

# Combustion, Performance, and Emission analysis of a CH<sub>3</sub>OH-Micro-Algae B20 Dual-Fuel CI Engine with CeO<sub>2</sub> Nano-particle Additives

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**Abstract.** This paper investigates the effect of adding cerium oxide (CeO<sub>2</sub>) nanoparticles to the pilot fuel during the operation of dual-fuel CI engine with a B20 microalgae biodiesel with diesel mixture and CH<sub>3</sub>OH at a fixed 10% energy share with respect to the performance, emission and combustion characteristics, through experimental testing over a array of operational conditions. The nanoparticles were dispersed in the B20 blend added to the engine at strengths of 5, 10, in addition to 15 ppm and the engine was tested under constant speed and varied load conditions. Results showed that the BTE(BTE) consistently improved with the dosage of nanoparticles. BTE showed an increase from 31.2% for the base B20 + M10 blend to 31.95%, 32.7%, and 33% at full load when 5, 10, and 15 ppm CeO<sub>2</sub> were used, representing improvements of 2.4%, 4.8%, and 5.8%, respectively. At the same time, it was reduced the BSEC from 9677 kJ/kWh (base fuel) to 9527, 9377, and 9227 kJ/kWh, presenting reductions of 1.6%, 3.1%, and 4.7%, respectively. The pollutants results showed that the incomplete combustion products were significantly reduced, HC emissions were reduced by 2.1%, 4.3%, and 6.4% at full load, while carbon monoxide emissions were significantly reduced by 31%, 62.5%, and 93.7% at 5, 10, and 15 ppm, respectively. As the concentration of nanoparticle content increases, smoke opacity was also reduced by 2.9%, 5.9%, and 8.8%. Alternatively, caused by the increased temperature of combustion, the NO<sub>x</sub> emissions were elevated by 5.2%, 10.5%, and 15.7% for the respective dosages. From combustion analysis, it was shown that nanoparticles promoted higher rates of pressure development and higher rates of heat-release. The peak pressure in the cylinder raised approximately 1–3%, and the premixed heat-release peak increased from 20.68 for the baseline blend to 21.31 for the 15-ppm case. Average results show that low-quantity CeO<sub>2</sub> nanoparticles function well to improve combustion efficiency and to lower incomplete combustion emissions in a B20–CH<sub>3</sub>OH(methanol) dual-fuel operation with 10–15 ppm providing the best performance–emission compromise.

## 1 Introduction

### 1.1 Literature review

The need for sustainable and low-emission alternatives for internal combustion engines is intensified by the increasing global energy demand and fossil fuel reserves depletion [15-16]. Compression ignition (CI) engines are very commonly used because of their high durability and efficiency; however, they are also known to be significant potentials for nitrogen oxides (NO<sub>x</sub>), particulate matter and greenhouse gases emissions. This has led to considerable interest in renewable fuels and advanced combustion approaches to reduce emissions while not sacrificing engine performance.[1]

Biodiesel is a renewable, biodegradable diesel-containing oxygen that has recently become an

important alternative to petroleum diesel. Microalgae-based biodiesel is an attractive third-generation biofuel among the various feedstocks. Microalgae have benefits which includes high lipid productivity, high growth rates and the possibility to use non-arable land or even wastewater. Due to these factors, algae biodiesel is sustainable and environmentally friendly characteristics in CI engine applications[2].The pure biodiesel may experience slightly reduced brake thermal efficiency which could cause higher emission based on nitrogen because of its LHV(latent heat of vaporization) and combustion characteristics.

In this context, dual-fuel and reactivity-controlled combustion strategies are investigated to help mitigate these challenges. These approaches involve adding a low-reactivity fuel along with a HRF to control ignition timing and heat release characteristics. CH<sub>3</sub>OH is one of the most suitable low reactive fuels owing to its

elevated oxygen inclusion, high LHV, and clean-burning characteristics[3]. CH<sub>3</sub>OH, regarded as a promising alternative fuel, gives an additional advantage, since it can also be produced from renewable feedstocks—for instance, biomass and waste. Biodiesel-CH<sub>3</sub>OH dual-fuel as diversified fuels can lead to an improvement of premixed combustion and smoke emission reduction. Nonetheless, CH<sub>3</sub>OH has a high LHV resulting in charge cooling, which can result in improved unburned hydrocarbons and carbon monoxide emissions at certain operating conditions[4]. Furthermore, in addition to fuel blending strategies, nanoparticle fuel additives have been known to enhance the combustion efficiency and emission characteristics of various fuels. Metal oxide nanoparticles such as cerium oxide (CeO<sub>2</sub>) have been extensively investigated for their catalytic performance and oxygen buffering properties. CeO<sub>2</sub> nanoparticles serve as oxidation promoters, assist in atomization of the fuel, and decrease the ignition delay, which increased thermal efficiency and decreased the emissions of CO, HC, and smoke emissions.[5] However, as nanoparticles have excellent properties only under a certain concentration range, excessive concentration may easily cause agglomeration, increased viscosity or lowered combustion benefits.[6]

### 1.2 Scope of the present study

The existing research experimental work on biodiesel fuel dual-fuel combustion and nanoparticle-assisted combustion is limited to isolated cases, and not in the context of their potential interaction effect in a microalgae biodiesel-CH<sub>3</sub>OH CI engine system. Especially for preparation conditions keeping ratio of biodiesel blend and CH<sub>3</sub>OH energy constant but varying only dosage of CeO<sub>2</sub>, such studies are rare. This phenomenon makes the isolated contribution of CeO<sub>2</sub> to combustion enhancement, but possible efficiency improvement or emission trade-off remains poorly understood. In this regard, the present work fills the low availability of controlled experimental study of graded concentrations of CeO<sub>2</sub> on B20 microalgae biodiesel with 10% CH<sub>3</sub>OH energy fraction.[7]The present work is novel in integrating the experimental performance investigation of a microalgae biodiesel-diesel B20/CH<sub>3</sub>OH dual-fuel CI engine field with adjusted CeO<sub>2</sub> nanoparticle dosing, thereby maintaining a constant base-fuel composition, while achieving constant CH<sub>3</sub>OH energy shares. Previous studies sought to simultaneously vary blend ratio, fuel type, or operating conditions in assessing their impacts on combustion, performance, and emissions, but the present study quantifies the impact of CeO<sub>2</sub> concentration (0, 5, 10, and 15 ppm) relative to a fixed blend ratio and fuel type and under a fixed set of engine conditions. This is in a deliberate manner that allows one to more elucidate on the role of CeO<sub>2</sub> as a catalyst within a third-generation biodiesel-alcohol dual-fuel system.

### 1.3 Present study

In this study, the CI engine was fuelled with algae biodiesel-diesel blend at 20% volume fraction (B20) as the HRF and CH<sub>3</sub>OH at 10% energy fraction and a constant share (10%) in energy (low-reactivity fuel). To investigate the catalytic effect of the nanoparticles, cerium oxide (CeO<sub>2</sub>) is added into the B20 fuel at amounts of 0, 5, 10, and 15 ppm.

The investigation presents the influence of varying CeO<sub>2</sub> dosages on performance of engine, emission characteristics and combustion characteristics at different loading... Several performance parameters like BTE and BSEC are studied and emissions such as NO<sub>x</sub>, CO, HC and smoke are quantified. Moreover, ICP and heat-release analysis is employed for combustion characteristics evaluation.

This work aims to find the optimal concentration of CeO<sub>2</sub> nanoparticle that will give a good trade-off between efficiency improvement and emission reduction in an algae biodiesel-CH<sub>3</sub>OH dual-fuel CI engine.

## 2 Materials and methods

### 2.1 Test Engine and Experimental Setup

All experiments were performed on a single-cylinder 4-stroke, table cooled, and DI compression ignition engine. An eddy current dynamometer was connected to the engine to apply and control the load accurately during the tests. Different load conditions were applied to drive the engine at a constant speed to assess the combustion characteristics, performance and emissions characteristics.

The test engine reflects a conventional research-grade variable compression ratio engine commonly utilized for laboratory studies. The key specifications of its engine are shown in Table 1 and Figure 1 represents the arrangement of the investigational arrangement.

**Table-1.** Engine specification

Parameter	Specification
Engine type	4-stroke, Single cylinder CI engine .
Make and model	Kirloskar TV1
Cooling system	Water
Power	5.2 kW
Speed	1500 rpm
Bore& stroke	87.5 mm x 110mm
Displacement volume	661 cc
Ratio of compression	17.5:1
Timing of Injection	23° before TDC
Injector pressure	210 bar or N/mm <sup>2</sup>
Combustion chamber	Direct injection, open chamber
Dynamometer	Eddy current dynamometer
Loading device	Computerized load control system
Fuel injection system	Mechanical fuel injection

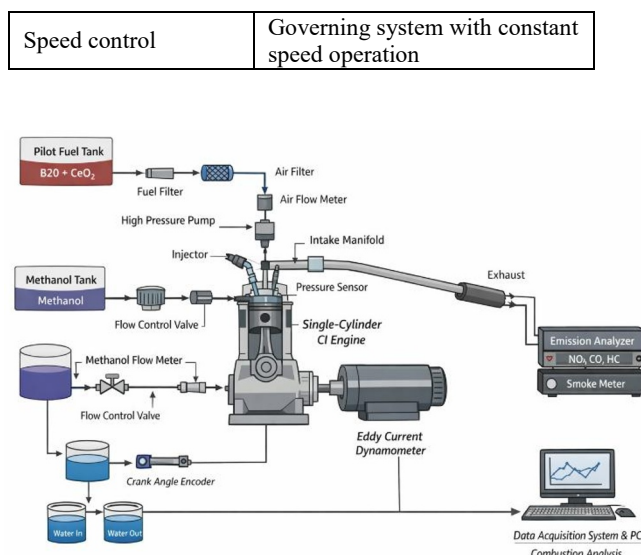


Fig.1. Schematic engine arrangement

## 2.2 Test Fuels and Blend Preparation

For this study, B20 blend was used as a base fuel. B20 fuel is 20% microalgae biodiesel and 80% regular diesel (volume basis). This ratio was selected as it provides an acceptable balance of performance, economy and emissions at a level that allows for use with existing diesel engine designs with little or no hardware changes. B20 has also been shown in previous work to give better combustion stability and smoke emissions than higher biodiesel blends.[8]

In the dual-fuel operation is a low-reactivity secondary-fuel CH<sub>3</sub>OH. It was provided at a constant 10% for fuel energy input as energy share of total fuel energy input. The reason CH<sub>3</sub>OH was chosen is because of its high O<sub>2</sub> content, high latent heat of vaporization and high-octane number; these properties lead to improved premixed combustion and reduced soot formation. The addition of CH<sub>3</sub>OH increases the total amount of oxygen present in the combustion chamber and thus increases the completeness of combustion.

In addition, to enhance both combustion efficiency and emission performance, cerium oxide (CeO<sub>2</sub>) nanoparticles were incorporated into the B20 blend, in different concentrations. The nanoparticle concentrations studied were 0, 5, 10 and 15 ppm for each of the nanoparticles. The oxygen-buffering capacity and catalytic activity associated with CeO<sub>2</sub> nanoparticles directly promote oxidation reactions during combustion and can reduce emissions and improve thermal efficiency, therefore these materials were selected. We chose 5, 10, and 15 ppm concentrations to cover a low-dose additive window in which catalytic advantages could be achieved while sustaining minimal particle agglomeration, or fuel property mixed-phase preferences in addition to injector issues. The selected range was based on previous literature on nano-additives and a viable working range for blending preparation, aiming to establish an optimum CeO<sub>2</sub> level under stable steady-state dual-fuel operating conditions.[9]

Initially, the desired dose of nanoparticles was weighed by an electronic balance with high accuracy. These nanoparticles were added to the B20 fuel with a magnetic stirrer and then subjected to ultrasonic dispersion to obtain a homogenous stable solution without agglomeration with span 80 surfactant to ensure stable mixture. The sonication was performed for a predetermined period to yield a stable and homogenous nano-fuel mixture for use in the engine tests[10]. The stability of the nano particle mixture is tested for 48 hours in the laboratory and found with zero sediments after the sonification process. Figure-2 shows the procedure for nano particle blending. Table-2 shows the fuel properties of B20 fuel and reference diesel fuel.

### Nanoparticle Fuel Blending Process

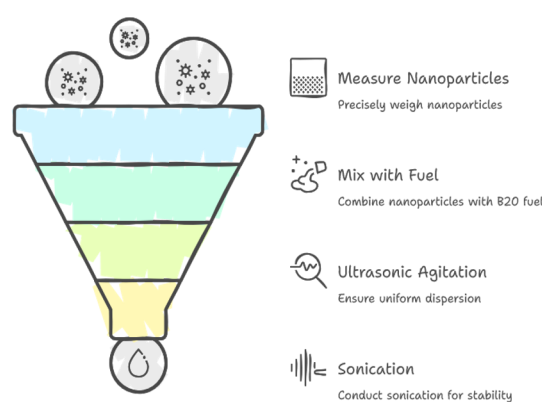


Fig.2. Nano particle blending Procedure

Table-2 Fuel properties

Property	Diesel	B20
Density kg/m <sup>3</sup> at 15°C)	820– 845	828–856
Kin. viscosity (mm <sup>2</sup> /s at 40°C)	2.0–4.5	2.4–4.8
LHV(MJ/kg)	42–45	41–44
Cetane Number	45–55	46–56
Flash point (°C)	60–80	74–98
Pour point (°C)	-15 to -5	-12 to -2.8
Cloud point (°C)	-10 to -2	-8.2 to -0.4
Oxygen content (%)	0	2–2.4
Sulphur content (%)	0.05–0.2	0.04–0.16
Stoichiometric A/F ratio	~14.5	14.1–14.3

## 2.3 Dual-Fuel Supply System

The engine was run in dual-fuel configuration with CH<sub>3</sub>OH as the secondary fuel and b20-derived fuel as the pilot fuel. Injection of the pilot fuel was achieved using the typical diesel injection system, which guaranteed stable combustion and ignition. A controlled fuel delivery system provided CH<sub>3</sub>OH

through the intake manifold with a constant energy share.

CH<sub>3</sub>OH flow rate was varied to maintain a constant 10% energy share relative to the total fuel energy input. Flow rate was controlled by a calibrated flow meter and control valve; and was maintained constant and repeatable during the tests.

## 2.4 Investigational Procedure

During the experiments, the engine was run at a fixed speed of 1500 rpm. The tests were done under varying load conditions which are generally at 20%, 40%, 60%, 80% and 100% of the rated load. The engine was kept at each load condition until stabilisation was achieved and steady-state operation was ensured before measurements were made. The experiments were conducted under laboratory ambient condition, however detailed temperature variations, humidity and pressure in the atmosphere were not continuously logged.

Measurable performance parameters: BTE, BSEC for each fuel configuration the emission amounts of nitrogen oxides, CO, unburned hydrocarbons, and smoke opacity were additionally measured. All the experiments were repeated and the average values were analysed and discussed.[8][11]

## 2.5 Measurement and Instrumentation

The engine test facility used for the current investigation was equipped with calibrated instruments to facilitate the measurement of all relevant performance, combustion, and emission parameters. The load was applied over dynamometer by using eddy current and the consumption of fuel was measured by burette and stopwatch set up. In the intake line, an air flow meter was installed to measure the airflow rate. A digital tachometer with a resolution of 0.1% was used for monitoring engine speed at constant speed during all test conditions.[12]

During combustion analysis, ICP was measured with a piezoelectric pressure transducer mounted on the cylinder head. The acquisition of the signals of pressure was synchronized with the data of angle of crank acquired by a great-resolution angle of crank encoder coupled to the shaft of the engine. Prior to the analysis these signals were collected by the data acquisition system and processed with a combustion analysing software to yield the HRR, peak cylinder pressure, ignition delay and the combustion duration. To lessen cyclic variances and present a more reliable measurement, pressure data were averaged over a few engine cycles.

Emission Limits: Exhaust emissions then were measured by normal gas analysis instruments. The exhaust gas concentrations of CO, unburned hydrocarbons (HC) and nitrogen oxides (NO<sub>x</sub>) were measured using a calibrated exhaust analyser and then the smoke opacity determined using a smoke meter mounted in the exhaust line [9]. Evaluation of all instruments were performed and calibrated before the

conduction of experiments to assure accurate measurements, and these values were taken in steady-state conditions for each fuel and load configuration, and averaged. Table-3 shows the instrument used in the experiment[1]

**Table-3.** Instrument used in the experiment

Parameter	Instrument	Measurement range	Accuracy
Engine load	Eddy current dynamometer	0–50 kg	±1%
Engine speed	Digital tachometer	0–3000 rpm	±10 rpm
Fuel consumption	Burette with stopwatch	0–50 ml	±1 ml
Air flow rate	Air flow meter / orifice with manometer	0–1000 kg/h (equivalent)	±1%
ICP	Piezoelectric pressure transducer	0–200 bar	±1%
Crank angle	Crank angle encoder	0–720°	±1° CA
CO emission	Exhaust gas analyzer	0–10% vol	±0.01%
HC emission	Exhaust gas analyzer	0–10,000 ppm	±10 ppm
NO <sub>x</sub> emission	Exhaust gas analyzer	0–5000 ppm	±10 ppm
SMOKE	Smoke meter	0–100 HSU	±1 HSU
Cooling water flow	Rotameter	0–10 L/min	±1%
Exhaust gas temperature	K-type thermocouple	0–1000 °C	±1 °C

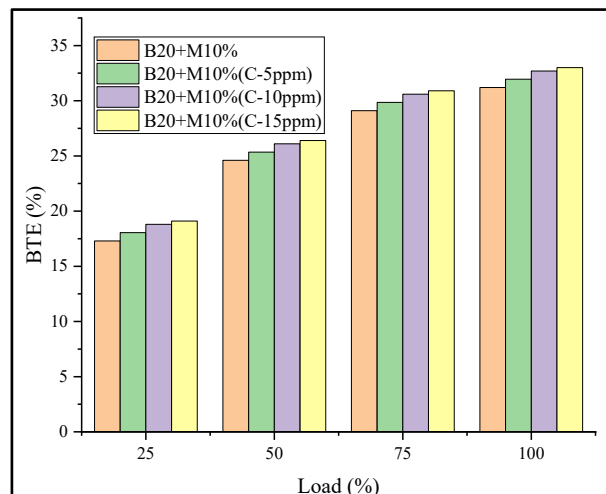
## 2.6 Uncertainty:

The experiment measurements were subjected to an Uncertainty-Analysis to estimate the confidence in obtaining these measurements. The standard error propagation methods were used to estimate the uncertainties associated with the primary measured parameters (brake power; fuel consumption; exhaust emissions; ICP). The combined uncertainty of the measured parameters are computed and the accuracy of measuring the investigated parameters is acceptable to perform experimental study on the internal combustion engines assuring the reliability of the results.

## 3 Discussion of Results

### 3.1 Parameters based on performance

#### 3.1.1 BTE



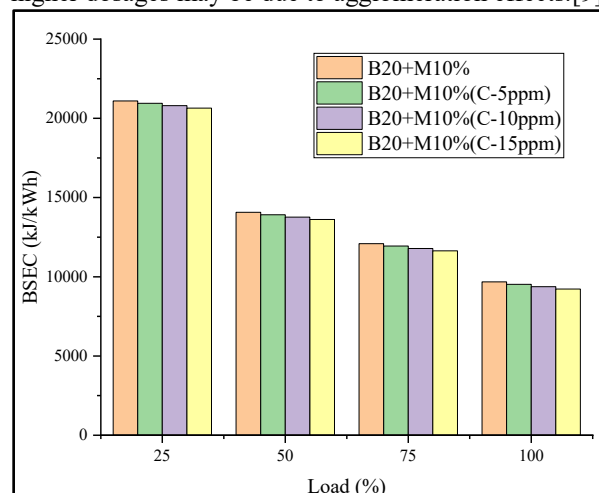
**Fig.3.** Load vs BTE

Figure-3 shows Load vs BTE. The BTE increased at all load conditions compared to base fuel B20 +M10 with the additional addition of CeO<sub>2</sub> nanoparticles progressively. BTE increased from 31.2% for the base fuel to 31.95%, 32.7%, and 33%, for 5, 10, and 15 ppm at full load, logistically signifying improvements of about 2.4%, 4.8%, and 5.8%, respectively. A similar trend of enhancement was observed at intermediate loads, which further indicates that the nanoparticles are acting as a consistent catalyst. This enhancement is primarily due to the oxygen buffering ability and catalytic oxidation performance of CeO<sub>2</sub>, which can facilitate more thorough combustion and rapid heat release. These nanoparticles facilitate atomization and shortens ignition delay, thereby improving thermal conversion efficiency as well. These trends are in accordance with earlier studies confirming that the redox properties as well as the catalytic activity of CeO<sub>2</sub> additives can result in better combustion efficiency and BTE. In comparison to its performance at 10 ppm which predicts diminishing returns, correlating with other nano-fuel studies, the marginal gain between 10 and 15 ppm indicates this trend may onset at higher nanoparticle concentrations.[13]

#### 3.1.2 BSEC

Figure-4 indicates Load vs BSEC, and all load conditions showed a steady decrease in BSEC (BSEC) with the increase in the number of nanoparticles CeO<sub>2</sub> compared to the base fuel B20+M10. The BSEC at full load decreased from 9677 kJ/kWh for base fuel to 9527, 9377, and 9227 kJ/kWh for 5, 10, and 15 ppm, which corresponded to approximately 1.6%, 3.1%, and 4.7 % reduction. The same decrease trend for part loads suggest increment of energy usage by adding nanoparticle. The decreased BSEC IS due mainly to the catalytic oxidation behavior of CeO<sub>2</sub> which is beneficial to the combustion completeness and heat release characteristic. Also, the oxygen storage-release mechanism of cerium oxide facilitates more effective

fuel-air reactions, which results in a lower energy consumption per load condition. Such reductions in consumption of fuel and improvement in fuel economy with optimal CeO<sub>2</sub> loadings are consistent with previous studies using these nano-fuels. The gradual decrease up to 15 ppm indicates better combustion efficiency, while the eventual decline in benefits at higher dosages may be due to agglomeration effects.[9]



**Fig.4.** Load vs BSEC

### 3.2 Emission parameters

#### 3.2.1 Unburned Hydrocarbon

Figure-5 Indicates the emission of UHC with respect to load in percentage. Compared to the base fuel B20+M10, there was a steady drop in the unburned hydrocarbons (HC) emissions with the use of CeO<sub>2</sub> nanoparticles across all load conditions. Compared to base fuel, emissions of HC reduced from 47 ppm for base to 46, 45 and 44 ppm for 5, 10 and 15 ppm, equivocal percent reductions of 2.1%, 4.3% and 6.4% respectively all at full-load. A corresponding trend of decrease at part loads was observed, suggesting that combustion completeness at part load conditions was improved through increased nanoparticle concentration. The decrease of HC emissions could be ascribed to the oxygen buffer and catalytic oxidation property presented by CeO<sub>2</sub>, which can promote the oxidation of the unburned fuel fragments in the combustion process. The nanoparticles as well help to improve atomization and flame propagation speed, minimizing quenching effects around the cylinder walls. These findings agree with previous reports of lower HC emissions during the combustion of nano-fuels on account of improved oxidation kinetics and improved combustion efficiency.[2]

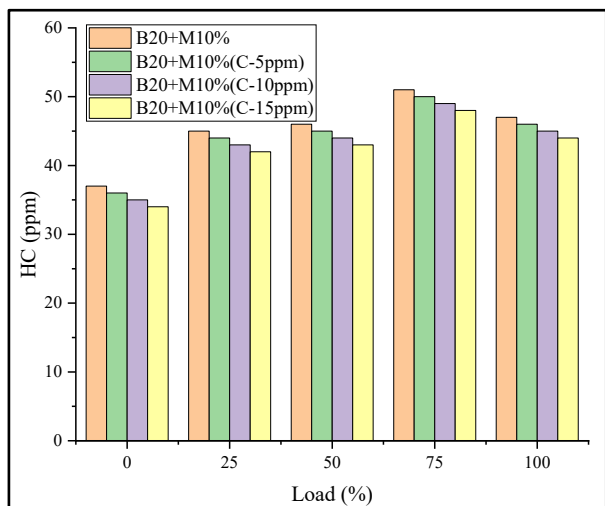


Fig.5. Load vs HC

### 3.2.2 Carbon monoxide emissions

Figure-6 Shows the emission of CO with respect to load in percentage. CO emissions were significantly decreased with the incorporation of CeO<sub>2</sub> nanoparticles under all load conditions in comparison with the base fuel B20+M10. Specific CO dropped from 0.032% (base fuel) to 0.022, 0.012, and 0.002% with 5, 10, and 15 ppm, respectively (reductions of 31%, 62.5%, and 93.7%, at full load). At part loads, such decreasing trends were also observed, indicating the considerably improved oxidation of HC and CO. This dramatic decrease in CO emissions is mainly attributed to the oxygen storage–release mechanism of CeO<sub>2</sub> nanoparticle and the catalytic activity of CeO<sub>2</sub> nanoparticles which favor the transition of CO to CO<sub>2</sub> during the combustion process. Moreover, the nanoparticles facilitate atomization of fuels and increase reaction rates for better combustion. Such findings are consistent with previous investigations of nano-fuel, showing significant reductions of CO due to the increased oxidation kinetics and combustion efficiency with the use of CeO<sub>2</sub> additives.[14][9]

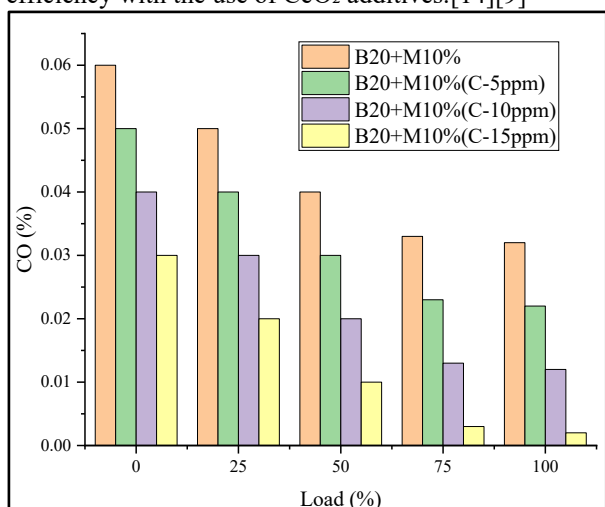


Fig.6. Load vs CO

### 3.2.3 SMOKE

Figure-7 Shows the emission of SMOKE with respect to load in percentage. Compared to base fuel B20+M10, smoke emissions were reduced consistently with the addition of CeO<sub>2</sub> nanoparticles at all loads conditions. At full load, smoke opacity decreased from 34 HSU for the baseline fuel to 33, 32, and 31 HSU for 5, 10, and 15 ppm, reductions of approximately 2.9%, 5.9%, and 8.8%, respectively. At part loads the reductions were similarly observed, suggesting better soot oxidation with increasing nanoparticle concentration[15], [16]. The reduction of smoke is mainly due to the high oxygen buffer capacity and catalytic oxidation characteristic of CeO<sub>2</sub>, which can not only assist in oxidizing soot precursors, but also improve the completeness of combustion. Nanoparticles also enhance fuel atomization and air–fuel mixing, thereby minimizing locally rich regions which would otherwise produce soot. Similar trends have already been reported in earlier work in which the use of nano-fuel combustion were able to show considerable smoke reduction compared to conventional combustion as a result of the promotion of oxidation kinetics and an increase in combustion efficiency.[7]

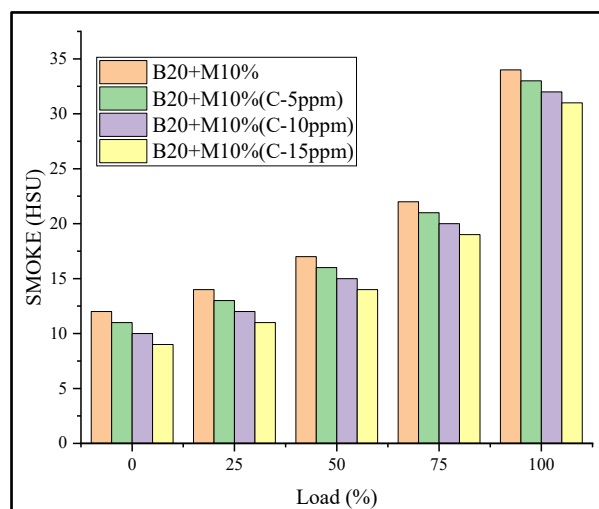
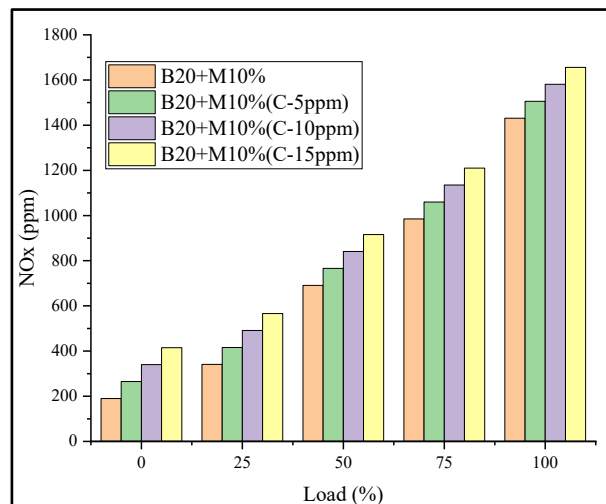


Fig.7. Load vs SMOKE

### 3.2.4 Oxides of Nitrogen



**Fig.8.** Load vs NO<sub>x</sub>

Figure-8 Shows the emission of oxides of nitrogen with respect to load in percentage. Compared to the base fuel B20+M10, compared to the base fuel B 20 + M 10, all-loads NO<sub>x</sub> emissions raised after adding CeO<sub>2</sub> nanoparticles. The values for NO<sub>x</sub> increased from 1431 ppm for the base fuel to 1506, 1581, and 1656 ppm at 5, 10, and 15 ppm at full load, corresponding to values of approximately 5.2% and 10.5% and 15.7%. At part loads, a similar increasing trend was obtained with respect to combustion temperatures, which also showed higher values with nanoparticle addition. The increase in NO<sub>x</sub> emissions is due to more complete combustion as well as higher in-cylinder temperature owing to the higher oxidation activity and oxygen buffering character of CeO<sub>2</sub>. [17], [18], [19] The better mixing in the engine approaching the crevice geometry and the reduced ignition delay strengthens the peak temperatures, which is beneficial for thermal NO<sub>x</sub> formation. Such trends agree with the previous trends noted for nano-fuels, where better combustion efficiency with metal-oxide based nanoparticles was found to reduce the emissions of the incomplete combustion products at the expense of higher NO<sub>x</sub> formation. [1]

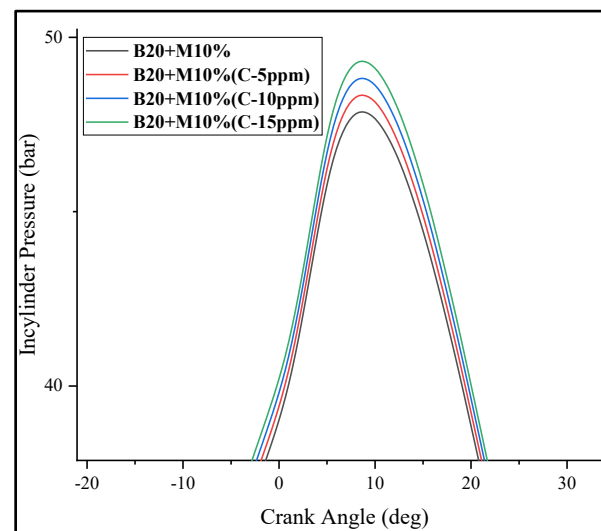
This observation leads to the conclusion that the observed NO<sub>x</sub> increase in the present work could be mitigated in future work via moderate levels of exhaust gas recirculation, injection timing adjustment, water-based charge cooling strategies, or finding an optimal level of CeO<sub>2</sub> that balances oxidation enhancement with control of peak-temperature.

### 3.3 Combustion Parameters

#### 3.3.1 ICP

Figure-9 Shows the ICP with respect to Crank angle. Details of ICP traces show that higher CeO<sub>2</sub> dosage appearing to affiliate to such a peak combustion process compared to the base blend as the pressure level gets higher in the magnitude pressure in diesel cylinder of B20+M10 fuel. The cylinder pressure

at TDC (0°CA) are about (+0.0, +1.0%, +2.0, +3.0) % higher for B20+M10 than that without catalyst for 5, 10 and 15 ppm CeO<sub>2</sub>, with a cylinder pressure of 39.03 bar, along with increases of 39.42, 39.81 and 40.21 bar, respectively [14]. Near the peak pressure location (approx. ~9°CA aTDC) a similar trend is apparent, where the peak increases from 47.85 bar (base) to 48.33, 48.81 and 49.30 bar for 5, 10 and 15 ppm, resulting in an approximate 1–3% increases respectively. This enhancement is primarily ascribed to the catalytic effect of cerium oxide and its oxygen storage–release character (Ce<sup>3+</sup>/Ce<sup>4+</sup> redox), which facilitates oxidation reactions, leads to a better local mixture preparation, and promotes a more complete combustion in both premixed and diffusion phases, all of which enhance pressure rise in proximity to TDC. The performance enhancements observed (higher BTE and lower BSEC) are consistent with higher pressure development, but a clear mechanistic rationale is also provided for the associated rise in NO<sub>x</sub>, since the combination of enhanced combustion, and the local provision of additional oxygen, will typically lead to stronger thermal NO formation and increased local temperatures. [20][8]

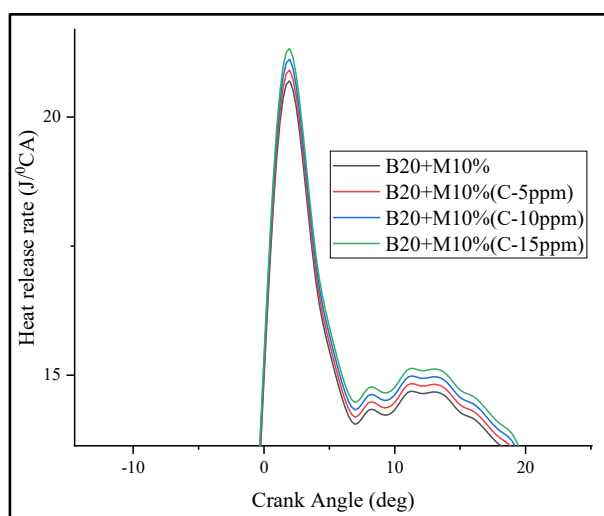


**Fig.9.** Crank Angle vs In-cylinder pressure

#### 3.3.2 HRR

Figure-10 shows the HRR relating to Crank angle. Among the HRR profiles this translates to a distinctive and staged increase in the strength of the premixed combustion phase as CeO<sub>2</sub> loading is increased on the B20+M10 blend while the overall combustion phasing is retained. The HRR is consistently low and mostly negative during compression (≈ -360 to ~-10°CA), capturing energy due to charge heating, wall heat transfer and mixture preparation in this phase of the operation. Near TDC the HRR jumps quickly to positive values (~-7 to -5°CA) which is followed by a steep premixed peak shortly thereafter, at ~2°CA aTDC. With increasing nanoparticle dosage, the maximum HRR rises monotonically from 20.6848 (B20+M10) to 20.8916, 21.1006, and 21.3116 for 5, 10, and 15 ppm CeO<sub>2</sub>,

respectively ( $\approx +1-3\%$ ). The higher, and slightly sharper premixed peak suggests faster kinetics of energy-release and a higher degree of oxidation, associated with the catalytic/oxygen-buffering nature of ceria to generate more local radical populations for more complete combustion of the premixed fuel-air fraction. Beyond the maximum, the decay of HRR with crank angle, characteristic of the transition to mixing-controlled burning and late-cycle heat losses, is more rapid with higher CeO<sub>2</sub>, which indicates improved intermediate species burnout, consistent with the increased cylinder pressure development and the typical combustion intensification trade-off toward higher NO<sub>x</sub> with more active combustion.[21]



**Fig.10.Crank Angle vs HRR**

The trends observed in this research are in accordance with earlier studies conducted on CeO<sub>2</sub>-based nano-additive biodiesel systems in chronology of CI engines. The increase in BTE and decrease in BSEC are mainly attributed to the catalytic oxidation activity of CeO<sub>2</sub>, and thus it leads to an enhancement of oxygen availability and a more complete combustion. Earlier studies using metal-oxide nanoparticles have observed similar efficiency enhancements of a similar magnitude (typically 2–6%). In addition, the improved emissions characteristics in the present work as compared to CeO<sub>2</sub>-supported catalyst were also observed earlier when CO, HC and smoke emissions were reduced due to oxidation of unburned hydrocarbons and soot precursors by CeO<sub>2</sub>. But it is worth mentioning that the literature also has reported the increment of NO<sub>x</sub> emissions with the rise of nanoparticle loading, which is caused by the higher in-cylinder temperatures and combustion intensity, as well. Overall, the consistency of the present findings with the past investigations validates the reliability of the combustion-emission characteristics observed and underscores the performance of CeO<sub>2</sub> as an effective combustion improvement nano-additive in biodiesel-alcohol dual-fuel CI engine.

## 4 Conclusion

In conclusion, the current research study demonstrates that CeO<sub>2</sub> nanoparticles dispersion in the B20-CH<sub>3</sub>OH (B20+M10) blend effectively enhances combustion in the test CI engine. The heat-release-rate analysis revealed an earlier and more pronounced transition from negative (compression heat-absorption) to positive HRR near TDC, accompanied by a higher premixed-combustion peak occurring just after TDC; additionally, the peak HRR increased progressively from the base B20+M10 case to 5, 10, and 15ppm CeO<sub>2</sub>, suggesting that improving reaction kinetics and improved premixed fuel oxidation. This trend indicates that CeO<sub>2</sub> can serve as efficient combustion promoter, contributing to an enhanced catalytic activity and an oxygen storage-release behaviour, which are, in turn, associated with an improved fuel-air mixing utilization and more complete combustion in the rapid combustion zone. The potential for future combustion efficiency improvement, based on the maximum premixed heat-release intensity delivered for the concentrations tested, lay with the highest dosage tested (15 ppm) while at the same time emphasizing the need for future optimization to weight combustion strengthening against emission trade-offs (notably NO<sub>x</sub>). Finally, the low-dose (5–15 ppm) CeO<sub>2</sub> approach is not only feasible but also scalable to improve the combustion performance of B20+M10 operation, and a relevant future work would be correlating the HRR results with the brake performance and complete emission measurements over the load range, also the stability/dispersion, and long-term durability tests to determine an optimal dosage range for real engine application.

Further studies should be concentrated on the maximal value of interacting CH<sub>3</sub>OH energy fraction and the peak dose of CeO<sub>2</sub> nanoparticles to reach a compromise between power improvement and NO<sub>x</sub> emissions. Furthermore, control methods such as EGR and injection timing can be tested on these prototypes to reduced NO<sub>x</sub> production from the improved combustion. Although the current work shows significant performance and emission advantages, some practical challenges should overcome for the implementation of CeO<sub>2</sub> nano-additives in real engines. Especially, the long-term stability of the dispersion during fuel storage is one of the significant issues since the agglomeration of nanoparticles could affect the fuel homogeneity and injection properties. Additionally, repeatable dosing of the nanoparticle is critical; uncontrolled dosing may lead to over-accumulation within the fuel system. Additionally, the economic aspects on nanoparticle production and mixing affect the overall feasibility of this method. This is important long-term durability testing, as it could affect the function of the injectors, lead to deposit formation, or change the wear properties of the engine. Moreover, these also need to be assessed for nanoparticle stability, surfactant-assisted dispersion methods and bulk blending viability for real-world application. Finally, techno-economic and environmental assessments should be performed to determine the feasibility of nano-additive-assisted dual-fuel CI engine systems for practical applications.

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