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Article

Investigation of Emission Characteristics and Lubrication Oil Properties in a Dual Diesel–Hydrogen Internal Combustion Engine

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Abstract: Hydrogen is considered one of the main gaseous fuels due to its ability to improve thermal performance in diesel engines. However, its influence on the characteristics of lubricating oil is generally ignored. Thus, in the present investigation, an analysis of the effect on the physical and chemical properties of lubricating oil with mixtures of diesel fuel–hydrogen was carried out, and the environmental impacts of this type of mixture were assessed. The development of the research was carried out using a diesel engine under four torque conditions (80 Nm, 120 Nm, 160 Nm and 200 Nm) and three hydrogen gas flow conditions (0.75 lpm, 1.00 lpm and 1.25 lpm). From the results, it was possible to demonstrate that the presence of hydrogen caused decreases of 3.50%, 6.79% and 4.42% in the emissions of CO, HC, and smoke opacity, respectively. However, hydrogen further decreased the viscosity of the lubricating oil by 26%. Additionally, hydrogen gas produced increases of 17.7%, 29.27%, 21.95% and 27.41% in metallic components, such as Fe, Cu, Al and Cr, respectively. In general, hydrogen favors the contamination and oxidation of lubricating oil, which implies a greater wear of the engine components. Due to the significantly negative impact of hydrogen on the lubrication system, it should be considered due to its influence on the economic and environmental cost during the engine's life cycle.

Keywords: tribological characteristics; emissions; lubricating oil; degradation; hydrogen

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1. Introduction

The reductions in energy reserves, the increase in the global population, and climate change are factors that impact the energy consumption of each country. The continuous contemporary use of fossil fuels has led to health and environmental problems worldwide. However, fossil fuels remain one of the main energy sources due to their relatively low cost compared with other energy sources [1–3]. Internal combustion engines (ICEs) are one of the main thermal machines consuming fossil fuels, and produce highly harmful emissions. Therefore, government organizations have established environmental regulation standards to reduce the environmental impacts on the planet [4–6]. In order to comply with new regulations, the search for new strategies has been encouraged, among which the use of alternative fuels stands out, such as biodiesel, alcohol, and biogas. These fuels can be used in combination with diesel fuel. Despite the environmental benefits derived from the use of alternative fuels, the investigations carried out have generally indicated a reduction in engine performance as well [7,8].

Hydrogen is a gaseous fuel that can be used in diesel engines. This fuel is characterized by having a high thermal efficiency, which is due to the high cetane index value, high calorific power, flammability, high flame speed, and low ignition capacity. Additionally, hydrogen is a fuel free of carbon molecules; therefore, it does not favor the formation of emissions such as carbon monoxide (CO), hydrocarbons (HCs), carbon dioxide (CO_2), and particulate matter (PM) [9]. Another advantage of this fuel is its capacity to be produced from renewable sources. In addition, hydrogen is highly available because it is the most common element on the planet [10]. Due to the advantages of hydrogen as an alternative fuel in internal combustion engines, different studies focusing on dual fuel modes in diesel engines have been carried out.

Castro et al. [11] carried out performance and emissions tests on a compression ignition engine fueled by diesel and hydrogen. The results described a reduction in specific fuel consumption of 54.2%. Additionally, decreases in CO_2 emissions and smoke opacity were reported. Dimitriou et al. [12] experimentally analyzed the addition of hydrogen in a diesel engine under different operating conditions. A decrease in harmful emissions from the engine was evidenced. However, with medium loads, an increase in NOx emissions was obtained. Mena et al. [13] studied the injection parameters in a single-cylinder diesel engine, in which hydrogen was injected through the manifold. The results of the analysis demonstrated a reduction in CO_2 emissions and an increase in combustion performance. Tutak et al. [14] analyzed the influence of the combination of natural gas–hydrogen in a diesel engine. The results indicated that an increase in the rate of hydrogen led to increases in combustion pressure and NOx emissions. Tripathi et al. [15] investigated the effect of hydrogen on performance, combustion, and emissions in a diesel–hydrogen dual combustion engine through numerical simulations. Decreases in HC and CO emissions was reported. Additionally, improvements were seen in the combustion process and engine performance. Ghazal [16] evaluated the injection of liquid water and hydrogen in the intake manifold of a diesel engine. Increases in the combustion pressure and temperature variables were found, along with an increase in the thermal efficiency. Saravanan et al. [17] studied the injection of hydrogen in the intake of a diesel engine. From the results, significant reductions in smoke emissions and improvements in the thermal efficiency of the engine brake were observed. Rajak et al. [18] analyzed the mixture of hydrogen, n-butanol, and biodiesel in a diesel engine. The analysis involved the study of combustion conditions, performance, and emissions. A 0.95% improvement in brake thermal efficiency and an 18.3% reduction in specific fuel consumption were reported. Li et al. [19] examined the effect of different hydrogen injection rates using numerical models. The results described decreases in emissions of 79.3%, 31.6% and 40.6% in CO, NOx and HC emissions, respectively.

The studies mentioned above demonstrate the potential of hydrogen as an alternative fuel in diesel engines. However, when evaluating alternative fuels, another aspect is their influence on engine lubrication. This is due to the significant impact of the lubrication film on friction forces and wear of engine components. Studies indicate that lubricating oil can be contaminated by up to 5% with fuel due to crankcase dilution [20,21]. This implies a change in the properties of lubricating oil that directly affects its tribological performance. Additionally, the change in the composition of the lubricating oil has an impact on fuel consumption [22,23]. Similarly, the by-products derived from the deterioration of lubricating oil can influence environmental pollution and human health [24]. Zbigniew [25] evaluated the premature degradation of lubricating oil during spark ignition engine operation. The results indicated that in real operating conditions, accelerated degradation in multidirectional lubricating oil can occur. Therefore, it is advisable to carry out replacements more frequently. Nikolakopoulos et al. [26] investigated the aging of commercial oils at different levels of performance. It was shown that pressure and temperature conditions affect the viscosity of oil throughout its useful life. Mujtaba et al. [27] studied the contamination of SAE-40 lubricating oil with different blends of palm and sesame biodiesel. Additionally, the influence of carbon nanotubes was evaluated. The results indicated that a blend of lubricating oil diluted with biodiesel presented greater abrasive and adhesive wear. On the other hand, the carbon nanotubes in contaminated lubricating oil reduced the friction characteristics. Singh et al. [28] evaluated the impact of the binary blend of biofuels on the degradation of lubricating oil in a compression ignition engine. It was observed that the change in the properties of the lubricant with the binary biodiesel could minimize the wear of the engine parts. Zare et al. [29] investigated the effect of NOx emissions in diesel engines with waste lubricating oil as an additive. Two percentages of waste lubricating oil (1% and 5%) were used in the study. The results indicated that the presence of lubricating oil favors the reduction in NOx emissions and increases the maximum pressure in the cylinder chamber.

Additionally, the greater control of environmental regulations has meant that lubricating oil has been considered an important factor due to its sulfur content and metallic components, which favor the formation of incombustible ash particles and can cause damage to systems in the aftertreatment of exhaust gas. On the other hand, the indentations of piston rings can result in the presence of oil droplets in the combustion chamber, directly affecting the quality of combustion and the levels of pollution in the combustion gases. Studies in the literature indicate that emissions are significantly affected by the contact of oil particles with the combustion flame in internal combustion engines [30].

Despite the importance of tribological performance, most of the research related to the use of hydrogen focuses on the performance parameters and emission characteristics of diesel engines. Therefore, this study analyzes the changes in the physicochemical and tribological characteristics of lubricating oil in diesel engines with hydrogen.

2. Materials and Methods

2.1. Experimental Setup

This study was carried out using a four-cylinder, direct injection, four-stroke diesel engine. The main technical characteristics of the engine are shown in Table 1.

Table 1. Experimental test diesel engine.

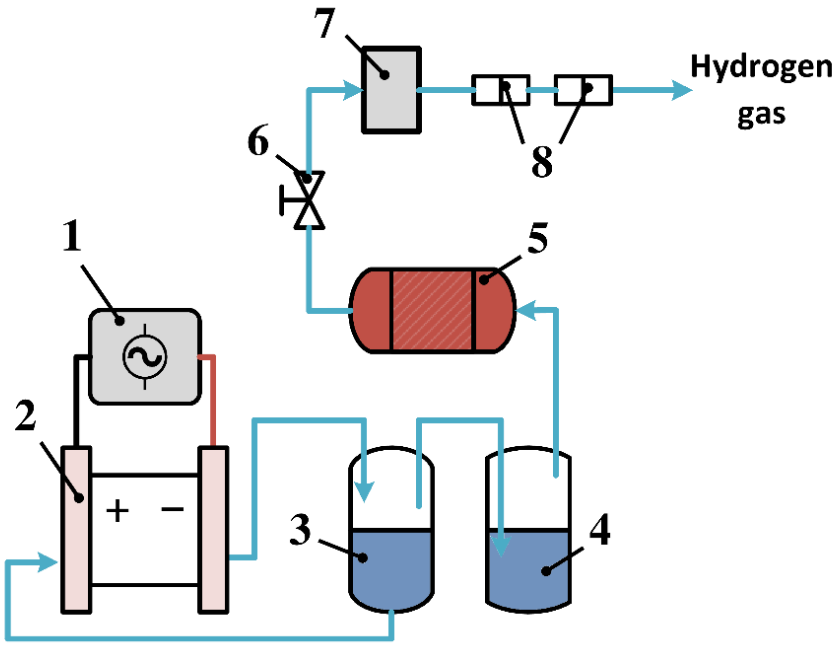
Property	Value	Unit
Model	4JJ1	-
Manufacturer	ISUZU	-
Bore	95.4	mm
Displaced volume	2999	cm^3
Stroke	104.9	mm
Compression ratio	17.5:1	-
Maximum torque @ 2000 rpm	408	Nm
Cycle	4 strokes	-
Rated output @ 2500 rpm	95.0	kW

The experimental test bench consisted of the diesel engine, the hydrogen generation bench, and the measuring instruments, as shown in Figure 1.

Rotational speed and engine load were controlled with an electrical load bank. The hydrogen gas supply was injected into the engine through the air intake system. The fuel consumption was measured with a gravimetric meter (OHAUS PA313: OHAUS, Bogota, Colombia) and a digital chronometer. A crankshaft angle (BECK ARNLEY 180–0420: Beck/Arnley, Smyrna, TN, USA) was installed on the engine crankshaft to perform rotational speed measurements. A piezoelectric pressure transducer (KISTLER 7063-A: KISTLER, Barcelona, Spain) was used to measure the combustion pressure in the cylinder chamber. The temperature of the engine exhaust gases was measured using type K thermocouples. A hot wire mass air flow sensor (BOSCH OE-22680 7J600: BOSCH, Bogota, Colombia) was used to determine the engine intake air flow. Two gas analyzers (BrainBee AGS-688: BRAIN BEE, Madrid, Spain) and (BrainBee OPA-100: BRAIN BEE, Madrid, Spain) were used for the analysis of engine exhaust gas emissions. The technical details of the measuring instruments are shown in Table 2.

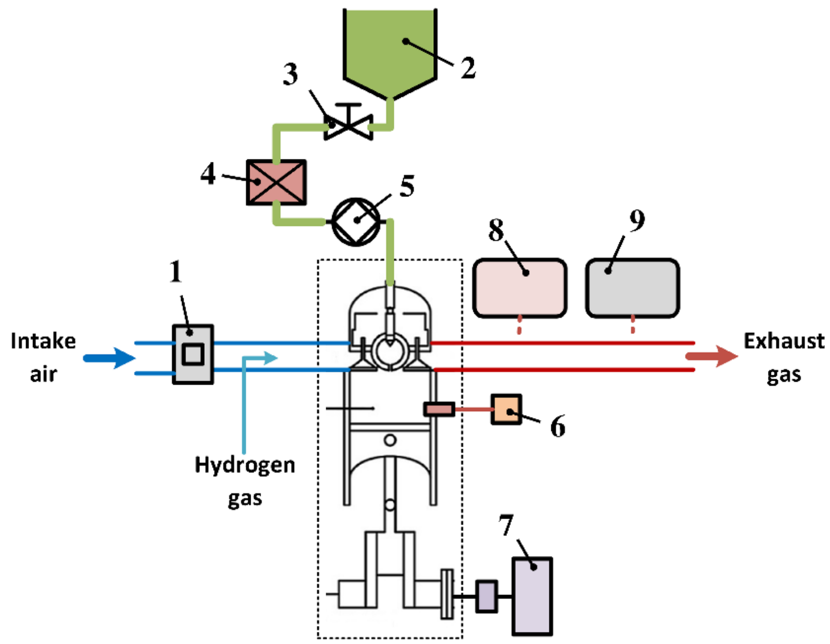
2.2. Hydrogen Gas Generation Bench

Hydrogen gas was produced through the electrolysis of water, which consisted of the separation of hydrogen molecules from water molecules. For the electrolysis process, a dry cell built with stainless steel plates was used. This material was selected due to its high conductivity, corrosion resistance, compatibility with electrolytic substances, and resistance to elevated temperature and voltage conditions. The dimensions of the steel plates were $200 \times 133 \times 1.5$ mm^3 with a separation between plates of 3 mm. The steel plates were joined by silicone gaskets. To improve the performance of the dry cell, a KOH catalyst was used with a concentration of 20%. This is due to the high conductivity of KOH [31].



1. AC-DC converter, 2. Dry cell, 3. Electrolytic tank, 4. Bubbler, 5. Storage tank, 6. Flow meter, 7. Silica gel filter, 8. Flame arrester.

(**a**)



1. Air flow meter, 2. Fuel tank, 3. Fuel inlet valve, 4. Fuel filter, 5. Injection pump, 6. Thermocouple, 7. Load bank, 8. BrainBee OPA-100, 9. BrainBee AGS-688.

(**b**)

Figure 1. Experimental test bench: (**a**) hydrogen gas generation and (**b**) test engine.

Table 2. Experimental bench measurement instruments.

Parameter	Manufacturer	Instrument	Range	Uncertainty [%]
Cylinder pressure	KISTLER type 7063-A	Piezoelectric transducer	0–250 bar	0.2%
Angle	Beck Arnley 180-042	Crankshaft angle	5–9999 rpm	0.5%
Temperature	Type K	Temperature sensor	−200–1370 °C	0.1%
Fuel mass	OHAUS-PA313	Gravimetric meter	0–310 g	1.0%
Air flow mass	BOSCH 22680-7J600	Air mass sensor	0–125 g/s	1.2%
Smoke opacity	BrainBee OPA-100	Opacimeter	0–9.99 m^{-1}	0.2%
CO	BrainBee AGS-688	Exhaust gas analyzer	0–9.99% vol.	0.25%
HC			0–9999 ppm vol.	0.30%
NOx			0–5000 ppm vol.	0.15%

A bubbler tank was installed to protect the engine from corrosion, which was responsible for retaining the water content present in the hydrogen gas. The hydrogen gas produced was stored in two high-pressure stainless-steel tanks. The sizing of the storage tank was based on the recommendations described in the ASME code section VIII division 1 for pressure vessels. Hydrogen gas flow control was performed by means of a regulating valve and a flow meter. Two flame arresters and a silica gel filter were installed as a safety measure for the hydrogen generation bench. This was in order to prevent the backflow of the flame during the combustion of hydrogen gas. The physical characteristics of the dry cell of the hydrogen gas generator bench are shown in Table 3.

Table 3. Dry cell characteristics.

Specification	Value	Unit
Number of electrodes in the cathodic chamber	18	-
Electrode spacing	3	mm
Number of electrodes in the anodic chamber	18	-
Construction material	PMMA	-
Electrode orientation	Vertical	-
Electrode material	Stainless steel 304	-
Electrolyte capacity	10	L
Solution temperature	40–50	°C
Electrolyte	KOH solution	-

2.3. Experimental Procedure

For the experimental tests, a variation range of 80 to 200 Nm in the engine torque with an interval of 20 Nm was selected. The minimum volumetric flow of hydrogen gas injected into the engine was defined by the proportionality correlation proposed in the literature, which establishes a quantity of 0.25 lpm for every 1000 cc (displaced volume of the engine) [32]. As such, three levels of hydrogen gas flow were established: 0.75 lpm, 1.00 lpm and 1.25 lpm. The test engine was fed with pure diesel fuel, whose properties are shown in Table 4.

Table 4. Properties of diesel fuel.

Property	Value	Unit
Kinematic viscosity @ 40 °C	3.125	mm^2/s
Water content	102	mg/kg
Density @ 15 °C	851	kg/m^3
Lower heating value	42.43	MJ/kg
Cetane number	45	-

For each of the mixtures of diesel fuel with hydrogen, the lubricating oil was drained, and was subsequently replaced with new lubricating oil. Additionally, after each test, disassembly and replacement of the internal engine components, such as piston rings, bearings, and pistons, was carried out. This was to establish a similar reference condition in each test.

The type of lubricating oil used in the experimental tests was SAE 10W40 (Castrol, Bogota, Colombia). The properties of the oil are described in Table 5.

Table 5. Lubricating oil properties.

Property	ASTM Method	Value	Unit
Type	-	SAE 10W40	-
Density @ 15.6 °C	D-1298	0.867	g/mL
Kinematic viscosity @ 100 °C	D-445	15.7	mm^2/s
Pour point	D-97	−39	°C
Kinematic viscosity @ 40 °C	D-445	113	mm^2/s
Flash point	D-92	222	°C

To determine the uncertainty error of the experimental measurements, the square root methodology proposed by Holman was used [33], which is described in Equation (1).

$$u = \sqrt{(y_1)^2 + (y_2)^2 + (y_3)^2 + \ldots + (y_n)^2} \tag{1}$$

where y_1, y_2, $y_3, \ldots, y_n$ are the uncertainties of the independent variables.

3. Results and Discussion

3.1. Characteristics of Engine Exhaust Gases

The temperatures of the exhaust gases for each of the mixtures of diesel with hydrogen are indicated in Figure 2.

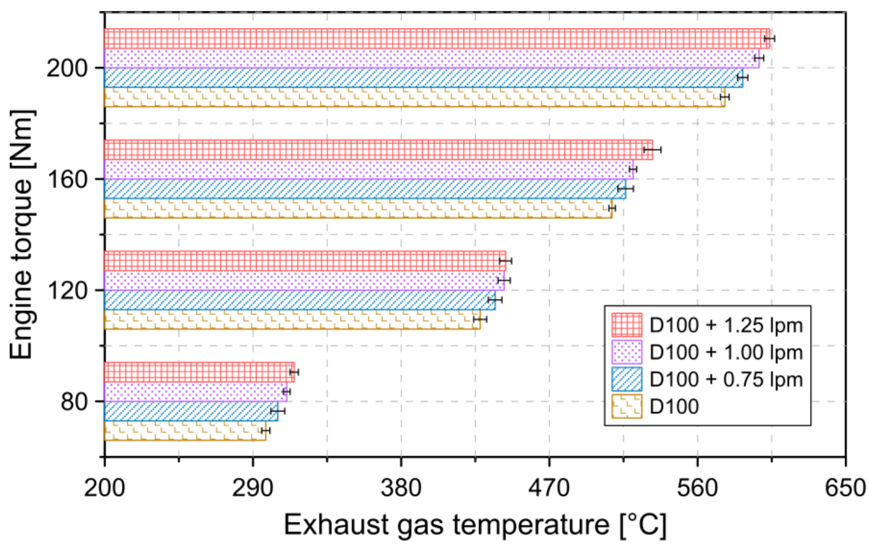


Figure 2. Engine exhaust gas temperature.

Figure 2 shows that the temperature of the exhaust gases increases with the increase in engine torque, which is a consequence of the greater thermal efficiency of the combustion process at higher loads. In general, it is evident that the presence of hydrogen in the combustion chamber leads to an increase in the temperature of the combustion gases. This behavior is associated with the high calorific value of hydrogen gas, as well as its high vaporization heat. Another factor that can contribute to the increase in temperature is the high autoignition temperature of hydrogen. For the conditions tested, increases of 2.29%, 3.02% and 4.77% in the temperature of the exhaust gases were obtained for the mixtures D100 + 0.75 lpm, D100 + 1.00 lpm, and D100 + 1.25 lpm compared with pure diesel, respectively.

Variations in carbon monoxide (CO) emissions from the engine are shown in Figure 3.

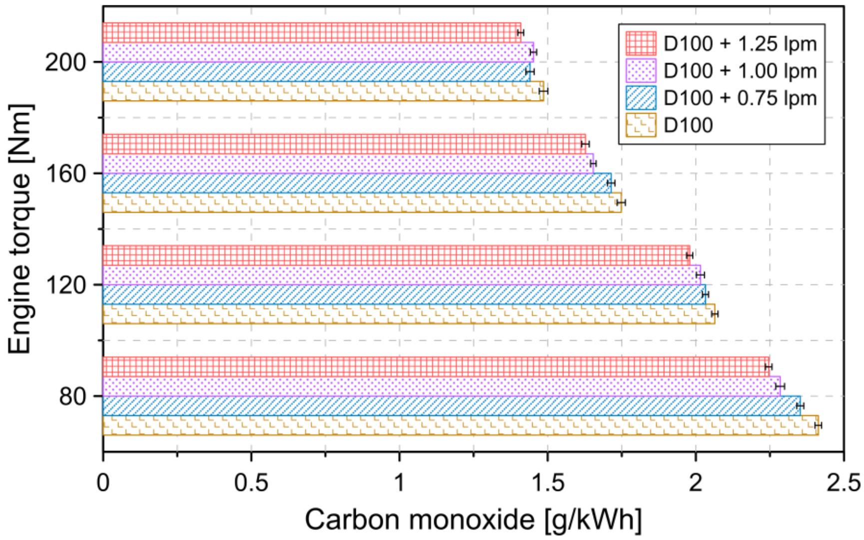


Figure 3. Carbon monoxide emissions.

The formation of CO molecules is associated with insufficient oxygen content during the combustion process, which causes an increase in unburned gases [34]. With the addition of hydrogen in the diesel engine, a reduction in CO emissions was evident. This may be due to the high flame velocity and the diffusivity of the hydrogen gas [35,36]. This allows a more homogeneous mix between diesel fuel and intake air. The reductions in CO emissions were 1.97%, 3.40% and 5.12% for volumetric flows of 0.75 lpm, 1.00 lpm and 1.25 lpm, respectively.

Figure 4 shows the change in hydrocarbon (HC) emissions concerning different engine torque conditions.

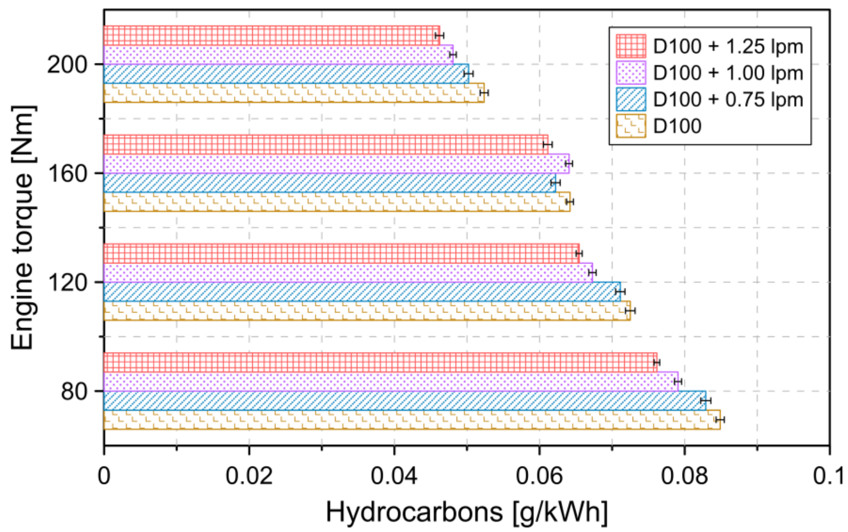


Figure 4. Hydrocarbon emissions.

The formation of hydrocarbons was a consequence of incomplete combustion and the short distance of extinction of the flame. In general, HC emissions decreased as engine torque increased. As hydrogen gas was added, less HC formation was obtained, which was attributed to the better oxidation during the combustion process as a result of the higher content of hydrogen atoms. The increase in the oxidation of emissions was the result of the higher temperatures in the cylinder chamber, as evidenced in Figure 2. Another factor that favored reducing HC emissions was the absence of carbon atoms from hydrogen. For the mixtures D100 + 0.75 lpm, D100 + 1.00 lpm and D100 + 1.25 lpm, there were decreases of 3.58%, 6.62% and 10.18%, respectively, compared with pure diesel.

Figure 5 presents the effect of hydrogen gas injection on nitrogen oxide (NOx) emissions.

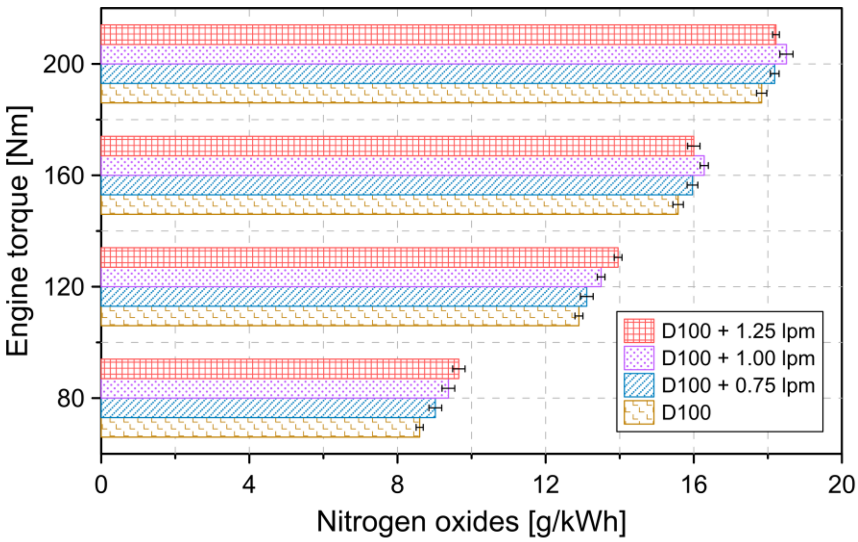


Figure 5. Nitrogen oxide emissions.

The main factors that affect the formation of NOx are the duration of the combustion process and the temperature inside the combustion chamber [37]. In general, the injection of hydrogen gas in the diesel engine favored an increase in NOx emissions. For the fuel conditions evaluated—D100 + 0.75 lpm, D100 + 1.00 lpm and D100 + 1.25 lpm—increases of 2.64%, 4.28% and 6.27% were obtained compared with pure diesel, respectively.

Figure 6 shows the smoke opacity levels for different engine torque conditions.

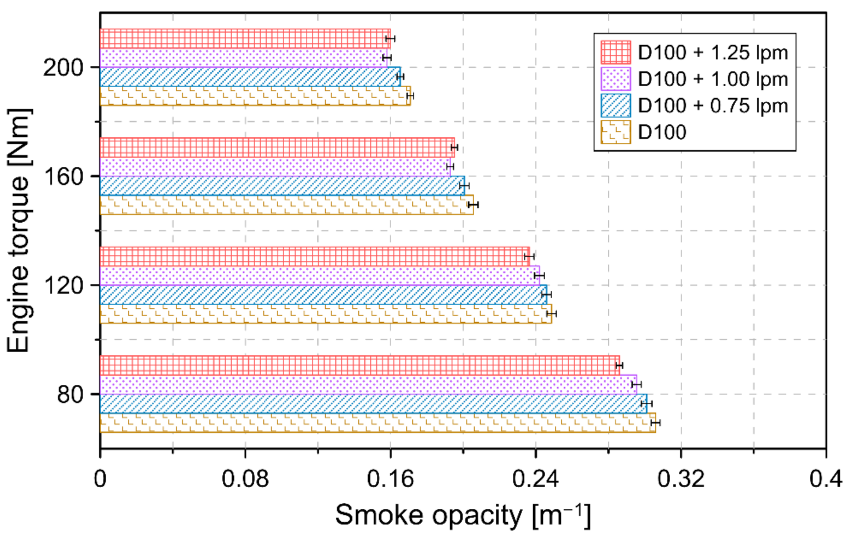


Figure 6. Smoke opacity emissions.

To analyze the smoke emissions, the opacity of the exhaust gases was measured, which is an indication of the particulate matter content. This is directly associated with the incomplete combustion of fuel. The inclusion of hydrogen in the engine implies a reduction in smoke opacity, which can be related to the oxidation of soot particles due to the higher temperature conditions inside the combustion chamber. For the conditions evaluated, decreases of 2.75%, 4.21% and 6.31% in smoke opacity were obtained with volumetric flow rates of 0.75 lpm, 1.00 lpm and 1.25 lpm of hydrogen gas in the diesel engine, respectively.

3.2. Characteristics of Lubricating Oil

Figures 7 and 8 show the variations in kinematic viscosity for temperatures of 40 °C and 100 °C.

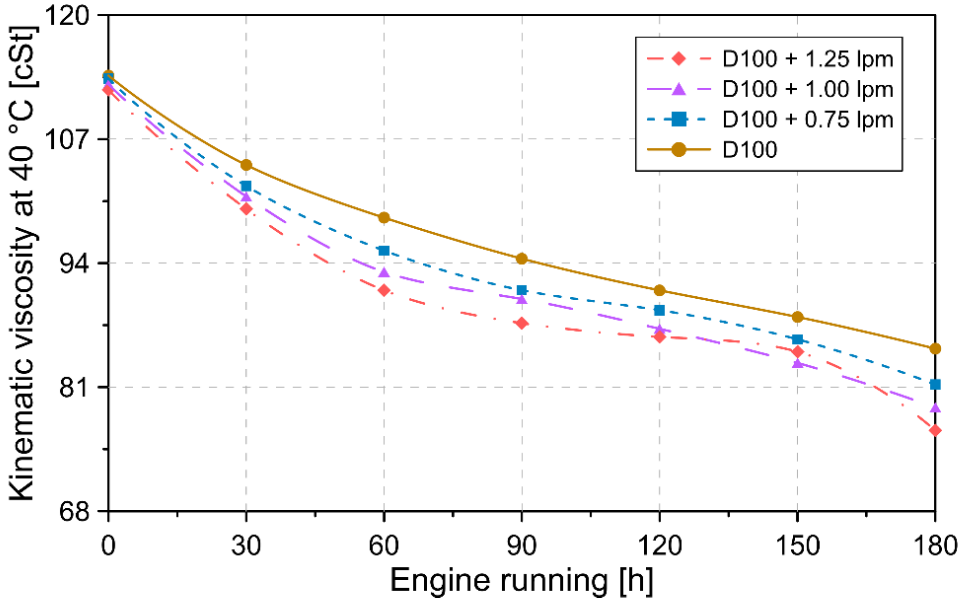


Figure 7. Kinematic viscosity variation at 40 °C.

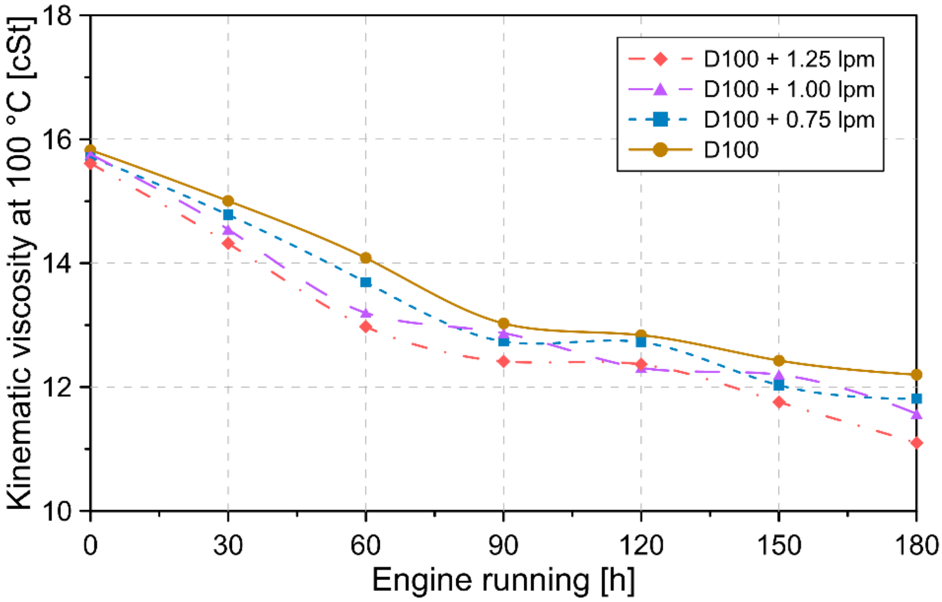


Figure 8. Kinematic viscosity variation at 100 °C.

From the results shown in Figures 7 and 8, it is evident that the addition of hydrogen gas in the diesel engine leads to a greater reduction in kinematic viscosity compared with pure diesel. This implies an increase in the contamination of insoluble agents and a loss of anti-wear additives in the lubricating oil. The increase in contaminating agents was evidenced by the increased concentrations of metals, such as Fe, Cu, Al and Cr in the lubricating oil, which are described in Figure 9. In general, increasing the engine operating time produced a constant decrease in kinematic viscosity.

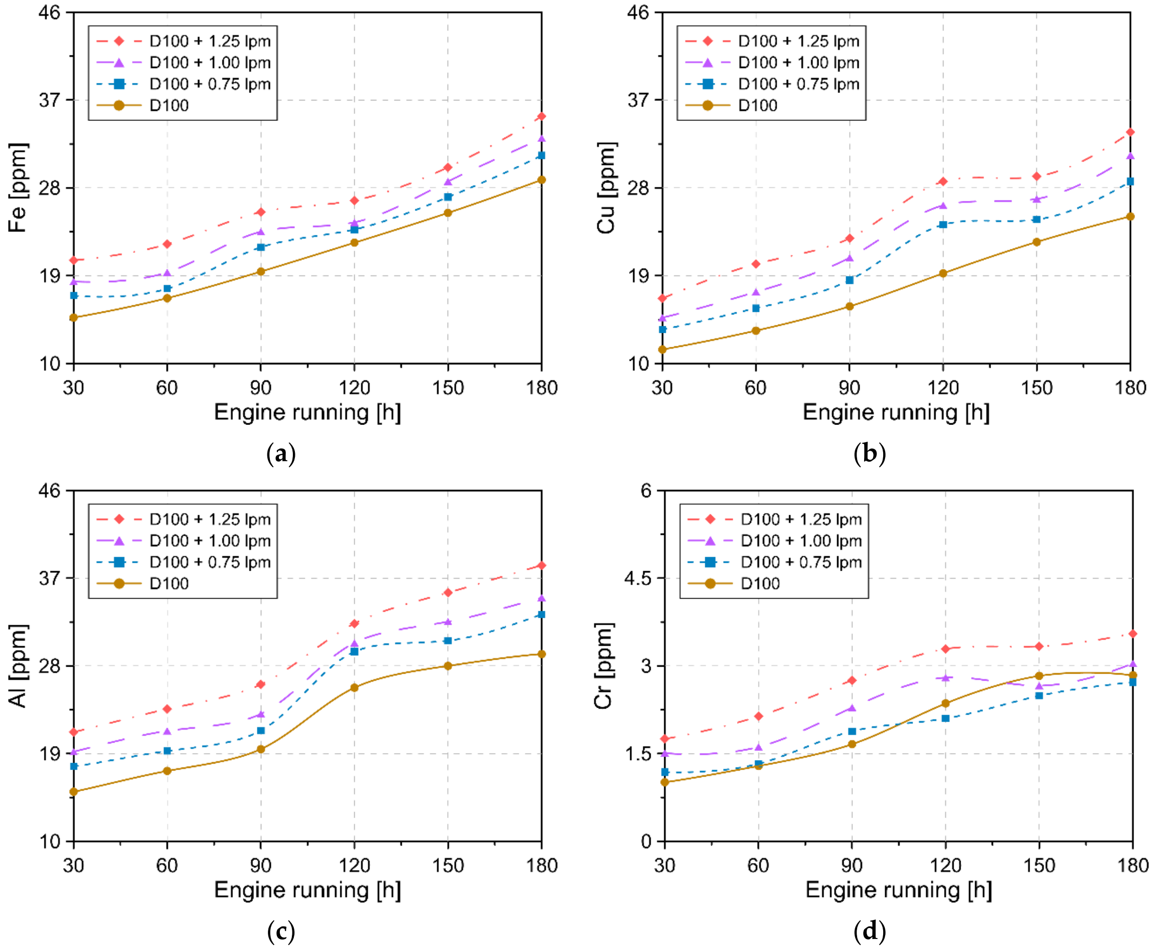


Figure 9. Analysis of wear debris in lubricating oil (**a**) Iron, (**b**) Copper, (**c**) Aluminum and (**d**) Chromium.

For the test conditions, a reduction of 25.18% in the kinematic viscosity (for a temperature at 40 °C) of the lubricating oil was observed when the engine was operating with pure diesel. However, the mixtures D100 + 0.75 lpm, D100 + 1.00 lpm and D100 + 1.25 lpm exhibited decreases of 28.29%, 30.05% and 31.83%, respectively. A similar behavior was observed in the kinematic viscosity analysis at 100 °C, in which reductions of 22.90%, 24.82%, 26.58% and 28.89% were obtained with D100, D100 + 0.75 lpm, D100 + 1.00 lpm and D100 + 1.25 lpm fuels, respectively. These behaviors can be attributed to the high temperatures in the combustion chamber caused by the presence of hydrogen gas, causing greater thermal shearing of the oil.

In order to analyze the effect of hydrogen gas on the quality of the lubricating oil, an analysis of wear debris was carried out. For analysis of the metal concentration, an operating period of 180 h was established, which is generally used for this type of study [38]. The results obtained are shown in Figure 9.

Figure 9 shows the trends in wear metals Fe, Cu, Al and Cr in the lubricating oil for the different fuel mixtures. In general, it was evident that the injection of hydrogen gas into the diesel engine produced a greater presence of Fe. This behavior can be attributed to wear in the engine's internal components, such as the cylinder, piston, and bearings, because they are designed to form iron alloys. The increased wear on engine components by hydrogen gas may be a consequence of the greater reduction in oil viscosity, as indicated in Figures 7 and 8. This causes a greater friction force between the contact surfaces due to the reduction in the thickness of the lubrication film. For the conditions evaluated, increases in the wear metal Fe of 9.17%, 16.47% and 27.46% were obtained in the mixtures

D100 + 0.75 lpm, D100 + 1.00 lpm and D100 + 1.25 lpm, respectively, as compared with pure diesel.

The presence of the wear metal Cu in the lubricating oil also increased with the addition of hydrogen gas in the engine. The results indicate increases of 17.06%, 28.41% and 42.34% in this type of metals for the mixtures D100 + 0.75 lpm, D100 + 1.00 lpm and D100 + 1.25 lpm compared with pure diesel, respectively. In the case of the wear metals Al and Cr, increases of 12.74%, 20.59% and 32.52% were observed for Al, and increases of 10.11%, 24.08% and 48.04% were observed for Cr, with the addition of volumetric flows of 0.75 lpm, 1.00 lpm and 1.25 lpm of hydrogen gas in the diesel engine, respectively. The incremental addition of these metals in the lubricating oil is associated with increased wear on the piston and piston rings.

The increases in wear metals such as Fe, Cu, Al and Cr implied that hydrogen gas accelerates the loss of lubricating oil performance and greater wear on internal engine components.

Variations in the flash point of lubricating oil during engine operation are shown in Figure 10.

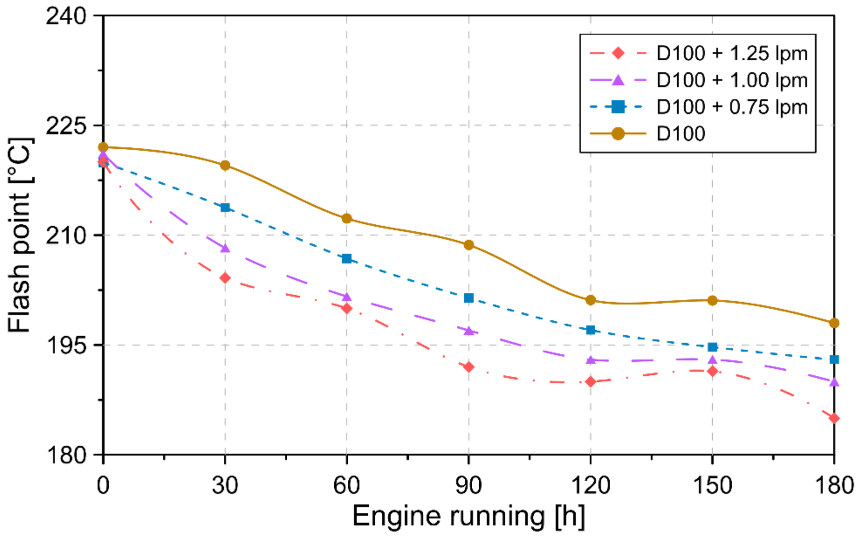


Figure 10. Lubricating oil flash point variation.

From the results described in Figure 10, reductions of 10.81%, 12.24%, 14.08% and 15.91% are evidenced in the flash point of the lubricating oil for fuels D100, D100 + 0.75 lpm, D100 + 1.00 lpm and D100 + 1.25 bpm, respectively. In general, the presence of hydrogen gas in the combustion chamber led to a greater reduction in the flash point, which implies greater decomposition of the lubricating oil.

Figure 11 shows the change in the total base number (TBN) of the lubricating oil during engine operation.

The TBN of lubricating oil is an indication of the number of alkaline derivatives. The results in Figure 11 describe a greater reduction in TBN for blends of diesel with hydrogen gas. In general, the addition of volumetric flows of 0.75 lpm, 1.00 lpm and 1.25 lpm of hydrogen gas caused decreases in the TBN of 6.49%, 9.36% and 11.84%, respectively, as compared with pure diesel. The greater decrease in TBN due to hydrogen led to a lower resistance to corrosion in the lubricating oil.

Figure 12 shows the total acid number (TAN) of the lubricating oil for the different conditions of fuel mixtures.

Figure 12 shows increases in the TAN of the lubricating oil with the addition of hydrogen in the diesel engine. The results indicate increases of 6.94%, 8.23% and 10.29% with the addition of volumetric flows of hydrogen gas of 0.75 lpm, 1.00 lpm and 1.25 lpm compared with pure diesel, respectively. This demonstrated that the presence of hydrogen favors the contamination and oxidation of lubricating oil. This may be a consequence of the greater increase in acidic components due to the increases in nitrogen oxide contents and the combustion temperature.

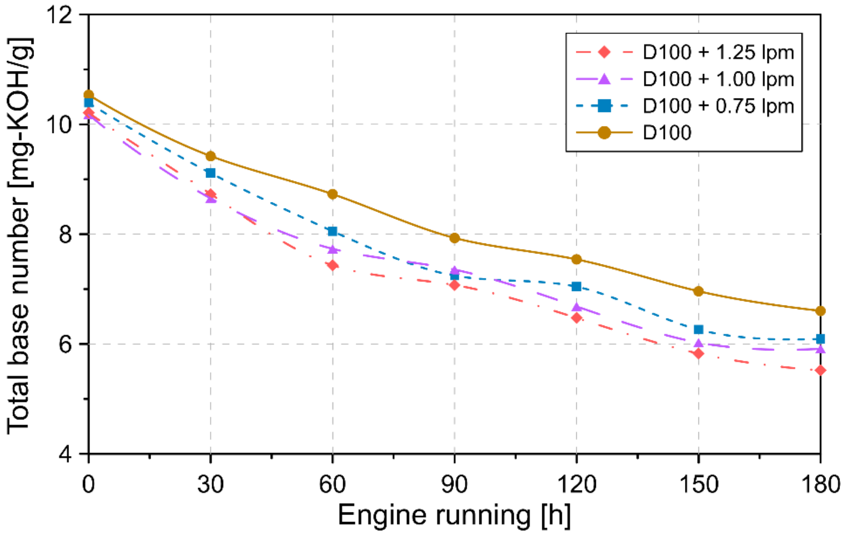


Figure 11. Total base number of the lubricating oil.

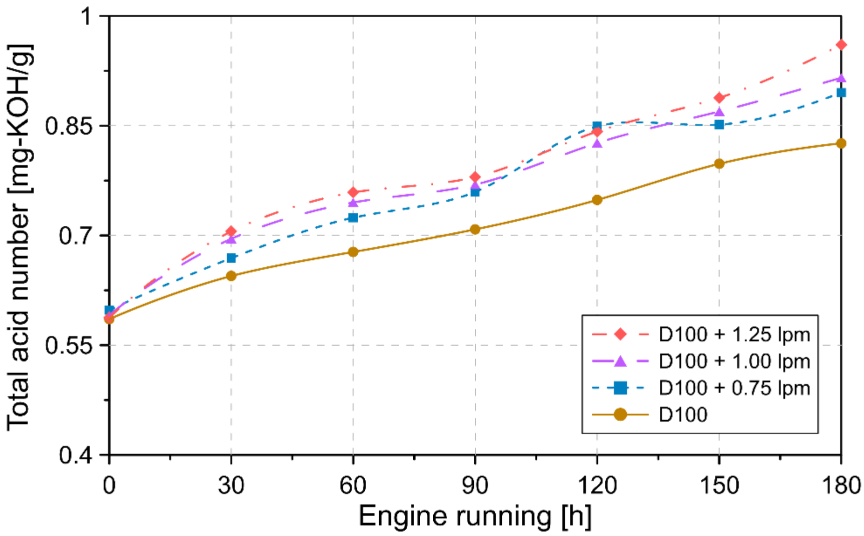


Figure 12. Total acid number of the lubricating oil.

The additives in lubricating oil improve the lubrication system's performance and minimize wear on the engine. In the particular case of zinc additives, its purpose is to protect engine components from wear when there is an excessive reduction in the thickness of the lubrication film. The properties of the lubricating oil with the zinc additive are shown in Table 6.

Table 6. Properties of lubricating oil with zinc additive.

Property	ASTM Method	Value	Unit
Type	-	SAE 10W40 + zinc	-
Density @ 15.6 °C	D-1298	0.887	g/mL
Kinematic viscosity @ 100 °C	D-445	16.1	mm^2/s
Kinematic viscosity @ 40 °C	D-445	118	mm^2/s
Flash point	D-92	210	°C

Figure 13 shows the depletion of the zinc additive for the different fuel mixtures. In general, the results show that after 180 h of operation, the zinc content was reduced by 31.83% when the engine was fueled with pure diesel. However, a higher level of zinc depletion was evidenced with the addition of hydrogen. For volumetric flows of hydrogen gas of 0.75 lpm, 1.00 lpm and 1.25 lpm, decreases of 33.38%, 39.46% and 41.10% were observed, respectively.

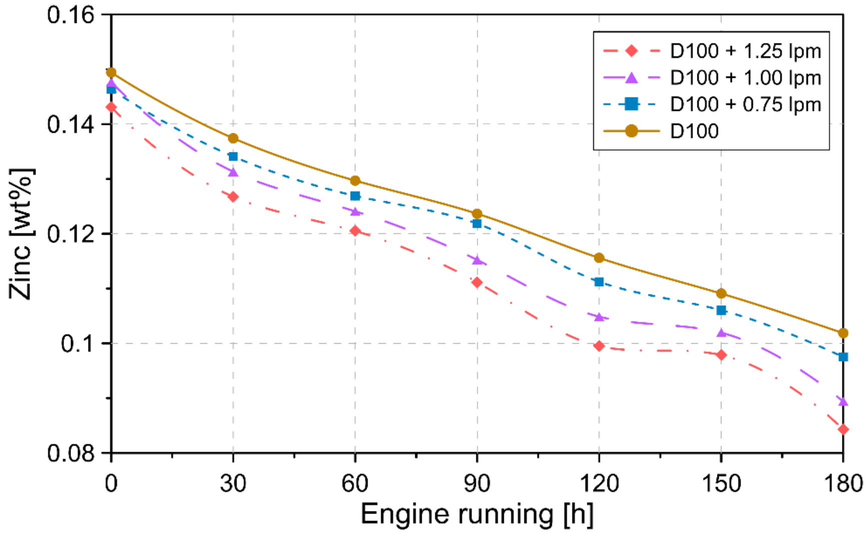


Figure 13. Variations in the content of zinc additives in the lubricating oil.

4. Conclusions

This investigation evaluated the impact of the addition of different volumetric flows of hydrogen gas (0.75 lpm, 1.00 lpm and 1.25 lpm) on the characteristics of emissions and physicochemical properties of lubricating oil in internal combustion engines fueled with diesel.

From the results obtained, it was possible to demonstrate that the addition of hydrogen in diesel engines significantly reduced polluting emissions from exhaust gases. In general, the presence of hydrogen caused decreases of 3.50%, 6.79% and 4.42% in CO, HC and smoke opacity emissions, respectively. This implies that hydrogen improves the mixture between diesel fuel and intake air, resulting in a more efficient combustion process. Despite the ability of hydrogen gas to reduce much of the engine's emissions, a 4.40% increase in NOx emissions was demonstrated. Therefore, it is necessary to implement strategies to minimize the increase in this type of emissions.

Analysis of the physicochemical characteristics of the lubricating oil operated with diesel and hydrogen gas mixtures demonstrated that the injection of this type of gaseous fuel in the engine caused a greater reduction in the viscosity of the oil. The results indicated up to a 26% decrease in kinematic viscosity compared with pure diesel.

The analysis of wear debris in lubricating oil showed that hydrogen injection produced a higher concentration of metallic components such as Fe, Cu, Al and Cr compared with pure diesel. In general, hydrogen gas caused increases of 17.7%, 29.27%, 21.95% and 27.41% in the previous elements. This demonstrated that the diesel–hydrogen mixture led to greater wear of the internal components of the engine, such as piston, cylinder, bearings, and piston rings.

In general, hydrogen gas resulted in a greater tendency to decrease the total base number and increase the total acid number of the lubricating oil compared with pure diesel. This implies greater contamination and oxidation of the oil when the engine was operating with the diesel–hydrogen mixture.

Despite the benefits of hydrogen as an alternative gaseous fuel due to its ability to improve thermal performance and minimize much of the emissions in diesel engines, it is necessary to consider its negative impact on the lubrication characteristics throughout the engine's life cycle. This also implies an impact on the economic cost and environmental care.

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Abbreviations

The following abbreviations are used in this manuscript:

ICE	Internal combustion engine
CO	Carbon monoxide
CO_2	Carbon dioxide
HC	Hydrocarbons
PM	Particulate matter
NOx	Nitrogen oxides
LPM	Liters per minute
TAN	Total acid number
TBN	Total base number
D100	Diesel 100%
D100 + 0.75 lpm	Diesel 100% + 0.75 lpm hydrogen gas
D100 + 1.00 lpm	Diesel 100% + 1.00 lpm hydrogen gas
D100 + 1.25 lpm	Diesel 100% + 1.25 lpm hydrogen gas

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