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Research Article

Performance and carbon emissions of a diesel/oxy-hydrogen dual-fuel engine with oxy-hydrogen injection variation under low and medium load conditions

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Abstract. Reducing carbon emissions such as carbon dioxide (CO_2) and carbon monoxide (CO) from diesel engines struggled with engine performance challenges and fossil fuel limitations. Besides, huge transportation such as ships hardly replaced diesel engines due to the higher thermal efficiency and low operation cost. Oxy-hydrogen gas, as a carbon-free gas, could potentially improve diesel engine performance and carbon emissions. Most of the studies tried to identify the effect of oxy-hydrogen induction into diesel engine combustion on performance and emissions. However, this study evaluated oxy-hydrogen injector sizes to the diesel engine performance and carbon emissions at several loads and several engine speed conditions. Overall, the result showed that the oxy-hydrogen gas injection into the diesel engine's intake port improved the performance and carbon emissions compared to the single diesel fuel as a baseline. High engine performance with low carbon emissions could be achieved at low and medium engine load conditions with high engine speeds. Moreover, smaller oxy-hydrogen injector sizes were suitable for the medium engine load and vice versa, to improve the performance and carbon emissions. At low load, the engine performance improvement of engine torque, specific fuel consumption, and thermal efficiency were 1800 to 2200 rpm. Moreover, the CO_2 and CO emissions reductions were also suitable with 2200 rpm with a bigger oxy-hydrogen gas injector (6 mm). Furthermore, at medium load, the engine performance improved at 1400 rpm but the CO_2 and CO emissions were lower at 2200 rpm with a small oxy-hydrogen gas injector (4 mm). The engine operation at 2200 rpm with a 4 mm injector also improved the engine performance regarding carbon emissions reduction. However, injecting oxy-hydrogen gas into diesel engines had the potential to enhance the engine performance and reduce carbon emissions, moving closer to achieving zero emissions.

Keywords: carbon, decarbonization, dual-fuel, efficiency, emissions, hydrogen.

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1. Introduction

Decarbonization is an important interest to all transportation modes such as land-based and water-based transportation which impacts the environment, especially on most of the ship transportation that utilizes diesel fuel as the main energy. Transportation represents 27% of the main contributors to greenhouse gas emissions, with CO_2 contributing 76% of the global total (Fan *et al.,* 2018). Most transportation nowadays uses fossil fuel utilization which is unavoidable due to the high power that can produced by converting internal combustion engines. However, the combustion of fossil fuels produces much carbon emissions which have to be controlled in the air due to the side effect on the environment and low-carbon limitation on the regulation (Balcombe *et al.,* 2021; Charabi *et al.,* 2020; Fan *et al.,* 2021). These carbon emissions must be reduced to ensure sustainable development in the future (Felayati *et al.,* 2022; Nguyen, 2018; Nnabuife *et al.,* 2022). Diesel fuel is the most favorable fuel for a high-duty engine that has a significant role in mass and huge transportation. Besides, diesel fuel has a higher carbon content than gasoline but the utilization of compressed ignition engines is significantly more efficient (Altosole *et al.,* 2020). Thus, the utilization is still favorable due to the efficiency and lower cost for the operation besides carbon taxes increase annually. The carbon dioxide emissions while using diesel engines should be reduced to ensure feasibility in terms of efficiency and its impact on the environment (Doukas *et al.,* 2021). Furthermore, the emissions reduction effort on diesel engines sometimes deteriorates the engine performance thus an appropriate development should be carefully decided.

A substitution of diesel fuel with gaseous fuel has proved that can reduce the carbon emissions, such as hydrogen-based fuels (Dimitriou *et al.,* 2018; Gholami *et al.,* 2022a; Tsujimura & Suzuki, 2017). Great interest in hydrogen-based fuels is gained due to their zero-carbon content and enhanced engine combustion characteristics (Butt *et al.,* 2021; Rajak *et al.,* 2022; Sadiq Al-Baghdadi *et al.,* 2023). A reachable hydrogen source to be produced is water electrolysis which contains hydrogen and oxygen (Baltacioglu *et al.,* 2019; Gad & Abdel Razek, 2021; Ozcanli *et al.,* 2017). The final product of the water electrolysis is hydrogen hydrogen-oxygen (HHO) gas or oxy-hydrogen or

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brown gas which can be easily combined with diesel fuel combustion as diesel/oxy-hydrogen dual-fuel. The oxy-hydrogen gas can be injected into the intake port while the diesel fuel is injected directly into the combustion chamber. Saravanan *et al.,* (2008) studied the hydrogen/diesel and hydrogen/dimethyl ether (DEE) dual-fuel engine compared with diesel engine. The hydrogen is injected in the intake port and the others in the combustion chamber. The hydrogen/DEE resulted in more attractive thermal efficiency compared with hydrogen/diesel, both dual-fuel mode still has higher thermal efficiency than diesel. Moreover, the hydrogen/DEE mode significantly reduces nitrogen oxides (NO_x), smoke, and CO_2 at most engine load conditions and yet higher CO emissions at low engine load conditions than both hydrogen/diesel and diesel. However, hydrogen/DEE mode is limited to knock intensity in high load conditions. Paparao *et al.,* (2023) optimized the oxy-hydrogen/biodiesel engine with pilot fuel injection pressure, pilot fuel injection timing, and engine compression ratio. However, the oxy-hydrogen was injected into the intake port while the diesel fuel was directly injected into the combustion chamber. The brake thermal efficiency increased with lower CO, hydrocarbon (HC), and smoke emissions, meanwhile, the NO emissions increased compared with the single biodiesel fuel. Sabeghi *et al.,* (2023) experimentally studied HHO gas injection on diesel engine emissions with idle speed. However, the NO_x, HC, CO, and CO_2 emissions were reduced significantly. Bhave *et al.,* (2022) added oxy-hydrogen with port fuel injection to a diesel engine with direct injection and port injection to overview the combustion, performance, and emissions. The main findings of that study were the reduction of CO and HC emissions while NOx and smoke emissions were negligible. Moreover, the brake thermal energy and the mean effective pressure were improved.

Overall, the admissions of oxy-hydrogen gas into the diesel engine were favorable since the carbon emissions improved with high engine performance thus an extended study is fascinating. The mentioned major research on the utilization of oxy-hydrogen gas in the diesel engine has positively improved engine performance and emissions. The combustion and emissions characteristics are found that should be discussed extensively. Saravanan and Nagarajan (2010) studied the effect of hydrogen admissions on diesel engine combustion as dual fuel by varying the hydrogen flow rates, injection timing, and duration. In dual-fuel operations, the smoke emissions were lower for the operations with low CO and CO_2 emissions. However, the HC and NO_x emissions were higher than single diesel but the brake thermal efficiency improved. Subramanian and Thangavel (2020) observed the diesel engine experiment combined with hydrogen and HHO gas. However, the experiment attempted several flow rate values of hydrogen and HHO into the intake port. The CO_2 emissions were significantly reduced while HC emissions decreased at high torque only and NO_x emissions significantly increased. Moreover, the brake thermal efficiency increased only with low flow rates of HHO gas injection. Kazim *et al.,* (2020) studied the diesel engine performance with oxy-hydrogen injection into the intake manifold with oxy-hydrogen flow rate, engine speed, and torque variations. The engine torque, power, and efficiency increased with oxy-hydrogen induction compared with diesel engines without oxy-hydrogen. Higher engine speed increased the engine performance which was observed due to the higher suction pressure.

The oxy-hydrogen gas injection into the diesel engine proved to significantly affect the engine performance and emissions. Besides, the oxy-hydrogen injection strategies are less attention to be studied, hence the extended discussion on this topic is limited. Several studies about gaseous fuel injection strategy found that it also impacts engine performance and emissions improvements (Felayati, Semin, Cahyono, *et al.,* 2021; Nguyen-Thi & Bui, 2023; Zaman *et al.,* 2019). However, the oxy-hydrogen injection strategy such as modifying the injector diameter on dual-fuel engines also possibly affects the engine performance and emissions. Thus, exploring oxy-hydrogen gas injection has a potential solution for decarbonizing diesel engines. In this study, the oxy-hydrogen gas injector diameter was varied to identify the effect on the engine performance and carbon emissions. An experiment was conducted with oxy-hydrogen injection into the engine intake port with direct diesel fuel injection. The oxy-hydrogen is produced from an oxy-hydrogen generator by water electrolysis. Moreover, the study was observed at low to medium engine load and low to high engine speeds. The engine performance and carbon emissions analysis are compared to diesel/oxy-hydrogen dual-fuel with single diesel fuel injection. Engine torque, specific fuel consumption, and thermal efficiency analysis were conducted for the performance, meanwhile, CO_2 and CO emissions analyses were studied for the carbon emissions.

2. Methodology

2.1 Experimental Setup

Direct-injection diesel engine with single-injection, four-stroke, and water-cooled configurations was used in this study. The diesel engine specification is shown in Table 1 and the experimental setup is shown in Figure 1. This setup uses a load system using an electrical load package, and an alternator (Shoda ST-5) which is connected to several lamps. The engine is connected to the alternator using pulleys and elastic belts. The load power was measured with a calibrated power monitor (Aventru). The exhaust emissions during the experiment were measured with an emissions detector for CO and CO_2 emissions (Stargas 898). A calibrated burrete (Vit Lab, ISO 385) was used to measure the diesel mass flow rate. The engine speed was indicated with a calibrated tachometer (DT-2234C) to the flywheel. Oxy-hydrogen gas was injected into the intake port and mixed with the airflow. This oxy-hydrogen was generated using an oxy-hydrogen generator (TRQ HHO Kit). Thus, the experiment was run in dual-fuel mode.

2.2 Fuels Injection and Supplies

This study used diesel fuel as the main fuel energy fraction, and oxy-hydrogen fuel was substituted into the combustion. Diesel

Table 1
Diesel engine specification

Specification	Details	Unit
Cylinder	Single cylinder	-
Combustion	4-stroke	-
Cooling system	Air-cooled	-
Bore	70	mm
Stroke	70	mm
Compression ratio	20.5:1	-
Maximum speed	2600	rpm

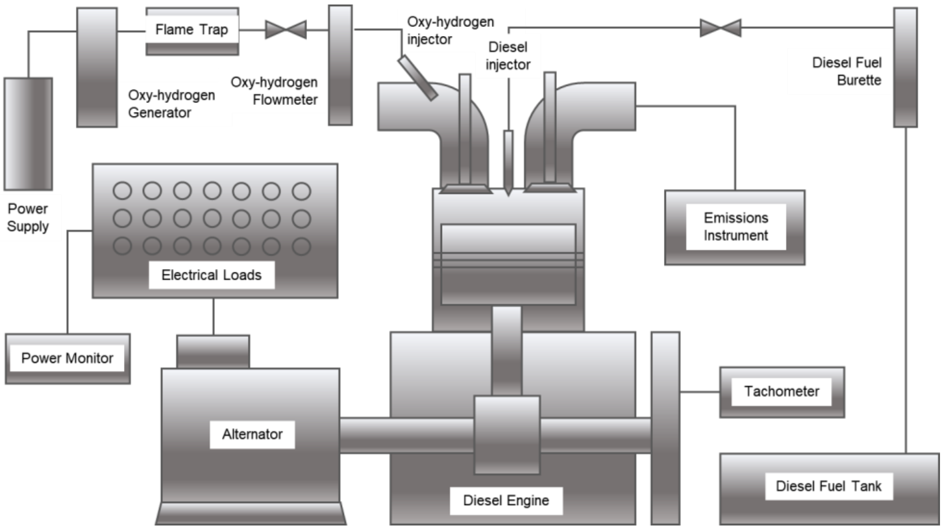

Fig 1 Experimental setup

Table 2
Diesel fuel specification

Fuel Characteristic	Value	Unit
Cetane number	51	-
Specific gravity (15°C)	815	kg/m^3
Viscosity (40°C)	2	mm^2/s
Flash point	52	°C

fuel specifications are given in Table 2, meanwhile, oxy-hydrogen fuel is mainly oxygen and hydrogen gases from the electrolysis process (Gad *et al.,* 2020; Khan *et al.,* 2021; Thangavel *et al.,* 2023). The diesel injection parameters were maintained at all experiment conditions as manufactured on the engine sets. However, the diesel injection was used as a conventional mechanical injection. Moreover, oxy-hydrogen gases were injected into the intake port using an injector. The position was fixed near the intake port to ensure the oxy-hydrogen gas freely entering to the combustion chamber., the oxy-hydrogen was produced using a hydrolysis system. The oxy-hydrogen generator used a 12-volt battery for the water hydrolysis which was mixed with potassium hydroxide (KOH) as an electrolyte. The oxy-hydrogen gas mass flow rate was maintained constant at a very low rate around 0.1 lpm. However, in this study, the injector diameter was varied into three diameters around 4 mm, 6 mm, and 8 mm. The oxy-hydrogen was injected into the whole cycle without a certain timing.

2.2 Test Condition

The engine was run in low load condition, specifically at 1 kW indicating a load about 25% from the maximum engine loads around 4 kW. Engine speeds were varied from 1400 to 2200 rpm on the same engine load condition. Each condition was tested for oxy-hydrogen injector diameter variations in dual-fuel conditions. The experiment was also performed with a single-fuel diesel as a reference to all experiment variations in dual-fuel mode. Note that the diesel injection was unmodified during the test as manufactured and only governed as achieving the load requirement. Table 3 shows the main test conditions for the study. The experiment was replicated five times to ensure experimental validity, especially on the engine performance.

Table 3
Test conditions

Engine load (kW)	Engine speed (rpm)	Oxy-hydrogen injector diameter (mm)
1	1400	4
	1800	6
	2200	8
2	1400	4
	1800	6
	2200	8

3. Result and Discussion

3.1 Effect of Oxy-Hydrogen Injector Variation at Low Load

3.1.1 Engine Performance

Figure 2 displays the effect of oxy-hydrogen injector diameter on the diesel/oxy-hydrogen engine torque in several engine speeds at low load compared with the baseline single diesel. It is important to note that the oxy-hydrogen gas production flow rates at those conditions were constant. At 1400 rpm shows that the engine torque decreased since the oxy-hydrogen was injected into the intake port. However, a longer oxy-hydrogen injector diameter decreases the engine torque at that engine speed by approximately 5.9% lower than the baseline at the 8 mm injector. In these low engine speeds, low diesel engine mass flow rates were injected into the combustion chamber, meanwhile, oxy-hydrogen gas injected into the intake port possibly prevents air from entering (Al-Dawody *et al.,* 2023). Diesel fuel was hard to ignite during the combustion thus the ignition was delayed and lowered the engine torque. Moreover, a higher oxy-hydrogen injector diameter lowered the gas velocity thus the air/oxy-hydrogen mixture was less

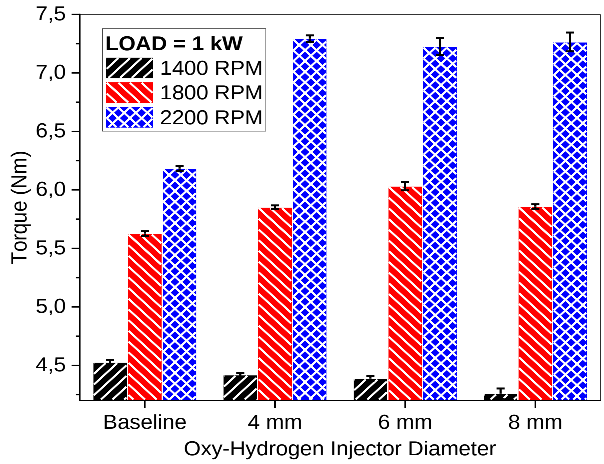

Fig 2 Effect of oxy-hydrogen injector diameter on engine torque at low engine load

homogenous increasing the ignition delay and lowering the engine torque as Ouchikh *et al.,* (2019) discussed in their research finding. Besides, the engine torque increased at 1800 rpm and 2200 rpm compared to the baseline case. At these engine speeds, higher diesel mass flow rates injected into the cylinder were sufficient enough to initiate the ignition even though oxy-hydrogen gas flows into the cylinder. The oxy-hydrogen gas also enriched the combustion phase thus lowering the combustion duration and then increasing the engine torque (Ouchikh *et al.,* 2019). High engine speed increased the airflow discharge then homogenously mixed with oxy-hydrogen gas. Kazim *et al.,* (2020) study also discussed this finding, the mixture of oxy-hydrogen and air affected the engine performance, besides it was ignoring the oxy-hydrogen injector size. The combustion quality increased and the engine torque followed. It was reported that the oxy-hydrogen injector diameter varied the effect on the engine torque. The best engine torque at 1800 rpm and 2200 rpm were with 6 mm and 4 mm oxy-hydrogen injector diameters, approximately 7.2% and 18% higher than the baseline, respectively. At 1800 rpm, the injection of oxy-hydrogen gas increased the engine torque, higher oxy-hydrogen injector diameter at 6 mm increased the engine torque but then slightly lowered it to 8 mm. It indicated that a proper oxy-hydrogen injector diameter was required to improve the combustion. But, at the very high engine speed at 2200 rpm, the oxy-hydrogen injector diameter seemed unrelated to the engine torque. All of the cases with oxy-hydrogen gas increased the engine torque compared with the baseline even slightly lower at 6 mm but it could be compromised.

Figure 3 depicts the engine-specific fuel consumption of a diesel engine combined with oxy-hydrogen gas injection with several oxy-hydrogen injector diameters at low load conditions and several engine speeds. Lower engine speeds required higher engine-specific fuel consumption as a consequence of the lower engine power output as represented by the engine torque (Figure 2). At 1400 rpm and 2200 rpm, the engine fuel consumption decreased at a 4 mm oxy-hydrogen injector diameter compared with the baseline of approximately 6.3% lower, but slightly increased with a higher oxy-hydrogen injector diameter (6 mm) then decreased with an 8 mm injector approximately 4.1% higher. Longer oxy-hydrogen injector diameter constantly decreased until 7.7% with an 8 mm injector of the fuel consumption at 1800 rpm. It indicated that the air/oxy-hydrogen mixture stratification at the intake port was complex (Arat *et al.,* 2016). The air/fuel mixture stratification highly affected the combustion quality (Felayati, Semin, & Cahyono, 2021). However, it indicated that the oxy-hydrogen gas injection on the diesel engine reduced the engine-specific fuel consumption in all conditions compared with diesel fuel only. The engine fuel consumption in Figure 3 was highly related to the thermal efficiency results in Figure 4. Higher engine fuel consumption indicated lower thermal efficiency. Shows in Figure 4 that the injection of oxy-hydrogen into the intake port increased the thermal efficiency even though there was a variation of thermal efficiency results as the variation on the oxy-hydrogen injector diameter at every engine speed. Higher engine speed increased thermal efficiency due to the lowered fuel consumption with higher engine power output. The highest thermal efficiency was at 1800 rpm with an 8 mm injector approximately 8.3% higher than the baseline.

In an overarching context, the performance of a diesel/oxy-hydrogen dual-fuel engine exhibited enhancements in low-load conditions with varying sizes of oxy-hydrogen injector orifices when compared to the baseline, i.e., a conventional diesel engine. This improvement was evidenced by an increase in torque during dual-fuel mode across all cases, particularly at

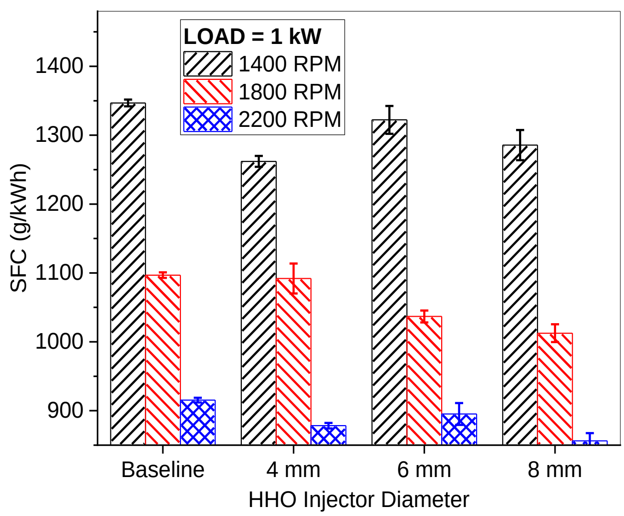

Fig 3 Effect of oxy-hydrogen injector diameter to engine-specific fuel consumption at low engine load

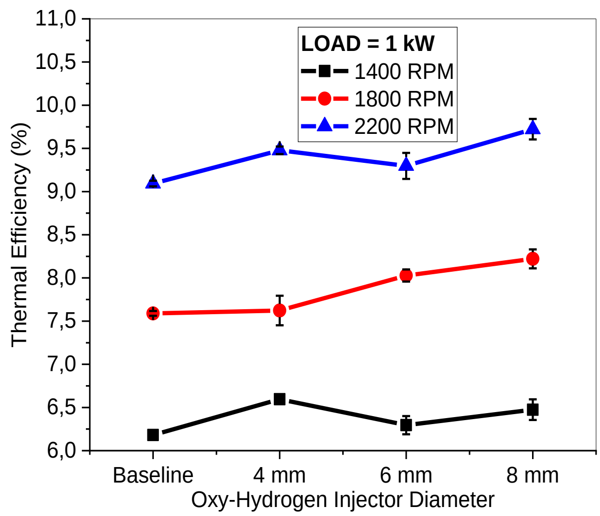

Fig 4 Effect of oxy-hydrogen injector diameter on engine thermal efficiency at low engine load

high engine speeds. Furthermore, fuel consumption and thermal efficiency experience a reduction in dual-fuel mode compared to single-fuel mode across all injector orifice sizes and engine speeds. This observation implied that the incorporation of oxy-hydrogen in diesel engines led to a more efficient combustion process, characterized by increased completeness. However, at low engine speeds, the addition of oxy-hydrogen results in a decrease in engine torque for all injector orifice variations. This phenomenon might be attributed to the oxy-hydrogen admixture in the intake port, which caused a stratification of the oxy-hydrogen mixture that could adversely affect the combustion process. Larger oxy-hydrogen injector orifices resulted in lower engine torque, indicating that larger orifices might lead to a deterioration in combustion pressure, subsequently reducing engine torque. Nevertheless, despite the decrease in pressure, combustion became more uniform, resulting in reduced fuel consumption and a more efficient combustion process. This suggests that the addition of oxy-hydrogen in diesel engines at low loads was more suitable for high engine speeds. Additionally, it was advisable to consider oxy-hydrogen injector orifices of moderate size to achieve efficient combustion processes with a relatively modest reduction in torque values.

3.1.1 Carbon Emissions

Figure 5 shows the effect of oxy-hydrogen injection on the diesel engine with several oxy-hydrogen injector diameters and engine speed conditions at low load on CO_2 emissions concentration. It shows that oxy-hydrogen injection increased CO_2 emissions in most cases. Higher CO_2 emissions indicated that the combustion of the carbon emissions increased. The oxy-hydrogen injection increased the diesel fuel mass burn which was contained with carbon bone as a consequence of hydrogen combustion with higher combustion temperature (Kanimozhi *et al.,* 2022). Moreover, more oxygen from oxy-hydrogen increased the initiation of the CO_2 emissions reactions (Gholami *et al.,* 2022a). However, the high CO2 emissions were generated with short and long oxy-hydrogen injector diameters, 4 mm, and 8 mm, respectively. Meanwhile, at the 6 mm oxy-hydrogen injector, the CO_2 emissions generated the lowest CO_2 emissions compared with the baseline of approximately 3.5% lower. But in some cases, it was still slightly higher than the

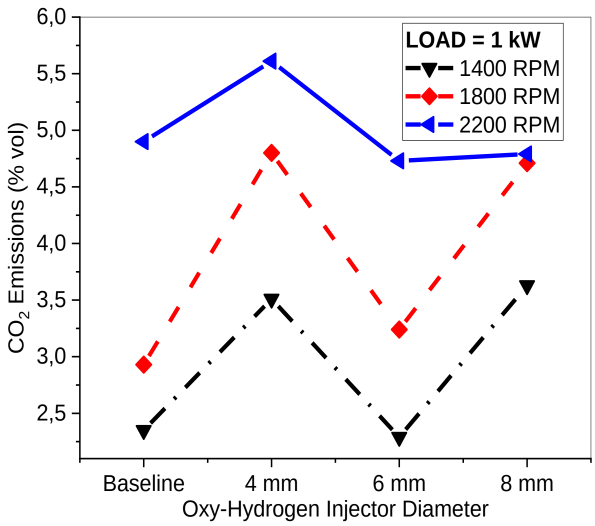

Fig 5 Effect of oxy-hydrogen injector diameter on engine CO_2 emissions at low engine load

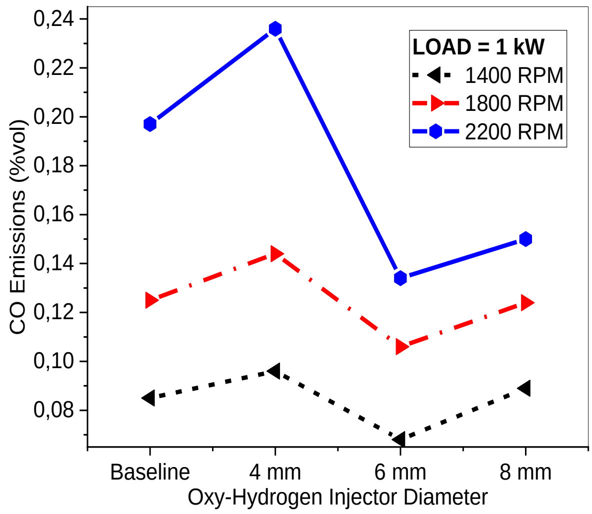

Fig 6 Effect of oxy-hydrogen injector diameter on engine CO emissions at low engine load

baseline such as at 1800 rpm. It indicated that more factors could affected this condition, not only from the thermal efficiency. However, the low CO_2 emissions at the 6 mm oxy-hydrogen injector with high thermal efficiency (Figure 4) probably due to the rapid combustion from the hydrogen combustion with most of the combustion process was slowly burning the diesel fuel. Further studies on the combustion characteristics are required for the extended analysis.

Figure 6 displays the CO emissions that are generated from the diesel engine combustion combined with oxy-hydrogen injection with several injectors and engine speed variations at low load conditions. It depicts that the oxy-hydrogen injection decreased the CO emissions with oxy-hydrogen injection in most cases, except with a 4 mm oxy-hydrogen injector. The CO emissions were generated from the uncompleted combustion due to lower oxygen concentration. This finding was also discussed in Köse & Ciniviz (2013) experiment which also identified the CO emissions of diesel/hydrogen dual-fuel engines. However, it shows that the lower oxygen concentration was due to the reaction to the CO_2 emissions (Figure 5). At 4 mm oxy-hydrogen injector cases, the CO_2 emissions were significantly high thus it probably reduced the oxygen concentration. Meanwhile, at 6 mm and 8 mm oxy-hydrogen injector cases the CO emissions significantly reduced and slightly increased but still lower than the baseline, approximately 32% lower and 23.9% lower compared to the baseline, respectively, especially at 2200 rpm. It indicated that at longer oxy-hydrogen injector diameters (6 mm and 8 mm) the rapid hydrogen combustion conducted after the diesel combustion with higher diesel fuel mass burned than short oxy-hydrogen injector diameter (4 mm). The carbon and oxygen reacted thoroughly at the rapid combustion phase thus increasing the CO_2 emissions while CO emissions were lower. However, the low CO and CO_2 emissions were favorable due to the low carbon emissions target from the internal combustion engine (Budiyanto *et al.,* 2022; Gholami *et al.,* 2022b).

Carbon emissions, encompassing both CO_2 and CO emissions from a diesel/oxy-hydrogen dual-fuel engine under low loads, exhibit a decrease when employing medium-sized oxy-hydrogen injector orifices compared to a single diesel configuration. Conversely, injector orifices that were either too small or too large resulted in an elevation of carbon emissions, particularly in CO_2 emissions. Concerning CO_2 emissions, the introduction of oxy-hydrogen into the diesel engine tended to escalate its concentration. In contrast, for CO emissions, the use of medium and large-sized oxy-hydrogen injector orifices decreased CO emissions compared to the single diesel configuration, with a significant reduction observed specifically for medium-sized injector orifices. This suggested an enhancement in the combustion zone's completeness within the combustion chamber with the addition of oxy-hydrogen gas to the diesel engine. The expansion of the perfect combustion zone led to an increase in the low-temperature zone around the combustion, indicating a rise in CO emissions. However, in this scenario, mitigating carbon emissions took precedence, and the implementation of medium-sized oxy-hydrogen injector orifices proved effective in substantially reducing carbon emissions compared to other orifice sizes.

3.2 Effect of Oxy-Hydrogen Injector Variation at Medium Load

3.2.1 Engine Performance

Figure 7 presents the engine torque on a diesel/oxy-hydrogen dual-fuel engine with several engine speeds and oxy-hydrogen injector diameter variations at medium load conditions. It shows that the engine torque was higher with oxy-hydrogen gas injection with a 4 mm oxy-hydrogen injector at all engine speeds compared with the single diesel baseline. The highest engine torque was at 1400 rpm and 4 mm injector approximately 3.3% compared to the baseline. However, the engine torque decreased at 6 mm and 8 mm oxy-hydrogen injector especially at 1800 rpm and 2200 rpm, while at 1400 rpm increased at 8 mm. As previously discussed, the shorter the oxy-hydrogen injector diameter the higher the oxy-hydrogen rate velocity. The 4 mm HHO injector at this medium load was more suitable to improve the engine torque. Air/oxy-hydrogen gas mixture tends to be more homogenous with a 4 mm oxy-hydrogen injector than the longer diameter. This was possibly due to the higher turbulent intensity of the higher velocity oxy-hydrogen injection into the intake port (Rajak *et al.,* 2022). The air/oxy-hydrogen mixture was sufficiently enough to burn hydrogen after the diesel ignition thus higher engine torque was achieved. Significantly reduced engine torque at 6 mm and 8 mm

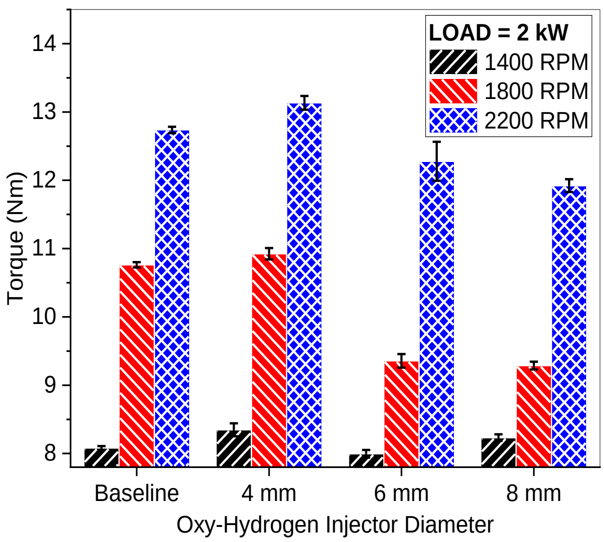

Fig 7 Effect of oxy-hydrogen injector diameter on engine torque at medium engine load

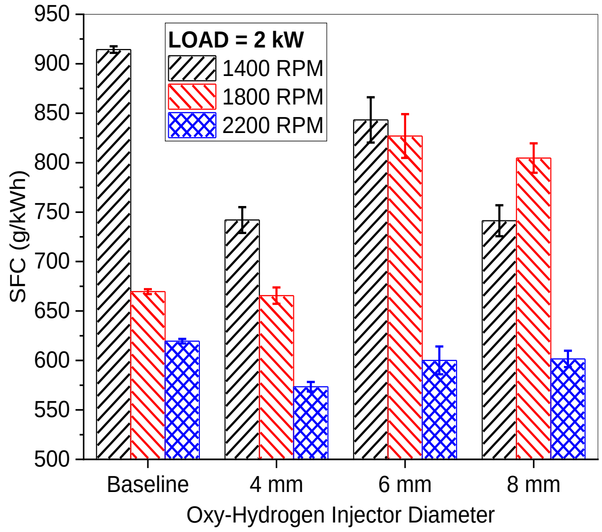

Fig 8 Effect of oxy-hydrogen injector diameter on engine-specific fuel consumption at medium engine load

indicated that the oxy-hydrogen gas injection prolonged the diesel ignition delay (Ouchikh *et al.,* 2019), especially at high engine speeds. Nevertheless, lower engine speeds allowed the hydrogen to be burned with less delay after the diesel combustion thus slightly increasing the engine torque.

Figure 8 shows the engine-specific fuel consumption of a diesel engine with oxy-hydrogen injection into the intake port at medium engine load. However, at low and high engine speeds (1400 rpm and 2200 rpm) the oxy-hydrogen injection reduced the engine-specific fuel consumption with a maximum reduction of approximately 18.9% and 7.4% compared with the baseline, respectively. But at medium engine speeds (1800 rpm) the fuel consumption increased to 23.5% at 6 mm injector compared with the single diesel baseline. The short oxy-hydrogen injector seems favorable due to the high contribution to the low fuel consumption than other oxy-hydrogen injector diameters. At all of the engine speeds, the longer oxy-hydrogen injector increased the fuel consumption then slightly reduced with the longest oxy-hydrogen injector diameter. The longer oxy-hydrogen injector diameter decreased the engine power output as represented by the engine torque (Figure 7), Dimitriou & Tsujimura (2017) discussed that it was a consequence of the diesel fuel's difficulty igniting at the early injection. It was highly related to thermal efficiency as shown in Figure 9 which indicated the combustion energy of the engine power. As shown in Figure 9, the oxy-hydrogen injection increased the thermal efficiency by approximately 23.3% and 8% higher compared to a single diesel baseline at 1400 rpm and 2200 rpm with 8 mm and 4 mm injector diameters, respectively. Higher engine power output with low engine-specific fuel consumption was the main factor in this result. As discussed previously, at 1800 rpm the engine torque was higher than the baseline at a longer oxy-hydrogen diameter injector and the specific fuel consumption was relatively high thus it decreased the thermal efficiency.

Nevertheless, the comprehensive performance of the diesel/oxy-hydrogen dual-fuel engine under medium loads exhibits enhancement when utilizing smaller oxy-hydrogen injector orifices, specifically sized at 4 mm, in contrast to the engine performance fueled solely by diesel. The reduced size of the oxy-hydrogen injector orifice elevated engine torque across all engine speeds, whereas larger injector orifices led to a

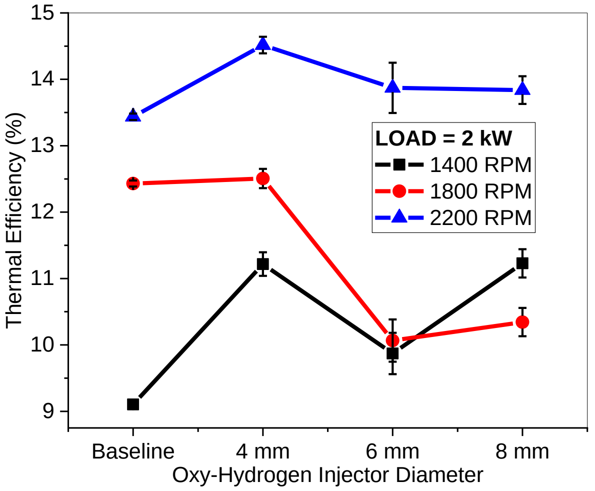

Fig 9 Effect of oxy-hydrogen injector diameter on engine thermal efficiency at medium engine load

notable decrease in most torque values. The injection of oxy-hydrogen fuel into the intake port remained consistent with the low-load scenario, while diesel fuel injection increased with the escalating load under medium conditions. Fuel energy demands were higher at medium loads compared to low loads. On the flip side, lowering the size of the oxy-hydrogen injector orifice resulted in increased oxy-hydrogen flow rates by the principle of continuity. The accelerated flow rates contributed to a more homogeneous mixture of oxy-hydrogen and air, providing advantages during the combustion process by ensuring uniformity and generating higher cylinder pressures. Consequently, this led to increased torque values, improved thermal efficiency, and reduced fuel consumption. Conversely, larger oxy-hydrogen injector orifices diminished the homogeneity of the oxy-hydrogen and air mixture, potentially exacerbating the combustion process.

3.2.1 Carbon Emissions

Figure 10 shows the CO_2 emissions measured from the experiment with diesel/oxy-hydrogen fuel which was compared

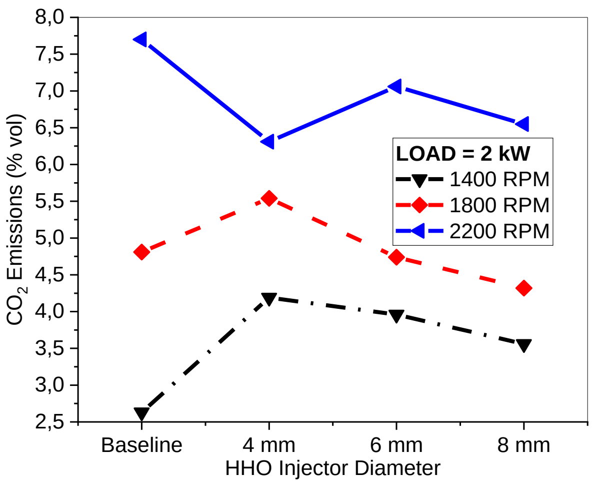

Fig 10 Effect of oxy-hydrogen injector diameter on engine CO_2 emissions at medium engine load

with single diesel at medium load conditions, at several oxy-hydrogen injector diameters, and several engine speeds. It depicts that oxy-hydrogen gas injection varied the CO_2 emissions concentration. Higher engine speeds with oxy-hydrogen injection decreased the CO_2 emissions compared with the single diesel. At 1400 rpm, the diesel engine's CO_2 emissions with oxy-hydrogen gas injection were higher than the engine without oxy-hydrogen gas injection at all oxy-hydrogen injector diameters but higher injector diameter decreased the CO_2 emissions exponentially. At 1800 rpm engine speed, the CO_2 emissions also decreased with the higher diameter of the oxy-hydrogen gas injector, but at 4 mm injector diameter the CO_2 emissions were higher than the baseline. Meanwhile, at 2200 rpm engine speeds, the CO_2 emissions with oxy-hydrogen gas injection were decreased compared with the baseline at all oxy-hydrogen injector diameters. The lowest CO_2 emissions were approximately 18.1% lower than the baseline at 2200 rpm with a 4 mm injector diameter. It indicated that the higher engine speeds with medium load lower the CO_2 emissions with oxy-hydrogen injection than single diesel and it could be optimized with a higher oxy-hydrogen gas injector size.

High engine speeds affected the airflow discharges thus the oxy-hydrogen gas mixing intensity increased and the oxy-hydrogen/air mixture was more homogenous (Khan *et al.*, 2021). In theory, the homogenous mixture can increase the combustion quality thus complete combustion can be achieved the CO_2 emissions will be higher. However, in this case, the CO_2 emissions decreased with high thermal efficiency thus it could be identified that rapid hydrogen combustion was possibly the main reason behind this phenomenon. The diesel injection on the oxy-hydrogen/air gas mixture initiated the ignition and then spontaneously burned (Paparao & Murugan, 2021). The high engine torque and thermal efficiency were achieved due to the high pressure on oxy-hydrogen gas combustion, but the late diesel mass injection was incompletely burned then CO_2 emissions decreased. Moreover, a higher oxy-hydrogen injector diameter allowed the oxy-hydrogen/air mixture turbulence intensity to be low thus the mixture stratification was achieved (Park *et al.*, 2019). The rapid combustion of hydrogen after the diesel ignition allowed a richer mixture zone thus higher CO_2 emissions were achieved (Felayati, Semin, & Cahyono, 2021). Furthermore, it could be identified in Figure 11 that this condition was highly related. The CO emissions were also produced with carbon which was from the diesel combustion assisted with hydrogen combustion after the diesel ignition. However, the CO emissions were produced from incomplete combustion (Hariharan *et al.*, 2021). In summary, the configuration of the diesel engine operating conditions was highly related to the utilization of the oxy-hydrogen gas injection parameter. The lowest CO emissions in medium load were approximately 41.2% lower than the baseline at 2200 rpm and 4 mm injector diameter.

In the aggregate, carbon emissions produced by the diesel/oxy-hydrogen dual-fuel engine under medium loads exhibit an overall increase, particularly in CO_2 emissions that dominate over CO emissions. Nevertheless, at high engine speeds (2200 rpm), CO_2 emissions decreased, with the most significant reduction observed when employing smaller oxy-hydrogen injector orifices compared to using only diesel fuel. This phenomenon could be attributed to efficient and uniform combustion, potentially resulting in a faster combustion process at elevated temperatures due to the lean mixture of air and fuel. Consequently, carbon emission outcomes were diminished at high engine speeds with the addition of oxy-hydrogen to the combustion process. However, it was noteworthy that carbon

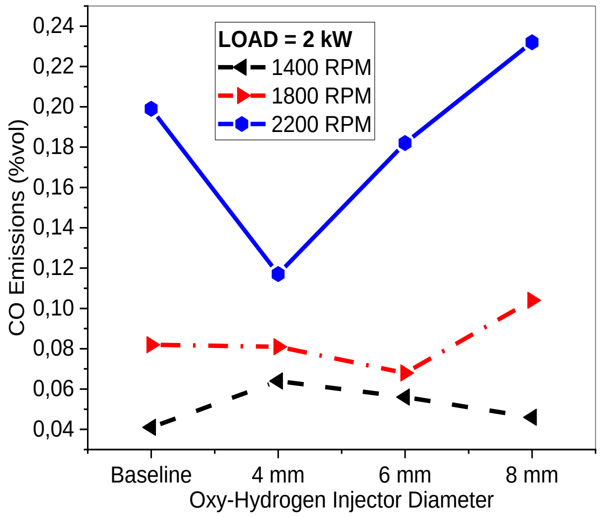

Fig 11 Effect of oxy-hydrogen injector diameter on engine CO emissions at medium engine load

emissions at high engine speeds surpassed those at low engine speeds, which was expected considering the higher mass of diesel fuel injection used at higher speeds as also studied by Henke *et al.,* (2018) and Yousefi *et al.,* (2019). Furthermore, a more in-depth and detailed investigation is warranted to discern and understand the intricacies of the combustion phenomena occurring within the combustion chamber.

3.3 Study Limitations and Future Works

The study exhibits several limitations that warrant consideration. Firstly, the investigation predominantly focused on low to medium load conditions and specific engine speeds, thereby limiting the breadth of its applicability. To offer a more comprehensive understanding, future research should encompass a broader range of operating conditions, including high loads and diverse engine speeds. Additionally, while the study examined the impact of oxy-hydrogen gas injector diameter on engine performance, a more exhaustive exploration across a wider range of injector sizes is essential for determining optimal dimensions for varying engine loads and speeds. Furthermore, the study assumed a single type of diesel fuel, potentially overlooking variations in responses to oxy-hydrogen gas injection among different diesel compositions. To enhance the generalizability of the findings, future investigations should explore the effects of a variety of diesel formulations. Finally, although the study discussed CO_2 and CO emissions, a more comprehensive analysis of other pollutants, such as NO_x and particulate matter, would provide a more holistic assessment of the environmental implications of oxy-hydrogen gas injection.

Several avenues for future research emerge from the identified limitations. Firstly, there is a need for studies that encompass a broader spectrum of engine operating conditions, ensuring a more realistic and diversified assessment. Exploring the effects of oxy-hydrogen gas injection with different types of diesel fuels, considering variations in chemical composition and cetane numbers, would enhance the applicability of the findings. Additionally, an extension of the emissions analysis to include other pollutants would offer a more complete evaluation of the environmental impact. Finally, in-depth research into the combustion characteristics of oxy-hydrogen gas is essential. This involves detailed studies on ignition timing, flame propagation, and overall combustion stability to identify the optimal mixture conditions for efficient combustion.

Notwithstanding the limitations, the study makes significant contributions to the understanding of oxy-hydrogen gas injection in diesel engines. Firstly, it underscores the potential of oxy-hydrogen gas to enhance engine performance and reduce carbon emissions, emphasizing the importance of rapid hydrogen combustion following diesel ignition. Secondly, the study identifies that high performance and low carbon emissions can be achieved at high engine speeds, particularly in low and medium engine load cases. This insight can guide future engine design and operation strategies. Lastly, the study suggests that the choice of oxy-hydrogen gas injector diameter is critical, with smaller diameters proving more effective at higher engine loads. This information is crucial for designing efficient oxy-hydrogen injection systems.

Overall, while the study provides valuable insights, addressing the identified limitations and pursuing the recommended avenues for future research will further advance the understanding of oxy-hydrogen gas injection in diesel engines and enhance its potential for achieving zero emissions.

4. Conclusion

An experimental study was conducted on a diesel engine fueled with both diesel and oxy-hydrogen gas, compared to running solely on diesel. The study encompassed low to medium load conditions, various engine speeds, and different oxy-hydrogen gas injector diameters. Oxy-hydrogen gas was introduced into the intake port, while diesel fuel was injected into the combustion chamber. The effects on engine performance and carbon emissions were thoroughly investigated, focusing on engine torque, specific fuel consumption, thermal efficiency, as well as CO_2 and CO emissions. Overall, the injection of oxy-hydrogen gas into the diesel engine combustion process demonstrated a notable enhancement in engine performance along with a reduction in carbon emissions. The rapid combustion of hydrogen after diesel ignition was perceived as the pivotal factor driving this improvement.

Under low load conditions, an 8 mm oxy-hydrogen injector diameter proved optimal for maximizing engine performance. Notably, engine torque increased by 18% at 2200 rpm, specific fuel consumption decreased by 7.7% at 1800 rpm, and thermal efficiency increased by 8.3% at 1800 rpm compared to the baseline. Additionally, lower carbon emissions were achieved with a 6 mm oxy-hydrogen injector diameter, leading to a 3.5% reduction in CO_2 emissions at 1800 rpm and a 32% reduction in CO emissions at 2200 rpm.

During medium load conditions, a 4 mm oxy-hydrogen injector diameter demonstrated greater advantages for engine performance. Engine torque increased by 3.3% at 1400 rpm, specific fuel consumption decreased by 18.9% at 1400 rpm, and thermal efficiency increased by 23.3% at 1400 rpm. Moreover, significant reductions in CO_2 and CO emissions were observed, with decreases of 18.1% and 41.2% respectively at 2200 rpm with a 4 mm oxy-hydrogen injector diameter.

Furthermore, while both 6 mm and 8 mm oxy-hydrogen gas injector diameters were suitable for low engine loads, the 4 mm diameter proved more effective for medium engine loads, offering improvements in both engine performance and carbon emissions. Proper selection of the oxy-hydrogen gas injector diameter was crucial for maintaining oxy-hydrogen/air mixture stratification.

This study underscores the potential of oxy-hydrogen gas injection in diesel engines to enhance performance and reduce carbon emissions towards achieving zero emissions. Further research is warranted to elucidate the optimal mixture conditions conducive to oxy-hydrogen gas combustion, with potential applications in various fuel combustion combinations.

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