Jurnal Polimesin
Department of Mechanical Engineering
State Polytechnic of Lhokseumawe
http://e-jurnal.pnl.ac.id/polimesin
e-ISSN : 2549-1999 No. : 2 Month : April
p-ISSN : 1693-5462 Volume : 24 Year : 2026

Processing dates: received on 2026-01-28, reviewed on 2026-02-23, accepted on 2026-03-05 and online availability on 2026-04-28

Effect of plasma–ozone injection on the performance of a B30 diesel engine under variable load

Alfian Ady Saputra[1],*, Muhammad Hardiman Nur Ramadhan[1], Melati Nurul Insani[2]
[1]Department of Mechanical Engineering, University of Pamulang, Serang 42183, Indonesia
[2]Department of Mechanical Engineering, University of Mangku Wiyata, Cilegon 42411, Indonesia
*Corresponding Author: alfianadys@gmail.com

Abstract

To improve thermal performance and energy conversion efficiency in biodiesel-fueled diesel engines, an active combustion control strategy through modification of the inlet air reactants is crucial. This study investigates the effect of injecting ozone (O_3) produced through a Dielectric Barrier Discharge (DBD) plasma reactor into the air intake of a single-cylinder diesel engine with a variable compression ratio (TV1). Key parameters evaluated included brake power, specific fuel consumption (SFC), air–fuel ratio (AFR), volumetric efficiency, and in-cylinder pressure under varying dynamic loads (1 kg to 9 kg). The experiments were conducted at three compression ratios (14, 16, and 18) with varying ozone doses of 0, 3, 12, 15, and 18 mg. The results showed that the addition of ozone was able to control the combustion duration and phase. The study observed a significant decrease in SFC of up to 25.57% at a compression ratio of 14, an increase in AFR of up to 34.29% at a compression ratio of 16, and an increase in volumetric efficiency of up to 18% at a compression ratio of 18. Cylinder pressure analysis showed an increase in peak pressure and a decrease in net heat release values, indicating a more stable and smoother combustion. These findings confirm that ozone injection acts as an effective chemical cetane improver, especially under operating conditions where the thermal energy of compression is low (compression ratio of 14).

Keywords:
Biodiesel B30, diesel engine performance, plasma-ozone, compression ratio, advanced combustion.

1 Introduction

1.1 Global energy context and the diesel engine paradox

The global energy landscape is currently in a critical transition phase characterized by a dual imperative: sustaining the growth of energy-intensive industries while drastically mitigating the environmental footprint of the power generation and transportation sectors. In this context, the Compression Ignition (CI engine), more commonly known as the diesel engine, remains the backbone of commercial transportation infrastructure, maritime logistics, industrial power generation, and mining operations worldwide. This technology's dominance is based on a thermodynamic cycle that offers superior thermal efficiency, high torque output, and exceptional durability compared to Spark Ignition (SI) engines [1]. An inherent characteristic of the diesel cycle is its operation at high Compression Ratios (CRs) without pumping (throttling) losses at the intake tract, enabling it to achieve energy conversion efficiencies far beyond other conventional internal combustion engines [2].

However, the supremacy of diesel technology faces an existential challenge often referred to as the "diesel paradox". Despite being the most efficient converters of fossil fuels, diesel engines are also a major source of Nitrogen Oxide (NOx) and Particulate Matter (PM) emissions [3], two pollutants now targeted by increasingly stringent global emissions regulations such as Euro 6 and EPA Tier 4. Furthermore, limited petroleum reserves and the volatility of the global oil market have created a strategic need to shift from fossil fuels to sustainable, renewable energy sources. In this scenario, biodiesel, particularly Fatty Acid Methyl Ester (FAME) derived from vegetable oils or animal fats, has emerged as a prime candidate to replace conventional diesel [4, 5].

1.2 Indonesian context: B30 strategic mandate and physicochemical challenges

Indonesia has positioned itself at the forefront of this renewable energy transition by implementing one of the world's most ambitious biofuel mandates. The B30 program, which mandates blending 30% palm oil-based FAME with 70% fossil diesel, is a strategic move that integrates energy security, agricultural policy, and environmental management. This policy aims to reduce dependence on petrochemical imports while capitalizing on the country's abundant palm oil production [6].

Despite its strategic advantages, the widespread adoption of the B30 presents significant technical challenges for both existing diesel fleets and new engine architectures. Biodiesel has a higher cetane number and inherent oxygen content, which theoretically improves combustion efficiency [7]. However, this fuel is also characterized by higher viscosity, greater density, and lower volatility compared to pure mineral diesel. These physicochemical differences fundamentally alter the fuel injection and mixture formation processes [8].

The high viscosity of B30 inhibits the atomization process in the combustion chamber, resulting in larger fuel droplets. These larger droplets slow the evaporation rate, prolonging the physical ignition delay and reducing the homogeneity of the air-fuel mixture. In conventional engines, especially those operating at low loads or low CRs where the in-cylinder temperature is not optimal, these characteristics can manifest as incomplete combustion, increased Specific Fuel Consumption (SFC), and reduced effective power. The phenomenon of "late combustion" often occurs, where most of the heat release takes place in the expansion stroke, thereby reducing thermodynamic efficiency [9].

1.3 Active combustion control strategies: the role of ozone oxidizing species

To bridge the gap between the thermochemical limitations of biofuels due to their high viscosity and the efficiency demands of modern engines, researchers have begun shifting from purely mechanical modifications to chemical interventions in the combustion process. One of the most promising and thermodynamically elegant approaches is the use of reactive oxidant species, such as Ozone (O_3), injected into the intake air stream (intake manifold) [10].

Ozone is known to be a much stronger oxidant than standard diatomic Oxygen (O_2). Theoretically, ozone has a high chemical potential and, when decomposed in a hot engine cylinder, releases atomic oxygen radicals (O) and excited oxygen molecules. Thermal decomposition of ozone occurs at relatively low temperatures (around 400–500 K), long before diesel fuel reaches its autoignition point [11]. Eq. (1) is the reaction for the decomposition of ozone, where M is the third molecule that absorbs the collision energy.

$$O_3 + \mathrm{M} \rightarrow O_2 + O + M \tag{1}$$

The oxygen atom radicals (O) produced are highly aggressive and react quickly with the hydrocarbon chains of the fuel, triggering chain-branching reactions at the beginning of the compression stroke. This process effectively accelerates the chemical kinetics of combustion, shortens the chemical ignition delay, and increases the reactivity of the fuel-air mixture, especially under conditions where the cylinder temperature is suboptimal [12].

Previous studies by various researchers have shown that the addition of ozone can have an effect equivalent to increasing the cetane amount of the fuel, allowing for more stable combustion at low loads or low CRs. The most relevant technology for ozone generation in automotive applications is the non-thermal plasma reactor, specifically the Dielectric Barrier Discharge (DBD) method [13, 14]. The DBD method allows for on-demand ozone production from atmospheric air with relatively low power consumption, without requiring the storage of hazardous pure oxygen gas [15].

1.4 Recent literature review

Research on ozone applications in internal combustion engines has progressed rapidly over the past five years (2020-2025). A study by Kobashi et al., on a micro-pilot natural gas diesel engine, showed that the addition of ozone effectively increased the lean-burn limit and combustion stability, although its effect on pilot diesel fuel ignition was limited to certain conditions [16]. Zhao et al., in their investigations on Reactivity Controlled Compression Ignition (RCCI) engines, found that ozone seeding up to 300 ppm reduced unburned hydrocarbon (HC) emissions by up to 36% and smoke opacity by up to 98.7%, while increasing Brake Thermal Efficiency (BTE) [17]. This finding is supported by research from Insani et al., which used the DBD method to produce ozone and reported increased cylinder pressure and volumetric efficiency in B30-fueled diesel engines, although the study did not explore the interactions with wide variations in CRs in depth [18].

In addition, chemical kinetics studies by Li et al. and Masurier et al. emphasized that ozone effectiveness is highly sensitive to the initial mixture temperature. At excessively high temperatures (such as at very high CRs), ozone tends to decompose prematurely before fuel injection, allowing the formed oxygen radicals to recombine into stable oxygen without interacting with the fuel [19]. Conversely, at low temperatures (such as during cold starts or at low CRs), ozone exhibits the most dramatic impact on increasing reactivity [20]. This phenomenon opens up the opportunity to design diesel engines with lower CRs, which have the advantage of reducing mechanical friction and engine weight while still maintaining high start ability and combustion efficiency through the aid of ozone [21].

1.5 Research novelty and objectives

While previous literature has explored ozone applications in advanced combustion modes (HCCI, RCCI) or gas-fueled engines, its interaction with high-viscosity biodiesel (B30) in conventional Direct Injection (DI) diesel engines remains critically underexplored. Most existing studies are constrained by the use of surrogate fuels or fixed CRs.

The distinct novelty of this study lies in the experimental isolation and quantification of the thermodynamic interaction between ozone injection, B30 biofuel, and mechanical CR variations in a DI diesel engine. By utilizing a TV1 engine with mechanically adjustable CRs, this research provides a new, fundamental understanding of how initial in-cylinder thermal conditions dictate the effectiveness of ozone as a chemical cetane improver. This explicitly addresses a critical knowledge gap in chemical combustion control strategies for high-viscosity biofuels.

The main objectives of this research are:

1. Analyzing the effect of increasing plasma-ozone concentration on the main performance parameters (power, SFC, AFR, volumetric efficiency) of B30-fueled diesel engines at various loading levels.
2. Evaluating the impact of varying CRs (14, 16, and 18) on the effectiveness of ozone performance enhancement, to test the hypothesis that ozone is more effective under lower compression temperature conditions.
3. Investigating in-cylinder combustion characteristics, including peak pressure and Heat Release Rate (HRR), to understand the fundamental mechanisms behind the observed performance changes.

Ultimately, this study contributes a targeted scientific justification for utilizing reactive oxidants to optimize the internal combustion process, advancing the development of low-emission, high-efficiency energy converters for the renewable energy transition**.**

2 Research method

2.1 Research design

This study used a laboratory-based experimental method with a quantitative approach. The independent variables manipulated included engine load, CR, and ozone concentration, while the dependent variables measured were engine performance parameters. Testing was conducted under steady-state conditions to ensure data reliability and repeatability.

2.2 Materials and equipment

2.2.1 TV1 diesel test engine

The experiments were conducted using a variable test machine setup. Compression The Kirloskar TV1 compression ratio (VCR) engine is a single-cylinder, four-stroke, water-cooled diesel engine specially modified for thermodynamic research. A unique feature of this engine is the ability to change the CR from 12 to 18 without stopping the engine or dismantling major components, through a cylinder head tilting mechanism, cylinder block. Detailed machine specifications are presented in Table 1.

Table 1. Technical specifications of the TV1 diesel engine

Parameter	Technical specifications
Type machine	4 Strokes, injection direct, water cooled
Amount cylinder	1 (Single)
Cylinder diameter (bore)	87.5 mm
Stroke length	110 mm
Displacement volume	661 cc
Ratio compression	Variable (12:1 - 18:1)
Maximum power	3.5 kW (5 HP) @ 1500 rpm
Maximum torque	Variables in accordance loads
System loading	Eddy current dynamometer
Nominal turn	1500 rpm (Constant)

2.3 Test device configuration (engine test bed)

This study uses experimental quantitative on the test machine. The essence of experimental arrangement is one diesel engine cylinder, four strokes, Kirloskar TV1 water-cooled, equipped with mechanism Variable CompresEq.sion Ratio (VCR). The VCR feature allows adjustment ratio compression in a dynamic way from 12:1 to 18:1 without stopping the machine, which is achieved with a tilt block cylinder relatively to the axis-axis crank. The technical details are presented in Table 1.

2.3.1 Plasma-ozone generation system

Ozone is produced using a Dielectric plasma technology-based ozone generator, Barrier Discharge (DBD). The DBD reactor was chosen because of its high efficiency in producing ozone at atmospheric pressure and its ability to operate over ambient air without the need for pure oxygen. This generator operates by applying high AC (Alternating Current) between two electrodes separated by a dielectric layer (glass or ceramic) [22]. As air passes through the discharge gap, high-energy electrons generated by the electric field strike oxygen molecules (O_2), breaking them down into oxygen atoms that then react with other oxygen molecules to form ozone (O_3). The ozone concentration is varied by adjusting the input voltage to the reactor, resulting in varying ozone masses of 0 mg (no ozone), 3 mg, 12 mg, 15 mg, and 18 mg. These concentrations are monitored using an Ozone meter O_3 Air Quality Detector, mounted on the inlet to ensure precise dosing.

2.3.2 Fuel

The fuel used is B30 Biodiesel, a mixture of 30% FAME from palm oil and 70% petroleum diesel, according to Pertamina standards. B30's physical characteristics, such as a density of 863 kg/m³ and a calorific value (LHV) of 36,417 kJ /kg, are used as the basis for calculating thermal efficiency.

2.4 Instrumentation and data acquisition

An integrated data acquisition system is used to record engine operating parameters in real-time:

- Cylinder pressure sensor: a piezoelectric transducer mounted *flush* on the cylinder head to measure in-cylinder pressure with high resolution.
- Encoder: an optical sensor mounted on the crankshaft provides a piston position signal with a resolution of 1-degree crank angle (CAD), allowing for the creation of diagrams $P-\theta$.
- Air flow measurement: using an air box with an orifice plate and differential pressure sensor (U-tube manometer) to measure pressure drop, which is converted to air mass flow rate.
- Fuel flow measurement: using a volumetric burette and a digital *stopwatch* to measure the time it takes the engine to consume a certain volume of fuel (e.g., 10 cc or 20 cc).
- Exhaust gas temperature: a type K thermocouple is installed on the exhaust manifold.

2.5 Experimental procedures

The testing procedure is carried out with the following systematic steps:

1. Preparation: Warm up the engine for 10-15 minutes until it reaches optimal operating temperature. Sensor calibration is performed under no-load conditions.
2. Condition variations: Testing was conducted at three different CRs: 14, 16, and 18.
3. Loading: At each CR, the engine was loaded gradually using an eddy current dynamometer starting from 1 kg, 3 kg, 5 kg, 7 kg, up to 9 kg. The engine speed was kept constant at 1500 rpm.
4. Ozone injection: At each load point and CR, ozone is injected into the intake manifold with predetermined concentration variations (0, 3, 12, 15, 18 mg).
5. Data recording: Performance data (torque, fuel consumption time, air flow) and combustion data (cylinder pressure) are recorded after the engine condition is stable (approximately 2-3 minutes after parameter changes).

2.6 Data analysis formulation

The raw data obtained is processed using standard thermodynamic equations to obtain performance parameters:

1. Effective power (*Brake Power*, BP): Calculated based on torque and the machine (Eq. (2)) [18].

$$BP = \frac{2\pi NT}{60000} = \frac{T \times N}{9549.3} \tag{2}$$

where T is torque (Nm), and N is engine speed (rpm).

2. SFC: Show mass material fuel required to produce one unit of power in one hour (Eq. (3)) [19].

$$SFC = \frac{FC}{BP}(kg/kW.h) \tag{3}$$

Where FC is the mass flow rate of fuel (kg/h). FC is obtained from Eq. (4), where V_{gelas} is the burette volume (cc), ρ_{bb}fuel density (kg/L), and (t) time (seconds) [23].

$$FC = \frac{V_{gelas} \times \rho_{bb} \times 3600}{t \times 1000} \tag{4}$$

3. Volumetric efficiency (η_{vol}): The ratio between the actual mass of air entering the cylinder to the theoretical mass of air that can fill the stroke volume under atmospheric conditions (Eq. (5)) [14].

$$\eta_{vol} = \frac{M_a}{M_{th}} \times 100\% \tag{5}$$

Where M_a is the mass flow rate of air (kg/s), M_{th} is the theoretical air mass flow rate (kg/s). M_a is obtained from Eq. (6) and M_{th} is obtained from Eq. (7), where C_d is the coefficient of discharge, A is the cross-sectional area (m^2), ρ_{air} is the density of air (kg/m^3), ΔP is the pressure drop (N/m^2), V_s is swept volume or displacement (m^3), and N is engine speed (RPM).

$$M_a = C_d \times A \times \sqrt{2\rho_{air}\Delta P} \tag{6}$$

$$M_{th} = V_s \times \frac{N}{2 \times 60} \times \rho_{air} \tag{7}$$

4. Net Heat Release (NHR): Calculated using the first law of thermodynamics analysis for a closed system (neglecting mass leakage), based on cylinder pressure (P) and cylinder volume (V) data against crank angle (θ) [24]. NHR is obtained from Eq. (8), where γ is the specific heat ratio (assuming 1.35 for the combustion gases).

$$\frac{dQ_{net}}{d\theta} = \frac{\gamma}{\gamma-1}P\frac{dV}{d\theta} + \frac{1}{\gamma-1}V\frac{dP}{d\theta} \tag{8}$$

Descriptive statistics are used to interpret data trends, and graphs are used to visualize the connection between variables.

3 Results and discussion

This is a deep analysis of the impact of ozone injection on performance parameters of the main B30 diesel engine, with a focus on the interaction between kinetic chemistry, ozone, load engine, and CR.

3.1 Effective power analysis (BP)

The data shows that Effective Power (BP) increases linearly with increasing load. This is the natural response of the engine governor mechanism, which adjusts fuel delivery to maintain a constant speed of 1500 RPM under varying dynamometer loads. However, the addition of ozone provides a consistent, albeit small, power increase at specific points, especially at high loads.

At a low CR of 14, the power output at a 9 kg load increases from 2.46 kW (baseline) to 2.52 kW with the addition of 12 mg of ozone. This increase of approximately 2.4% indicates a slight improvement in the torque produced. The underlying mechanism for this increase is rooted in improved combustion stability and altered chemical kinetics. Diesel engines operating at low CR typically suffer from low end-of-compression temperatures, which leads to a prolonged ignition delay. This delay causes late combustion (burning during the expansion stroke), thereby reducing the effective mechanical work transferred to the piston.

The presence of ozone mitigates this by acting as a strong chemical accelerator. Existing literature indicates that ozone addition alters the chemical kinetics by decomposing and providing highly reactive oxygen species during the compression stroke [7, 19]. These reactive radicals accelerate the chain-branching reactions of the fuel, significantly advancing the low-temperature oxidation and the start of combustion [3, 10]. Consequently, the Heat Release Rate (HRR) shifts closer to Top Dead Center (TDC) [6]. This optimized combustion phasing ensures that peak cylinder pressure is utilized at the most effective crank angle, improving the engine's thermal efficiency and conversion of thermal energy into mechanical work [8]. See Table 2 and Fig. 1.

Table 2. Effective power data (kW) at the ratio compression 14

Load (kg)	Ozone 0 mg	Ozone 3 mg	Ozone 12 mg	Ozone 15 mg	Ozone 18 mg
1	0.29	0.28	0.29	0.32	0.31
3	0.87	0.91	0.88	0.84	0.87
5	1.39	1.42	1.44	1.44	1.40
7	1.95	1.95	1.95	1.96	1.99
9	2.46	2.50	2.52	2.46	2.49

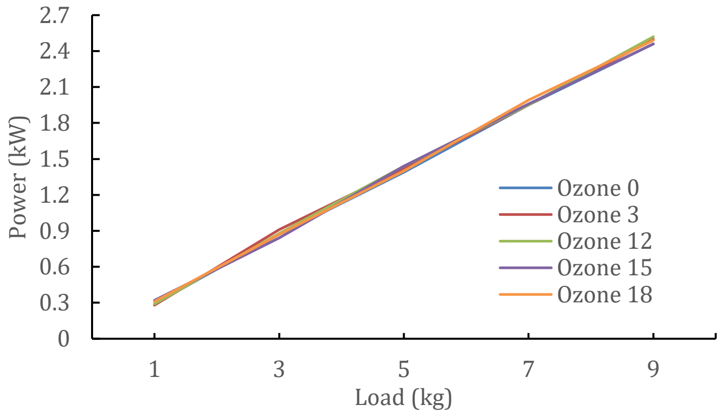

Fig. 1. Effective power (kw) vs load – ratio compression 14

From Fig. 1, the overall trend shows that the addition of ozone did not provide a massive, statistically transformative increase in effective power across all load points compared to the baseline. This behavior is expected due to the test methodology. Because the engine operates in a constant-speed mode with a load dictated by the dynamometer, the engine power output is essentially "forced" to match the braking load. Therefore, effective power here acts primarily as a control variable rather than a purely independent response variable.

Nevertheless, the engine's ability to maintain stable power at a marginal CR of 14 with ozone is a critical finding. Without ozone, diesel engines under these marginal auto-ignition conditions are highly susceptible to cyclic variability, partial burns, or outright misfires. The stable power output demonstrates that ozone effectively compensates for the deficiency in compression temperature by enhancing the low-temperature chemical reactivity of the air-fuel mixture [3, 10]. This firmly aligns with the findings of Kobashi et al. [5, 20], who established that ozone enrichment successfully improves thermal efficiency and extends the stable operational limits of internal combustion engines under challenging lean or low-temperature combustion environments.

3.2 SFC analysis

The reduction in SFC was the most significant finding in this study, highlighting the economic and functional potential of plasma-ozone technology in improving engine performance [7, 9]. The data demonstrates that ozone is highly effective under non-ideal operating conditions for diesel engines.

- Low Load Sensitivity: At a low CR 14 and low load (1 kg), the SFC drops drastically from 1.76 kg/kW.h (baseline) to 1.31 kg/kW.h with the addition of 15 mg of ozone. This represents a substantial fuel saving of 25.57%.
- Thermochemical Interpretation: Low-load operation in diesel engines is notoriously inefficient due to low cylinder wall temperatures and a lean, poorly combusted mixture. The low volatility and specific physical properties of B30 biodiesel exacerbate this, often causing the fuel to burn incompletely or very slowly under light loads [8, 21]. The high baseline SFC values clearly reflect this inefficiency. The injection of 15 mg of ozone introduces an aggressive oxygen radical pool, which facilitates faster and more complete oxidation of the B30 hydrocarbons, even at lower combustion temperatures [2, 5]. This aligns with recent studies demonstrating that ozone addition extends the operational limits of lean-burn characteristics and improves overall thermal efficiency [5, 20].
- Convergence at High Loads: As the engine load increases to 9 kg, the SFC values tend to converge (e.g., 0.40 kg/kW.h without ozone vs. 0.36 kg/kW.h with 15 mg ozone). At high loads, the combustion chamber temperature is naturally high enough to vaporize and auto-ignite the B30 efficiently. While the chemical assistance from the ozone becomes less critical for basic ignition, it still provides a notable fuel saving of approximately 10%. See Table 3 and Fig. 2.

Table 3. SFC data (kg/kWh) at the CR 14

Load (kg)	Ozone 0 mg	Ozone 3 mg	Ozone 12 mg	Ozone 15 mg	Ozone 18 mg
1	1.76	1.64	1.43	1.31	1.50
3	0.72	0.62	0.59	0.68	0.66
5	0.48	0.48	0.47	0.43	0.44
7	0.40	0.40	0.37	0.40	0.39
9	0.40	0.35	0.37	0.36	0.33

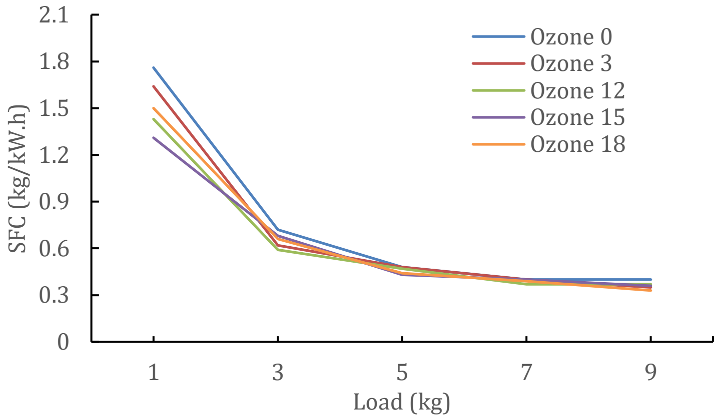

Fig. 2. Variation of SFC with load at CR 14

Visual Analysis: The chart shows a sharp decline in SFC on load low (1 kg) at ozone added (ozone line is below the baseline). At a load of 1 kg, the SFC drops from 1.76 (without ozone) to 1.31 (15 mg ozone), indicating far greater efficiency.

Mechanism Discussion: The significant decrease in SFC, especially at a low CR, is direct evidence of an increase in the indicated thermal efficiency. This mechanism can be thoroughly explained through chemical kinetics and plasma-assisted combustion principles [7, 18].

During the compression stroke, the introduced ozone (O_3) decomposes into highly reactive atomic oxygen (O) [25]. These O atoms aggressively attack the long-chain hydrocarbon molecules (RH) present in the B30 biodiesel, triggering the formation of peroxyl (RO_2) and hydroxyl (OH) radicals through low-temperature combustion (LTC) pathways [10, 18]. The simplified reaction can be modeled as Eqs. (9) and (10). The symbol RH represents a hydrocarbon fuel molecule.

$$O_3 \rightarrow O_2 + O \tag{9}$$

$$RH + O \rightarrow R + OH \tag{10}$$

This accelerated radical activity speeds up the pre-flame reactions, effectively shortening the ignition delay [10]. Because combustion initiates earlier and propagates much faster (resulting in a shorter heat release duration), the thermodynamic process is brought closer to the ideal constant-volume combustion cycle (Otto cycle), where combustion occurs near Top Dead Center (TDC). This shift increases the effective expansion work of the combustion gases, resulting in more work generated per unit mass of fuel burned, thereby lowering the SFC. These findings are highly consistent with recent literature demonstrating that ozone addition significantly enhances fuel reactivity and improves the thermal efficiency of advanced combustion strategies, such as RCCI engines [3, 10].

3.3 Air–Fuel Ratio (AFR analysis)

The data indicates that the addition of ozone allows the engine to operate with a significantly leaner fuel mixture while still producing the required power output.

- AFR Increase: At a CR of 16 and a low load (1 kg), the AFR increased from 52.04 (Baseline) to 63.89 with the injection of 15 mg of ozone.
- Implication: An increase in AFR at a constant load signifies that the engine is utilizing less fuel mass for the same volume of intake air. Given the corresponding decrease in SFC, this confirms that the injected fuel mass is significantly reduced to maintain the low load or idle speed.
- Flammability Limits: Ozone effectively extends the "lean flammability limits" of the B30 mixture. In conventional diesel combustion, localized areas within the cylinder possessing an ultra-lean AFR (such as 64:1) frequently experience local flame extinction. However, the introduction of highly reactive oxygen radicals from ozone sustains the chemical chain reactions in these ultra-lean zones. This ensures that pockets of fuel, which would conventionally escape as unburned hydrocarbons (UHCs), are fully oxidized. See Table 4 and Fig. 3.

Table 4. AFR data on the ratio compression 16

Load (kg)	Ozone 0 mg	Ozone 3 mg	Ozone 12 mg	Ozone 15 mg	Ozone 18 mg
1	52.04	57.54	58.14	63.89	56.36
3	45.99	50.08	46.34	44.92	45.57
5	40.77	39.83	40.84	39.61	37.17
7	33.94	33.26	33.42	33.56	31.25
9	26.77	26.25	26.64	26.46	26.45

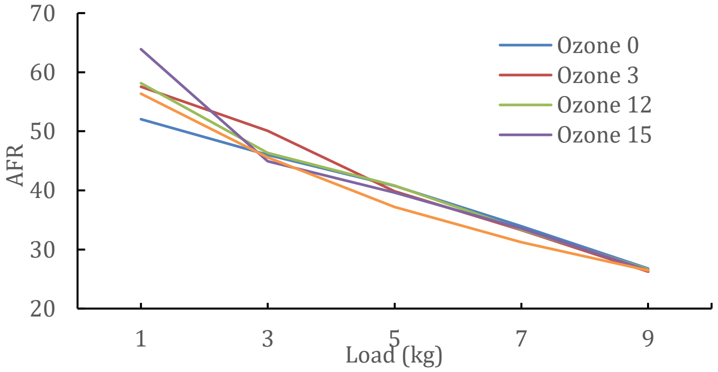

Fig. 3.Variation of AFR with load at CR 16

The graph clearly demonstrates that at a low load (1 kg), the ozone lines (particularly the 15 mg dosage) jump well above the baseline, reaching an AFR of approximately 64. This visually confirms that the engine requires significantly less fuel mass to maintain a low-speed or idle load when ozone is present.

Mechanism discussion: This observed increase in AFR is not primarily due to an increase in intake air mass, but rather a direct result of the decreased fuel mass required to sustain the engine load. Because the engine's thermal efficiency is improved by the plasma-assisted ignition, the engine governor automatically reduces the amount of injected fuel, thereby increasing the air-to-fuel ratio.

The implication of a higher AFR (a leaner mixture) is the availability of abundant oxygen during combustion. B30 biodiesel is characterized by higher viscosity compared to standard diesel, which often leads to inferior atomization and the formation of localized fuel-rich zones within the fuel spray. The introduction of ozone creates a leaner, highly reactive, oxygen-rich environment that is uniquely capable of penetrating and oxidizing soot and unburned hydrocarbons within these localized rich zones.

This mechanism comprehensively explains the correlation between ozone injection and the reduction in opacity and particulate emissions reported in recent studies. Ultimately, ozone enables the engine to operate smoothly under extreme lean conditions without misfiring, a phenomenon strongly supported by Kobashi et al., who report improved lean-burn characteristics with ozone addition.

3.4 Volumetric efficiency analysis(η_{vol})

The volumetric efficiency results present an interesting anomaly and require in-depth physical analysis. At a CR of 18 and a 1 kg load, the efficiency increases significantly from 74.16% (Baseline) to 87.46% upon adding 15 mg of ozone, as shown in Table 5. The graph of the variation of volumetric efficiency with load at CR 18 can be seen in Fig. 4.

Table 5. Volumetric efficiency at CR 18

Load (kg)	Ozone 0 mg	Ozone 3 mg	Ozone 12 mg	Ozone 15 mg	Ozone 18 mg
1	74.16	85.86	87.50	87.46	87.18
3	72.74	85.38	85.60	85.90	85.51
5	71.33	84.36	84.16	84.06	83.98
7	69.75	82.83	82.44	82.14	81.97
9	69.06	81.00	80.92	80.36	79.4

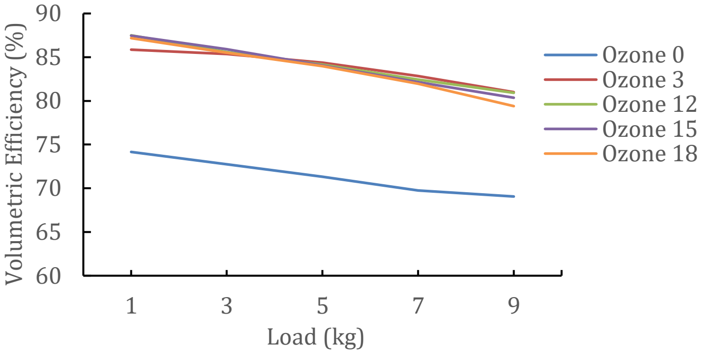

Fig. 4. Variation of volumetric efficiency with load at CR 18

3.5 Cylinder pressure and combustion characteristics

While the EHD "ionic wind" provides a strong mechanical explanation, the increase in volumetric efficiency is also supported by secondary thermochemical and fluid dynamic effects:

- Improved scavenging effect: faster and more efficient combustion, which is a direct consequence of ozone addition, alters the engine's thermodynamic cycle. This rapid combustion can result in a higher exhaust pressure when the exhaust valve initially opens (blowdown). A stronger blow-down pulse pushes the remaining exhaust gas out of the cylinder more effectively. A cylinder that is more thoroughly cleared of residual exhaust gases naturally has a larger effective volume for fresh intake air to fill on the subsequent intake stroke.
- Fluid property modifications: non-thermal plasma produced from DBD reactors can induce complex thermal effects and alter fundamental gas mixture properties. These plasma-induced changes to the fluid's viscosity or flow characteristics might inherently increase the discharge coefficient at the inlet valve port, although this specific flow dynamic requires further Computational Fluid Dynamics (CFD) verification.

Ultimately, this significant increase in volumetric efficiency contributes directly to higher oxygen availability (higher AFR), creating a positive feedback loop for overall combustion efficiency.

4 Conclusion

This study demonstrates that plasma–ozone injection significantly improves the performance of a B30 diesel engine under varying loads and CRs. The most substantial effect was observed in fuel efficiency, with SFC reduced by up to 25.57% at low load and a CR of 14. Ozone addition enhances combustion reactivity, compensating for the limited thermal energy available under low-compression conditions. The air–fuel ratio increased by up to 34.29%, indicating an expansion of lean operating limits, while volumetric efficiency improved by up to 18%, suggesting enhanced air intake and combustion effectiveness. These improvements are supported by in-cylinder pressure results, which show higher peak pressure and more stable heat release behavior. Overall, ozone injection acts as a combustion enhancer by accelerating oxidation reactions and stabilizing ignition, leading to improved efficiency and operational stability. The technique is particularly effective under low-load and low-compression conditions, where conventional biodiesel combustion is less efficient. These findings confirm the potential of plasma–ozone technology as a practical approach to improving biodiesel engine performance and fuel economy.

References

[1] M. Insani, A. Hayat, N. Amaliyah, dan A. E. Putra, "Plasma-Ozone Treatment of Air Supply on Performance and Emissions of Diesel Engine," *IOP Conf. Ser. Earth Environ. Sci.*, vol. 927, hal. 12026, 2021, doi: 10.1088/1755-1315/927/1/012026.

[2] Surahman, A. Hayat, N. Aziz, N. Amaliyah, dan A. E. E. Putra, "Effect of dissolving ozone in biodiesel fuel on diesel engine performance," *AIP Conf. Proc.*, vol. 2630, no. 1, hal. 20018, 2023, doi: 10.1063/5.0126568.

[3] Z. Zhiqing, D. Rui, G. Lan, T. Yuan, dan D. Tan, "Diesel particulate filter regeneration mechanism of modern automobile engines and methods of reducing PM emissions: a review," *Environ. Sci. Pollut. Res.*, vol. 30, hal. 39338–39376, 2023, doi: 10.1007/s11356-023-25579-4.

[4] M. Fırat, Ş. Melih Şenocak, M. Okcu, Y. Varol, dan Ş. Altun, "Ozone-assisted combustion and emission control in RCCI engines: A comprehensive study," *Energy*, vol. 284, hal. 129247, 2023, doi: https://doi.org/10.1016/j.energy.2023.129247.

[5] N. Zuev, A. Kozlov, A. . Terenchenko, dan K. Karpukhin, "Detailed Injection Strategy Analysis of a Heavy-Duty Diesel Engine Running on Rape Methyl Ester," *Energies*, vol. 14, hal. 1–25, 2021, doi: 10.3390/en14133717.

[6] M. Lang, Y. Su, X. Li, Y. Wang, Y. Zhang, dan H. Zhao, "Optical study on the effect of ozone addition on a diesel/ammonia dual fuel engine with pilot injection," *Process Saf. Environ. Prot.*, vol. 188, hal. 1437–1449, 2024, doi: https://doi.org/10.1016/j.psep.2024.06.061.

[7] S. Yubaidah, E. Agustian, I. Haryono, H. Setiapraja, dan A. Sulaswaty, "Study on the effect of the use essential bio-additives on the biodiesel characteristics (B20) and its performance using a 20 kVA generator," in *AIP Conference Proceedings*, 2023, hal. 50081. doi: 10.1063/5.0113133.

[8] Y. Kobashi, R. Inagaki, G. Shibata, dan H. Ogawa, "Improvements in thermal efficiency and exhaust emissions with ozone addition in a natural gas-diesel dual fuel engine," *Int. J. Engine Res.*, vol. 24, no. 8, hal. 3544–3555, 2023, doi: 10.1177/14680874231162144.

[9] T. Iamcheerangkoon *et al.*, "Promotion of the NO-to-NO2 Conversion of a Biofueled Diesel Engine with Nonthermal Plasma-Assisted Low-Temperature Soot Incineration of a Diesel Particulate Filter," *Energies*, vol. 15, hal. 9330, 2022, doi: 10.3390/en15249330.

[10] Y. Choi dan J. Hwang, "Review on Plasma-Assisted Ignition Systems for Internal Combustion Engine Application," *Energies*, vol. 16, hal. 1604, 2023, doi: 10.3390/en16041604.

[11] E. Saputro, W. Saputro, dan B. Saputro, "An Investigation of Engine Performance and Exhaust Gas Emissions under Load Variations using Biodiesel Fuel from Waste Cooking Oil and B30 Blend," *Evergreen*, vol. 10, hal. 2255–2264, 2023, doi: 10.5109/7160901.

[12] H. M. Anantama, E. A. Fuad, dan B. Waluyo, "Improved Engine Performance Using Ozone Generator," vol. 03, no. 02, hal. 39–47, 2023, doi: 10.31603/benr.9083.

[13] K. Zhu, Y. Cai, Y. Shi, Y. Lu, Y. Zhou, dan Y. He, "The effect of nonthermal plasma on the oxidation and removal of particulate matter under different diesel engine loads," *Plasma Process. Polym.*, vol. 19, no. 1, hal. 2100104, 2022, doi: https://doi.org/10.1002/ppap.202100104.

[14] M. Tański, A. Reza, D. Przytuła, dan K. Garasz, "Ozone Generation by Surface Dielectric Barrier Discharge," *Appl. Sci.*, vol. 13, hal. 7001, 2023, doi: 10.3390/app13127001.

[15] A. Gharehghani, M. M. Salahi, A. M. Andwari, M. Mikulski, dan J. Könnö, "Reactivity enhancement of natural gas/diesel RCCI engine by adding ozone species," *Energy*, vol. 274, hal. 127341, 2023, doi: https://doi.org/10.1016/j.energy.2023.127341.

[16] E. Purwanto, B. Cahyono, P. Syamrahmadi, dan A. Faisol, "Analysis of Diesel Engine Components Durability on Fishing Vessel Fueled with Biodiesel (B30)," *Int. J. Mar. Eng. Innov. Res.*, vol. 6, 2021, doi: 10.12962/j25481479.v6i3.9451.

[17] S. S. Wirawan, M. D. Solikhah, H. Setiapraja, dan A. Sugiyono, "Biodiesel implementation in Indonesia: Experiences and future perspectives," *Renew. Sustain. Energy Rev.*, vol. 189, hal. 113911, 2024, doi: https://doi.org/10.1016/j.rser.2023.113911.

[18] N. Mengistu, M. Mekonen, Y. Gzate, L. Fenta, dan T. Nega, "Experimental investigation on diesel engine performance and emission characteristics using waste cooking oil blended with diesel as biodiesel fuel," *Discov. Energy*, vol. 4, 2024, doi: 10.1007/s43937-024-00051-7.

[19] A. Mch, M. Abi, dan A. Rahman, "Effects of bioethanol addition to the biodiesel-diesel fuel blend on diesel engine exhaust emissions," *J. Polimesin*, vol. 21, hal. 292–296, 2023, doi: 10.30811/jpl.v21i3.3460.

[20] J. Li, C. Li, W. Liang, H. Wenhu, dan C. Law, "Ozone Doping and Negative Temperature Response in the Explosion Limits of Ethylene-Oxygen Mixtures," *J. Phys. Chem. A*, vol. 128, 2024, doi: 10.1021/acs.jpca.4c04778.

[21] H. Fakher *et al.*, "Effects of ethanol addition to diesel–biodiesel blends on the CI engine characteristics," *Sci. Technol. Energy Transit.*, vol. 79, 2024, doi: 10.2516/stet/2024033.

[22] Y. Miao, A. Yokochi, G. Jovanovic, S. Zhang, dan A. von Jouanne, "Application-oriented non-thermal plasma in chemical reaction engineering: A review," *Green Energy Resour.*, vol. 1, no. 1, hal. 100004, 2023, doi: https://doi.org/10.1016/j.gerr.2023.100004.

[23] H. Aulia, "Kinetics of transesterifying multifeedstock oil into biodiesel," *J. Polimesin*, vol. 22, hal. 620, 2024, doi: 10.30811/jpl.v22i6.5609.

[24] M. Xu *et al.*, "Design and Characterization of an Upscaled Dielectric Barrier Discharge-Based Ten-Layer Plasma Source for High-Flow-Rate Gas Treatment," *Appl. Sci.*, vol. 14, hal. 27, 2023, doi: 10.3390/app14010027.

[25] S. Reyes dan S. Dhali, "Streamer Discharge Modeling for Plasma-Assisted Combustion," *Plasma*, vol. 8, hal. 28, 2025, doi: 10.3390/plasma8030028.

[26] Y. Kobashi, S. Miyata, N. Kawahara, dan R. Inagaki, "Improvement of Lean Burn Characteristics with Ozone Addition in a Diesel Micro-pilot Natural Gas Engine," in *SAE International Journal of Advances and Current Practices in Mobility*, 2025. doi: 10.4271/2024-32-0104.

[27] M. Tamam *et al.*, "Engine performance and emissions evaluation of surfactant-free B30 biodiesel–diesel/water emulsion as alternative fuel," *Sci. Rep.*, vol. 13, 2023, doi: 10.1038/s41598-023-37662-4.