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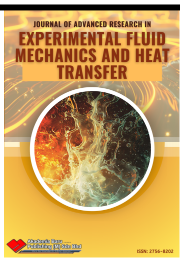

Diesel and Oxyhydrogen Dual-Fuel: Reducing Emissions of a Diesel Engine using Diesel-Oxyhydrogen Dual Fuel Combustion

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ABSTRACT

Diesel engines are frequently used because of their high efficiency and durability. However, they are also known for emitting high amounts of pollutants, including CO_2, CO, NO_x and particulate matter. Current studies have focused on alternate fuel techniques to reduce these emissions. An effective method involves using oxyhydrogen (HHO) with diesel and biodiesel can increase combustion efficiency and minimize harmful emissions. Additionally, HHO serves as a viable alternative to hydrogen, especially considering the current challenges in global hydrogen production and storage, which may not be sufficient to meet the increasing demand for transportation applications. Hence, the current study investigated the effect of using a diesel-HHO dual fuel on the emission characteristics of a single-cylinder, four-stroke diesel engine. The engine was operated at a constant speed of 1500 rpm and was tested under varying loads of 0%, 50% and 75%, with diesel (D100) serving as the primary fuel and HHO gas as the inducted fuel. The HHO gas, produced at a constant flow rate of 0.80 LPM through alkaline water electrolysis was continuously injected into the combustion chamber through air suction manifold. The results revealed that compared to diesel fuel, the injection of HHO has increased the CO_2 emissions by 23.08, 23.81 and 20.0% at an engine load of 0, 50 and 100%. The CO emissions were reduced by 23.53, 34.78 and 41.38% at 0, 50 and 100% engine load. Similarly, the HC emissions were reduced by 26.09, 23.08 and 23.33% at 0, 50 and 100% engine load. The NO_x emissions were increased by 25.0, 10.53 and 4.17% at 0, 50 and 100% engine load. Overall, introducing HHO has increased the CO_2 and NO_x emissions as the hydrogen and additional oxygen in the HHO gas promote more complete combustion and higher combustion temperatures. However, this enhancement in combustion efficiency has resulted in a significant reduction in CO and HC emissions.

Keywords:
Diesel-HHO dual fuel; emissions reduction; HHO production; hydrogen fuel

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1. Introduction

Internal combustion (IC) engines are known for their excellent thermal efficiency, wide power range and good fuel economy and they are widely used as power sources in many engineering sectors [1,2]. However, rapid advancements in science and technology have led to increased energy

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consumption and pollution. The world consumes approximately 3.30-3.50 billion tons of fossil fuels annually and maintaining the balance between fossil fuel storage and consumption is highly challenging. There is a risk that fossil fuels may become unavailable in the future [3,4]. Moreover, the combustion of fossil fuels releases hazardous pollutants such as carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO_x) and smoke, which are major contributors to global warming [5-7]. Various low-carbon renewable fuels like methanol, butanol, dimethyl ether, biodiesel and biodiesel-emulsified fuel [8-10] have been extensively studied and used in diesel engines. However, even with the adoption of these fuels, they alone are insufficient to completely reduce carbon emissions [11].

Hydrogen (H_2) is favoured among various gaseous fuels because of its superior performance and lower emissions, attributed to its carbon-free nature and high calorific value [12,13]. However, its high auto-ignition temperature makes direct use in CI engines challenging. Therefore, CI engines can operate in dual fuel mode, with diesel as the primary fuel and H_2 as the inducted fuel [14,15]. Due to its status as the lightest element, hydrogen has a very low density, which presents significant storage challenges. Additionally, the annual demand for H_2 surpasses its supply, creating a major hurdle for power production applications due to its limited availability [16].

Researchers are investigating alternative hydrogen (H_2) production methods and utilization in the energy and automotive sectors to tackle these challenges. One promising approach is electrochemical H_2 production through water electrolysis, also known as oxy-hydrogen (HHO) gas, which is considered a renewable energy source for heat and power applications, including in vehicles. An electrical current splits water molecules into H_2 and O_2 gases during the electrolysis process. The electrodes are immersed in an electrolyte solution, with H_2 gas produced at the cathode and oxygen gas at the anode [17,18]. Common electrolytes used in water electrolysis due to their high reactivity include potassium hydroxide, sodium hydroxide and sodium chloride. HHO gas has garnered attention as a renewable energy source because it is a clean-burning fuel that produces only water as a by-product during combustion. Additionally, it can be produced locally or on demand using various energy sources like solar and wind energy, making it a compelling alternative to traditional fossil fuels for a wide range of applications [19].

The impact of adding HHO as an inducted fuel with diesel as the primary fuel has been investigated in various studies. For instance, Sharma *et al.,* [20] produced HHO gas through water electrolysis and used it as an inducted fuel at different flow rates (0.25-0.75 LPM) to examine engine performance and emissions. At the maximum flow rate of 0.75 LPM, emissions of CO, HC and smoke were reduced by 49.0%, 60.0% and 58.0% respectively, compared to diesel. Rimkus *et al.,* [21] used a diesel-HHO dual fuel setup to study its effects on engine performance and emissions at various engine speeds (1900-3700 rpm) and loads (25-100%), maintaining a constant HHO flow rate of 3.0 LPM. The addition of HHO reduced CO, HC and smoke emissions by 15.0%, 9.0% and 25.05%, respectively. However, it also increased CO_2 and NO_x emissions by 6.0% and 10.0%, respectively. Jakliński *et al.,* [22] investigated engine emissions by supplying HHO gas at different flow rates (1.0-3.0 LPM). Their findings indicated that while HHO addition reduced CO and HC emissions, it led to an increase in NO_x emissions. Furthermore, Sharma *et al.,* [23] conducted an experimental study on the effect of HHO addition on engine performance and emissions at a constant speed of 1500 rpm. Their findings showed that adding HHO reduced CO and HC emissions but increased NO_x emissions by 35.0% compared to diesel.

Furthermore, Thangaraj *et al.*, [24] utilized HHO gas with a flow rate of 0.73 LPM into the suction line of a single-cylinder, four-stroke diesel engine led to significant changes in emission characteristics. They found that the CO emissions were reduced by 19.4, 64.3 and 34.6% at 25, 50 and 75% load. HC emissions decreased by 11.3 and 33.5% at low and full loads. However, NO_x

emissions increased slightly, with a rise of 1.79 and 1.76% at 75% and full load conditions compared to neat diesel operation. Selvi Rajaram *et al.,* [25] investigated the effect of HHO addition on the emission performance of a single-cylinder, four-stroke diesel engine. Introducing HHO with a flow rate of 1.0 and 3.3 LPM led to significant changes in emission characteristics. The results showed that with the induction of HHO gas, CO emissions decreased by 15.38% and HC emissions decreased by 18.18%. However, CO_2 emissions increased by 6.06% and NOx emissions increased by 11.19%. Kamaraj *et al.,* [26] injected onsite HHO production (average 4.0 LPM) into the intake manifold of a CI engine to improve fuel economy and reduce emissions. The results showed that CO emissions were reduced by 25%, HC emissions by 22.22% and smoke emissions by 11.38%. However, CO_2 emissions increased by 3.41% and NOx emissions increased significantly by 22.43%. The study highlighted that these changes were achieved without significant modifications to the engine, though the exact HHO flow rate was not specified.

The current study investigated the effect of diesel-HHO dual fuel with diesel (D100) as primary fuel and HHO as inducted fuel on the emission characteristics of a single-cylinder, four-stroke diesel engine operated at a constant 1500 rpm and various engine loads (0, 50 and 100%). An HHO generator produces 0.8 LPM of gas through alkaline water electrolysis was continuously supplied through the air suction manifold. The study revealed that H_2 in HHO gas has notably increased the combustion temperature, which resulted in higher CO_2 emissions. The study further highlighted that the additional oxygen present in HHO promoted more complete combustion, thereby leading to higher NOx emissions. However, the use of D100-HHO dual-fuel noticeably reduced CO and HC emissions due to the more efficient and complete combustion process. This research provided valuable insights into the trade-offs associated with using HHO as a supplementary fuel in diesel engines and contributed to a better understanding of how dual-fuel systems can be optimized for improved emission control.

2. Methodology

2.1 HHO Generator

As shown in Figure 1, the HHO gas was continuously injected into the combustion chamber through the air suction manifold. The HHO generator was capable of producing 0.8 LPM of HHO gas using a DC power supply rated at 12 V and 3 amps. To facilitate the electrolysis process, 25 gm of potassium hydroxide (KOH) mixed with one litre of distilled water was used as an electrolyte solution. The KOH increases the electrical conductivity of water, making the electrolysis process more efficient. During the electrolysis process, water molecules (H_2O) were split into their constituent elements. At the anode (the positive electrode), oxygen was produced, while at the cathode (the negative electrode), hydrogen was produced. The separation of hydrogen and oxygen at their respective electrodes is a critical aspect of the electrolysis process, ensuring that the gases are produced in their pure forms. For the engine applications, the hydrogen and oxygen were mixed together and injected into the combustion chamber. This is because the engine requires pure oxygen to achieve complete combustion, whereas atmospheric air is composed of approximately 21% O_2 and 79% N_2. Thus, the extra O_2 in the HHO gas could further improve engine combustion and reduce harmful emissions. This setup ensures a continuous and efficient production of HHO gas for the experimental analysis.

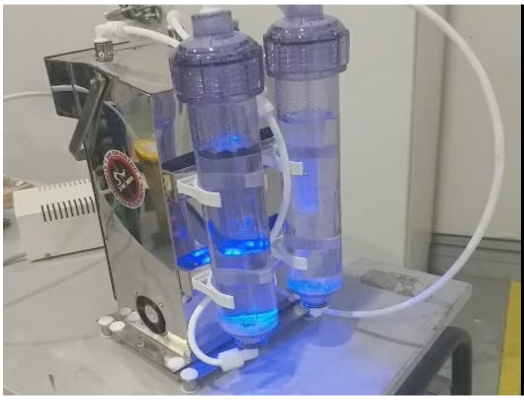

Fig. 1. HHO generator integrated with the air suction manifold of engine

The specifications of the various components of the HHO generator are shown in Table 1.

Table 1
Materials and specifications of different components of the HHO generator

Components	Materials and specifications
Dry cell reactor	Grade 316L stainless steel plates
Plate thickness	1.5 mm
X-cell reactor	Titanium Grade A
Plate thickness	1.2 mm
Gasket seal	Rubber sheet (chemical resistant)
Electrolyte	Potassium hydroxide (KOH)
Body and reservoir	Acrylic and polypropylene
Box/body/tank	304 stainless steel plates
HHO production capacity	0.80 LPM

2.2 Experimental Setup

This study employs a single-cylinder, four-stroke, air-cooled diesel engine, as specified in Table 2, to conduct the experiments. The engine was operated under an environmental temperature of 27°C and at atmospheric pressure throughout the experiments. To facilitate accurate performance and emission testing, the dual-fuel engine was connected to an electrical dynamometer, which maintained a constant engine speed of 1500 rpm while varying the load from 0% to 100%. The engine load was applied using a resistive load bank connected to the dynamometer, which was coupled to the engine shaft.

Table 2
Specifications of the diesel engine

Engine type	250cc, air-cooled, DI, diesel engine
Max. power	6.5kw @ 8200rpm
Max. torque	9.0 Nm @ 4000 rpm
Compression ratio	20:1
Displacement volume	435 cm^3
Bore × stroke	86×75 mm
Fuel delivery advance (°CA)	21 BTDC

To prevent overheating, a cooling system was connected to the engine. The schematic of the experimental setup with the HHO generator is illustrated in Figure 2.

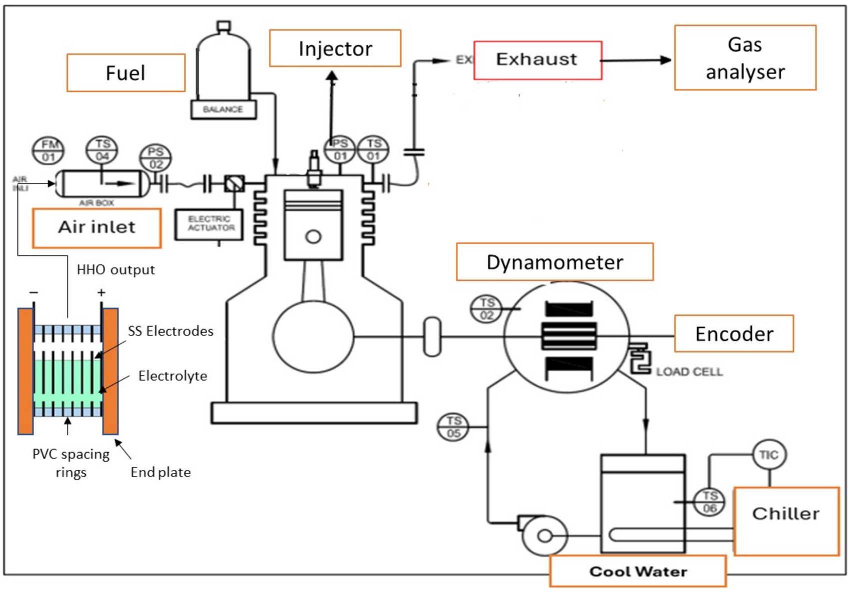

Fig. 2. Schematic of the experimental setup with HHO generator

The accuracy of the pressure sensors and gauges employed in the experiments is detailed in Table 3. The air intake temperature was regulated using an intercooler, maintaining it at a constant 28 ± 1°C. Additionally, the engine temperature was controlled using a cooling water system, which kept it steady at 80 ± 2°C. For precise measurement of the engine intake vacuum temperature and pressure, a K-type thermocouple temperature sensor (with a range from 0 to 1100 ºC) and a pressure sensor (with a range from -1 to 1 bar) were installed. It is important to note that throughout all experiments, the injection quantity of diesel was adjusted as necessary to ensure that the engine speed remained constant at 1500 rpm. This particular setup and control allow for a comprehensive evaluation of the engine's performance and emission characteristics under various operating conditions.

Table 3
Specifications and accuracy of the engine instruments

Instrument	Range	Accuracy
Pressure gauge	0-200 bar	± 1%
K-type thermocouple	0-1100 °C	± 0.1 °C
Fuel flow burette	0-100 ml	± 1%
Crank angle encoder	0-360 °	± 1%
Torque measuring instrument	0±100 to 0±5000 Nm	0.05%

This research utilizes the Kane AUTO Plus Exhaust Gas Analyzer, a portable and lightweight handheld device specifically designed for emission diagnostics. This advanced analyser is capable of measuring five different gases: Carbon dioxide (CO_2), Carbon monoxide (CO), Oxygen (O_2), Hydrocarbons (HC) and Nitrogen oxides (NO_x). In addition to these gas measurements, the device also records the exhaust temperature, which provides valuable supplementary information on the emission characteristics of the engine. The Kane AUTO Plus Exhaust Gas Analyzer is equipped with high-precision sensors to ensure accurate and reliable data collection, making it an essential tool for analysing exhaust emissions in various engine conditions. The specifications and accuracy of the analyser are detailed in Table 4.

Table 4
Specifications and accuracy of the gas analyser

CO_2	0-16 %	± 0.1%
CO	0-10 %	± 0.01%
HC	0-5000 ppm	± 1%
NO_x	0-5000 ppm	± 0.1%
O2	0-21 %	± 0.1%

3. Results

3.1 Emissions Characteristics

3.1.1 CO_2 emissions

CO_2 emissions result from the incomplete oxidation of carbon in the fuel, contributing to global warming. Reducing the carbon content in the fuel can lead to lower CO_2 emissions and improving the combustion process can also help decrease CO_2 output [27]. Typically, D100 combustion results in the highest CO_2 emissions, which increase with the increase in engine load due to the rise in the equivalence ratio. Introducing HHO gas into the combustion chamber has further increased the CO_2 emissions. For instance, at no load conditions, the CO_2 emissions using only diesel were 1.3, 2.1 and 5.0% at 0, 50 and 100% engine load. In contrast, as shown in Figure 3, the CO_2 emissions using HHO with D100 were further increased to 1.6, 2.6 and 6.0% at 0, 50 and 100% engine load.

The increase in CO_2 emissions when using dual fuel can be attributed to several factors. Firstly, the induction of HHO in a diesel engine enhances the combustion efficiency of diesel fuel. The high flame speed of H_2 gas leads to a more complete and faster combustion process, which results in higher CO_2 emissions [28]. Additionally, the extra oxygen present in HHO gas can raise the flame temperature during combustion. The higher combustion temperatures promote the complete oxidation of carbon-containing species, thus converting more carbon into CO_2. Moreover, the improved combustion characteristics provided by HHO allow for more efficient burning of diesel fuel. This increased fuel utilization results in a corresponding rise in CO_2 production, as CO_2 is the final product of complete HCs combustion [29].

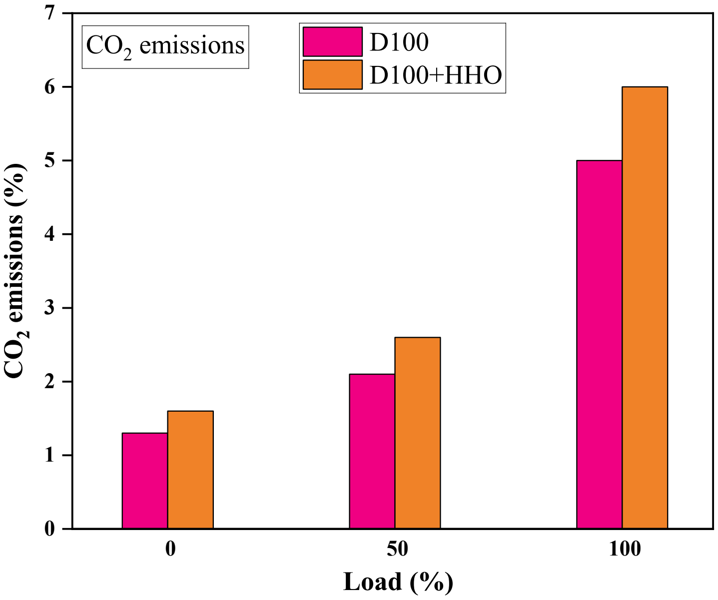

Fig. 3. CO_2 emissions using D100 and D100-HHO dual fuel at various engine loads

3.1.2 CO emissions

Unlike CO_2, carbon monoxide (CO) is an extremely hazardous pollutant with serious health and environmental implications. Therefore, it is crucial to minimize CO emissions during fossil fuel combustion. The majority of CO emissions are produced due to the incomplete combustion of diesel fuel. As shown in Figure 4, the induction of HHO gas into the combustion chamber has reduced the CO emissions. For instance, at no load conditions, the CO emissions using only diesel were 0.17, 0.23 and 0.29% at 0, 50 and 100% engine load. In contrast, the CO emissions using HHO with D100 were reduced to 0.13, 0.15 and 0.17% at 0, 50 and 100% engine load.

From the experimental results, it was found that using HHO with D100 has reduced the CO emissions compared to only D100. The reduction in CO emissions using HHO was due to several factors. The use of HHO along with D100 improves the combustion efficiency of a diesel engine, which results in a reduction in CO emissions. The additional O_2 in HHO increases the flame temperature, promoting complete combustion and reducing CO production. Moreover, the extra oxygen creates a more oxidizing environment in the combustion chamber, ensuring that any CO formed is further oxidized to CO_2 [28]. HHO also helps reduce fuel-rich zones within the combustion chamber, which are prone to incomplete combustion and CO formation. Additionally, HHO improves the mixing of diesel fuel with air, ensuring a more homogeneous mixture and more complete combustion [30]. These factors collectively contribute to a significant reduction in CO emissions when using HHO with D100 in a diesel engine.

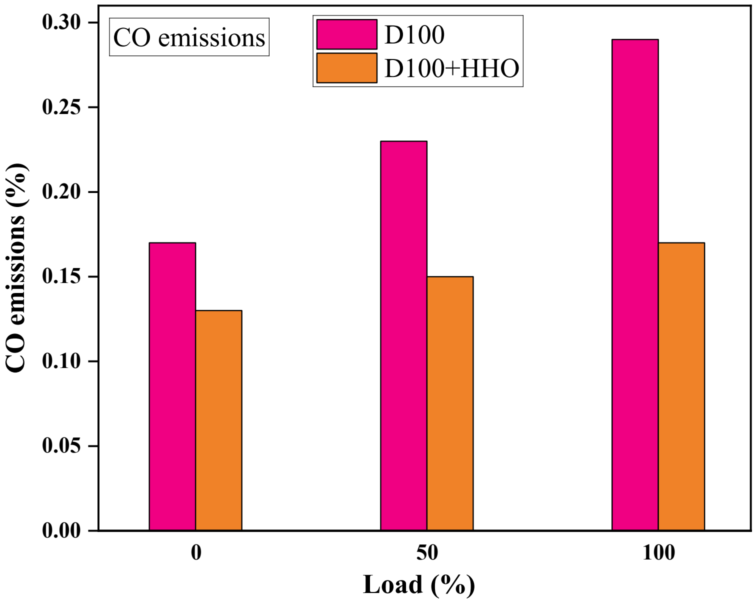

Fig. 4. CO emissions using D100 and D100-HHO dual fuel at various engine loads

3.1.3 Unburned HC emissions

Hydrocarbon (HC) emissions from diesel engines result from the incomplete combustion of diesel fuel. These unburned or partially burned HCs are harmful to air pollution. Injecting HHO gas into the combustion chamber facilitates combustion and reduces unburned or partially burned HCs. As shown in Figure 5, the injection of HHO gas into the combustion chamber has reduced the HC emissions. At no load conditions, the HC emissions using only diesel were 23, 26 and 30 ppm at 0, 50 and 100%

engine load. On the other hand, the HC emissions using HHO with D100 were reduced to 17, 20 and 23 ppm at 0, 50 and 100% engine load.

The experimental results demonstrated that introducing HHO gas into the combustion chamber of a diesel engine reduced the HC emissions. Firstly, the rapid flame speed of H_2 enhances combustion efficiency, resulting in faster and more complete combustion. Additionally, the presence of extra O_2 in HHO increases the flame temperature, facilitating the complete oxidation of HCs and reducing the number of unburned HCs [28]. Furthermore, HHO improves air-fuel mixing, creating a more oxidizing environment that further reduces HC emissions. HHO also minimizes quenching zones near the cylinder walls, promoting more complete combustion of the fuel [31]. These combined factors lead to a substantial reduction in HC emissions compared to diesel.

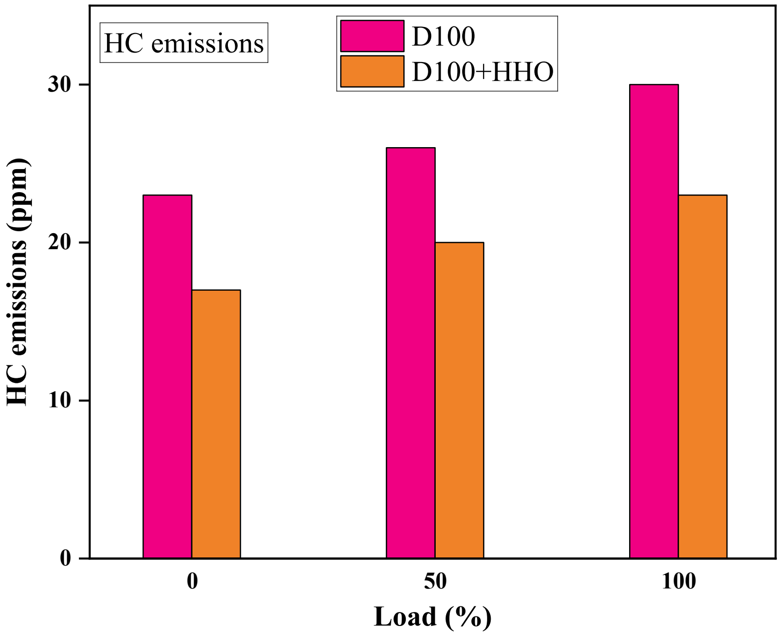

Fig. 5. Unburned HC emissions using D100 and D100-HHO dual fuel at various engine loads

3.1.4 NO_x emissions

Figure 6 shows the NO_x emissions for both D100 and D100+HHO, indicating a linear increase in NOx emissions with rising engine load for both cases. The NO_x here refers to the combined emissions of NO and NO_2. It is important to note that NO_x emissions in diesel engines are mainly caused by excessively high cylinder temperatures [32]. At no load conditions, the NO_x emissions using diesel were 8, 19 and 120 ppm at 0, 50 and 100% engine load. On the other hand, the NO_x emissions using HHO with D100 were increased to 10, 21 and 125 ppm at 0, 50 and 100% engine load.

According to the previous studies and our experimental results, diesel fuel alone often produces lower NO_x emissions than diesel-HHO mixtures. Meanwhile, there is no additional oxygen in diesel fuel as the combustion only depends on the O_2 in the intake air, reducing the possibility of high temperatures and NO_x production [28]. In contrast, HHO gas consists of both H_2 and oxygen. The additional oxygen from HHO makes the combustion chamber more oxygen-rich, leading to higher flame temperatures. The increase in the temperature facilitates the interaction between N_2 and O_2, increasing NO_x emissions. Similarly, the fast flame speed of H_2 improves combustion efficiency, which not only helps the diesel fuel burn more quickly and completely but also increases the peak temperatures [32]. Furthermore, HHO induction can lead to a leaner air-fuel mixture because of the additional oxygen in HHO, which increases the overall oxygen content in the combustion chamber. A leaner mixture tends to result in higher combustion temperatures, which promotes NO_x formation, as nitrogen in the air reacts with the excess oxygen at higher temperatures [32-34].

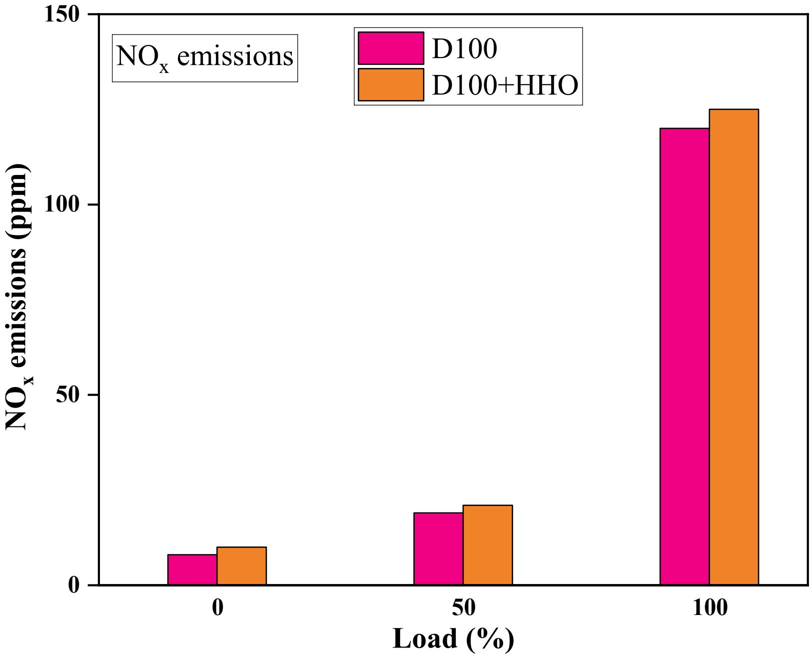

Fig. 6. NO_x emissions using D100 and D100-HHO dual fuel at various engine loads

4. Conclusions

The study investigated the effect of D100-HHO dual fuel on the emissions performance of a single-cylinder, four-stroke diesel engine. The engine was operated at a constant speed of 1500 rpm under different loads of 0%, 50% and 100%. The HHO gas produced through an alkaline water electrolysis process at a constant flow rate of 0.80 LPM was injected into the combustion chamber through an air suction manifold. A Kane AUTO Plus exhaust gas analyser was used to record the emissions of D100 only and D100-HHO dual fuel at various loads. The results showed the injection of HHO has increased the CO_2 emissions by 23.08, 23.81 and 20.0% at an engine load of 0, 50 and 100%. The CO emissions were reduced by 23.53, 34.78 and 41.38% at 0, 50 and 100% engine load. Similarly, the HC emissions were reduced by 26.09, 23.08 and 23.33% at 0, 50 and 100% engine load. The NO_x emissions were increased by 25.0, 10.53 and 4.17% at 0, 50 and 100% engine load. The introduction of HHO gas into the combustion chamber has increased the combustion efficiency and promoted complete combustion which resulted in higher CO_2 emissions. The complete combustion using HHO has reduced the hazardous CO emissions as the CO is converted into CO_2 at elevated temperatures, resulting in lower CO emissions. The HHO induction also minimizes the quenching zones near the cylinder walls, promoting more complete combustion of the fuel and resulting in lower HC emissions. The additional oxygen in HHO made the combustion chamber more oxygen-rich, thus increasing the flame temperature and facilitating the interaction between N_2 and O_2 which resulted in higher NO_x emissions. Further research could focus on optimizing the HHO amount and injection timings. Similarly, the use of HHO with various biodiesel blends needs further exploration before considering large-scale implementations.

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