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# Experimental Analysis of Oxy-Fuel Combustion in Diesel Engines with Insights on Adaptations and Performance

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## ABSTRACT

Oxy-fuel Combustion (OFC) in diesel engines is a transformative advancement, replacing traditional air intake with pure oxygen to enhance combustion efficiency and enable precise control over engine performance. This study adapted a Conventional Air Combustion (CAC) diesel engine to OFC by sealing the air intake and introducing oxygen directly into the inlet manifold. Precise oxygen injection via a Tomasetto Achille IT01 rail gas injector and enhanced sealing mechanisms ensured a stable, uncontaminated combustion environment, critical for assessing OFC performance. Experimental trials at 25% engine load demonstrated that 0.77 grams of oxygen per cycle maintained stable combustion under OFC. Introducing 40% Exhaust Gas Recirculation (EGR) reduced oxygen consumption to 0.462 grams per cycle. Performance comparisons revealed that Brake Thermal Efficiency (BTE) dropped from 20.1% under CAC to 16.2% in OFC and further to 14.8% in OFC+EGR. Brake Specific Fuel Consumption (BSFC) increased from 420.2 g/kWh in CAC to 473.5 g/kWh in OFC and 527.7 g/kWh in OFC+EGR. These findings underscore the need for optimization to recover efficiency losses. They also establish essential insights into OFC's potential as a cleaner and potentially more efficient combustion method for diesel engines, emphasizing its promise for future advancements.

**KEYWORDS**

Diesel combustion, engine optimization, oxygen Injection, oxygen injection, specific fuel-consumption, thermal efficiency

**CITATION**

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## 1. Introduction

The imperative to reduce emissions and improve fuel efficiency in diesel engines has driven substantial research into alternative combustion techniques. Among these, OFC has emerged as a promising method for achieving near-zero emissions while potentially optimizing combustion performance. In CAC, the presence of nitrogen in the intake air leads to the formation of NOx, which contributes to environmental pollution and health concerns. OFC, by introducing pure oxygen in place of air, eliminates nitrogen from the combustion environment, thereby reducing or even eliminating NOx emissions. This transformative approach could pave the way for cleaner diesel engine technologies, positioning OFC as a potentially viable pathway toward environmentally sustainable combustion systems. OFC has been mainly explored in large-scale applications like gas turbines and coal-fired power plants. Studies on OFC in gas turbines have highlighted efficiency gains and emission reductions (Liu *et al.*, 2012). Carbon capture methods, including OFC, have been assessed for IGCC plants, emphasizing emissions reduction (Kunze and Spliethoff, 2012). Reviews of closed-cycle gas turbines have discussed OFC's role in enhancing power generation efficiency (Olumayegun *et al.*, 2016). A novel combustion cycle involving oxygen and water injection has demonstrated improved thermal efficiency and emissions control (Osman, 2009). The implementation of OFC in diesel engines requires a fundamental redesign of the engine intake system, as traditional air intake setups are not compatible with the requirements for pure oxygen delivery. The air intake manifold must be completely sealed to prevent any ambient air from entering the combustion chamber, as even minor leaks could compromise the oxygen purity and disrupt the combustion process. Precision oxygen injection technology is also essential to achieve stable and efficient combustion. Research in this area emphasizes the importance of accurately metered oxygen delivery for optimizing engine performance (Serrano *et al.*, 2022). Controlled oxygen injections enable researchers to study the effects of oxygen concentration on combustion characteristics under diverse operating conditions, a factor that has been shown to influence thermal efficiency and fuel consumption. While OFC has been shown to dramatically reduce emissions, achieving optimal performance metrics, such as BTE and BSFC, poses a unique set of challenges. Managing these trade-offs requires a comprehensive approach, considering injector design, fuel-oxidizer mixing, and timing adjustments. The potential efficiency losses in OFC highlight the importance of ongoing research to develop optimization strategies that preserve fuel economy while delivering cleaner emissions. Research has discussed the trade-offs associated with OFC in diesel engines, noting that while OFC may reduce NOx and other harmful emissions, it often results in a drop in efficiency due to changes in combustion dynamics (Mobasheri *et al.*, 2020). Studies have also investigated the effects of oxygen-enriched air combustion in diesel engines, focusing on combustion characteristics, engine performance, and emissions. These investigations have demonstrated the trade-offs involved in optimizing oxygen-enriched combustion for improved engine performance and emissions control (Zhao *et al.*, 2018). The exploration of OFC in diesel engines is a crucial step toward developing combustion systems that are both efficient and environmentally responsible. As combustion science advances, it is anticipated that refinements in OFC technology will allow for improved injector designs and enhanced sealing techniques. Ensuring sealing integrity in modified OFC diesel engines is crucial, as even minimal air leaks can lead to reduced oxygen purity, significantly affecting combustion efficiency. Research has examined the thermo-mechanical stress and fatigue life of diesel engine pistons under oxy-fuel combustion conditions, highlighting that the altered combustion environment in OFC can impose different thermal and mechanical stress on engine components, necessitating careful consideration of sealing materials and engine design to maintain performance and durability (Ugraram *et al.*, 2023). Other studies have focused on the injector design for OFC, showing that high-precision injectors could increase BTE by up to 7% under controlled oxygen flow rates. These investigations highlighted the role of injector timing and pulse synchronization in achieving optimal fuel-air mixing and combustion

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stability (Patel and Lin, 2020). A micro-motion mass flow meter can be used to monitor oxygen intake, enabling a more precise correlation between oxygen levels and combustion parameters. Research suggests that using Coriolis technology in mass flow meters allows for accurate measurement of oxygen gas flow in real-time, which is critical for optimizing oxygen combustion and engine efficiency. This method ensures precise oxygen control, leading to enhanced combustion stability and improved engine performance in diesel applications (Emerson, 2022). Due to the use of pure oxygen and the absence of nitrogen's dilutive effect, OFC is more prone to combustion instabilities. To address this, insights from studies on knock and irregular combustion phenomena in conventional diesel engines are being explored for adaptation to OFC. Research has analyzed combustion instabilities and control strategies in compression ignition and low-temperature combustion, emphasizing the role of ignition delay, heat release fluctuations, and pressure oscillations. These findings are relevant to OFC, where high oxygen levels and nitrogen absence alter combustion kinetics, increasing instability risks. Studies suggest that injection timing optimization and EGR can enhance stability (Krishnamoorthi and Agarwal, 2022). Additionally, knock characteristics in dual-fuel diesel engines indicate that prolonged ignition delay intensifies knock, which is a key concern in OFC due to oxygen enrichment. Optimizing pilot injection can help mitigate this issue, while poor oxidizer-fuel mixing remains a crucial challenge in OFC's altered combustion environment (Nwafor, 2002). Knock in diesel engines under altitude-induced oxygen depletion has been numerically studied, showing its impact on combustion phasing. While OFC enriches oxygen, improper control can exacerbate knock. Research suggests precise oxygen injection and turbulence enhancement to ensure stable combustion in OFC (Li *et al.*, 2022).

One of the key challenges in OFC is managing the highly reactive nature of pure oxygen combustion, which can lead to issues such as engine knocking, elevated temperatures, and increased oxygen consumption. To address this, researchers have explored the integration of EGR with OFC as a strategy to moderate the oxygen content in the combustion chamber. EGR, which involves redirecting a portion of the exhaust gases back into the intake, can help stabilize combustion by reducing oxygen concentration and lowering peak temperatures. Research has analyzed the integration of EGR with alternative combustion strategies and found that EGR significantly reduced NOx emissions while maintaining combustion stability. Although the study focused on a methanol–diesel reactivity-controlled compression ignition (RCCI) engine, the findings are relevant to OFC applications where EGR plays a crucial role in moderating combustion temperatures and mitigating emissions (Huang *et al.*, 2023). Further experiments highlighted the beneficial impact of EGR on diesel engine performance, particularly in terms of reducing peak combustion temperatures by up to 10%, which helped mitigate NOx emissions (Hountalas *et al.*, 2008). In the context of OFC, integrating EGR with controlled oxygen levels can further stabilize the combustion process by moderating the thermal conditions, thereby enhancing performance and reducing harmful emissions. Similarly, combining EGR with oxygen-enriched air has been shown to reduce NOx emissions by up to 45% while maintaining stable smoke emissions (Zhang *et al.*, 2013). This combination improves combustion efficiency and reduces particulate emissions, offering insights for enhancing OFC performance by balancing oxygen concentration and EGR for better emissions control. Additionally, experimental studies on the effects of OFC and EGR in a homogeneous charge compression ignition engine demonstrated that precisely timed injection at elevated pressure and temperature effectively stabilized combustion, improving thermal efficiency (Kang *et al.*, 2018). Although these findings highlight the emission-related benefits of OFC, they also underscore the need for further experimental validation to improve efficiency and stability.

### 1.1. Motivation:

Despite significant advancements, current OFC research lacks comprehensive experimental validation under real-world operating conditions, particularly at partial loads where performance and stability remain challenging. Many studies emphasize emissions reduction but fall short of quantifying the efficiencies, performance metrics, and quantity of oxygen. This study aims to bridge these gaps by experimentally evaluating diesel engine performance under OFC and OFC+EGR at a 25% load, focusing on metrics such as Oxygen consumption per cycle, BTE and BSFC. This research seeks to provide new insights into OFC's practical viability, emphasizing combustion stability and performance evaluation.

## 2. Methods

### 2.1. Experimental Setup:

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.

**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 |

### 2.2. OFC Design and Experimental Configuration:

The successful design and implementation of the OFC system for diesel engines require substantial alterations to the engine structure, specifically focusing on the integration of controlled oxygen injections for combustion enhancement. Central to this process is the modification of the air intake system, where oxygen is directly injected into the intake manifold. This oxygen injection is synchronized with the engine's crank angle, ensuring precise control to optimize combustion efficiency. A mass flow controller is used to regulate the oxygen flow rate, maintaining a stable oxygen concentration throughout the combustion cycle. This ensures that the combustion process is optimized for higher efficiency and lower emissions. Safety is paramount in the implementation of the OFC system. Flame arresters are strategically placed both upstream of the oxygen supply and before the engine to prevent any risk of flashbacks or misfires when operating under high-pressure oxygen conditions. Moreover, the intake system is rigorously sealed to eliminate the possibility of unwanted air ingress, ensuring that only the controlled oxygen enters the combustion chamber. The importance of precise oxygen flow control, system sealing, and safety protocols for successful OFC implementation has been highlighted in previous works. Controlled oxygen enrichment significantly improves combustion efficiency in diesel engines by optimizing fuel oxidation and reducing incomplete combustion. Studies have emphasized the necessity of regulating oxygen flow to maintain stable combustion characteristics (Rajkumar and Govindarajan, 2010). Additionally, safety guidelines stress the critical role of flame arresters and proper intake system sealing in preventing hazards such as flashbacks and misfires, especially in high-oxygen environments. Ensuring these measures enhance both engine performance and operational safety in OFC applications. The careful integration of these design considerations is fundamental for creating a reliable and safe experimental setup, ensuring accurate and repeatable results in OFC studies (Occupational Safety and Health Administration [OSHA], 2009).

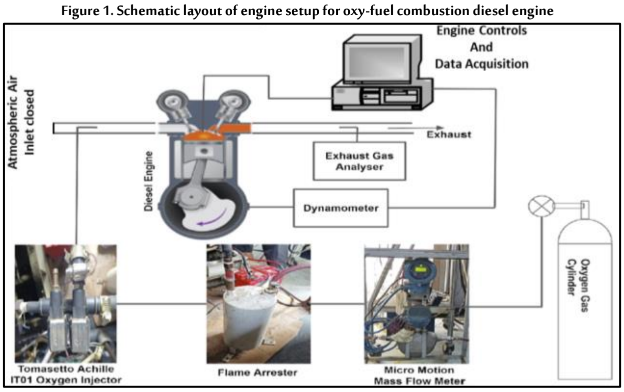
### 2.3. Diesel Engine Adoption:

The diesel engine is modified to operate in OFC mode by sealing the air inlet manifold and directly injecting oxygen into the inlet pipe. This modification necessitates a thorough examination of the engine's air intake system to ensure that all potential air entry points are completely sealed, eliminating unwanted air ingress that could compromise the accuracy and reliability of the OFC process.

Oxygen is supplied from a cylinder equipped with a pressure regulator, calibrated to maintain consistent oxygen line pressure, as controlled oxygen flow is essential for optimizing combustion efficiency and performance outcomes. The Tomasetto Achille IT01 rail gas injector is used for oxygen injections and is known for its accuracy and dependability in providing consistent gas quantities. Its robust design withstands high pressures and varying flow rates, allowing for accurate combustion conditions through modulated oxygen flow, synchronized with the crank angle. To monitor the injected oxygen flow rate, a micro-motion mass flow meter is utilized. This device provides real-time, high-precision measurements crucial for evaluating OFC performance and ensuring adherence to experimental parameters. The micro-motion mass flow meter is recognized for its accuracy and sensitivity in low-flow applications, enhancing the reliability of experimental data. Safety measures include flame arresters, installed upstream of the oxygen cylinder and prior to the engine, preventing potential misfires or flashbacks during operation under high-pressure conditions. Together, these modifications and safety protocols ensure the effective implementation of OFC in the diesel engine, facilitating accurate experimentation while upholding safety standards.

Figure 1 illustrates the experimental setup used for OFC in the diesel engine. The experiments were conducted at a constant engine speed of 1500 rpm under steady-state conditions at 25% load. Before data collection, the engine was running for 6 minutes to reach a stable operating condition. Combustion data were collected only after the engine attained a steady state, ensuring the reliability, repeatability, and consistency of the experimental results. This setup ensures effective implementation of OFC by maintaining precise oxygen injection control, enabling accurate evaluation of combustion performance under OFC conditions while adhering to safety protocols and experimental parameters.

**Figure 1. Schematic layout of engine setup for oxy-fuel combustion diesel engine**




### 2.4. Error Analysis:

In this study, error analysis was essential to ensure the accuracy and consistency of the experimental results under OFC conditions. The primary parameters for which experimental uncertainties were considered include oxygen consumption, BTE, oxygen cylinder pressure, nozzle diameter, and end of oxygen injection.

The oxygen consumption was measured using a Micro-Motion mass flow meter with a measurement uncertainty of ±0.2% of full scale. The nozzle diameter was precisely controlled, with a tolerance of ±0.05 mm to ensure consistent oxygen flow into the combustion chamber. Oxygen cylinder pressure, recorded at various test points, was measured with an uncertainty of ±0.1 bar, and it played a crucial role in determining the mass flow of oxygen into the engine. The end of oxygen injection, defined in terms of CAD, was carefully monitored during the experiment. The uncertainty associated with this parameter was ±0.5 CAD, ensuring that the timing of oxygen injection was consistent for each experimental run.

To ensure the accuracy and reliability of the measurements, the experimental setup was designed to minimize external variables. Ambient conditions, such as temperature, pressure, and humidity, were monitored and controlled throughout the tests, although ambient temperature and pressure were not directly measured. Multiple repetitions of each experimental condition were performed to assess the repeatability and consistency of the data. For each experimental condition, the engine was allowed to stabilize to a steady-state operation before measurements were taken. The steady-state achievement duration was carefully monitored to ensure accurate readings, with a stabilization period of at least 5 minutes for each test point. The results were analyzed for consistency, and any outliers were excluded from the final dataset to ensure the reliability of the data.

Overall, using the calibration of sensors and taking appropriate precautions to mitigate error propagation, the overall uncertainty in the key experimental parameters was estimated at approximately 3.1%. This uncertainty was primarily influenced by the fuel flow measurements, oxygen consumption, uncertainties in the oxygen cylinder pressure, and nozzle diameter, all of which contributed significantly to the experimental error.

## 3. Results and Discussion

### 3.1. Engine Load Conditions:

Selecting appropriate engine load conditions is crucial for a reliable experimental analysis of OFC in diesel engines. This study carefully considers load conditions to balance meaningful data generation while considering the experimental setup's limitations. The 0% load (idle) condition is deemed unsuitable for OFC analysis due to its highly unstable combustion dynamics. At idle, minimal fuel injection and inconsistent oxidizer-fuel mixtures lead to erratic data, compounded by excess oxygen in the exhaust that exacerbates issues such as backfiring, knocking, and irregular firing pulses, resulting in significant combustion instabilities. Furthermore, the low power output at idle generates insufficient heat, complicating the calculation of performance metrics such as BTE and BSFC. Idle conditions also fail to represent typical engine operations, where engines primarily function under load.

In contrast, the 25% load condition is identified as optimal for conducting OFC experiments, offering more stable combustion dynamics. At this load, oxidizer-fuel ratios can be better controlled, ensuring consistent pressure, temperature, and fuel injection parameters. This stability enables reliable data collection and sufficient power generation for accurate performance analysis, including BTE and BSFC calculations.

Attempts to increase the load to 50%, 75%, or 100% faced operational challenges, including engine knocking, unstable pressure fluctuations, and oxidation-related safety concerns. These complications posed risks to both engine durability and experimental safety. Consequently, testing at higher loads was deemed impractical, as the conventional engine setup used was not designed to manage the unique thermal and oxidative stresses of OFC. Future research should focus on developing specialized engines tailored to OFC conditions, with improved thermal resilience, oxidation control, and fuel injection optimization. By selecting the 25% load, this study achieves a balance between combustion stability and accurate performance data collection, minimizing risks associated with higher loads in OFC conditions.

### 3.2. Limitations on Data Acquisition:

A key limitation encountered in this experimental analysis was the absence of sensors for direct data acquisition. The extreme conditions associated with OFC such as rapid heat release, elevated temperatures, and increased oxidation risks, made it impractical to install sensors within the combustion chamber. The presence of pure oxygen significantly accelerates oxidation, posing a risk of damage to conventional sensors. Moreover, high temperatures in the chamber exceed the maximum operating range of standard sensors.

Another concern was sensor placement, which could inadvertently allow air to enter the engine, compromising the controlled OFC environment and introducing errors in the data collection. Consequently, performance metrics like BTE and BSFC were calculated indirectly. These metrics were derived from the applied engine load, controlled via electrical loading, and the mass of fuel injected, monitored over specific operating times. While this method yields reliable performance data, it relies on estimations for detailed combustion characteristics. Despite these limitations, the calculated BTE and BSFC are sufficient to draw conclusions regarding the feasibility of applying OFC to diesel engines. Addressing these challenges through a customized experimental setup equipped with appropriate sensors will be essential for further validating the findings and enhancing the reliability of future studies.

### 3.3. Experimental Data and Performance Metrics:

In this study, the performance metrics of the modified diesel engine under OFC conditions are evaluated based on three key parameters Oxygen Consumption, BTE, and BSFC. Oxygen Consumption (g/cycle) is calculated by measuring the amount of oxygen injected into the engine per cycle, which is regulated and monitored using a mass flow controller. The oxygen flow rate is synchronized with the crank angle and recorded in real-time. BSFC is calculated by dividing the fuel mass consumed by the brake power output. BSFC is a critical indicator of fuel efficiency in internal combustion engines, with lower values reflecting better efficiency. BTE is determined by the ratio of the brake power output to the total energy input, which is calculated from fuel consumption. This metric indicates the efficiency with which the engine converts the fuel's energy into useful work. These parameters are critical for assessing the impact of oxygen-enriched combustion on engine performance.

### 3.4. Challenges in Customization of the OFC Experimental Setup:

The diesel engine's air isolation was rigorously evaluated to facilitate an effective transition to OFC. Several potential air leak zones were identified, such as the air box inlet, hose connections, intercooler, intake manifold gaskets, and the EGR valve. The objective was to ensure the engine would shut down in the absence of air intake, indicating successful air isolation. Initially, the air box inlet was closed off, but the engine continued to operate, revealing inadequate air isolation. Figure 2. illustrates the air box inlet and its assembly designed to block air entry. Additional trials, including sealing the turbocharger intake and inspecting the crankcase ventilation system for leaks, uncovered further air entry points. Ultimately, the air inlet assembly was determined to be the primary source of leaks, necessitating its removal and replacement with an airtight system on the inlet manifold. The before and after scenarios of the air inlet assembly are depicted in Figure 3.

With the air inlet securely isolated, the engine was successfully shut down, confirming the airtight integrity required for OFC operation. This enabled the introduction of pure oxygen as the oxidizer, a critical step in transitioning from CAC to OFC. Oxygen was injected directly into the cylinder using a Tomasetto Achille IT01 rail gas injector, which precisely controlled the mass flow rate through pulsed injections synchronized with the crank angle. The engine was initially operated at 25% load under CAC, followed by a gradual reduction of air intake through the manifold cover. Upon the onset of combustion subsidence, oxygen injection was initiated, and the air manifold was fully sealed to facilitate pure oxygen combustion. The air manifold sealing used to transition from air to OFC is illustrated in Figure 4.

**Figure 2. Air box inlet and its blocking assembly**

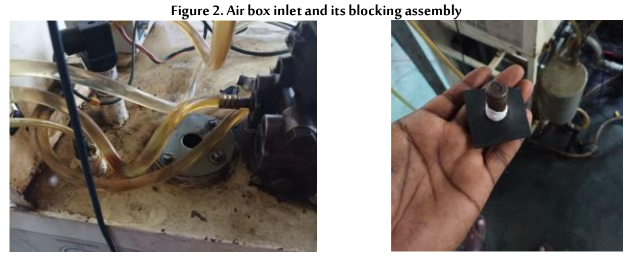
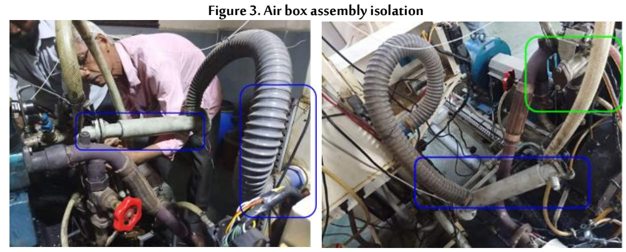


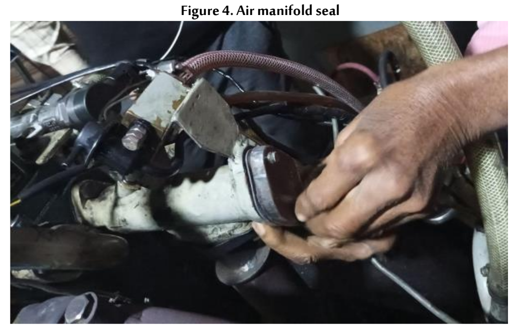
**Figure 3. Air box assembly isolation**



(a) (b)

**(a) Air box is connected to the engine intake manifold**
**(b) Air box assembly is removed, and the intake manifold is closed to ensure no air entry**

**Figure 4. Air manifold seal**



### 3.5. Optimization of OFC:

In the absence of direct temperature, pressure, or combustion characteristic measurements, the classification of combustion conditions in this study was based primarily on qualitative assessments derived from engine performance indicators, such as exhaust behavior, engine load stability, and fuel consumption rates. This classification approach was adapted to suit the specific limitations of the experimental setup, where traditional measurements of combustion processes were not feasible due to the extreme conditions associated with OFC, such as rapid heat release and high oxidation risks that hinder the installation of sensors within the combustion chamber. Similar classification methodologies based on performance indicators have been widely discussed in internal combustion engine studies, where the limitations of sensor-based measurements necessitate indirect assessment techniques (Heywood, 1988; Zhao, 2009).

Stable combustion was identified by consistent engine performance, where the combustion process appeared smooth, without irregularities such as knocking, misfiring, or backfiring. This was inferred from the stability of the engine load, continuous fuel injection without interruptions, and the absence of any discernible combustion anomalies. The smooth operation of the engine, with no signs of abnormal exhaust gases, led to classifying these cycles as stable, as corroborated in studies on internal combustion systems under varying operational conditions. The combustion stability can be classified based on the uniformity of exhaust emissions and smooth engine cycles under optimized fuel-oxidizer conditions. Stable combustion in IC engines is typically marked by consistent combustion behavior, without significant fluctuations in engine performance or exhaust characteristics (Heywood, 1988; Zhao, 2009).

Unstable combustion was characterized by fluctuating engine performance, including irregular firing pulses in the exhaust and noticeable misfiring or knock events. These irregularities, observed through visual inspection and exhaust behavior, led to the classification of combustion as unstable. Since temperature and pressure data were unavailable, the focus was placed on the consistency of the combustion cycles, which in this case showed pronounced fluctuations in exhaust pulses. Studies have classified unstable combustion using similar operational indicators, where the occurrence of knock and misfiring suggested instability in the combustion process (Heywood, 1988).

Irregular combustion was identified when combustion exhibited inconsistent patterns of fuel consumption and exhaust pulse irregularities, without showing the extreme instability seen in backfiring or knock. These irregularities were quantified indirectly by observing the frequency of misfires and irregular firing pulses in the exhaust gases. Similar indicators have been used in the literature to classify irregular combustion, where variations in combustion characteristics, such as incomplete combustion or fluctuating exhaust behavior, were used to categorize it. The irregular combustion could be identified by such inconsistencies in the combustion process, where the engine exhibited occasional misfiring but did not experience the complete instability typical of knock or backfiring (Zhao, 2012; Kirkpatrick, 2020).

Partial combustion was determined when incomplete fuel combustion was evident, which manifested as an irregular engine load and excessive fuel consumption for a given engine load. In this condition, exhaust gases showed signs of inefficiency, potentially contributing to higher levels of particulate matter or unburned hydrocarbons, despite the lack of direct combustion monitoring. The classification of partial combustion has been supported in studies on IC engines, where similar methods of assessing fuel efficiency and exhaust emissions were used to evaluate the combustion process. The partial combustion can be identified by the imbalance between fuel input and engine load, as well as by inefficient exhaust gases, even in the absence of direct temperature or pressure measurements (Heywood, 1988; Kirkpatrick, 2020).

Finally, Uncontrolled Combustion was classified in cases where extreme combustion irregularities were observed, including continuous backfiring and knocking. This condition indicated a complete failure of the combustion process to stabilize, which resulted in engine instability. While direct combustion measurements were not available, the combustion was inferred to be uncontrolled through the erratic engine behavior and violent exhaust emissions. This classification is well-documented in combustion research, while identifying the uncontrolled combustion through similar symptoms of combustion instability, such as backfiring, knocking, and erratic exhaust behavior (Heywood, 1988; Zhao, 2009). The classification of combustion conditions in this study follows these established methodologies, adapted for the limitations of the experimental setup, and is supported by a body of literature that utilizes similar operational performance indicators to categorize combustion stability under IC engine conditions.

Initial trials with stoichiometric oxygen quantities at 25% load failed to maintain stable combustion. A rapid increase in oxygen supply led to challenges such as backfiring, knocking, and irregular firing pulses in the exhaust due to excess oxygen accumulation. To achieve stable combustion, various combinations of oxygen cylinder pressure, gas injector nozzle diameter, and injection timing were evaluated to optimize combustion in the OFC diesel engine setup. The primary goal was to establish stable and sustained combustion at 25% engine load by fine-tuning the oxygen delivery into the combustion chamber. Oxygen injection began at approximately 180 CAD, with its duration extended beyond the fuel injection cut-off to ensure proper mixing and combustion.

Each combination aimed to optimize the oxygen supply in relation to the dynamic combustion characteristics, thereby mitigating issues such as knocking, backfiring, and incomplete combustion that were prevalent in earlier iterations. By systematically varying the nozzle size and oxygen cylinder pressure, the effects of these parameters on combustion behavior were carefully observed. Table 2 summarizes the results, offering insights into the impact of each parameter on combustion stability. Iteration 6 emerged as the optimal configuration for sustained combustion conditions, with the required oxygen per cycle recorded at 0.77 g. This finding indicates that a significant portion of the supplied oxygen remained unused, highlighting the need to balance the cylinder volume to compensate for the absence of nitrogen in the combustion chamber.

**Table 2. Iterations on oxygen injection for OFC**

| Iteration | O2 Cylinder Pressure (bar) | Nozzle Diameter (mm) | End of Oxygen Injection (CAD) | Combustion Status | Observations |
|---|---|---|---|---|---|
| 1 | 1.5 | 1.5 | 350.0 | Unstable Combustion | Uneven combustion, misfiring. |
| 2 | 1.5 | 1.8 | 370.0 | Irregular Combustion | Irregular firing and misfires. |
| 3 | 1.8 | 1.8 | 360.0 | Knock and Instability | Knock and unstable combustion cycles. |
| 4 | 1.8 | 2.0 | 375.0 | Unstable Combustion | Weak and incomplete combustion. |
| 5 | 2.0 | 2.0 | 355.0 | Partial Combustion | Misfiring and partial combustion. |
| 6 | 2.0 (Best) | 2.0 | 375.0 | Stable and Sustained Combustion | Smooth combustion with no signs of knocking or backfiring. |
| 7 | 2.0 | 2.3 | 365.0 | Mild Combustion Instability | Minor instability but maintained acceptable combustion conditions. |
| 8 | 2.0 | 2.3 | 385.0 | Combustion Variations | Combustion irregularities, discontinuous combustion |
| 9 | 2.3 | 2.5 | 355.0 | Backfiring and Misfiring | Backfiring and uncontrolled combustion events. |
| 10 | 2.5 | 2.8 | 365.0 | Severe Backfiring and Knock | Disruptive combustion process, causing severe backfiring and knock. |
| 11 | 2.5 | 2.8 | 385.0 | Uncontrolled Combustion | Erratic combustion and engine instability. |

### 3.6. EGR Integration:

The current engine setup allows for a maximum EGR rate of 40%. Exceeding this threshold reduces the engine's ability to maintain stable combustion due to the excessive buildup of residual gases, which diminishes available oxygen and hampers flame propagation, leading to incomplete combustion and instability. EGR was controlled by mass flow rather than volume to ensure accurate and precise regulation of the exhaust gas recirculated into the intake manifold. This approach is crucial since mass flow directly correlates with the combustion dynamics, as it influences the oxygen concentration and thermal capacity in the combustion chamber. The engine initially operated using CAC before transitioning to OFC. Once stable combustion in OFC was established, the EGR valve was gradually adjusted to achieve the 40% mass-based rate through a controlled process, carefully monitored to maintain combustion stability.

To optimize oxygen consumption under the OFC+EGR configuration, a series of tests systematically varied the gas injector nozzle diameter while keeping the oxygen cylinder pressure constant at 2 bars and the oxygen injection duration fixed at 375° CAD. The nozzle diameter was reduced in increments of 0.1 mm to assess its effect on combustion stability and engine performance. The trials indicated that a nozzle diameter of 1.8 mm provided the most stable and consistent combustion under the OFC+EGR setup, facilitating optimal mixing of oxygen and fuel. Further reductions in nozzle diameter led to combustion instability, characterized by misfires and incomplete combustion due to inadequate oxygen availability, which disrupted the formation of a homogeneous oxidizer-fuel mixture.

Table 3 illustrates the reduction in oxygen consumption per cycle when implementing EGR alongside OFC. Maintaining a constant oxygen cylinder pressure at 2 bar, along with EGR introduction, increased in-cylinder pressure, which reduced the pressure differential between the oxygen cylinder and combustion chamber. This resulted in a decreased oxygen flow rate. With the optimized nozzle diameter of 1.8 mm, the oxygen required for sustained combustion was reduced to 0.462 g/cycle, a significant decrease from the 0.77 g/cycle required under OFC alone. This highlights the effectiveness of EGR and nozzle optimization in minimizing oxygen consumption while maintaining combustion stability.

**Table 3. Comparison of oxygen consumption (g/cycle)**

| Output Variable | Units | OFC | OFC + EGR |
|---|---|---|---|
| Oxygen Consumption | g/cycle | 0.77 | 0.462 |

### 3.7. Performance Comparison:

To ensure a fair comparison between CAC, OFC, and OFC+EGR, key engine parameters such as fuel injection pressure, mass of fuel injected, injection timing, and crank angle were kept consistent with those used during CAC trials. This approach ensured that the only variable influencing combustion was the nature of the oxidizer.

The experimental results highlight notable differences in performance across the three combustion modes at 25% load. Under sustained combustion conditions, the BTE for OFC was measured at 16.2%, significantly lower than the 20.1% observed for CAC. The efficiency further decreased to 14.8% for OFC+EGR. This decline in BTE across the combustion modes can be attributed to the absence of nitrogen in OFC and OFC+EGR, which results in elevated combustion temperatures and increased heat losses through the exhaust. While the OFC environment accelerates combustion, it also increases thermal dissipation. The lack of inert gases diminishes the dilution effect, resulting in a faster burn rate and improved heat transfer to the cylinder walls. In the OFC+EGR setup, the introduction of exhaust gases further reduces the available oxygen, negatively affecting both combustion stability and efficiency.

Similarly, BSFC showed a significant increase across the combustion modes. For CAC, the BSFC was recorded at 420.2 g/kW-hr, while OFC exhibited a higher consumption rate of 473.5 g/kW-hr. In the OFC+EGR configuration, BSFC further escalated to 527.7 g/kW-hr. This increase in fuel consumption directly correlates with the reduced thermal efficiency observed in OFC and OFC+EGR, as more fuel is required to sustain the same power output. The absence of nitrogen alters flame propagation dynamics, necessitating a higher fuel mass for stable combustion, further elevating BSFC. Additionally, in the OFC+EGR setup, the reduced oxygen availability compared to pure OFC limits combustion efficiency by lowering flame temperatures and slowing combustion reactions, leading to even higher fuel consumption and reduced thermal efficiency.

Table 4 summarizes the performance comparisons among CAC, OFC, and OFC+EGR. The results indicate a clear decline in efficiency as the system transitions from CAC to OFC and further to OFC+EGR. While EGR effectively reduces excess oxygen, it compromises the combustion process due to the increased presence of in-cylinder residual gases, impairing flame propagation and stability. As a result, while excess oxygen is reduced, this trade-off results in a marked decrease in overall efficiency and increased fuel consumption across all combustion modes.

**Table 4. Performance comparison of CAC, OFC, and OFC+EGR**

| Output Variable | Units | CAC | OFC | OFC + EGR |
|---|---|---|---|---|
| BTE | % | 20.1 | 16.2 | 14.8 |
| BSFC | g/kW-hr | 420.2 | 473.5 | 527.7 |

In the current research, the thermal efficiency and fuel consumption characteristics of a diesel engine were analyzed under CAC, OFC, and OFC+EGR conditions. The BTE dropped from 20.1% under CAC to 16.2% under OFC, and further to 14.8% with OFC+EGR, which is in line with the findings of Ugraram *et al.* (2022) who reported a significant drop in indicated brake power and indicated mean effective pressure for OFC, suggesting efficiency losses, which aligns with the present findings. These results can be attributed to the absence of nitrogen in the combustion process, which increases the combustion temperatures. Hong *et al.* (2010) explained that this effect occurs due to the altered heat capacity ratio in oxy-fuel environments. Additionally, the increased exhaust heat losses contribute to the reduction in efficiency, as observed in the present study. Similarly, the BSFC increased from 420.2 g/kW-hr under CAC to 473.5 g/kW-hr under OFC, and further to 527.7 g/kW-hr under OFC+EGR. This increase in fuel consumption aligns with the observations made by Mobasheri *et al.* (2022) who found a significant reduction in thermal efficiency, with a corresponding increase in fuel consumption under oxy-fuel combustion conditions. The elevated fuel consumption in the present study mirrors this trend, highlighting the challenges of maintaining combustion stability while compensating for the absence of nitrogen in the oxy-fuel combustion system. These findings further validate the reduction in thermal efficiency and increased fuel consumption observed in OFC and OFC+EGR conditions in comparison to CAC, underscoring the need for performance optimization to recover efficiency losses.

## 4. Conclusion

This study underscores the successful adaptation of oxy-fuel combustion in diesel engines, highlighting the challenges encountered, the quantitative performance outcomes, and the necessity for further optimization to enhance overall efficiency and stability.

- Engine customization efforts included rigorous testing for air isolation, leading to successful shutdowns of the engine under OFC conditions, confirming effective adaptation to pure oxygen as an oxidizer.
- Challenges such as incomplete combustion and knocking were addressed through systematic optimization of the gas injector nozzle diameter, with an optimal size of 1.8 mm identified for stable combustion.
- The introduction of EGR successfully reduced excess oxygen but resulted in compromised combustion stability and further increased BSFC.
- Significant adjustments were necessary to counter the adverse effects of reduced nitrogen levels in the combustion process, which affected flame propagation and thermal efficiency.
- The transition from CAC to OFC demonstrated a decrease in BTE from 20.1% (CAC) to 16.2% (OFC) and further to 14.8% (OFC+EGR).
- BSFC increased significantly, with values of 420.2 g/kW-hr (CAC), 473.5 g/kW-hr (OFC), and 527.7 g/kW-hr (OFC+EGR), indicating reduced thermal efficiency.
- The study's findings indicate that while initial performance metrics reveal efficiency losses, the potential for enhanced combustion stability and efficiency through ongoing modifications remains.
- A comprehensive assessment of the performance outcomes suggests a critical need for further optimization of the combustion system to recover lost performance and improve operational stability.

Further optimization is crucial to address the performance losses observed under OFC conditions. With these enhancements, OFC could become a highly effective and environmentally friendly technique for diesel engine operation, positioning it as a superior alternative to conventional combustion methods while improving both performance and emissions control.

## Abbreviations

BSFC : Brake Specific Fuel Consumption

BTE : Brake Thermal Efficiency

CAC : Conventional Air Combustion

CAD : Crank Angle Degree

EGR : Exhaust Gas Recirculation

NOx : Nitrogen Oxides

OFC : Oxy-Fuel Combustion

OFC+EGR : Oxy-Fuel Combustion with Exhaust Gas Recirculation

## Data Availability Statement

The data that supports the findings of this study are available from the corresponding author, upon reasonable request.

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## Conflict of Interest

The authors declare no conflict of interest.

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