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Research Paper

Experimental Analysis of the Influence of a Compressed Natural Gas (CNG) - Air Mixer on Performance and Emissions in Partial Load CNG-Diesel Dual Fuel Engines

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Abstract

The shipping industry is one of the contributors to global emissions that has received particular attention due to the increasing demand for maritime transportation services. The use of natural gas is considered a potential solution due to its relatively clean nature, abundant availability, and competitive pricing. The CNG-Diesel Dual Fuel Engine design is developed with the principle of using natural gas as an alternative fuel without replacing the existing diesel engine. Minimal modifications are made to the intake manifold to accommodate CNG entry. Despite its advantages, the development of dual fuel engines faces challenges, such as increased methane emissions due to the potential for incomplete combustion. This study conducts experimental research on the influence of mixer and non-mixer utilization in the intake manifold on the performance and emissions of a diesel-CNG dual fuel engine."Testing the mixer's influence is carried out under various CNG injection durations at low and high engine loads at constant speeds. The results indicate that the addition of the mixer does not immediately improve combustion quality or reduce emissions. Attention to conditioning the homogenous mixture at the required air-fuel ratio before entering the combustion chamber is crucial. The selection of the appropriate mixer design, diameter size, and placement of holes needs careful consideration.

Keywords: Combustion homogeneity; CNG, Dual Fuel Engine; Emission reduction; Global climate change; Venturi-like mixer

1. Introduction

The maritime transportation sector is the most reliable sector in global logistics delivery, with extremely large vessel sizes capable of accommodating large quantities of cargo. The continuous improvement in efficiency has led to an estimated 101% increase in cargo traffic volume over the past 20 years. This trend is directly proportional to the expected increase in emissions, which are projected to rise by up to 40% [1], [2]. However, when compared to other modes of transportation in the supply chain, shipping ranks lowest in emissions. In their statements [3], [4] t is explicitly stated that emissions are mainly caused by fuel usage, which accounts for 50% of shipping operational costs. The selection of fuel and more environmentally friendly fuel technologies is crucial in de-carbonization efforts and zero-carbon programs. Current data indicates that shipping currently contributes to 3% of total carbon dioxide emissions [5] and although this figure is not as significant as sulfur emissions at 15% and particulate emissions at 11%, it remains a serious concern due to its impact on global warming and climate change.

The increasing demand for environmental protection standards has driven the International

Maritime Organization (IMO) to monitor and tighten regulations related to emissions generated by maritime activities and shipping. Through the International Convention for the Prevention of Pollution from Ships (MARPOL) in 1997 and subsequent revisions in 2005, Annex VI on the prevention of air pollution was established. This annex aims to minimize greenhouse gas emissions, as well as other gas emissions, and prevent adverse effects of pollution on the environment and human health [6], [7]. IMO policies and regulations focus on implementing operational measures and technical steps to enhance energy efficiency on ships, including the use of alternative energy sources [8].

Natural gas is one of the alternative fuels offering lower emissions compared to current liquid fossil fuels [9]–[12]. Its relatively clean nature, with emissions of sulfur oxides (SOx) and particulates meeting standards, makes it a breath of fresh air for the development of alternative fuel use in shipping [13]. Additionally, the competitive pricing of natural gas compared to low-sulfur fossil fuels serves as a positive driver for its adoption in the maritime industry [14], [15]. However, the use of natural gas still poses climate change issues. The methane content in natural gas, a byproduct of incomplete combustion or methane slip, increases the potential for greenhouse gas effects, which are several times more potent than carbon dioxide at equivalent levels [16], [17]. Moreover, the potential for methane leakage during production and transportation processes presents challenges and contributes to climate change issues [18], [19]. In its operations, natural gas can function as a single fuel with spark ignition or as a dual fuel with compression ignition.

Dual fuel diesel natural gas is one of the technological breakthroughs emerging as a response to de-carbonization challenges. By making slight modifications to diesel engines, such as installing a gas converter in the intake manifold, natural gas can be utilized as the primary fuel with diesel as the pilot fuel. Several previous studies on dual fuel diesel-natural gas engines, such as [20]–[22] have indicated that this technology is acceptable in terms of performance and emissions. However, some research has highlighted weaknesses in the dual fuel system, such as methane slip and knocking, especially under low load conditions [23], [24] The possibility of natural gas pressure in the combustion chamber reducing oxygen availability increases the likelihood of incomplete combustion. Some researchers have conducted studies to help address these issues, as demonstrated by [25] who attempted to reduce methane slip with premixed micro pilot [23], by adding O^2, and [17] by adjusting gas injection.

Knocking is a phenomenon closely associated with incomplete combustion in compression engines. The occurrence of knocking in dual fuel engines can be attributed to several factors and is highly dependent on temperature, pressure, fuel characteristics, mixture composition, and mixing time span [24]. Knocking has the potential to transpire during the incomplete combustion process. It is partly induced by the presence of unburned mixtures at high pressure and temperature, creating favorable conditions for pre-ignition formation [26]. Regarding the use of CNG, it has been observed that CNG exhibits the highest resistance to knocking compared to LPG and LNG, which can be understood in relation to the fuel's characteristics corresponding to its composition [27].

The use of a mixer enables mixing and interaction between CNG and air before entering the combustion chamber. Combustion efficiency, engine performance, air-fuel ratio, and emission reduction are directly proportional to the degree of mixture homogeneity. Studies on mixer utilization [28], [29] conducted using computational fluid dynamic (CFD) methods indicate that mixer performance needs to be optimized to achieve the desired homogeneity under the appropriate air-fuel ratio conditions before entering the combustion chamber. This often triggers an increase in fuel consumption and emissions levels in the engine.

This article will demonstrate the experimental influence of adding a venturi mixer model to a laboratory-scale CNG-Diesel Dual Fuel prototype on performance and emissions, with variations in CNG injection duration, low and high load conditions, at constant engine speed.

2. Experimental Set-Up

The experimental stages conducted in this study can be outlined as follows. In the first step, testing was performed on a single-cylinder

Yanmar TF 85 diesel engine with a displacement volume of 493 cm^3 and a compression ratio of 18:1. Testing involved conditioning premixed air and non-premixed air at various loads and speeds. Test results included engine performance and emissions. Subsequently, modifications were made to the intake manifold, and a gas converter was added to the diesel engine. Natural gas injection was controlled by an electronic control unit (ECU). Below are the specifications of the engine and fuel properties used.

The testing was conducted under two conditions: low load and high load. During the testing, an additional venturi-like mixer unit was installed Figure 2b. Testing was performed at various loads and natural gas injection durations. Below is the configuration of the dual fuel engine setup with the mixer unit Figure 1, along with the previously designed laboratory-scale prototype Figure 2a. To ascertain the significance of changes and the influence of the parameters on the performance and emissions generated, the data is presented in two major groups: comparison of single fuel performance as a baseline, CNG-Diesel Dual Fuel with and without mixer at low and high loads, and comparison of single fuel emissions as a baseline, CNG-Diesel Dual Fuel with mixer (referred to as premixed) and without mixer (referred to as non-premixed) at low and high loads. The variations in CNG injection duration utilized were 5 Ms, 7.5 Ms, and 10 Ms, all observed at a constant engine speed of 1800 RPM. The injection pressure of CNG fuel remains constant at 2 bar, with the dominant influence on the amount of CNG fuel entering the intake manifold being the injection duration setting. Code A was used for low load conditions, and code B for high load conditions. Code 1 for 5 Ms, code 2 for 7.5 ms and code 3 for 10 ms. A1 signifies an injection duration of 5 milliseconds under low load conditions. A2 signifies an injection duration of 7.5 milliseconds under low load conditions. A3 signifies an injection duration of 10 milliseconds under low load conditions. B1 signifies an injection duration of 5 milliseconds under high load conditions. B2 signifies an injection duration of 7.5 milliseconds under high load conditions. B3 signifies an injection duration of 10 milliseconds under high load conditions.

The testing was conducted experimentally with a testing scheme as outlined in Table 1. The data collection phase commenced with preparation, involving a preheating period of approximately 30 minutes prior to data acquisition. The tests were performed under two conditions: with and without a mixer. The rotational speed setting was maintained constant at 1800 RPM. The initial testing utilized dex diesel fuel as single fuel data, followed by dual fuel Dex-CNG testing involving variations in CNG injection duration. The properties of the two fuels can be seen on Table 2. The CNG ECU settings were adjusted manually. The distribution of injection duration data in the system ranged from 0 to 10 milliseconds. Parameters considered for analysis were 5, 7.5, and 10 milliseconds, representing intermediate to maximum durations, correlating with an increase in the amount of CNG entering the combustion chamber with increasing injection duration values. Engine loading was achieved using lamps with a 1000-watt increment. Current and voltage values were obtained from

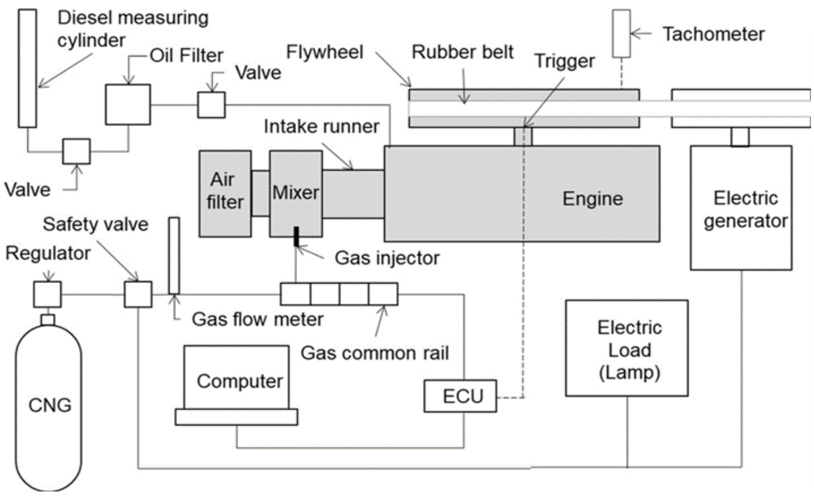


Figure 1. The configuration of dual fuel engine + mixer

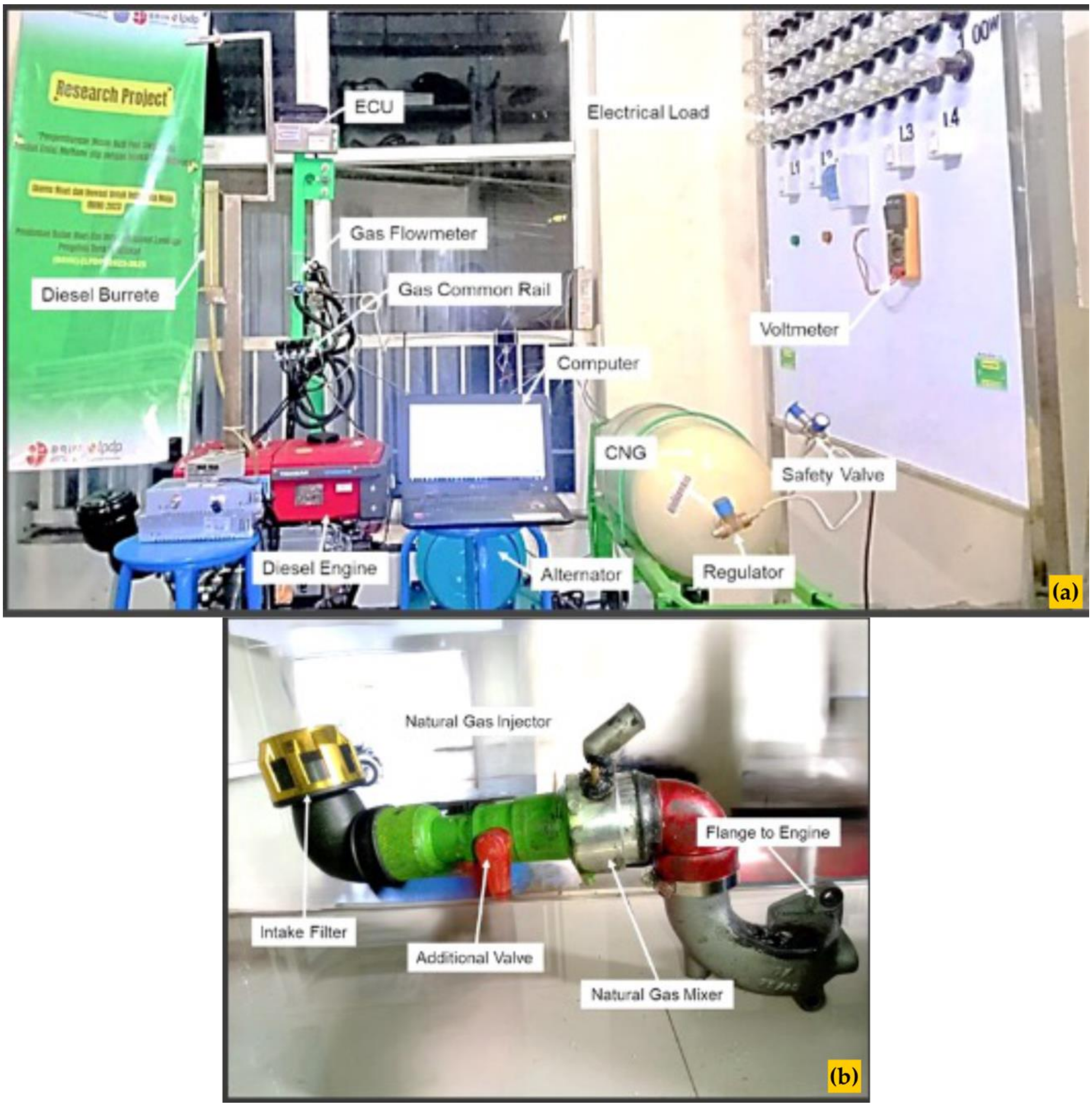


Figure 2. Prototype in lab scale of dual fuel engine (a) and mixer unit (b)

Table 1. Main engine characteristic

Characteristic	Value (m)
Engine type	DI – 4 stroke, natural aspirated, water cooled
Bore x Stroke (mm)	85 x 87
Volume Displacement (cm^3)	493
Diesel Injection Pressure (kg/cm^2)	200
Diesel Injection Timing °CA TDC	-18
Compression Ratio	18:1
Cylinder	1

Table 2. Fuel properties

Properties	Diesel Oil	CNG
Molar mass (kg/kmol)	200	16.04
Density (kg/m^3)	840 (l)	0.72 (g)
Stoichiometric A/F	14.7	17.2
Auto ignition C	254-285	595
LHV (Mj/kg)	42.61	47.14
HHV (Mj/kg)	45.58	52.23

digital multimeter readings, subsequently utilized to calculate engine performance metrics such as power, BMEP, torque, and SFC. The data collection process proceeded sequentially, starting from CNG injection duration variations of 5 to 10 milliseconds under loads of 1000 watts (representing low load) and 4000 watts (representing high load). Emission data were collected concurrently with engine performance data using a gas analyzer, including HC, CO, and NOx data points, considered representative at low to high loads, during single fuel and dual fuel (varied CNG injection duration) conditions, and with mixer and non-mixer setups. The spesifications of the measuring instrument is presented on **Table 3**.

3. Results and Discussion

3.1. Engine Performance; Single Fuel Baseline, Dual Fuel Mixer – Non Mixer

3.1.1. Engine Power

Figure 3 illustrates the influence of injection duration variation on engine power under low load conditions, where the loading is conducted at 1000 watts of testing load, and high load conditions, where the loading is conducted at 4000 watts of testing load. The figure depicts the power conditions at baseline, representing the engine operation with single fuel, and the power conditions under dual fuel operation at various injection duration variations: 5 ms (1), 7.5 ms (2), and 10 ms (3). Additionally, the figure shows the difference between system operations with the use of a mixer and without a mixer.

Generally, increasing the engine load correlates with an increase in engine power. However, in the transition from single fuel as a baseline to dual fuel, there is a slight decrease in the generated power. This occurs because the engine maintains a constant speed by adding diesel fuel; when CNG enters the combustion chamber, there is a decrease in rotational speed. The influence of injection duration is not significantly altering the power required at both low and high loads at constant speed. Changes in injection duration only affect power by 1 – 1.5%, either in decrease or increase. The addition of a mixer slightly causes a decrease in power, but it is

Table 3. The specification of the measuring instrument

Device	Property
QRETECH Gas Analyser	CO : 0.00~ 9.99%, HC : 0~ 9999ppm CO2 : 0.0~ 20.0% O2 : 0.0~ 25.0% Lamda : 0.000~ 2.000 AFR : 0.0~ 99.0%
Burrete Meter	0 – 100 ml
Multimeter Digital	
Flowmeter	1 - 25 L/Min,20' C 0.15 MPa

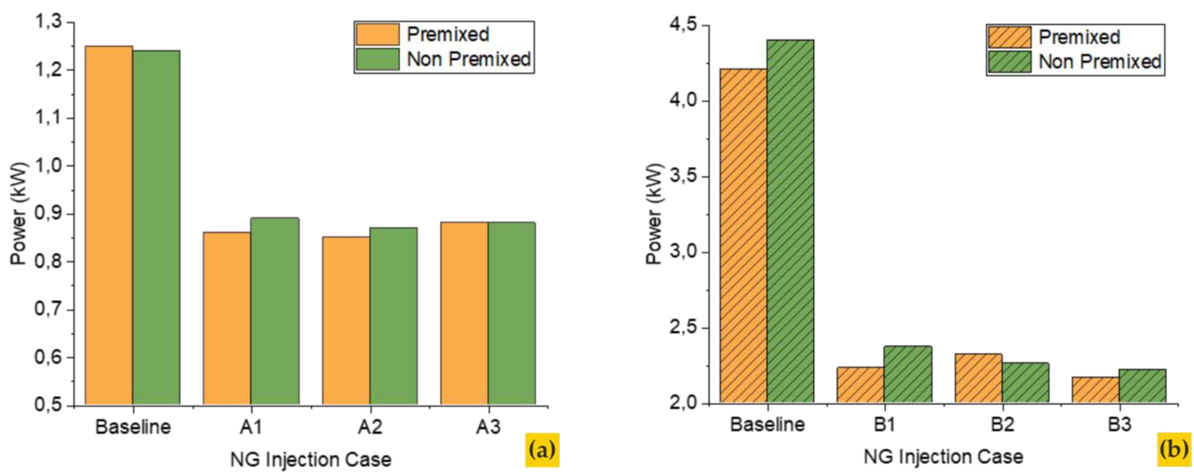


Figure 3. Engine Power baseline, dual fuel mixer-non mixer low load (a) and high load (b)

not significant. The power decrease observed after transitioning to dual fuel mode is attributed to the engine speed being maintained constant in both operational models, whether single fuel or dual fuel. The decline in power data following the shift to dual fuel mode is due to the introduction of CNG into the intake manifold, which cannot be balanced with the available oxygen for combustion. This results in incomplete combustion, as evidenced by the significant increase in HC and CO emissions in **Figure 5** and **Figure 6**. The addition of diesel fuel alone is insufficient to counteract this power decrease. Interventions such as air supply through a supercharger, as conducted in prior research [30], demonstrate that in dual fuel scenarios, the oxygen requirement increases, necessitating specific interventions to maintain the air-fuel ratio (AFR) before entering the combustion chamber.

3.1.2. *Thermal Efficiency*

Figure 4 illustrates the influence of injection duration variation on thermal engine efficiency under low load conditions, where the loading is conducted at 1000 watts of testing load, and high load conditions, where the loading is conducted at 4000 watts of testing load. The figure showcases the power conditions at baseline, representing the engine operation with single fuel, and the thermal efficiency conditions under dual fuel operation at various injection duration variations: 5 ms (1), 7.5 ms (2), and 10 ms (3). Additionally, the figure shows the difference between system operations with the use of a mixer and without a mixer.

Generally, thermal efficiency increases with engine load. The increase in thermal efficiency of this dual-fuel engine is low at low loads but significantly higher at higher engine loads because at low loads, the air-fuel ratio of the air-CNG mixture becomes very low in incomplete combustion propagation, and most of the fresh air-gas mixture remains unburned. At higher engine loads, the air-fuel ratio decreases, resulting in complete combustion and increased thermal efficiency. This is consistent with research conducted by [31]. Based on the test data, there is an increase in thermal efficiency from low to high load by 7% for a 5 Ms injection duration, 13% for 7.5 Ms, and 7% for 10 Ms.

From the test results, it is observed that the addition of a mixer generally decreases the thermal efficiency at both low and high load conditions. The mixer's inability to condition the mixture to the required air-fuel ratio before entering the combustion chamber results in unstable combustion quality. This is evident at low loads, where a 10 Ms CNG injection duration shows an increase in thermal efficiency of up to 6% compared to without the mixer and 11% compared to the baseline. Similarly, at high loads, a 10 Ms CNG injection duration also shows an increase in thermal efficiency of 5% compared to without the mixer. The improper design of the mixer exacerbates flow characteristics and obstacles in oxygen intake, worsening the AFR values due to the decreasing oxygen supply. This results in incomplete combustion, leading to a decrease in power in **Figure 3** and an increase in HC and CO emissions in **Figure 5** and **Figure 6**. The power decrease will be linear with the decrease in thermal efficiency. It is not easy to determine the appropriate mixer design for dual fuel engines.

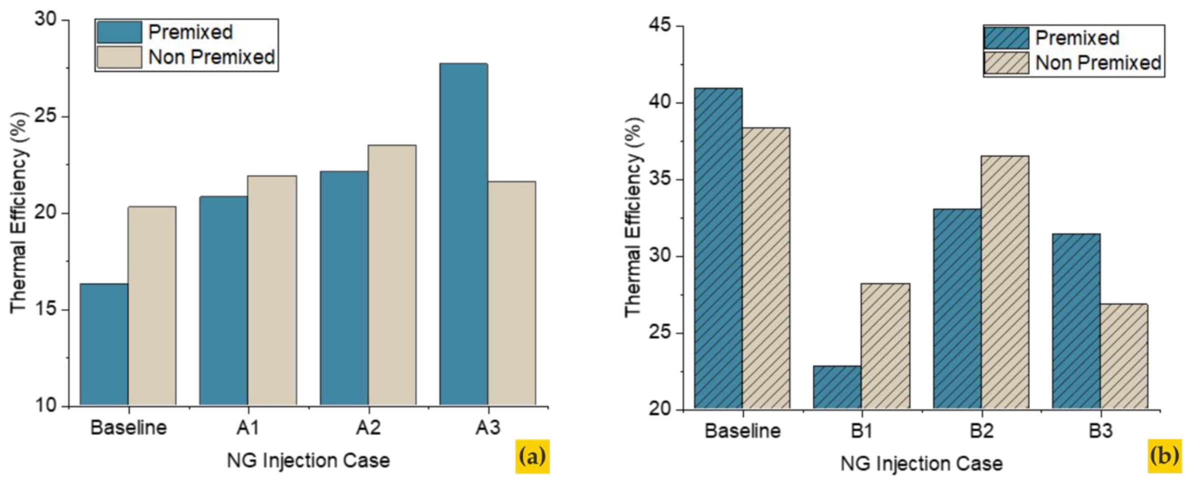


Figure 4. Thermal efficiency baseline, dual fuel mixer-non mixer low load (a) and high load (b)

Problem always arise in the form of the inability to prepare a homogeneous air-fuel mixture at specific air-fuel ratios before entering the engine [32].

Figure 4a presents the thermal efficiency display graph of the baseline, dual fuel with mixer, and dual fuel without mixer under low load conditions (A), while **Figure 4b** represents the thermal efficiency display graph of the baseline, dual fuel with mixer, and dual fuel without mixer under high load conditions (B).

3.2. Emision; Single Fuel baseline, Dual Fuel Mixer – Non Mixer

3.2.1. HC Emission

Figure 5 depicts the influence of injection duration variation on HC emissions under low load conditions, where the loading is conducted at 1000 watts of testing load, and high load conditions, where the loading is conducted at 4000 watts of testing load. The figure illustrates the HC emission conditions at baseline, representing the engine operation with single fuel, and the HC emission conditions under dual fuel operation at various injection duration variations: 5 ms (1), 7.5 ms (2), and 10 ms (3). Additionally, the figure shows the difference between system operations with the use of a mixer and without a mixer.

From the test results, there is a significant increase in HC emissions in the dual fuel engine system compared to the baseline. At low engine loads, HC emissions increase within the range of 97.6% to 98.7% with increasing CNG injection duration from 5 Ms to 10 Ms. Meanwhile, at high engine loads, HC emissions increase by 97.1% to 97.8% with increasing CNG injection duration. In the dual fuel engine system, the presence of CNG with a majority composition of methane CH4 increases the potential for HC emissions compared to the baseline condition where the engine is only fueled by diesel. Increasing the CNG injection duration from 5 Ms to 10 Ms has increased HC emissions by 46%. The significant increase in CNG content leads to a decrease in oxygen levels, which increases the potential for HC emissions. Changing the engine load significantly reduces HC emissions by 50.7% at a 5 Ms injection duration, 67.4% at 7.5 Ms, and 64.5% at 10 Ms. This is consistent with research conducted by [33], [34] which states that HC emissions increase rapidly at low loads and increase slowly at high loads. The increased combustion chamber temperature with load increases enhances the combustion process of rich fuel, thereby reducing HC emissions.

The test results reveal an opposite trend between the baseline and dual fuel with mixer regarding HC emissions. The decrease in HC emissions observed in the baseline does not occur in the dual fuel, both at low and high load conditions. This indicates a mismatch or inability of the mixer to condition the mixture homogeneity at a certain air-fuel ratio before entering the combustion chamber.

Figure 5a presents the HC emission display graph of the baseline, dual fuel with mixer, and dual fuel without mixer under low load conditions (A), while **Figure 5b** represents the HC emission display graph of the baseline, dual fuel with mixer, and dual fuel without mixer under high load conditions (B).

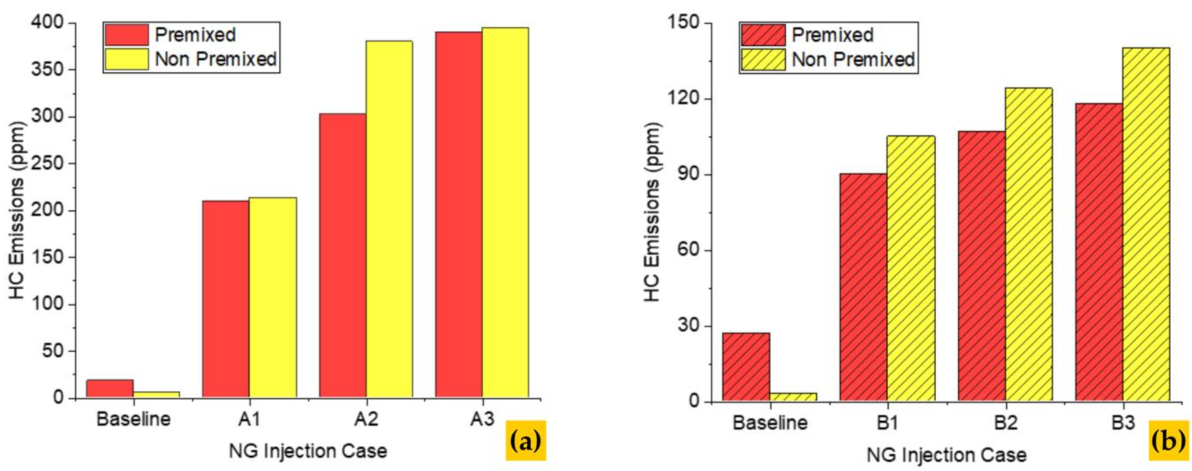


Figure 5. HC emission baseline, dual fuel mixer-non mixer low load (a) high load (b)

3.2.2. CO Emission

Figure 6 illustrates the influence of injection duration variation on CO emissions under low load conditions, where the loading is conducted at 1000 watts of testing load, and high load conditions, where the loading is conducted at 4000 watts of testing load. The figure depicts the CO emission conditions at baseline, representing the engine operation with single fuel, and the CO emission conditions under dual fuel operation at various injection duration variations: 5 ms (1), 7.5 ms (2), and 10 ms (3). Additionally, the figure shows the difference between system operations with the use of a mixer and without a mixer.

Similarly to HC, CO emissions in dual fuel also experience an increase compared to the baseline. The addition of CNG influences the formation of a rich fuel mixture and oxygen deficiency, leading to the potential for increased incomplete combustion, resulting in CO formation in the exhaust gas. At low loads, the potential for CO emissions increases with longer injection durations. The presence of the mixer does not significantly assist in reducing emissions. In fact, it tends to result in increased CO emissions, although at high load conditions, there is a decrease in CO by 10.4% for a 5 Ms injection duration and 26.3% for a 10 Ms injection duration. The inconsistent performance of the mixer is due in part to its failure to align the proper air-fuel ratio when introducing the mixture into the combustion chamber. With the increase in engine load, which also affects the increase in combustion chamber temperature, it can help improve combustion quality. The research results are consistent with those produced by [35] which states that the failure of the mixer to provide a homogeneous mixture of gas and air fuel will lead to increased emissions and decreased performance.

Figure 6a presents the CO emission display graph of the baseline, dual fuel with mixer, and dual fuel without mixer under low load conditions (A), while **Figure 6b** represents the CO emission display graph of the baseline, dual fuel with mixer, and dual fuel without mixer under high load conditions (B).

3.2.3. NOx Emission

Figure 7 illustrates the influence of injection duration variation on NOx emissions under low load conditions, where the loading is conducted at 1000 watts of testing load, and high load conditions, where the loading is conducted at 4000 watts of testing load. The figure depicts the NOx emission conditions at baseline, representing the engine operation with single fuel, and the NOx emission conditions under dual fuel operation at various injection duration variations: 5 ms (1), 7.5 ms (2), and 10 ms (3). Additionally, the figure shows the difference between system operations with the use of a mixer and without a mixer.

A relatively positive trend is observed from the dual fuel system regarding the emitted NOx compared to the baseline [25], [27]. At low load conditions, a significant decrease is observed, with a declining trend as the injection duration increases. At low load, a 5 Ms CNG injection duration results in a 13.1% decrease in NOx compared to the baseline, showing increasingly better performance with a 81.5% reduction for a 7.5 Ms injection duration and a 89.9% reduction

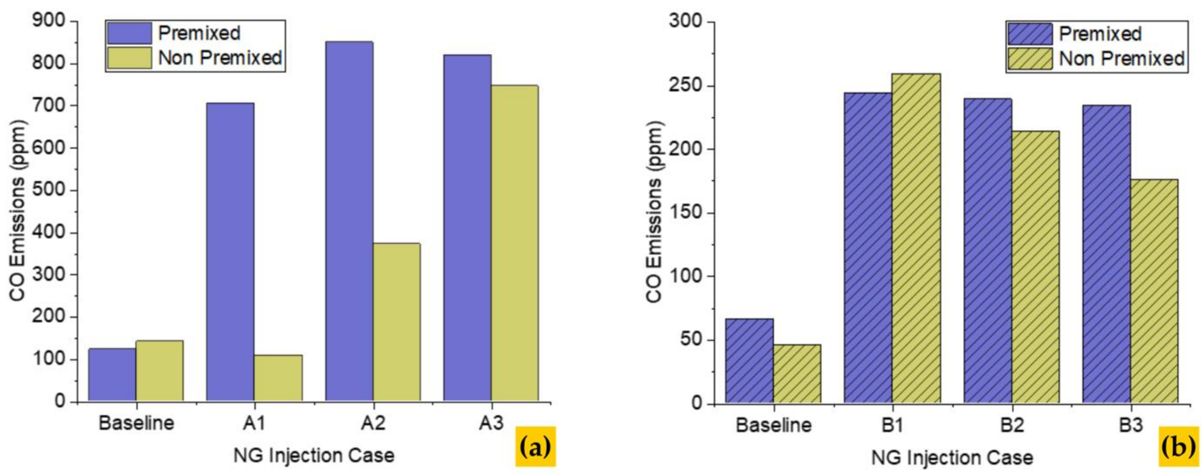
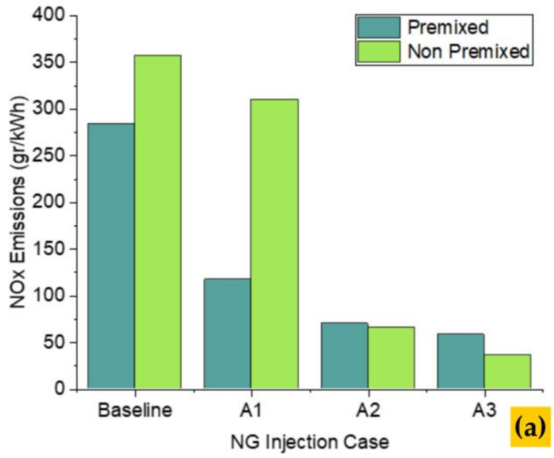


Figure 6. CO Emission baseline, dual fuel mixer-non mixer low load (a) high load (b)



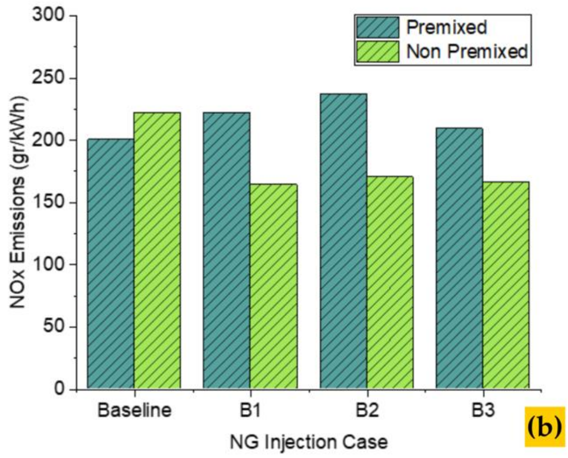


Figure 7. NOx Emission baseline, dual fuel mixer-non mixer low load (a) high load (b)

for a 10 Ms injection duration. The presence of CNG lowers the combustion chamber temperature, reducing the potential for NOx formation. The longer the injection duration, the more CNG accumulates in the combustion chamber. Under high load conditions, the reduction in NOx is not as significant as at low load, with a 26.1% decrease compared to the baseline for a 5 Ms injection duration, 23.4% for a 7.5 Ms duration, and 25.2% for a 10 Ms duration. The addition of the mixer also does not perform well in reducing NOx emissions under both low and high load conditions. There is an increase in NOx values for almost all injection durations, except for the 5 Ms injection duration under low load conditions.

Figure 7a presents the NOx emission display graph of the baseline, dual fuel with mixer, and dual fuel without mixer under low load conditions (A), while **Figure 7b** represents the NOx emission display graph of the baseline, dual fuel with mixer, and dual fuel without mixer under high load conditions (B).

4. Conclussion

From the experimental investigation on the impact of utilizing a mixer for conditioning premixed diesel-CNG dual fuel engines:

a. Changes in injection duration have only a marginal effect on power, ranging from a 1-1.5% increase or decrease. The incorporation of a mixer results in a slight decrease in power, albeit not significantly. It is observed that the addition of a mixer generally decreases thermal efficiency under both low and high load conditions.. This is evident at low loads, where a 10 ms CNG injection duration demonstrates a thermal efficiency increase of up to 6% compared to operation without the mixer and 11% compared to the baseline. Similarly, at high loads, a 10 ms CNG injection duration also exhibits a thermal efficiency increase of 5% compared to operation without the mixer.
b. HC emissions increase within the range of 97.6% to 98.7% with an increase in CNG injection duration from 5 ms to 10 ms. Meanwhile, at high engine loads, HC emissions increase by 97.1% to 97.8% with increasing CNG injection duration. At low loads, longer injection durations show a potential for increased CO emissions. The presence of the mixer does not significantly aid in emission reduction. In fact, it tends to result in increased CO emissions, although at high load conditions, there is a decrease in CO by 10.4% for a 5 ms injection duration and 26.3% for a 10 ms injection duration.
c. The addition of a mixer does not automatically enhance combustion quality or reduce emissions. It is crucial to consider conditioning a homogeneous mixture at the required air-fuel ratio before entering the combustion chamber. Selecting the appropriate mixer design, diameter size, and hole placement are essential factors to consider.

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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.

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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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