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Experimental Analysis on Combustion Characteristics, Performance and Emissions of Oxygen-Enriched Diesel Engine

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Abstract

Oxygen-enriched combustion technology is an appealing option for enhancing the combustion process with reduced exhaust emissions in diesel engines. A study was conducted on a four-stroke single cylinder diesel engine to investigate how the combustion characteristics, exhaust emissions and performance are affected by oxygen-enriched air during partial and full load operating conditions. Specifically, the study focused on analyzing the impact on diesel combustion when the intake air was enriched with 10%, 15% and 20% of oxygen by conventional berating engine air flow rate. Results from the experiments demonstrated that an oxygen-enriched diesel engine resulted in improved combustion characteristics as enhancing the oxygen in the intake charge led to elevated peak cylinder pressure, rate of pressure rise and faster burn rates. The improved combustion process is resulting in a maximum of 13% additional cumulative heat release, 5% to 9% increase in thermal efficiency and an average of 12% decrease in brake-specific fuel consumption. A significant reduction in unburned hydrocarbon, carbon monoxide is noted, nevertheless presence of extra oxygen and elevated combustion temperature are yielding a notable increase in nitrogen oxide emissions.

Keywords: Brake-Specific Fuel Consumption, Brake Thermal Efficiency, Exhaust Emissions, Oxygen-Enriched Diesel Combustion, Performance.

Introduction

Oxygen-enriched diesel combustion is an unconventional combustion technology proposed by researchers to enhance the combustion mechanism and minimize the exhaust emissions by ensuring the availability of oxygen for complete combustion of the fuel molecules. Addition of oxygen in the intake minimizes the production of carbon monoxide and particulate matter, as it encourages the complete combustion of hydrocarbon elements of fuel.

Conventionally the diesel engines are operated with excess air to ensure complete combustion, meaning an additional amount of air is introduced through the intake valve than is chemically necessary to achieve complete combustion. However, the additional air carries heat in the exhaust gases, which results in a loss of heat energy. Typically diesel engines are designed to function with an excess of air ranging from 15% to 40% resulting in a larger engine size for a given output and a heterogeneous air-fuel mixture. On the other hand, oxygen-enriched diesel combustion technique liberates designers to minimize the difference between the air-fuel ratio and stoichiometry while still achieving optimal mean effective pressure and thermal efficiency at full load.

In the recent past, several analytical and experimental studies have highlighted the advantages of oxygen-enriched diesel combustion. The findings reveal a noteworthy decrease in hydrocarbon emissions and smoke, while there was a proportional increase in nitrogen oxide emissions. Plee *et al.,* (1) conducted experiments on diesel engines by varying the engine speed and load with both enrichment and dilution of intake charge. The results with additional nitrogen indicated an increase in carbon monoxide and smoke, while these emissions were decreased with added oxygen. On the other hand, the nitrogen oxide emissions exhibited opposite trends in the experiments. Karim and Ward (2) examined the influence of oxygen partial pressure in the intake charge of a direct injection diesel engine and

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conducted heat release diagram analysis. By enriching the engine's intake with up to 50% oxygen, a substantial increase in cylinder pressure, reduction in smoke emissions, and decrease in ignition delay are observed. At 38% of additional oxygen. The rate of pressure rise reached its peak at approximately 38% oxygen and it tended to stabilize at significantly higher concentrations. Tsunemoto and Itani (3) studied the impact of intake dilution in turbocharged diesel engines using Exhaust Gas Recirculation (EGR). Their findings indicated that decreasing oxygen concentration with EGR resulted in a decrease in nitric oxide (NO) and increase in smoke with a reduction in brake mean effective pressure. According to Chin (4), oxygen enrichment in combustion chambers tends to lower the amount of energy needed to burn combustible mixtures. Lida *et al.,* (5) found that increasing the amount of oxygen results in better combustion and reduces particulate emissions from the exhaust. Poola and Sekar (6) established an operating regime of an oxygen enriched diesel engine that achieved increased gross power with reduced peak cylinder pressure and improved brake-specific fuel consumption. Also, the particulates and NOx are significantly reduced. Lahiri and Mehta (7) studied the influence of oxygen content on the in-cylinder gas properties, fuel evaporation rates and premixed burnt fraction. Their observations had shown a considerable increase in thermal conductivity of gases resulting maximum adiabatic temperature and reduced ignition delay. Watson *et al.,* (8) performed experimental analysis on oxygen enriched air at full load condition. Although the NOx emissions have increased, there is a 5% to 12% increase of thermal efficiency with reduction of about 80% in smoke. Udayakumar *et al.,* (9) studied the optimum flowrate of the oxygen in an oxygen enriched diesel engine and concluded the optimum oxygen flow rate is 18% of full load air consumption of the base engine. Salzano *et al.* (10) and Cammarota *et al.,* (11) explained the influence of intake enriched oxygen on flame velocity, temperature and observed that the oxygen enrichment led to combustion induced rapid phase transition that is not deflagration. Marr *et al.,* (12) indicated that Oxygen-enriched diesel combustion has a great comparative advantage of using inferior quality fuels without affecting engine performance. Mohsen *et al.,* (13) performed experiments on an Oxygen-enriched combustion diesel engine in a pilot ignited natural gas diesel engine and concluded that oxygen enrichment had reduced the knock tendency at maximum load. Song *et al.,* (14), Jianxi *et al.,* (15) and Baskar *et al.,* (16) observed that Oxygen-enriched diesel combustion has immense potential in reducing diesel particulate matter, yet the NOx emissions would be increased due to the cumulative effect of increased atomic oxygen and higher combustion.

Numerous investigations have been conducted on Oxygen-enriched diesel combustion equipped with additional technologies to address the tradeoff between the reduced carbon emissions and increased nitrogen oxide emissions. Cole *et al.,* (17) research on water injection into combustion chamber demonstrated a positive effect in controlling the nitrogen oxide emissions. Subramanian *et al.,* (18) and Youcai Liang *et al.,* (19) presented that emulsified diesel is a reliable option to control the nitrogen oxide emissions in oxygen enriched combustion.

To address global warming and stringent emission regulations, Oxygen-enriched diesel combustion has received considerable attention as a highly appealing combustion technology with improved performance and reduced emissions. Therefore, the objective of this study is to conduct an experimentation on a four-stroke single cylinder Oxygen-enriched diesel combustion engine enriched with 10%, 15% and 20% of oxygen by conventional berating engine air flow rate, to analyze the combustion characteristics, performance, heat release and exhaust emissions.

At 10% additional oxygen the enrichment is at a moderate level and the study observes noticeable improvements in combustion efficiency without drastic changes to engine conditions. The 15% enrichment level provides insights into the progressive, nonlinear effects of increased oxygen on combustion efficiency and emissions. 20% is a substantial enrichment level, where the research aims to examine the maximum potential benefits in combustion efficiency and emissions. The chosen levels (10%, 15%, 20%) allow for a detailed study of how incremental oxygen impacts the combustion temperature, flame speed and overall efficiency. Higher oxygen levels significantly reduce CO and HC emissions due to more complete combustion. However, NOx emissions may tend to increase due to elevated combustion temperatures at higher oxygen levels. The incremental approach helps to identify the optimal balance between reduced CO, HC emissions and controlled NOx emissions. The selected enrichment levels are practical limits that most diesel engines can operate without significant modifications, making the findings relevant to real-world scenarios.

Methodology

Engine Specifications

The experimental analysis is performed using a naturally aspirated, direct injection, single-cylinder water-cooled four-stroke engine. Table 1 presents the specifications of the engine used in the study.

Experimental Test Setup and Test Procedure

The study adopts a 4-stroke, 1-cylinder, water-cooled, and direct injection Kirloskar engine for the research. The experimentation has been performed at engine rated speed of 1500 rpm with a compression ratio of 15.6:1 and at part load conditions, viz. 50%, 75% and 100%. The experimental test bed layout of the engine is shown in Figure 1. The experimentation is equipped with a piezoelectric pressure sensor mounted in the combustion chamber and K type thermocouples placed at inlet and exhaust. The high-speed data from the engine is acquired using an AVL data acquisition system and all the data is recorded with 1-degree crank angle resolution. A DI GAS 437 model AVL gas analyzer is utilized to measure carbon monoxide, hydrocarbon, and nitrogen oxides emissions.

The oxy enrichment of intake air is done by injecting additional oxygen into the air inlet pipe post to the intake air box. Tomasetto Achille IT01 rail gas injector is used to inject the oxygen and the mass flow rate of the injected oxygen is controlled by injection pulses with respect to the crank angle. To safeguard the setup in the situations of misfiring, a flame arrester is placed in the upstream of the oxygen cylinder and before the engine. Throughout the experimentation, the engine is operated at a constant speed of 1500 rpm and the steady state combustion data were collected at 50%, 75%, and 100% of full load. To ensure the reliability, repeatability and consistency of combustion data, the engine was run for 12 minutes to attain steady state operating condition before data collection. Engine load conditions are incrementally adjusted by 5%, transitioning from 50% to 100%. The engine was operated continuously for a duration of 5 minutes at every engine load condition followed by the data collection. The data acquisition is initially done by operating the engine under conventional air combustion and then at 10%, 15%, 20% oxygen enriched conditions. The injection pressure, fuel injection timing is set constant in both the combustion environments, to have the best comparison of the conventional air combustion versus Oxygen-enriched diesel combustion. The oxy enrichment of the inlet air is achieved by injecting oxygen into the intake manifold box. The oxygen injection percentage is controlled by the injection timing of the solenoid injector to achieve 10%, 15% and 20% of oxygen additional to the conventional berating engine air flow rate.

Table 1: Engine Specifications

Parameter	Units	Value
Engine type	%	4-Stroke, Single Cylinder water-cooled Diesel Engine
Rated Speed	rpm	1500
Bore Diameter	mm	87.5
Stroke	mm	110
Compression ratio	--	15.6:1
Orifice Diameter	mm	29.6
Loading	--	Electric loading

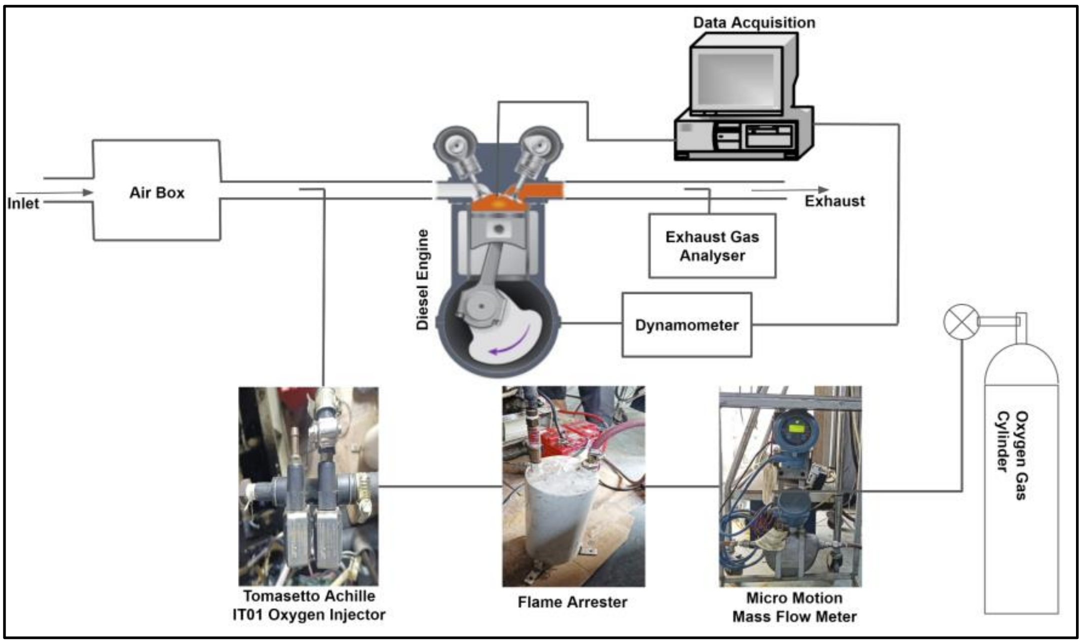

Figure 1: Schematic Diagram of Experimental Setup

Error analysis

Sensitivity analysis is a systematic approach to assess the diesel engine's performance and emissions across different load conditions. The process begins by setting the engine speed to a constant value on a dynamometer test bench. The engine is then subjected to varying loads, typically at increments of 50%, 75% and 100% of its full load capacity. At each load level, precise measurements are taken for the selected key parameters using calibrated sensors and data acquisition systems. Before commencing the experiments, all measurement instruments underwent meticulous calibration against traceable standards, including pressure sensors accurate to within ±0.1 bar, temperature sensors precise to within ±1°C, fuel flow rate sensors with a tolerance of ±0.5%, and exhaust emissions analyzers calibrated against certified gas standards. Calibration procedures were regularly conducted throughout the experimental campaign to maintain measurement accuracy and consistency. The test conditions, including ambient temperature and pressure are controlled and recorded to maintain consistency. Each load point is evaluated multiple times to ensure repeatability and reliability of the data. The collected data is then analyzed to identify trends and correlations between load levels and engine performance, emissions. This comprehensive approach provided a detailed understanding of how different loads affect engine behavior under conventional and enriched combustion conditions.

The experimental data acquisition accuracy is subjected to the parameters considered during the test, equipment errors and uncertainty. The calibration of the devices, their use, the observer's ability to interpret the data, and the constancy of the ambient conditions all has a significant impact on the uncertainties. The instrument's related uncertainties are assessed using a partial differentiation method and the independent parameter uncertainties are considered by determining the mean values of 16 repeated readings. The experimental absolute uncertainty using the mentioned methods is discovered to be 2.8%.

Results and Discussion

This experimental analysis focuses on evaluating the Oxygen-enriched diesel combustion engine performance, combustion characteristics and emissions at 50%, 75% and 100% load conditions. Also reports the comparison of these parameters of Oxygen-enriched diesel combustion with Air combustion.

Variation of Cylinder Pressure with Oxy Enrichment

With increased oxygen content, the combustion rate accelerates due to the availability of more oxygen molecules for the fuel oxidation process. The faster combustion rate leads to a more rapid heat release within the combustion chamber influencing the rate of pressure rise.

$$\frac{dP}{dt} = \gamma \frac{dQ}{dt}\frac{1}{V} \quad [1]$$

Equation 1 represents the rate of pressure raise variation with heat release rate. Where γ is the specific heat ratio, V is the cylinder volume and $\frac{dQ}{dt}$ is the rate of heat release. With increased oxygen content, rate of heat release increases leading to a higher rate of pressure rise, resulting a steeper pressure rise within the cylinder.

Figure 2 represents the comparison of in-cylinder pressure versus crank angle data of the air combustion and 10%, 15%, 20% oxygen enrichments at 100% load condition. The trend of the pressure curve indicates that the maximum in-cylinder pressure increases with increase in oxygen enrichment and no major changes in the combustion process. The peak pressure in 20% oxygen enrichment (76.3 bar) condition is increased by 6% compared to air combustion (72.6 bar) and the corresponding crank angle degree is almost the same for both the conditions. The rise in peak pressure in oxygen enrichment illustrates better combustible mixture conditions, which in turn could yield a relatively higher engine power output.

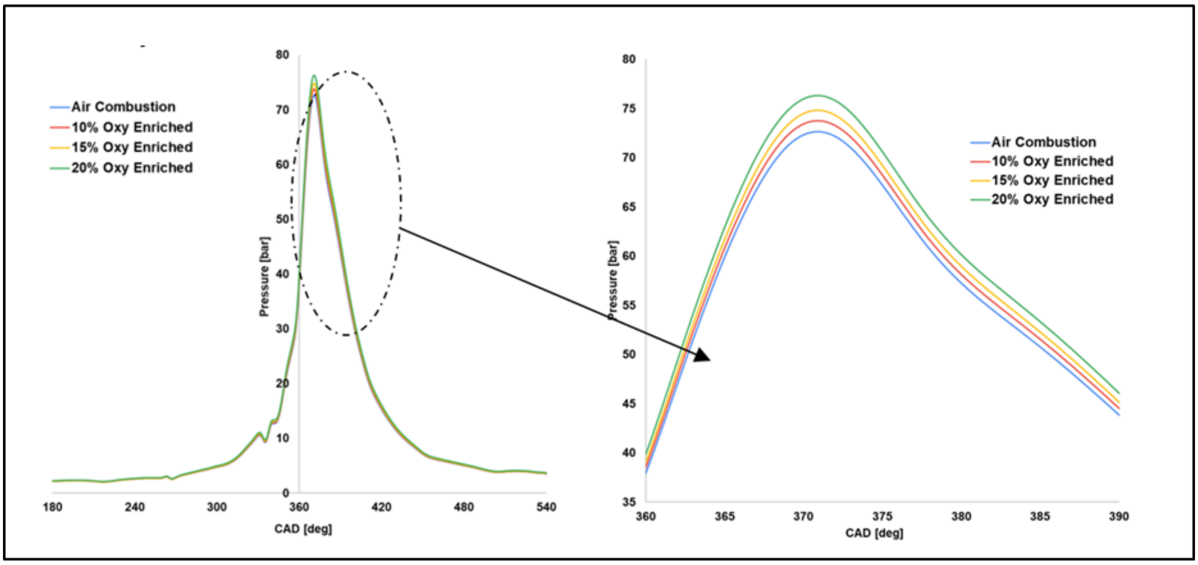

Figure 2: Cylinder Pressure vs CAD at 100% Load Condition

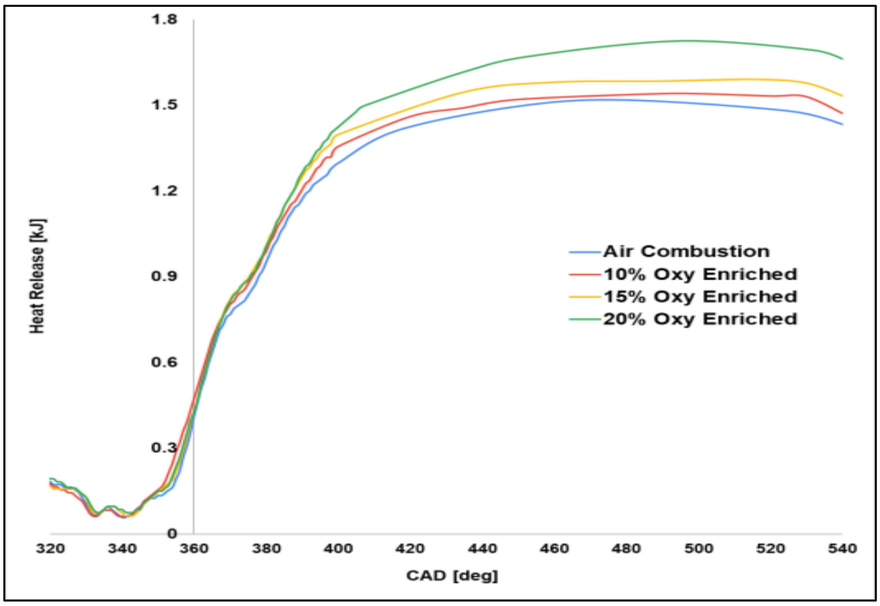

Figure 3: Cumulative Heat Release vs CAD at 100% Load Condition

Variation of Cumulative Heat Release with Oxy Enrichment

Oxygen enrichment enhances the reaction rates by increasing the availability of reactant molecules. Equation 2 represents the Arrhenius correlation on temperature and reaction rate, where k is the reaction rate constant, A is the pre-exponential factor, Ea is the activation energy, R is the universal gas constant and T is the temperature. With higher oxygen content, the effective combustion temperature rises, which in turn raises the reaction rate constant? This accelerates the combustion process resulting in a more rapid and completes release of energy, thereby increasing the cumulative heat release.

$$k = Ae^{-\frac{E_a}{RT}} \quad [2]$$

The cumulative heat release comparison is indicated in Figure 3. In oxygen enrichment conditions the rate of heat release is higher than the air combustion at all the engine load conditions. A 13% raise in peak cumulative heat release is observed in 20% oxygen enrichment than the air combustion at 100% load condition. With the increase in the oxygen enrichment, the curves indicate a faster combustion process, early start of combustion and shorter combustion duration, which will have a positive influence on the engine thermal efficiency.

Variation of BTE with Oxy Enrichment

As indicated in Figure 4 the BTE at 3 engine load conditions of air combustion and oxy enrichment, computed as the ratio of measured brake power to the total power generated by the fuel combustion. An increase in oxy enrichment is resulting in a significant increase in brake thermal efficiency. Compared to the air combustion, the 20% oxy enrichment condition has an increase in BTE of 5% at 50% load, 6% at 75% load and 9% at 100% load. Although the compression ratio of the engine is unaltered, the increase in thermal efficiency is attributed to the increased oxygen content, which is influencing the thermodynamic properties of the in-cylinder combustible mixture and encouraging relatively excessive conversion of thermal energy into useful work.

Variation of BSFC with Oxy Enrichment

The BSFC is one of the key performance indicators of the diesel engine, which is computed as the rate of fuel consumed divided by the power produced. The improved combustion efficiency in oxy enrichment conditions is yielding in reduced brake specific fuel consumption. As indicated in Figure 5 BSFC in oxy enrichment conditions at all the engine load conditions is reduced by an average of 12% when compared to the air combustion. The decrease in BSFC in oxy enrichment conditions is the cumulative effect of increased heat release rate, combustion reaction rate and flame velocity.

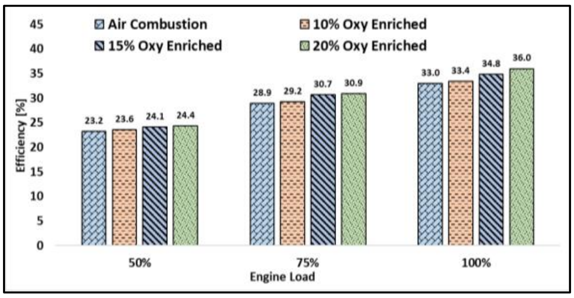

Figure 4: BTE Comparison

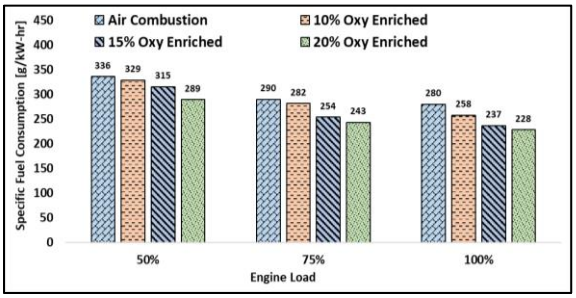

Figure 5: BSFC comparison

Variation of exhaust emissions with oxy enrichment

The primary mechanism of CO, HC emission formation is due to incomplete combustion of fuel. The equation 3 and 4 represents the rate of CO oxidation, rate of HC oxidation, respectively. Where rate constant k is a constant proportionality factor that quantitatively relates the rate of a chemical reaction to the concentrations of its reactants. Oxygen enrichment leads to higher rate constants by increasing the concentration of oxygen available for combustion reactions. Additionally, the surplus oxygen improves the frequency and effectiveness of collisions between carbon monoxide, hydrocarbons, and oxygen molecules. These collisions play a vital role in determining how quickly and efficiently hydrocarbons and CO are converted into CO_2.

$$R_{CO} = k[CO][O_2] \quad [3]$$

$$R_{HC} = k[C_xH_y][O_2] \quad [4]$$

Overall, oxygen enrichment optimizes the combustion process, leading to cleaner and more efficient fuel usage by enhancing both HC and CO oxidation rates. This reduces HC emissions and leads to a more efficient conversion of CO to CO_2, resulting in a lower equilibrium concentration of CO as more CO is converted to CO_2.

The improved combustion efficiency in oxy enriched conditions has a considerable influence on the exhaust emissions of the engine. In an oxy enriched combustion environment, availability of the additional oxygen in the combustible mixture is establishing complete oxidation; thereby the CO formation is substantially reduced. In comparison to the air combustion, an average reduction of 49% in CO emissions is observed across all the oxy enrichment and engine loading conditions and the quantitative representation is given in Figure 6. The primary cause for HC emissions formation is the unavailability of sufficient oxygen to the fuel during combustion. From Figure 7 it is noted that the HC emissions in oxy enrichment conditions are lower by an average value of 45% than the air combustion. The reduction in HC emissions is primarily due to the availability of adequate oxygen to the fuel prior to the end of combustion and also due to increased flame temperatures, reduced quenching distances.

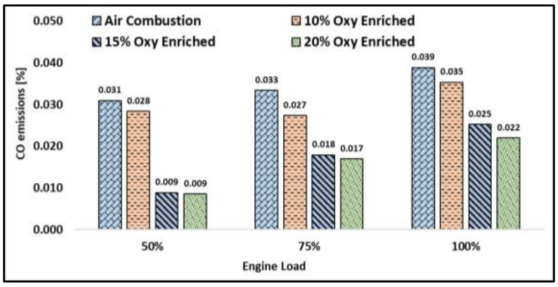

Figure 6: Carbon Monoxide Emissions Comparison

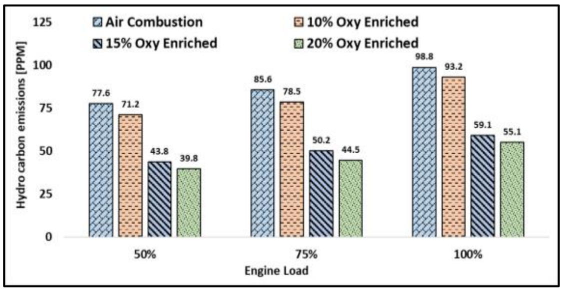

Figure 7: Hydrocarbon Emissions Comparison

In spite of the fact that oxy enrichment has increased combustion efficiency, engine performance and reduced the CO, HC emissions, but the oxides of nitrogen emissions are remarkably high. Availability of excess oxygen and relatively higher flame temperatures are the prime reasons for increased thermal NO formation, which is the major constituent of diesel engines NOx. From the Figure 8, an average increase of 225% of oxides of nitrogen emissions are noted in oxy enrichment conditions than the air combustion, which is a serious environmental concern. Nevertheless, the admissible amount of NOx emission in oxy enrichment combustion can be achieved with water injection; fuel split injection and advanced after treatment techniques.

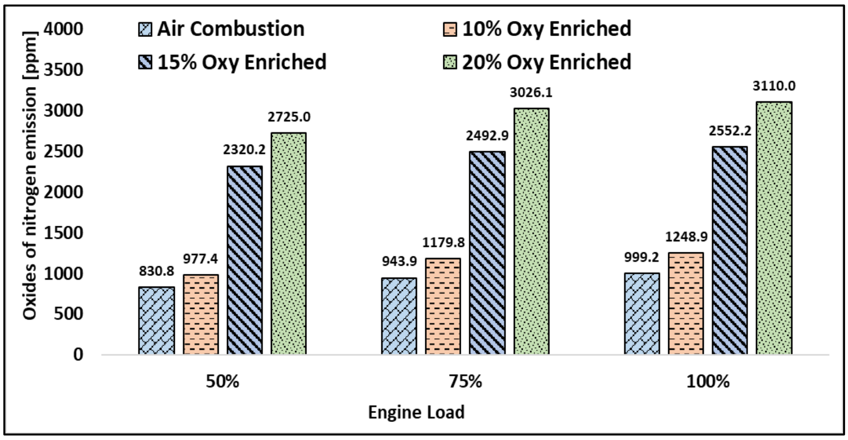

Figure 8: Oxides of Nitrogen Emissions Comparison

In the current research, the thermal efficiency is increased by 5% to 9% with oxygen enrichment levels of 10%, 15%, and 20%. This aligns with the findings of other researchers like Wang *et al.,* (20), who reported a 6% to 8% increase in thermal efficiency at similar oxygen enrichment levels. However, other studies, such as the one by Kumar and Gupta (21), indicated a slightly higher improvement, up to 12%, especially at higher enrichment levels. The variations in results could be attributed to differences in engine types, operating conditions, and fuel properties. These results fall within the expected range, suggesting that the moderate increase in thermal efficiency is a consistent benefit of oxygen enrichment. This consistency reinforces the general understanding that oxygen enrichment enhances combustion efficiency across different experimental setups. The experiment showed a maximum of 13% additional cumulative heat release with oxygen enrichment. This result is comparable to the study by Lee *et al.,* (22), where a 15% increase in heat release was observed with a 20% oxygen-enriched intake. Conversely, a study by Chen and Xu (23) recorded a lower increase of around 10% under similar conditions. The slight differences in heat release rates might be due to variations in engine configurations and specific measurement techniques employed. Additionally, the research reported an average 12% decrease in brake-specific fuel consumption (BSFC) with oxygen-enriched air. This is consistent with findings from Song *et al.,* (24), who documented a 10% to 14% reduction in BSFC under similar oxygen enrichment levels. Zhao *et al.,* (25) found that oxygen enrichment led to a 20% reduction in CO and HC emissions. Compared current study, which showed an average reduction of 49% in CO and 45% in HC emissions with oxygen enrichment levels. The greater emissions reductions in the current results could be attributed to relatively higher levels of oxygen enrichment and different engine configurations. These results fit well within the observed range, indicating that oxygen enrichment generally leads to significant fuel savings, likely due to improved combustion efficiency and reduced heat losses.

Conclusion

This experimental investigation on an oxygen-enriched diesel combustion engine at three different oxygen enrichment conditions yielded several key findings. The study concluded that the peak cylinder pressure and cumulative heat release are increased, indicating potential for engine downsizing while maintaining the same power output. Both thermal efficiency and combustion efficiency are relatively higher under oxygen enrichment conditions due to a shorter delay period, higher diffusion burn rates, and increased flame temperature. Additionally, the BSFC is lower in these conditions because the excessive oxygen results in a leaner air–fuel mixture. The progressive increase in oxygen percentage further leans the air-fuel mixture, contributing to a reduction in brake specific fuel consumption. CO, HC emissions are reduced under oxygen enrichment as a result of complete oxidation, reduced quenching distances, and more complete combustion. However, a significant drawback of oxygen enrichment is the notable increase in NOx emissions caused by the availability of excess oxygen at relatively higher flame temperatures. Consequently, the application of oxygen enrichment methods necessitates additional after-treatment techniques to control NOx emissions to admissible levels.

Abbreviations

BSFC: Brake Specific Fuel Consumption
BTE: Brake Thermal Efficiency
CAD: Crank Angle Degree
EGR: Exhaust Gas Recirculation
HC: Hydrocarbon
NO: Nitric Oxide
NOx: Nitrogen Oxides

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Author Contributions

All authors contributed to the study conception and design. Data collection, simulations and analysis were performed by Raghavendra Ugraram. The first draft of the manuscript was written by Raghavendra Ugraram, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Conflict of Interest

The authors declare no conflict of interest.

Ethics Approval

Not applicable.

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