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Article

Impact of Air Intake Restriction on the Performance and Emissions of a Dual-Fuel Ethanol-Diesel Compression Ignition Engine

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Abstract: In Brazil, diesel engines are widely used in freight transportation, particularly in the agricultural and agribusiness sectors, as well as in a significant portion of passenger transport. The main concern associated with these engines lies in the combustion of diesel fuel due to its harmful impacts on both the environment and human health. In order to mitigate these impacts, the replacement of diesel fuel, a fossil energy source, with renewable fuels has been extensively investigated. In this context, the present study evaluates the performance and emission characteristics of a single-cylinder diesel engine operating with partial substitution of diesel by ethanol. Ethanol was injected into the engine intake manifold, while diesel fuel was directly injected into the combustion chamber. Dual-fuel operation tests were conducted with the engine operating at the same power range (approximately 60% of its rated capacity), for four different ethanol flow rates and two distinct intake air flow rates. Overall, for all ethanol flow rates applied and for both adjusted intake air flow conditions, the results showed an increase in thermal efficiency of approximately 9% compared to conventional diesel operation. Regarding emissions, ethanol led to a maximum reduction of approximately 50% in exhaust gas opacity and about 22.8% in NOx emissions, but increased CO. The results indicate that ethanol, a widely commercialized fuel in Brazil, may represent a viable path towards reduced emissions in the transportation sector, while requiring very little modification in current diesel engines.

Keywords: Internal Combustion Engines; Dual Fuel; Ethanol; Diesel; Emissions

1. Introduction

Compression ignition (CI) engines are the most common and widely used internal combustion engines (ICE) worldwide, mainly for transporting goods, agriculture, and in emergency generator sets. This is mainly due to their higher thermal efficiency, reliability, and durability [1]. They play an important role in the transportation matrix of most countries; however, they are also among the main contributors to environmental pollution, as they convert the energy of fossil fuels into mechanical energy through the diesel combustion process [2]. Furthermore, these engines rely on fossil fuels, which are finite resources, and whose prices and consumption tend to increase continuously due to population growth and improvements in quality of life. In this context, the replacement of diesel fuel with biodiesel, alcohol, or other renewable fuels becomes inevitable [3].

Ethanol is a renewable fuel produced through the fermentation of renewable feedstocks, with sugarcane, sugar beet, and corn starch being the main raw materials [4]. Global ethanol production is significant and continues to grow. In 2023, the United States accounted for 52% of the total global ethanol production, followed by Brazil, with 28% of the total worldwide production [5]. The main advantage of using ethanol in internal combustion engines is its renewable and alternative nature, which helps reduce dependence on fossil fuels and lowers greenhouse gas and pollutant emissions. However, the use of ethanol in CI engines is challenging due to its low cetane number and low lower heating value [6].

In recent years, several researchers have investigated the feasibility of using ethanol in CI engines by employing different methods and substitution ratios under dual-fuel operation. According to Imran et al. [7], the most common approaches are ethanol–diesel blends and ethanol fumigation. In the fumigation method, ethanol is vaporized or directly injected into the engine intake manifold. This technique offers several advantages, including minimal engine modifications, separate ethanol and diesel injection systems that allow operational flexibility, no need for additives to improve miscibility or physicochemical properties, and the capability of easily substituting up to 50% of diesel fuel [7].

Pandey et al. [8] investigated a CI engine operating with ethanol injected into the intake manifold and diesel directly injected into the engine cylinder. A fixed ethanol fraction of 15% was employed along with exhaust gas recirculation. At moderate and high loads, the results showed reductions in NOx emissions and exhaust opacity, along with improvements in thermal efficiency. In the study conducted by Chuepeng et al. [9], the performance and emissions of a diesel engine operating in dual-fuel mode were analyzed using palm oil ethyl ester (POEE) as the main directly injected fuel and ethanol as a supplementary fuel. The results indicated a reduction in engine performance with increasing ethanol vaporization in dual-fuel mode when compared to POEE and conventional diesel operation. However, fuel economy in POEE dual-fuel operation increased by 40% compared to operation with POEE alone. It was observed that POEE combined with ethanol fumigation resulted in reductions in CO_2, NOx, and particulate matter emissions, while CO emissions increased significantly.

In studies conducted by the research group, Telli et al. [10] investigated the effects of a compression ignition engine operating with diesel containing 7% biodiesel (B7) and hydrated ethanol using the fumigation method. Hydrated ethanol was injected into the intake manifold through a fuel injector installed in the intake duct, corresponding to ethanol energy fractions ranging from 11.5% to 52.3%. The results indicated a maximum reduction of approximately 69% in smoke opacity and decreases in both CO and CO_2 emissions. A maximum increase of 26.2% in thermal efficiency and 22.9% in exergy efficiency was also observed. However, increases in HC emissions and brake-specific fuel consumption were reported. Other studies conducted by the group have also addressed dual-fuel operation in diesel engines [11,12]. Similarly, a study by da Costa et al. [13] indicated that the addition of ethanol through an electronic port-fuel injection system in a single-cylinder 7.4 kW diesel engine led to lower in-cylinder temperature, reduced soot emissions, and presented lower diffusive and total combustion durations.

Asad et al. [14] evaluated the performance and emissions of dual-fuel combustion of ethanol and diesel compared to conventional diesel combustion. They found that dual-fuel combustion significantly reduces NOx and soot emissions while achieving higher thermal efficiency at higher engine loads, making it a viable alternative for heavy-duty transport applications. The authors conclude that dual-fuel combustion using ethanol and diesel results in lower exhaust gas temperatures compared to traditional combustion methods.

Chaudhari and Deshmukh [15] employed ethanol and biodiesel in a compression ignition engine. They applied 30% EGR, which led to near-zero NOx emissions. However, the combination showed high specific fuel consumption and lower thermal efficiency compared to strategies that applied diesel. Furthermore, even under load dilution, soot emissions remained above the minimum desirable levels. Some studies, such as that carried out by Wei et al. [16], focus on the use of EGR to improve the performance of the dual-fuel ethanol/diesel engine. The authors found that the application of EGR reduces emissions but also reduces the thermal efficiency of the engine. Vasanthakumar et al. [17] studied the use of hydrogen as an additive in dual-fuel ethanol/diesel engines. The use of ethanol and diesel mixtures with hydrogen enrichment increased the thermal efficiency of the brake compared to pure diesel, in addition to resulting in lower carbon dioxide emissions, but higher nitrogen oxide emissions. The authors also noted challenges with engine stability at higher ethanol proportions.

Domínguez et al. [18] investigated the performance and emissions of dual fuel engines using renewable alcohols (methanol and ethanol) along with hydrogen-treated vegetable oil (HVO). The authors highlight that HVO-ethanol achieves the highest substitution rate (84%) while maintaining low NOx emissions, presenting a viable option to reduce carbon intensity in compression ignition engines. The study demonstrates that this type of operation can also reduce particulate emissions, while achieving high efficiency, particularly with higher EGR rates.

Elbanna et al. [19] present a novel approach to Direct Dual Fuel Stratification (DDFS) that increases combustion efficiency and reduces emissions using a diesel/ethanol blend. The authors highlight the benefits of load stratification in minimizing vibration intensity and achieving lower nitrogen oxide and carbon monoxide emissions compared to conventional methods. The study found that a diesel/ethanol blend (75% diesel, 25% ethanol) significantly reduces CO emissions by up to 34% compared to PCCI (Premixed Charge Compression Ignition). DDFS achieves a brake thermal efficiency (BTE) of 51%, surpassing that of conventional combustion techniques. Fırat et al. [20] explored the dual direct injection (DI2) strategy using ethanol in a diesel engine, comparing it with conventional diesel and reactivity-controlled compression ignition (RCCI) modes. The results indicate that DI2 can reduce emissions while maintaining efficiency, addressing some limitations of the RCCI mode, particularly in reducing CO and unburned HC emissions.

Ramalingam et al. [21] explored the use of ternary mixtures of biodiesel, ethanol, and hydrogen in compression ignition engines, highlighting improved performance and reduced emissions. The study found that the ternary mixture B20E05 (20% biodiesel and 5% ethanol) with added hydrogen significantly reduces hydrocarbon (HC) and carbon monoxide (CO) emissions, with values of 28 ppm and 0.02% respectively, compared to B20 assisted only with hydrogen.

John Varghese et al. [22] investigated the combustion characteristics and performance of a dual-fuel ethanol and diesel engine, highlighting that up to 40% of the diesel can be replaced by ethanol, resulting in a 5.5% reduction in specific energy consumption and significant reductions in smoke and NOx emissions under full load conditions. Significant reductions in smoke emissions were achieved at higher loads due to homogeneous combustion and a reduction in the amount of diesel injected. Balakrishnan and Prakash [23] researched low-temperature combustion (LTC) as a promising method to reduce NOx and particulate matter emissions while maintaining thermal efficiency. They highlight the use of a reactivity-controlled compression ignition (RCCI) engine, which can replace a significant portion of the fuel with hydrated ethanol, leading to lower overall emissions. The authors conclude that the combination of diesel and hydrated ethanol fuels offers superior performance compared to other fuel combinations in terms of emissions and efficiency.

Atelge [24] investigated the effects of a ternary mixture of diesel, ethanol, and n-butanol on combustion and emissions in compression ignition engines. He also explores the addition of nanoparticles to improve fuel properties and performance, aiming to contribute to cleaner energy solutions. The findings suggest that mixing diesel with ethanol and n-butanol affects the calorific value of the fuel, leading to an increase in BSFC. The study concludes that the use of some specific fuel mixtures can significantly reduce NOx emissions in dual-fuel mode. Sule et al. [25,26] investigated the effects of hybrid ethanol and butanol additives with magnetite nanoparticles on biodiesel performance. The results show significant improvements in fuel efficiency and reductions in harmful emissions, highlighting the potential of combining biofuels and nanoparticles for enhanced energy solutions. Also analyzing applications with nanoparticles, Kamble and Karale [27] studied the performance and emission characteristics of a compression ignition engine using ethanol-diesel emulsions containing $NiZnFe_2O_4$ nanoparticles. A test bench with a four-stroke, single-cylinder diesel engine was used to evaluate different ethanol concentrations (5%, 10% and 15%) and nanoparticle levels (25 ppm, 50 ppm and 100 ppm) in the emulsions. The tests demonstrated significant improvements in engine performance, fuel consumption and emissions.

Yang et al. [28] investigated the impact of pilot injection strategies on the performance of a dual-fuel diesel/ethanol engine and found that adjusting the timing and amount of pilot injection can significantly reduce NOx emissions without compromising combustion efficiency or fuel economy. Zhang et al. [29] investigated the effects of diesel and ethanol blended fuels on engine performance and emissions, revealing that increasing ethanol content improves emission characteristics but negatively affects performance metrics such as power and fuel consumption. The study uses a simulation model validated by experimental results to analyze these effects. Han et al. [30] investigated the impact of ethanol blending ratios on combustion and performance of dual-fuel diesel and ethanol engines under varying load conditions, using an engine simulation tool to analyze performance indices, revealing that the ideal ethanol content varies with load, affecting efficiency and emissions. Parthasarathy et al. [31] studied the use of a mixture of tamanu methyl ester and ethanol (TMEE10) with compressed natural gas (CNG) in dual-fuel mode for compression ignition engines. The research indicates that the use of CNG in dual-fuel operation significantly improves combustion rates and overall engine performance, resulting in lower emissions of hydrocarbons (HC), carbon monoxide (CO) and smoke compared to traditional fuels.

Depending on the fuel injection method and engine type, the use of alcohol-based fuels presents different performance levels in terms of emissions and power. Dual-fuel combustion, with alcohol injection into the intake manifold and direct diesel injection, emits higher amounts of HC and CO, while diesel-alcohol blends have similar performance to diesel. In general, blends with lower alcohol concentrations than dual-fuel blends show higher indicated thermal efficiency. Significant benefits are observed in the NOx and soot ratio, regardless of the fuel injection method, NOx concentration, and engine type, with the use of alcohol. Soot reduction reaches values of up to 70%, and the lower carbon content of alcohol-based fuels reduces CO emissions by up to 15% [32].

Jayaraman et al. [33] investigated the performance and emissions of engines fueled with various blends, including n-butanol and biodiesel, and concluded that using a dual fuel mode with n-butanol and a 60% Deccan hemp oil methyl ester blend can improve engine performance compared to traditional diesel. Müller and Günthner [34] compared two dual fuel combustion methods of bioethanol and diesel: premixed charge (PCO) operation and premixed fuel (PFO) operation. They assessed their effects on emissions and engine efficiency, finding that while PCO allows for higher amounts of ethanol at low loads, PFO performs better at medium and high loads. Bhowmik et al. [35] investigated the effects of ethanol inclusion on the performance, exhaust emissions and combustion parameters of a dual-fuel diesel and CNG engine. The study concludes that the inclusion of 10% (v/v) ethanol in dual-fuel diesel and CNG strategies significantly improves engine performance and exhaust emission parameters.

Finally, it is important to highlight that ethanol is a viable fuel option for internal combustion engines due to its potential to minimize harmful emissions. Its physicochemical properties make it suitable for highly efficient engines. Furthermore, ethanol is CO_2 neutral in principle, as its net emissions can be offset by biomass growth [36]. Sahu et al. [37] highlight that ethanol is a more suitable fuel for spark ignition (SI) engines, because of its high octane rating, but that lower mixture ratios can also be used for compression ignition (CI) engines, as evidenced by the literature presented earlier.

The literature shows that different strategies for optimizing ethanol use in compression ignition engines have been analyzed. These include EGR, hydrogen supplementation, nanoparticle addition, stratified injections, ternary mixtures with natural gas or other alcohols, and other alternatives. Unlike most previous investigations on ethanol–diesel dual-fuel operation, which typically evaluate ethanol fumigation under fixed air intake conditions or focus on exhaust gas recirculation and fuel blending strategies, this study introduces a combined and systematic experimental assessment of ethanol injection rate and controlled intake air restriction in a compression ignition engine. The novelty of this work lies in the explicit analysis of how variations in intake air flow, imposed through a throttle valve, interact with different ethanol substitution levels to influence engine performance, fuel conversion efficiency, and emission characteristics. By maintaining a constant power output and applying two distinct air admission conditions, this approach isolates the role of air–fuel interaction mechanisms that are often overlooked in dual-fuel studies. The results provide new experimental evidence that intake air management can be an effective parameter for optimizing ethanol–diesel dual-fuel combustion, enabling efficiency gains and significant reductions in particulate opacity and NOx emissions with minimal engine modification. In addition, the use of commercially available ethanol and a simple intake restriction device reinforces the practical relevance of the proposed strategy, bridging the gap between laboratory-scale investigations and real-world applications. Consequently, this work advances the current understanding of dual-fuel combustion in diesel engines by demonstrating that air flow control, when combined with ethanol fumigation, represents a viable and previously underexplored pathway for improving engine efficiency and environmental performance.

In addition, ethanol has a significantly lower stoichiometric air requirement than diesel fuel, requiring approximately 38% less air for complete combustion. Considering that, in the present study, ethanol is injected during the intake stroke with the aim of forming an air–fuel premixed charge, partially or fully replacing diesel, it becomes relevant to assess a reduction in the excess air admitted into the cylinder. This strategy seeks to prevent ethanol from combusting under excessively lean conditions, which could adversely affect combustion efficiency and overall engine performance. In this context, adjusting the air–fuel ratio emerges as a key factor for effectively utilizing ethanol under the proposed combustion mode. This premise constituted the central motivation for the investigation presented in this paper.

2. Materials and Methods

The experimental tests for this research were conducted at the Engine Laboratory of the University of Caxias do Sul. The engine used in the study was an Agrale M93 ID diesel engine, designed for rural applications such as mini-tractors and power generation. This engine is single-cylinder, air-cooled and four-stroke. Additional data is shown in **Table 1**. Three modifications were implemented to enable operation under the investigated conditions: an external fuel tank was installed to supply ethanol; a fuel injection system was installed in the intake manifold for ethanol delivery; and a throttle valve was installed at the intake to restrict the air supply to analyze its effects in combination with ethanol fumigation.

Table 1. Engine and generator data.

Characteristic	Data
Engine manufacturer/model	Agrale/M93ID
Type of engine	Single-cylinder, vertical, 4 strokes, compression ignition, air-cooled
Displacement	668 cm^3
Compression ratio	20:1
Overlap	80°
Fuel injection (Diesel)	Direct Injection (DI)
Fuel injection (Ethanol)	Port Fuel Injection (PFI)
Injection timing (Diesel)	17° BTDC
Injection timing (Ethanol)	Intake Stroke
Diesel Pressure	18 MPa
Ethanol Pressure	0.5 MPa
Alternator manufacturer	Kolbach
Power/Voltage	8.0 kW/220 V

No other physical modifications were made to the engine, thus preserving its original configuration, particularly with respect to its internal components. A three-phase alternator, model 132LA, rated at 10 kVA, was coupled to the engine through a pulley and belt system and was responsible for applying load to the engine. The generated electrical power was dissipated through a set of electrical resistors located outside the engine laboratory.

2.1. Experimental Setup and Instrumentation

The experimental setup used in this study is shown in **Figure 1**. Ethanol was supplied by means of a low-displacement automotive fuel injector (3) installed in the intake manifold. The injector was controlled using a programmable electronic fuel injection unit, FuelTech FT300 (18). In this control unit, the injector opening time was programmed to different values for each dual-fuel test, with the aim of progressively increasing the ethanol fraction in the combustion process. The injector was actuated whenever the control unit detected the signal from the engine position sensor (16), which was installed near the flywheel.

A manually controlled throttle valve was installed in the intake manifold to investigate the effects of air restriction on engine operation, since ethanol requires a lower air–fuel ratio for combustion. A mass air flow (MAF) sensor was installed in the intake manifold to measure the intake air flow rate. This sensor is essential to the experiment, as it provides accurate information on the air flow rate under each throttle position. The original diesel fuel supply system of the engine was not modified, except for the inclusion of an external fuel tank installed on a weighing scale, which enabled the measurement of diesel fuel consumption.

Ethanol consumption was determined through a series of preliminary tests that established the ethanol injection rate for different injector opening times. Based on these tests, a lookup table was developed in which each injector opening time corresponded to a specific flow rate, with intermediate values obtained by interpolation. Exhaust gas temperature was measured using a thermocouple connected to a Novus 305 temperature monitor, with a measurement range from −50 °C to 1300 °C. During the operation of the engine–generator set, an Embrasul RE6000 power analyzer was employed to measure the alternator load, which was maintained at approximately 6 kW, and to adjust the generation frequency to 60 Hz, resulting in an engine speed of 2600 rpm.

Smoke opacity emitted by the engine was evaluated using a Napro NA9000T opacimeter. The device consists of an optical bench and a probe that is inserted directly into the exhaust pipe. During the tests, the opacimeter probe was kept at the exhaust outlet to ensure continuous data acquisition. The data were automatically transmitted to a computer located in the engine laboratory, where proprietary software allowed real-time monitoring of exhaust gas opacity. The gas analyzer used in this study was a Eurotron Greenline 8000. This portable device was employed to measure carbon monoxide (CO) and nitrogen oxides (NOx) emissions.

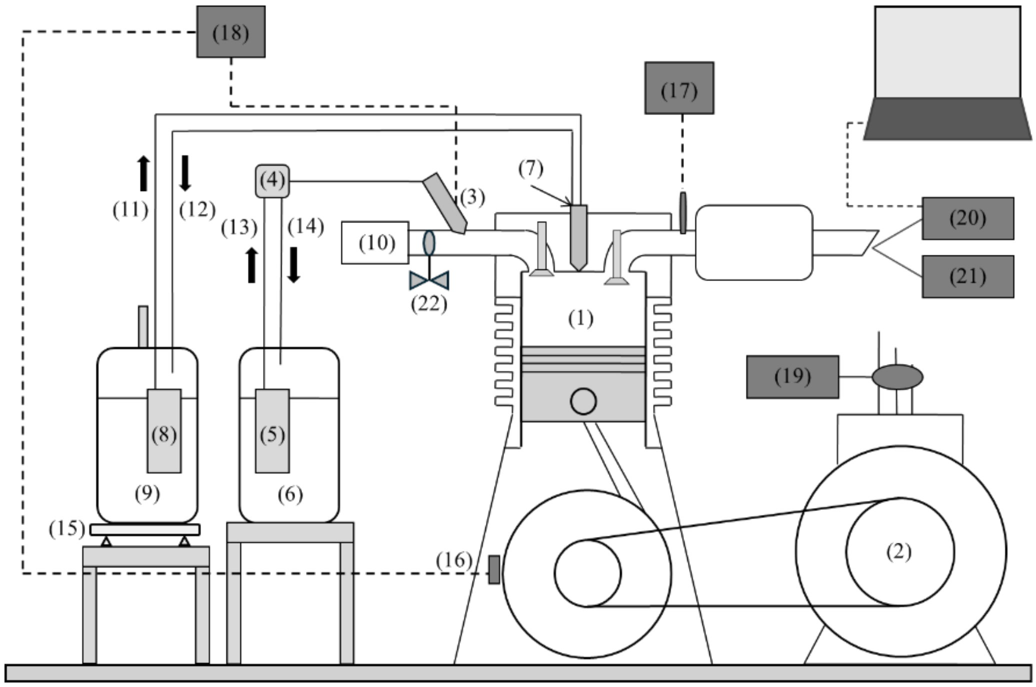

Figure 1. Experimental setup: (1) Compression ignition engine; (2) Alternator; (3) Ethanol injector; (4) Ethanol pressure regulator valve; (5) Ethanol pressurization pump; (6) Ethanol tank; (7) Diesel injector; (8) Diesel pressurization pump; (9) Diesel tank; (10) Air flow meter; (11) Diesel supply line; (12) Diesel return line; (13) Ethanol supply line; (14) Ethanol return line; (15) Diesel weighing scale; (16) Engine position sensor; (17) Exhaust gas temperature sensor; (18) Ethanol injection controller; (19) Power analyzer; (20) Opacimeter; (21) Gas analyzer.

Table 2 presents additional data from the instruments used.

Table 2. Instrumentation characteristics.

Instrument	Measuring Range	Uncertain	Manufacturer/Model
Energy analyzer	<22 kW	0.5%	Embrasul/RE6000
Opacimeter	0–99%	±2%	Napro/NA 9000T
Mass air flow meter	8–370 kg/h	<3%	Bosch/PBT-GF 30
Digital balance	0–5 kg	1 g	Marte/As5500c
Thermocouple K type	−50 to 1300 °C	Meter ± 2.2 °C ou ± 0.75%	Novus/305
Gas analyzer CO	0 to 20,000 ppm	4% up to 2000 ppm	Eurotron Greenline 8000
Gas analyzer NOx	0 to 4000 ppm	4% up to 3000 ppm	Eurotron Greenline 8000

2.2. Tests Performed

Initially, the engine was operated using only diesel fuel to reach the ideal operating temperature and to verify the proper functioning of all instrumentation and control systems. Once stable operating conditions were achieved, data were recorded in specific data sheets developed for this study. The combinations of tests performed are shown in **Figure 2**. A total of nine tests were conducted, including a baseline condition with diesel-only operation and the throttle fully open. The electrical power generated by the alternator was around 6 kW.

Each test condition was assigned an identification abbreviation according to the following logic: OD_NEAT refers to tests conducted using only diesel fuel with the throttle fully open; OD_ET_1.5_TFO refers to tests using diesel (OD) and ethanol (ET) with an injector opening time of 1.5 ms and the throttle fully open (TFO). When identified with TPC, the test refers to operation with the throttle partially closed.

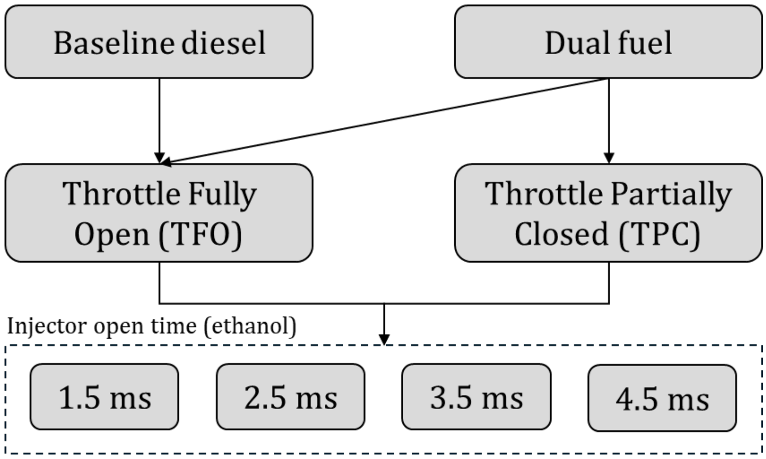

Figure 2. Combination of tests performed.

2.3. Calculation Parameters

Based on fuel consumption and air mass flow rate measurements, the air-fuel ratio was calculated using the equation below.

$$\lambda = \frac{\dot{m}_{ar}}{\dot{m}_d \mathrm{AFR}_{\mathrm{est,d}} + \dot{m}_e \mathrm{AFR}_{\mathrm{est,e}}} \tag{1}$$

where:

λ: relative air-fuel ratio,
$\dot{m}_{ar}$: air mass flow rate,
$\dot{m}_d$: diesel mass flow rate,
$\dot{m}_e$: etanol mass flow rate,
$\mathrm{AFR}_{\mathrm{est,d}}$: stoichiometric air/diesel ratio,
$\mathrm{AFR}_{\mathrm{est,e}}$: stoichiometric air/diesel ratio.

Conversion efficiency (η) and specific fuel consumption (SFC) were calculated using the equations below.

$$\eta = \frac{\dot{W}}{\dot{m}_d \mathrm{LHV_d} + \dot{m}_e \mathrm{LHV_e}} \tag{2}$$

$$SFC = \frac{\dot{m}_d + \frac{\mathrm{LHV_e}}{\mathrm{LHV_d}} \dot{m}_e}{\dot{W}} 3600 \tag{3}$$

where:

$\dot{W}$: power generated by the alternator,
$\mathrm{LHV_e}$: low heating value of ethanol (26.5 MJ/kg),
$\mathrm{LHV_d}$: low heating value of diesel (42.5 MJ/kg),
$\mathrm{AFR}_{\mathrm{est,d}}$: stoichiometric air/diesel ratio,
$\mathrm{AFR}_{\mathrm{est,e}}$: stoichiometric air/diesel ratio.

The $\mathrm{LHV_e}/\mathrm{LHV_d}$ in Equation (3) represents how much the ethanol is equivalent to diesel in terms of energy.

For the analysis of instrumental uncertainties propagated to the calculated parameters (Equations (1)–(3)), the method proposed by Kline and McClintock was used [38]. Assuming that the R parameter is a function of two or more independent variables, x_1, x_2, x_3, ..., x_n, i.e.,

$$R = R(x_1, x_2, x_3, \ldots, x_n) \tag{4}$$

The total uncertainty of the *R* parameter is calculated from:

$$I_R = \sqrt{\left(\frac{\partial R}{\partial x_1} I_1\right)^2 + \left(\frac{\partial R}{\partial x_2} I_2\right)^2 + \left(\frac{\partial R}{\partial x_n} I_n\right)^2} \quad (5)$$

where I_1, I_2 and I_n are the independent uncertainty variables.

The results indicated an uncertainty of ±3.05% for λ and ±0.3% for η/SFC.

3. Results and Discussions

Table 3 presents the fuel flow rates and the diesel substitution percentages by ethanol, on a mass basis, for each tested condition.

Table 3. Fuel flow rates and substitution percentage.

Test	Diesel Mass Flow Rate (g/s)	Ethanol Mass Flow Rate (g/s)	Diesel Substitution Percentage by Ethanol
OD_NEAT	0.680	0.00	0
OD_ET_1.5_TFO	0.533	0.11	17.1%
OD_ET_2.5_TFO	0.465	0.21	31.1%
OD_ET_3.5_TFO	0.386	0.31	44.5%
OD_ET_4.5_TFO	0.320	0.41	56.2%
OD_ET_1.5_TPC	0.534	0.11	17.1%
OD_ET_2.5_TPC	0.466	0.21	31.1%
OD_ET_3.5_TPC	0.392	0.31	44.2%
OD_ET_4.5_TPC	0.339	0.41	54.7%

It can be observed that the throttle position had a minor impact on fuel consumption. Only at the highest substitution level did this difference exceed 1%. Regarding the efficiency of converting the chemical energy of the fuels into electrical energy, the results are presented in **Figure 3** together with the brake specific fuel consumption, as a function of the diesel substitution percentage by ethanol. An increasing trend in efficiency can be observed as the ethanol fraction increases. Under the baseline condition, operating with diesel only, the efficiency was 21.73%, which is lower than all values obtained in the dual-fuel tests with ethanol and diesel. The efficiency values were higher when the throttle was fully open compared to the tests with the throttle partially closed.

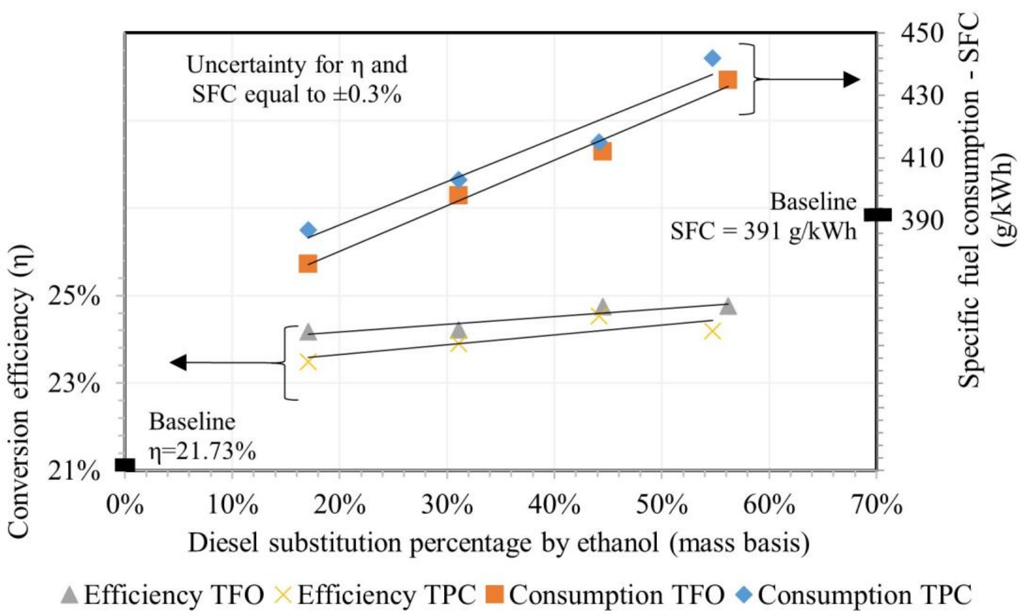

Figure 3. Efficiency and specific fuel consumption.

The increased efficiency observed with the addition of the ethanol fraction can be interpreted considering combustion mechanisms with a higher degree of premixing and controlled reactivity. The literature shows that low-reactivity fuels, such as ethanol, when introduced by manifold injection, promote a more homogeneous mixture with air before the start of combustion, favoring a combustion regime closer to pressurized and reducing the diffusive combustion fraction associated with diesel. Chaudhari and Deshmukh [15] demonstrate that increasing reactivity stratification and controlling the delay of combustion onset shifts heat release closer to or slightly after TDC (Top Dead Center), reducing heat losses and increasing useful work during expansion. Furthermore, Wei et al. [16] highlight that, even with the increased ignition delay caused by the high latent heat of vaporization of ethanol, the greater availability of oxygen in the fuel molecule favors more efficient oxidation reactions, which contribute to improved thermal efficiency, provided that the combustion regime remains stable and without excessive increase in the rate of pressure rise.

The reduction in efficiency observed in tests with the throttle partially closed can still be largely attributed to the increased pumping losses associated with the restriction of airflow in the intake. Under these conditions, the engine operates with a higher negative mean effective pressure during the intake stroke, since the piston needs to perform additional work to overcome the pressure drop imposed by the throttle. This work is not converted into useful power at the shaft, being dissipated throughout the cycle, which reduces the overall energy conversion efficiency. In engines operating with dual-fuel strategies, this effect becomes even more relevant, as the partial closure of the throttle reduces the mass of air admitted, increases the relative dilution of the charge, and intensifies the impact of the ignition delay promoted by ethanol. Therefore, part of the efficiency gain associated with more pressurized combustion is offset by the increase in pumping losses, explaining the lower efficiency values observed compared to conditions with the throttle fully open.

The brake-specific fuel consumption under diesel-only operation was 391 g/kWh. The specific fuel consumption with the throttle partially closed was higher than that observed with the throttle fully open. The increase in brake-specific fuel consumption observed with increasing ethanol substitution is attributed to the lower heating value of ethanol, which leads to a higher mass consumption of this fuel and, consequently, a higher total fuel mass consumption. This phenomenon was also observed and explained by Atelge [24]. The excess air coefficient (lambda) and the exhaust gas temperature are shown in **Figure 4**.

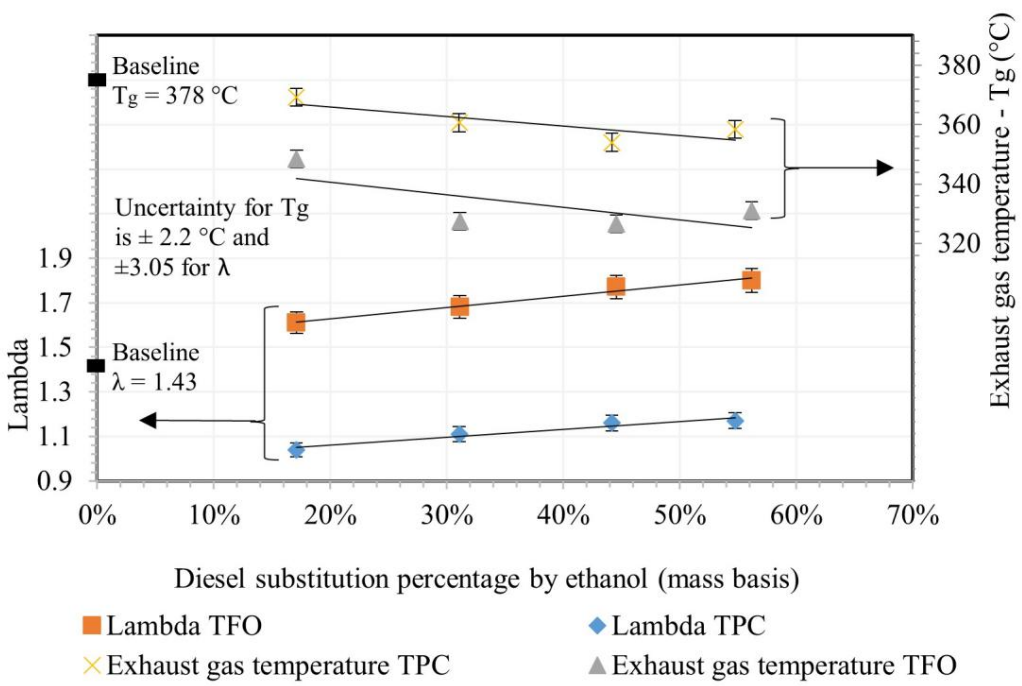

Figure 4. Lambda and exhaust gas temperature.

A reduction in the excess air coefficient (lambda) was effectively observed when the air flow was restricted by the throttle, as expected. In the diesel-only test, lambda was equal to 1.43. As the ethanol fraction increased, the lambda value also increased, which can be attributed to the lower stoichiometric air–fuel ratio of ethanol compared to diesel. It is also evident that the exhaust gas temperature tends to decrease as the contribution of ethanol to the combustion process increases. This behavior can be explained by several factors: (a) the higher energy conversion efficiency results in less fuel energy being dissipated in the exhaust gases, leading to a reduction in their temperature; (b) the higher lambda values indicate a larger amount of excess air within the combustion chamber, which contributes to energy dilution and cooling of the exhaust gases; and (c) ethanol has a high latent heat of vaporization, which reduces the temperature of the air–fuel charge admitted into the engine. Under the diesel-only operating condition, the exhaust gas temperature was 378 °C, which was the highest value among all tested conditions.

CO and NOx emissions are shown in **Figure 5**. In the diesel-only test, CO emissions were 762 ppm. The addition of ethanol significantly increased CO emissions, which is characteristic of incomplete combustion and may be associated with lower combustion temperatures. As the ethanol substitution percentage increased, the CO concentration in the exhaust gases also increased. The increase in CO emissions is linked to the "cooling effect" caused by the fuel. As discussed by Domínguez et al. [18], the high latent heat of vaporization of ethanol removes heat from the combustion chamber, reducing peak temperatures. According to Asad et al. [14], this drop in temperature hinders the complete oxidation of CO to CO_2, resulting in higher emissions of incomplete combustion products. The reduction in exhaust gas temperature observed in the tests validates the analysis of Domínguez et al. [18], demonstrating that fuel evaporation cools the admitted charge and compromises the kinetics of total carbon oxidation.

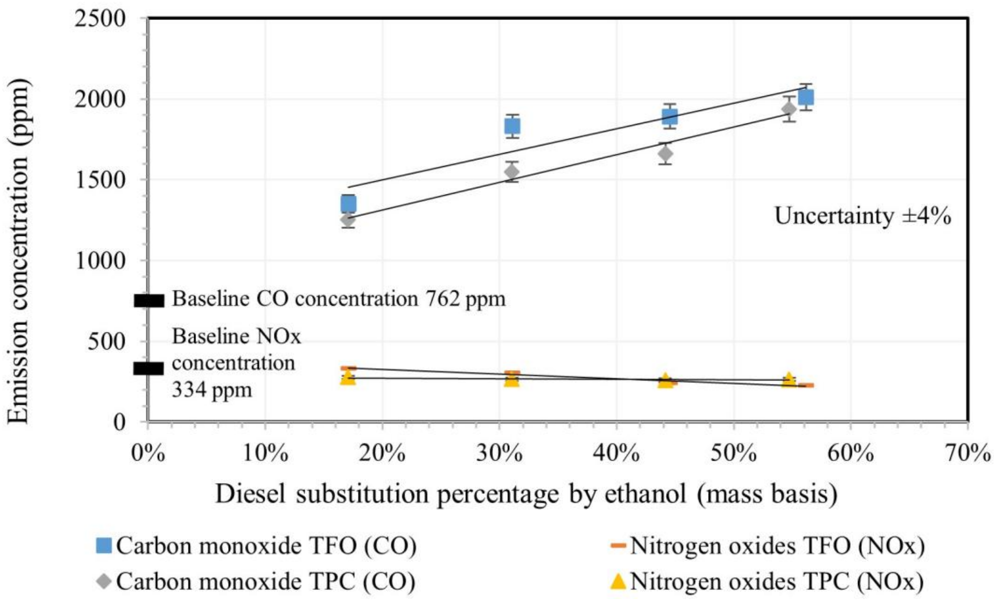

Figure 5. Carbon monoxide (CO) and nitrogen oxides (NOx) emissions.

Regarding NOx emissions, the concentration in the diesel-only test was 334 ppm, and all ethanol dual-fuel tests resulted in lower values. The NOx emission levels obtained under fully open and partially closed throttle conditions were very similar, which did not allow a clear conclusion regarding the influence of throttle position on NOx emissions. As observed by Domínguez et al. [18], the drop in NOx is a direct consequence of the lower average combustion temperature caused by the vaporization of ethanol.

Finally, the results related to exhaust gas opacity are shown in **Figure 6**. In the diesel-only test, the opacity was 52.3%. In all tests involving ethanol, both with the throttle fully open and partially closed, opacity values were lower than those obtained under diesel-only operation. Tests conducted with the throttle fully open resulted in lower opacity compared to those with the throttle partially closed, which is likely due to the greater air availability within the cylinder. Exhaust gas opacity decreased with increasing ethanol substitution, as expected, due to the reduced contribution of diesel and, consequently, the lower amount of fuel consumed during the diffusion combustion phase.

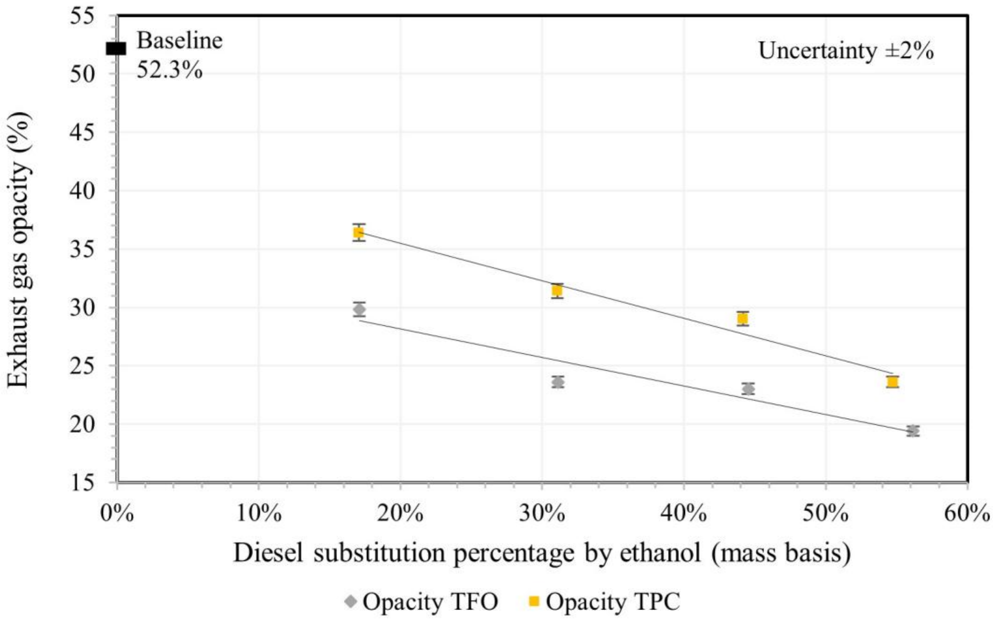

Figure 6. Exhaust gas opacity.

About opacity, Domínguez et al. [18] argue that the supply of intrinsic oxygen by ethanol inhibits the formation of soot nuclei in the reaction zones. Additionally, Vasanthakumar et al. [17] point out that the use of ethanol tends to increase the ignition delay period, which favors a more intense premixed combustion phase, reducing the formation of particles that typically occurs in the diffusion combustion phase.

4. Conclusions

This research demonstrated that dual-fuel operation in an Agrale M93 ID single-cylinder engine, integrating ethanol fumigation in the intake manifold and direct diesel injection, yields satisfactory results in both performance and sustainability. Overall, the application of ethanol allowed for an average increase of approximately 9% in the engine's thermal efficiency compared to conventional operation using only diesel, highlighting the potential of this configuration to optimize the conversion of chemical energy into mechanical work. Among the combinations tested, the operating point with an ethanol injection time of 1.5 ms and a fully open throttle valve (TFO) stood out as the most balanced, providing a 4% reduction in total fuel consumption. It is important to note that, although thermal efficiency improved, specific fuel consumption (SFC) showed a growing trend as the rate of diesel substitution with ethanol increased, a phenomenon explained by the lower calorific value of ethanol, which requires a greater mass of fuel to maintain the same power. Analysis of air restriction revealed that operation with the throttle valve fully open is energetically superior to the partially restricted throttle position (PTC), as closing the throttle generates higher pumping losses, dissipating some of the energy that would be converted into useful power. Regarding environmental emissions, the use of ethanol has promoted significant benefits, with a maximum reduction of approximately 50% in exhaust gas opacity and a 22.8% decrease in NOx emissions. The reduction in opacity is directly linked to the lower participation of diesel in the diffusive combustion phase and the intrinsic oxygen content in the ethanol molecule, which aids in soot oxidation. The decrease in NOx is a consequence of the cooling of the admitted charge due to the high latent heat of vaporization of ethanol, which reduces peak temperatures within the combustion chamber. However, a significant increase in CO emissions was observed, reaching 263% higher compared to pure diesel under certain conditions, reflecting incomplete combustion caused by the temperature drop in the load and the carbon oxidation kinetics impaired by the cooling effect. Adjusting the excess air coefficient (lambda) via the throttle allowed operation under conditions closer to stoichiometry, although the greater availability of air in the TFO condition proved preferable to minimize opacity. Finally, it is worth noting as a limitation of this research the fact that detailed measurements and analyses of internal combustion (such as cylinder pressure and heat release rate) were not performed, which restricts the phenomenological interpretation of the results to external performance and emissions data.

Author Contributions

Conceptualization, J.S.R. and G.D.T.; methodology, J.S.R. and G.D.T.; formal analysis, J.S.R., T.A.Z.d.S., T.H., and G.D.T.; investigation, J.S.R.; data curation, J.S.R. and T.A.Z.d.S.; writing—original draft preparation, J.S.R., T.H., and G.D.T.; writing—review and editing, T.A.Z.d.S., J.S.R., T.H., and G.D.T. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

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