Automotive Experiences
Vol. 8 No. 1 (2025) pp. 216-226
p-ISSN: 2615-6202 e-ISSN: 2615-6636

Research Paper

Effect of Hydroxy Gas Enrichment and Higher Biodiesel Concentration on Diesel Engine Performance

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https://doi.org/10.31603/ae.12903

Published by Automotive Laboratory of Universitas Muhammadiyah Magelang

Article Info
Submitted: 26/12/2024
Revised: 14/04/2025
Accepted: 23/04/2025
Online first: 30/04/2025

Abstract

The hydroxy gas enrichment as an additive of biodiesel fuel for internal combustion engines affected the combustion characteristics. Hydroxy gas can be produced through water electrolysis to produce hydrogen and oxygen, significantly enhancing the combustion rate. This combined effect increased efficiency, reduced pollution, and improved air quality. This study aims to determine the impact of hydroxy enrichment generated from water electrolysis on engine performance with biodiesel-diesel fuel blends. The experimental work was conducted under diverse operating conditions and tested on a 418 cc single-cylinder engine. Experiments have been performed at a constant hydroxy gas flow rate of 500 mL/min and a constant speed of 2000 rpm under various torques. The result shows that B30 and B40 without hydroxy gas decreased diesel engine performance across various engine torque. The addition of hydroxy has been observed to positively impact the combustion reaction and increase the energy conversion efficiency of diesel engines. Compared to pure diesel fuel, the efficiency of B30 and B40 decreased by 9.26% and 11.59%, respectively. The enrichment of hydroxy gas increases the engine efficiency by an average increase of all torque to 7.95% for B30H (B30 with hydroxy) and 8.68% for B40H (B40 with hydroxy). Therefore, compared to pure diesel fuel, the efficiency slightly decreases by an average of 1.31% for B30H and 2.91% for B40H at all tested torques. This phenomenon indicates that the presence of hydroxy gas in a diesel engine increases the stability of the combustion process, which results in higher cylinder pressure with lower energy input.

Keywords: Hydroxy gas; Hydrogen; Biodiesel; Diesel; Specific fuel consumption; Efficiency

1. Introduction

The rapid industrial and technological revolution has increased energy demand caused by population growth, industrialization, and the transportation sector. It presents a significant challenge in meeting the world's energy needs, with an associated rise in toxic gas emissions, depletion of natural resources, and growing concerns about future global warming, which threaten environmental sustainability and public health worldwide.

Sustainable management of fuel energy sources is the key to preventing environmental impacts, especially from emissions generated by diesel and gasoline engines that are still the main drivers in the industrial, transportation, power generation, and agricultural technology sectors. Diesel engines are preferred due to their high power, torque, and thermal efficiency. However, they have a detrimental impact on the environment through harmful emissions, including particulate matter (PM), carbon monoxide (CO), nitrogen oxides (NOx), and hydrocarbons (HC), due to incomplete combustion of diesel engines [1]. Previous studies have shown innovations to enhance the combustion efficiency of alternative fuels, such as using alcohol class and enrichment of hydrogen as additives in diesel-biodiesel blended fuels.

The characteristics of biodiesel, such as high viscosity and low heating value, make it difficult to atomize and increase delay combustion and fuel consumption [2]. As a result, researchers have explored several avenues, including adding ethanol to diesel fuel to reduce fuel viscosity [3]. Biodiesel is being investigated as a substitute for diesel fuel [4], and bioethanol up to 10% is being used in biodiesel-diesel blends, with researchers working at a concentration of 30-50% biodiesel to reduce viscosity and improve vaporizing biodiesel [5]. Other researchers are exploring using biodiesel-ethanol-diesel blends as diesel engine fuel, with concentrations varying from 10% to 50%, as observed by Wai, et al. [1], Kim, et al. [3], Krishna, et al. [6], and Rosa, et al. [7]. Another research reported that adding additive diethyl ether (DEE) to B35 reduced the viscosity and density, increased the cetane number, and reduced emissions [8]. Regarding the previous research, the engine's performance was enhanced at biodiesel concentrations below 30%, and CO and HC emissions were reduced at all concentrations of biodiesel and ethanol. Furthermore, using gas-phase fuel additives such as pure hydrogen gas as a diesel fuel additive is an effective approach in application on the internal combustion engine [9].

Hydrogen has a higher calorific value and offers better flame propagation characteristics, and the addition of hydrogen extends the flammability limit of the blend to a leaner fuel-air equivalence rasio [10], [11], [12], [13]. The properties of the fuels are shown in **Table 1**. A previous study showed that adding 2.5 L/min of hydrogen to biodiesel resulted in optimal engine performance, improved brake thermal efficiency, and reduced fuel consumption. While this hydrogen enrichment positively affected exhaust emissions (HC, CO_2, and smoke opacity), and increased NO emissions [14]. Moreover, other researchers have employed hydrogen and oxygen gas as fuel additives for biodiesel-diesel blends to improve engine efficiency, such as Gad and Abdel Razek [15], Bhave, et al. [16], Babu, et al. [17], Khan, et al. [18], and Elgarhi, et al. [19]. Another researcher also added hydroxy gas to the engine fueled by 5% ethanol, 10% biodiesel, and 85% diesel to enhance engine performance [20].

The experiment by using up to 100% biodiesel resulted in a decrease in efficiency and an increase in fuel consumption, and the optimal blend was obtained at a concentration of 10% biodiesel, where CO and HC decreased [4]. The reduction in combustion efficiency at high concentrations of biodiesel is attributed to the high latent heat of vaporization of biodiesel compared to pure diesel. The latent heat of vaporization of methyl esters is observed to increase with increasing carbon chain length. However, the latent heat of vaporization decreases with increasing pressure and temperature while phase change [21]. Reducing the latent heat of vaporization enhanced fuel ignition characteristics and augmented combustion efficiency [22]. An alternative solution to reduce the latent heat of fuel vaporization is to utilize hydrogen gas additives, that increase flame speed in lean mixtures by enhancing the combustion process [23]. Enrichment of hydrogen and oxygen in the fuel mixture by adding 0.5 and 0.75 liters per minute of hydroxy gas to a 10% biodiesel blend has been demonstrated to reduce specific fuel consumption, increase efficiency, and reduce emissions [15]. Another study shows the relevant results were achieved using 1 L/min of hydroxy [17]. Hydroxy gas contains oxygen, which enhances the homogeneity of the mixture and expands the flammability limit, rendering it carbon-free and reducing the nitrogen from the air that absorbs the heat of combustion.

Table 1. Fuels properties [6], [22], [24]

Properties	Fuel Type		
	Diesel	Biodiesel	Hydrogen
Viscosity (@40 °C mm²/s)	4.127	1.13	-
Low heating value (MJ/kg)	43.61	26.78	120
Oxygen content (% weight)	0	34.75	-
Latent heating (@25 °C kJ/kg)	270	916	-
Cetane number	53	61	-
Density (@20 °C kg/m³)	830.4	788	0.49
Stoichiometric air/fuel ratio	15	9	34.3

Preliminary studies have demonstrated that the utilization of biodiesel leads to enhanced energy conversion efficiency and reduced CO and HC emissions. This phenomenon is affected by the higher oxygen content of the fuel. However, using biodiesel in concentrations exceeding 30% decreased engine performance and increased fuel consumption. Thus, conducting studies combining hydrogen and oxygen from water electrolysis is necessary to enhance combustion efficiency and reduce emissions at higher biodiesel concentrations. This research aims to determine the specific effects of hydroxy gas addition on the operational performance of diesel engines fueled with high concentrations of biodiesel blends and constant flow rate of hydroxy gas enrichment, enhancing the current understanding of this fuel combination.

This research presents a potential solution to enhancing combustion quality, increasing energy conversion efficiency in diesel engines, and reducing emissions. These represent a solution to the issue of increasing the utilization of clean, carbon-free (hydrogen-oxygen) energy, as well as forming part of the transition to a renewable energy source. It can mitigate the risk of environmental degradation by reducing the emission of carbon and other noxious gases. Furthermore, the advancement of this technology has the potential to enhance the utilization of bioenergy across a range of sectors, including industry, transportation, power generation, and agricultural technology.

2. Methods

2.1. Hydroxy Engine Testbed

The experiments employed a standard single-cylinder 418 cc, four-stroke, air-cooled, and direct-injection diesel engine. Minor modification for diesel engine limited to additional gas supply system directly from the electrolyzer to the intake manifold. The engine shaft was directly connected to the eddy current dynamometer shaft to measure engine torque. The performance of a diesel engine using pure diesel fuel (Pertamina Dex, marketed by Pertamina) and palm biodiesel with hydroxy gas enrichment. The experiment was conducted using pure diesel, blends by volume fraction of 70% (v/v) diesel with 30% biodiesel (B30), and 60% diesel with 40% biodiesel (B40). The enrichment hydroxy gas for B30 and B40 fuel blends was identified as coded by B30H and B40H. The constant supply of hydroxy gas was determined by the flow rate sensor and controlled by Pulse Width Modulation (PWM) from the electrolyzer. All fuel blends were evaluated by the engine performance at various loads from 6 N.m to 30 N.m of an eddy current dynamometer, while maintaining a constant engine speed of 2000 rpm.

The braking force was measured by a load cell, which produced a signal that was analyzed to determine engine torque, and controlled by an electronic system. Variable of measurements included the intake temperature, exhaust temperature, air intake pressure, hot wire type of air flow rate sensor, and rotary encoder to measure the engine speed. All sensor signals are recorded in real-time on a personal computer (PC) connected to the MyRio microcontroller using the LabView software interface platform, with a data record interval of 0.5 seconds. The schematic of the test apparatus is shown in **Figure 1**. The data is employed to analyze diesel engine performance parameters, including brake torque, brake power, brake-specific fuel consumption (BSFC), and thermal efficiency. The setup of experiments of diesel engines and electrolyzers is presented in **Figure 2**.

2.2. Dry Cell Electrolyzer

The electrolyzer utilizes a dry cell configuration comprising a 316L stainless steel plate. The electrolyzer is comprised of an array of plates, with a total of 17 cells arranged in a configuration of (- N N N N +), utilizing three neutral plates (N). The overall cell configuration comprises 12 neutral plates, two positive electrode plates, and three negative electrode plates. The electrolyte temperature is regulated via a heat exchanger, which facilitates circulation. Tests were conducted using an electrolyte solution comprising water and potassium hydroxide (KOH) as a catalyst, with a KOH concentration of 5% by mass (m/m). The rate of hydroxy gas production is regulated by pulse width modulation (PWM), which controls the power requirements supplied to the electrolyzer. The overall reaction, anode, and cathode as specified in Eq. (1) to Eq. (3) [25].

$$Overall\ reaction: 2H_2O_{(l)} + Energy \rightarrow 2H_{2(g)} + O_{2(g)} \tag{1}$$

$$Anode\ reaction: 4OH^-_{(aq)} \rightarrow O_{2(g)} + 2H_2O_{2(l)} + 4e^- \tag{2}$$

$$Cathode\ reaction: 2H_2O_{(l)} + 2e^- \rightarrow H_{2(g)} + 2OH^-_{(aq)} \tag{3}$$

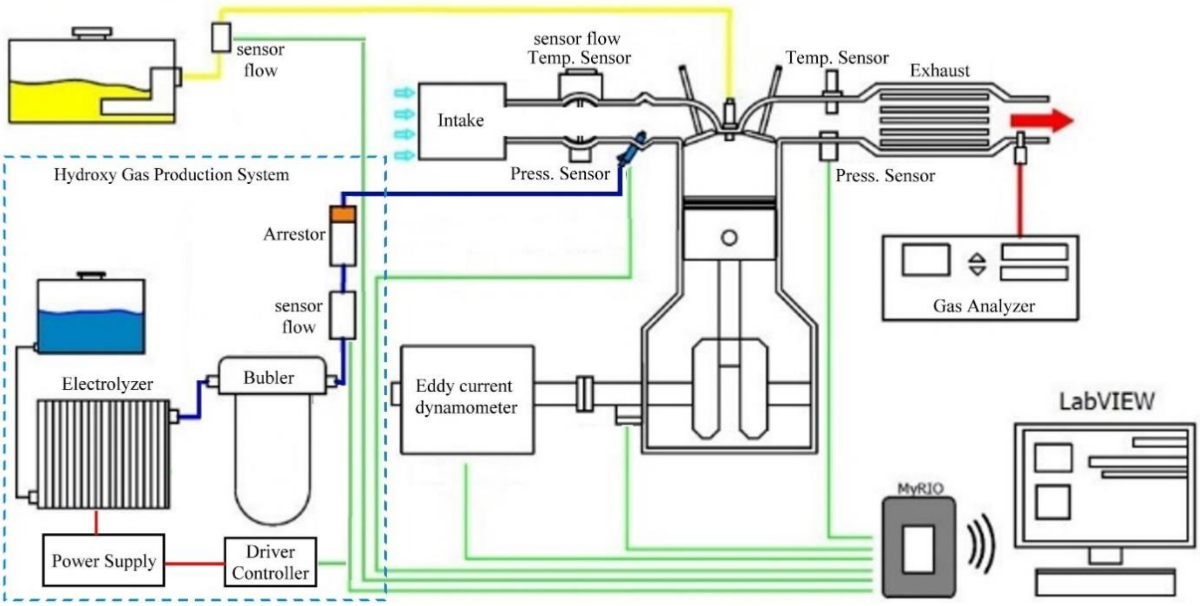

Figure 1. Experimental setup

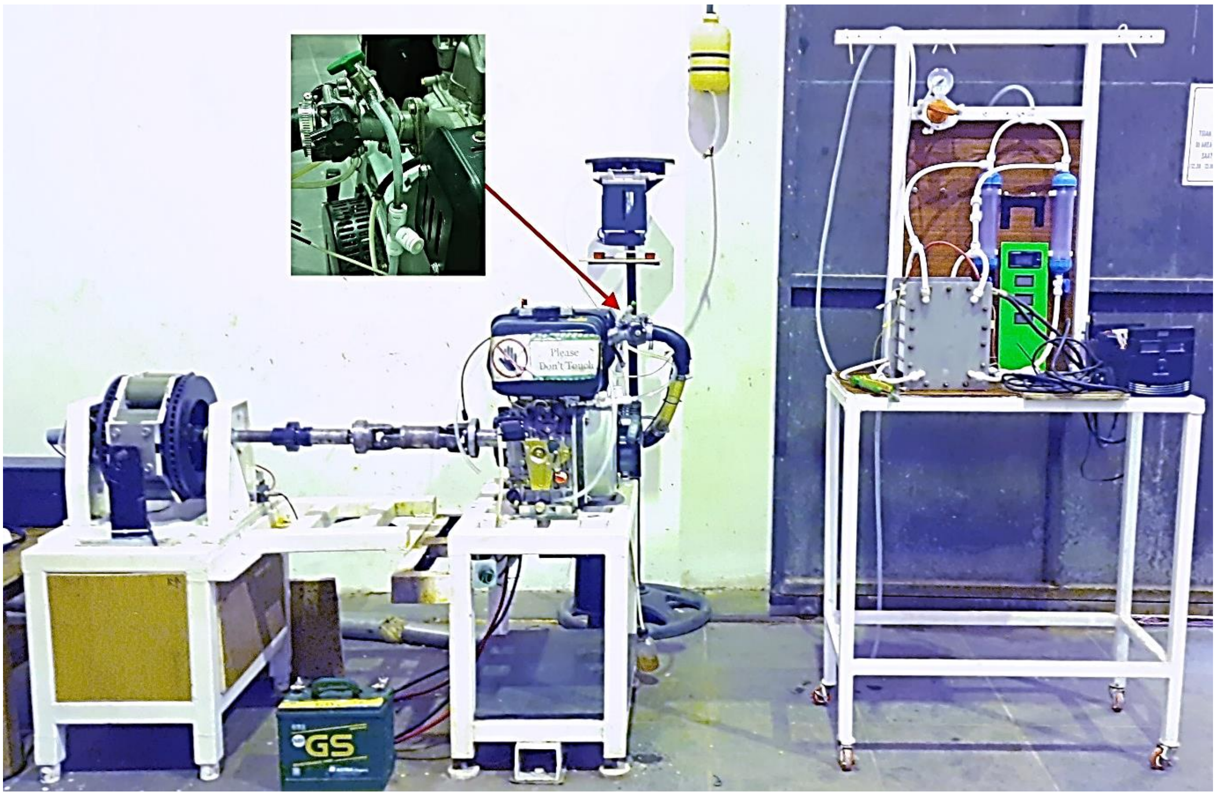

Figure 2. Engine test bed

The flow rate of hydroxy gas production depends on several factors, such as electrode material, electrode geometric parameters, electrode gap, electrolyte type, electrolyte concentration, and the amount of current applied [26]. The hydroxy gas production flow rate can be calculated by accumulating gas volume in the cylinder per time [27], as shown in Eq. (4).

$$HHO_{production} \rightarrow \frac{Volume}{time} \tag{4}$$

The mass of hydrogen produced refers to the concentration of hydrogen and oxygen, which is 2:1 or with a fraction of 2/3 hydrogen and 1/3 for oxygen. The mass of H_2 can be calculated using Eq. (5).

$$m_{H_2} = \frac{V_{H_2}}{V_{kmol}} M_w \tag{5}$$

where, m_{H_2} mass of hydrogen, V_{H_2} molar volume of hydrogen, and M_w molecular weight of hydrogen. Eq. (5) can be used to calculate the mass flow rate of hydroxy gas supplied to the cylinder.

$$\dot{m}_{H_2} = \dot{V}_{HHO} \times \rho_{H_2(HHO)} \tag{6}$$

$$\rho_{H_2(HHO)} = \frac{2.M_{H_2}}{3.V_m} \tag{7}$$

where, $\dot{m}_{H_2}$ the mass flow rate of hydrogen, $\dot{V}_{HHO}$ the volume flow rate of hydrogen, $\rho_{H_2(HHO)}$ the density of hydrogen in hydroxy gas, M_{H_2} the molar mass of hydrogen, and V_m molar volume of gases.

The production capacity resulting from the electrolyzer ranges from 196.74 to 1501.62 mL/min within a 40%–100% PWM range. The rate of hydroxy gas production is controlled by a PWM, which is pre-calibrated by a hot-wire flow meter and maintained to the percentage of PWM according to distributed gas requirements. The adjustment of PWM by 53% to 55% is necessary to maintain a constant flow rate of 500 mL/min supplied to the engine. The mass of hydrogen gas entering the cylinder is calculated using Eq. (5) to Eq. (7), which are needed to calculate the amount of energy input from the hydrogen into the cylinder. The profile of the electrolysis production rate is shown in **Figure 3**, which illustrates the relationship between production rate and PWM. Compositions of hydrogen and oxygen were calculated based on the rate of production of hydroxy gas by volume fraction of 2/3 for hydrogen, and 1/3 for oxygen. The distribution of hydroxy gas to the intake manifold is directed through a one-way valve to prevent the back pressure at the end of the exhaust stroke and the beginning of the suction stroke.

3. Results and Discussion

This section presents the measurements and calculations obtained for five different engine loads and five different fuels at constant speed in the experimental study: energy input, thermal efficiency, and brake-specific fuel consumption.

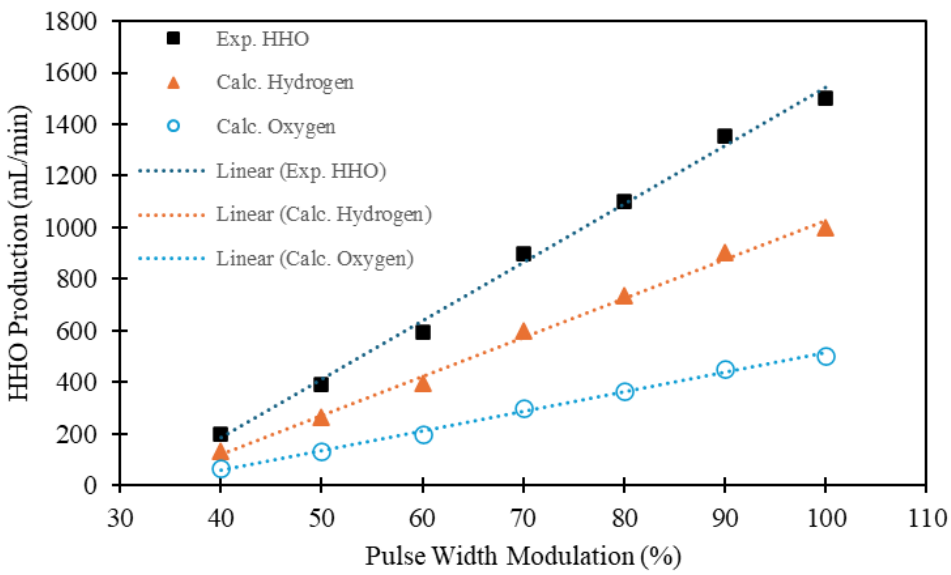

Figure 3. Hydroxy gas production at various PWM

3.1. *Engine Performances*

3.1.1. *Energy Input on Various Engine Torque*

The ability of an internal combustion engine to generate torque and power is significantly affected by the amount of energy contained within the fuel it consumes. **Figure 4** shows the energy required to produce the same torque from five different fuels. Pure diesel fuel has the lowest energy input across the entire torque range, indicating its high energy density. At a torque of 6 N·m, the input energy was 9.06 kJ/s, and at 30 N·m, it was 19.76 kJ/s. In comparison, B30 and B40 required 35.56 kJ/s and 39.58 kJ/s, respectively, to produce the same torque at 30 N·m. This shows that B30 and B40 fuels require a higher amount of fuel compared to pure diesel fuel, particularly at mid to high torques. This is due to the fatty acid methyl ester content in biodiesel, which has a lower energy density than pure diesel, thereby requiring more energy to generate equivalent power. Increasing the amount of fuel in the combustion chamber increases the input energy [14]. Adding hydroxy gas to the engine running with B30H and B40H significantly reduced the input energy consumption compared to B30 and B40 without hydroxy, especially at low to medium torque. It is caused by the enrichment of hydrogen in the combustion process, which results in higher energy input and significantly increases the laminar flame speed with increasing hydrogen concentration in the fuel at all fuel-air equivalence ratios [28]. The addition of hydroxy gas to B30 and B40 significantly reduces the input energy requirement. Specifically, B30 approaches the input energy level of pure diesel across the entire range of tested torque. Thereby, the presence of hydroxy fuel in a diesel engine contributes to increasing combustion stability, improved combustion efficiency, and optimized engine performance.

3.1.2. *Hydroxy Gas Effect on Brake Specific Fuel Consumption*

Brake Specific Fuel Consumption (BSFC) is a measure of the efficiency with which fuel chemical energy is converted to engine power [4]. The BSFC uses the unit g/kW.h, which is the ratio of fuel consumed to power produced over one hour. This value indicates the fuel required to produce one unit of power. The BSFC decreases with increasing braking power, indicating that the relationship between power output and BSFC is inversely proportional [29]. It affects the decrease in the BSFC as the load increases [30].

Figure 5 shows that the BSFC consistently rises across all biodiesel mixtures compared to pure diesel. Moreover, a direct correlation exists between the biodiesel blend percentage and BSFC, with the B40 blend exhibiting the highest BSFC. This increased fuel consumption for biodiesel blends is caused by lower energy content relative to diesel fuel. Moreover, BSFC decreased with increasing engine torque from 6 N.m to 24 N.m and increased again at higher torque for fuels without hydroxy gas addition. However, the addition of hydroxy gas significantly affects the

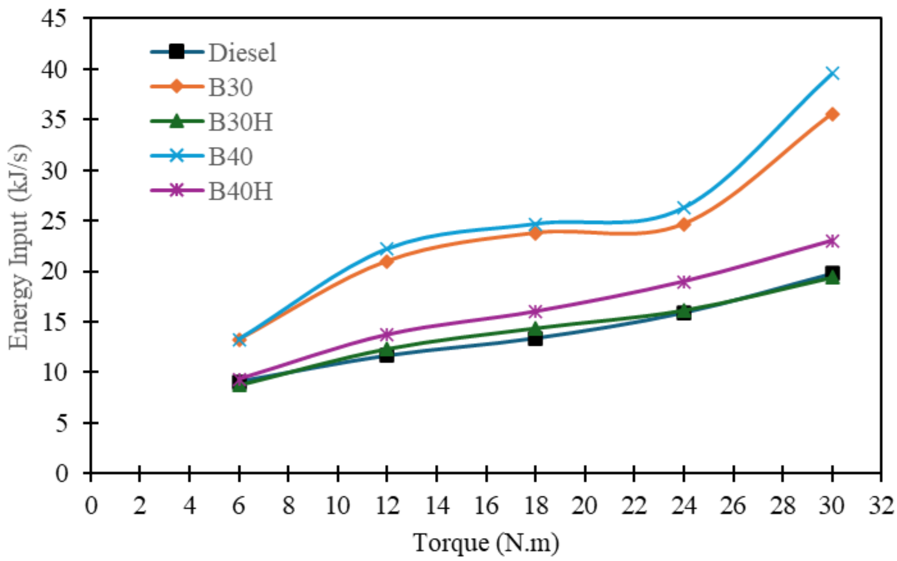

Figure 4. Energy supply with various torque

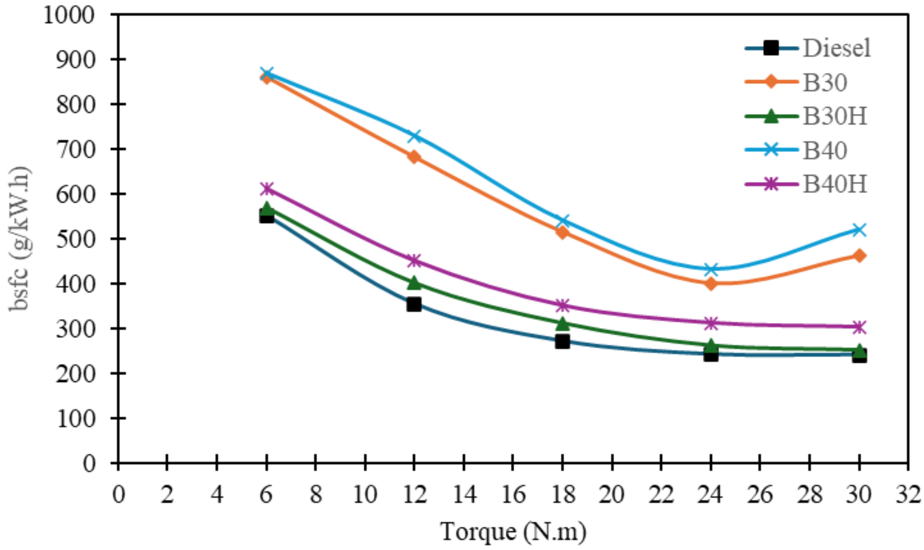

Figure 5. Brake specific fuel consumption with various torque

decrease of BSFC at all torque variations, especially at a torque of 30 N.m for B30H and B40H, compared to B30 and B40 by increasing at 30 N.m engine torque. It shows that the presence of hydrogen and oxygen in the biodiesel fuel mixture improves combustion efficiency. The lowest BSFC was obtained at 24 N.m for B40, which was 432 g/kW.h, and decreased for B30, which was 400.74 g/kW.h. Both fuels produced much greater values than diesel fuel at 242.14 g/kW.h at all torque variations. The addition of hydroxy gas lowered the BSFC close to diesel fuel, to 262.42 g/kW.h for B30 and 311.76 g/kW.h for B40. The average decrease in BSFC due to the addition of hydroxy gas in the various torques obtained 35.82% for B30 and 27.83% for B40. Compared to pure diesel, the average BSFC increases by 7.91% for B30H and 19.25% for B40H. Consistent with findings reported in [31], this phenomenon suggests that hydroxy gas addition to Biodiesel 20% (B20) leads to improved engine torque. The significant reduction in BSFC is due to improved flame propagation, which makes the combustion reaction zone more active and accelerates the combustion of the air-fuel mixture. Thus, the combustion process is complete and faster, resulting in lower BSFC for the same power output.

The decrease in BSFC was also obtained in previous studies, which showed that the enrichment of hydrogen and oxygen had a good impact on increasing torque, and the decrease in BSFC was very close to diesel fuel, compared to the addition of pure hydrogen in B20, the study shows hydroxy gas is superior in producing high torque [31]. Another experiment also obtained a decrease of BSFC due to the addition of hydroxy gas [32].

3.1.3. Hydroxy Gas Effect on Efficiency

Figure 6 shows the thermal efficiency at different torques for five different fuels. Thermal efficiency is defined as the ratio of the power output of a diesel engine to the heat energy contained in the fuel input to the cylinder. The Brake Thermal Efficiency (BTE) parameter indicates an engine's ability to convert fuel energy into mechanical power. The test results showed that diesel fuel achieved the highest energy conversion efficiency compared to other fuels. The efficiency increased with increasing load, and the highest efficiency for all fuels without hydroxy gas was obtained at a 24 N.m load, which afterward decreased at higher torque. In contrast, the efficiency obtained by adding hydroxy gas continued to improve at loads exceeding 24 N.m. In addition, the high concentration of biodiesel decreased the thermal efficiency of the diesel engine, where B40 had the lowest efficiency, even the lowest compared to B30 fuel. At a low torque of 6 N.m, the efficiency of B30 decreased by 5.14% and 8.41% at a high load of 30 N.m. At the same time, B40 decreased more at loads of 6 N.m and 30 N.m, by 6.44% and 11.57% respectively.

The more significant decrease in efficiency with increasing biodiesel concentration is due to biodiesel's higher viscosity and surface tension, which can cause poor injection and atomization, resulting in incomplete combustion and increased BSFC at various loads [33]. The effect of the addition of hydroxy gas shows a significant increase in efficiency, an average increase of 7.95% for B30 and 8.68% for B40 at a torque of 6 N.m to 24 N.m. However, efficiency slightly decreases compared to diesel fuel, with an average decrease of 1.31% for B30H and 2.91% for B40H at all tested torques. Previous studies indicate that adding hydrogen at 10 L/min improves the thermal efficiency from 13.91% with biodiesel to 23.32% with hydrogen [14]. This phenomenon results from the increased flame speed of the combustion process, reduced ignition delay, and high cylinder temperature, resulting in rapid vaporization of the injected fuel. Another contributing factor is the higher calorific value of hydrogen gas. The speed of the hydrogen flame, which is enhanced by the combustion process facilitated by the homogeneous mixture of hydrogen and oxygen molecules, results in a significant increase in engine power [32].

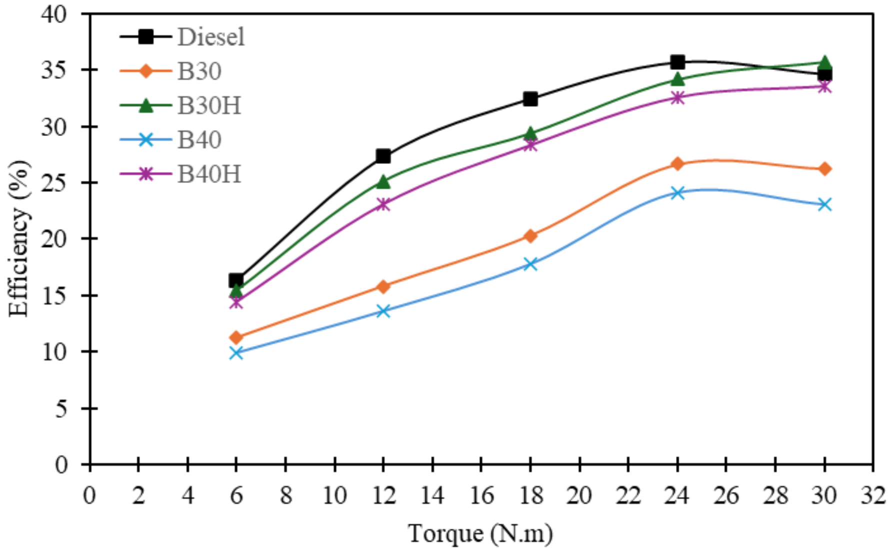

Figure 6. Thermal efficiency versus various engine torque

4. Conclusion

This study investigated the effect of hydroxy gas addition on diesel engines running on 30% and 40% biodiesel concentrations. It significantly affected combustion efficiency, fuel consumption, and overall engine performance. The addition of hydroxy gas improves combustion rate and efficiency and significantly reduces energy consumption compared to biodiesel without hydroxy, especially at low to medium torque levels. Hydroxy gas reduces BSFC across all torque ranges, bringing fuel consumption closer to pure diesel engines.

The enrichment of hydroxy results in improved thermal efficiency and continuously increases, particularly at higher torque, over diesel fuel at 30 N.m for B30. While high biodiesel blends tend to reduce efficiency due to their higher viscosity, low-calorie value, and surface tension, hydroxy effectively mitigates these issues. Although biodiesel's thermal efficiency remains slightly lower than pure diesel, adding hydroxy narrows the gap. Compared to pure diesel, the average decrease in thermal efficiency was only 1.31% for B30H and 2.91% for B40H. Due to its high flame speed and heating value, hydroxy gas reduces ignition delay and accelerates ignition and fuel vaporization, resulting in higher engine performance.

Acknowledgement

The authors are grateful to the Ministry of Higher Education, Science and Technology for financing this study under the Fundamental Research Scheme with contract number 058/E5/PG.02.00.PL/2024 and 191/UN45.3.1/AL.04/VI/2024.

Author's Declaration

Authors' contributions and responsibilities

The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation and discussion of results. The authors read and approved the final manuscript.

Funding

Ministry of Higher Education, Science and Technology for financing this study under the Fundamental Research Scheme with contract number 058/E5/PG.02.00.PL/2024 and 191/UN45.3.1/AL.04/VI/2024.

Availability of data and materials

All data are available from the authors.

Competing interests

The authors declare no competing interest.

Additional information

No additional information from the authors.

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