and T. Chen, “Experimental investigation of the impact of CO, C_2H_6, and H_2 on the explosion characteristics of CH4,” *ACS Omega*, vol. 5, no. 38, pp. 24684–24692, 2020.

[37] A. Karelin, E. F. Karpov, A. V. Baranov, S. Mironov, and E. E. Karpova, “Method for determining the concentration of unknown combustible gas,” *Proceedings*, vol. 1, no. 422, pp. 1–4, 2017.

[38] J. Cao, L. Ding, Y. Pan, and J. Zhao, “Lower explosion limits measurements and prediction for binary liquid mixtures,” *Conference Series: Materials Science and Engineering*, vol. 5, no. 585, pp. 1–11, 2019.

[39] B. Saini, R. Verma, S. K. Himanshu, and S. Gupta, “Analysis of exhaust emissions from gasoline powered vehicles in a sub-urban Indian town,” *International Research Journal of Environmental Sciences*, vol. 2, no. 1, pp. 37–42, 2013.

[40] M. H. Hsueh, C. N. Wang, M. C. Hsieh et al., “An analysis of exhaust emission of the internal combustion engine treated by the non-thermal plasma,” *Molecules*, vol. 25, no. 24, pp. 6041–6120, 2020.

[41] I. N. Aquigeh, M. Z. Ayissi, and D. Bitondo, “Multiphysical models for hydrogen production using NaOH and stainless steel electrodes in alkaline electrolysis cell,” *Journal of Combustion*, vol. 2021, Article ID 6673494, 11 pages, 2021.

[42] The Japan Society for Occupational Health, “Recommendation of occupational exposure limits (2021-2022),” *Environmental and Occupational Health Practice*, vol. 3, pp. 1–34, 2021.

[43] E. G. Cauda, *Monitoring Exposure to Gases, Workshop on Aerosols and Gases in Underground Metal and Nonmetal Mines*, Intechopen, Salt lake city, Utah, USA, 2012.