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RESEARCH ARTICLE

Impact of Hydrogen Enriched Air and Ethanol-Diesel Fuel Blends on Combustion, Performance and Emission behaviour of CI Engine

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Abstract

The rapid depletion of fossil fuels and harmful tile pipe emissions form internal combustion engines at an alarming rate make the finding for alternative fuels to power the engines. This article investigates the diesel engine capability by the combined effects of ethanol and diesel fuel blending and hydrogen enriched intake air on the performance, combustion, and emission characteristics of 4-stroke diesel engine. These experiments were conducted using three different fuel configurations such as 20% ethanol–80% diesel blend (E20D80), neat diesel (D100), and ethanol diesel blend (E20D80), supplemented with hydrogen enriched air (E20D80+H26LPM). The hydrogen was supplied to engine at constant flow rate of 6 LPM through manifold along with air. Three distinct fuels were used in the engine, and its performance, emissions, and combustion characteristics were assessed under load conditions ranging from 0% to 100%. Hydrogen enrichment of the intake air improves the combustion efficiency of ethanol by accelerating flame speed and enhancing thermal conversion, offsetting ethanol's lower calorific value. A peak in-cylinder pressure of approximately 69 bar was achieved, indicating more effective combustion. CO emissions decreased significantly under part-load conditions due to improved oxidation kinetics. Ethanol's high latent heat of vaporization helped maintain NOx emissions at levels comparable to diesel 1023 ppm. However, a slight increase in smoke emissions was observed with hydrogen addition, possibly due to richer local equivalence ratios and altered combustion dynamics.

Keywords: Diesel engine, CO emissions, Hydrogen enrichment, Ethanol, Manifold injection.

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1. Introduction

Energy is essential for supporting human life and driving functions of modern civilization. Currently, around 84% of world energy consumption is fulfilled by conventional fossil fuels and nuclear energy, while the remaining 16% is sourced from renewables such as solar, wind, hydroelectric, biodiesel and biomass derivative [1], [2]. Conventional fossil fuels are depletable and non-renewable whereas, biodiesel is produced from renewable feedstocks, offering a more sustainable solution [17], [18]. Additionally, ethanol is derived from biologics and provides notable environmental advantages, including a substantial reduction in greenhouse gas emissions and air pollutants when compared to traditional fossil fuel alternatives. Diesel engines emit harmful pollutants that pose significant risk to both human health and the environment. Specifically, diesel exhaust is linked to severe respiratory and cardiovascular disorders. Raising global concern over pollutants generated from combustion such as oxides of nitrogen, carbon monoxide and particulate matter ozone depletion has driven the

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development of stringent regulatory frameworks. These regulations mandate emission limits and promote the adoption of advanced emission control technologies to ensure compliance and mitigate environmental and health impacts. Hydrogen has been explored as an internal combustion fuel since the 1970s, due to its clean energy potential. Hydrogen is the most plentiful element in nature, supports better cold start and less emissions compared to gasoline and diesel engines [3]. Hydrogen is considered as a long-term solution to energy crisis and emissions. Further, major challenges with hydrogen involved fuel storage and handling cost [4].

Brazil is one of the world's largest producers of ethanol, contributes approximately 90% of biofuel production in central south America [5]. Biodiesel is a renewable, environmentally friendly fuel containing 10% oxygen, which promotes complete combustion of fuel and reduces unburnt hydrocarbons and particulate emissions [6]. Direct use of ethanol in diesel engines is not feasible due to its low cetane number around 6, compared to diesel whereas, diesel has typically cetane number between 45–40 [7]. Use of oxygenated compounds like ethanol, methanol or dimethyl ether to the diesel promotes clean burning of fuel results reduction in CO emissions by 20% and a significant decrease in particulate matter [8].

Mario et al. [9] examined the effect of ethanol and soybean biodiesel on a turbo-charged CI engine. Their findings showed that addition of ethanol up to 10% notably decreased emissions of (NO_x) Nitrogen Oxides, (HC) hydrocarbon and (CO) Carbon monoxide emissions but increases specific fuel consumption (SFC). Shahir et al. [10], concluded that optimum results were obtained by blending up to 5% ethanol with a concentration of $> 90\%$. The primary concern of diesel engines was emissions of PM and NO_x. This blend shows significant lower emissions of HC, PM, CO and smoke emissions. Anyway, it also resulted higher NO_x emissions and brake specific fuel consumption.

Elumalai et al. [11], assessed the performance of the diesel engine using Mahua biofuel and n-pentanol (20–30% by volume) and 80% diesel. They found that combined effects of biodiesel and pentanol improves BTE by 15% HC, CO and NO_x emissions reduced by 5.8%, 40% and 49% respectively related to neat diesel oil. Noorollahi et al. [12], reported the impact of incorporating graphene oxide nano particles into diesel-ethanol blends at various concentrations of 25ppm and 50ppm. The findings revealed that the combined use of graphene oxide nanoparticles and ethanol significantly enhanced the engine performance and lowered emissions. Brake thermal efficiency of the engine reached up to 28.75% due to combined action of nanoparticles and higher oxygen content of ethanol. Additionally, there was a substantial reduction in emissions of CO, UHC and NO_x by 38.845%, 21.243% and 19.923% respectively compared to neat diesel fuel.

Kumar et al. [13] examined the impact of using hydrogen and ethanol-diesel blend in dual fuel diesel engine. The dual fuel engine was run with 5%,10% and 15% ethanol and with constant flow rate of hydrogen of 9 lpm mixed with air in manifold intake. The results revealed that combined effect of hydrogen and ethanol improves the BTE of engine, shown 4.845% than the conventional diesel engine. A greater amount of CO emissions reduced by 49.98%, due to no carbon element in hydrogen and oxygen content of ethanol. On the other hand, nitrogen oxide emissions are slightly rose compared to clean diesel oil.

Rakopoulos et al. [14], conducted an experiment on direct injection diesel engine and found the effects of using ethanol blends with 5% and 10% by volume and diesel fuel. A marginal reduction in NO_x emissions was observed relative to pure diesel. Further use of ethanol blends resulted slight improvement in BTE, although this was accompanied by an increase in brake specific fuel consumption due to inferior calorific value of ethanol.

Thanigaivelan et al. [15], evaluate the effectiveness of direct injection diesel engine using cashew nutshell (CNSL) biodiesel along with ethanol at rates of 5%,10% and 15% along with hydrogen enriched air. The engine was run with pure diesel D100, 20% CNSL biodiesel (B20CNSL), 20% CNSL biodiesel with 4LPM hydrogen (B20CNSLH24LPM), 20% CNSL biodiesel with 8LPM hydrogen (B20CNSLH28LPM), 20% CNSL biodiesel with 12LPM hydrogen (B20CNSLH212LPM). Out of which B20CNSLH28LPM demonstrated superior performance characteristics and significant reduction in exhaust emissions than the conventional diesel oil.

2. Materials and methods

2.1. Preparation of blend

The blend E20D80 was made of mixing 200 ml of ethanol with 800 ml of diesel fuel. The resulting blend contains 20% ethanol by volume, contributes approximately 2-4% oxygen by weight, which helps to improve combustion there by decreasing smoke emissions [16]. However, further increasing ethanol content reduce the energy density of the fuel, which deteriorate the performance of the engine. No cetane improvers or surfactants were added in the blend. To ensure homogeneity and stability the mixture was stirred using a magnetic hot plate stirrer as shown in Figure 1. The principal physicochemical properties of diesel, ethanol, and hydrogen used in the present investigation are summarized in Table 1.

Table 1: Properties of various oils.

Property	Diesel	Ethanol	Hydrogen
Molecular weight	183	46	–
Calorific Value (kJ/kg)	42600	26700	141790
Mass Density (kg/m^3)	846	789	0.08988 (g/l)
Dynamic Viscosity (mPa-s)	3.546	1.074	0.089

Figure 1: Preparation of blend.

Figure 2: Experimental setup.

2.2. Hydrogen enrichment

Hydrogen was inducted into the engine through intake manifold at constant flow rate of 6 LPM along with incoming air during suction stroke. While the blended fuel E20D80 is directly infused into the cylinder through the fuel injector. Flow meter was used to indicate the flow of hydrogen into the manifold.

2.3. Experimental setup

The tests were conducted on 4-stroke single cylinder water-cooled Compression Ignition engine. The engine was provided with port fuel and direct injection system. The specifications of test engine are listed in Table 2, and the experimental setup was depicted in Figure 2.

2.4. Uncertainty analysis

Uncertainties and errors arise from various paths such as change in environment conditions, Instrument selection, calibration and observation, deterioration of parts. The overall uncertainty can be computed by using Holman equation. The Uncertainty in measured parameters demonstrated in Table 3.

3. Results and discussions

3.1. Combustion attributes

Figure 3 illustrates the change of the combustion pressure within the cylinder during combustion of the fuel. In-cylinder pressure reflects the capability of the fuel to mix effectively with air and burn efficiently. A higher rate of pressure corresponds to the complete combustion of fuel burned in premixed combustion stage. The variation of peak pressure inside the cylinder for the operation of the engine at full load with diesel, ethanol-diesel blend (E20D80) and enriched hydrogen air ethanol diesel blend (E20D80+H26LPM) are shown in Figure 3. From Figure 3, it can be recorded that the in-cylinder peak pressure for the hydrogen blends is closer to diesel. The maximum cylinder pressure recorded for

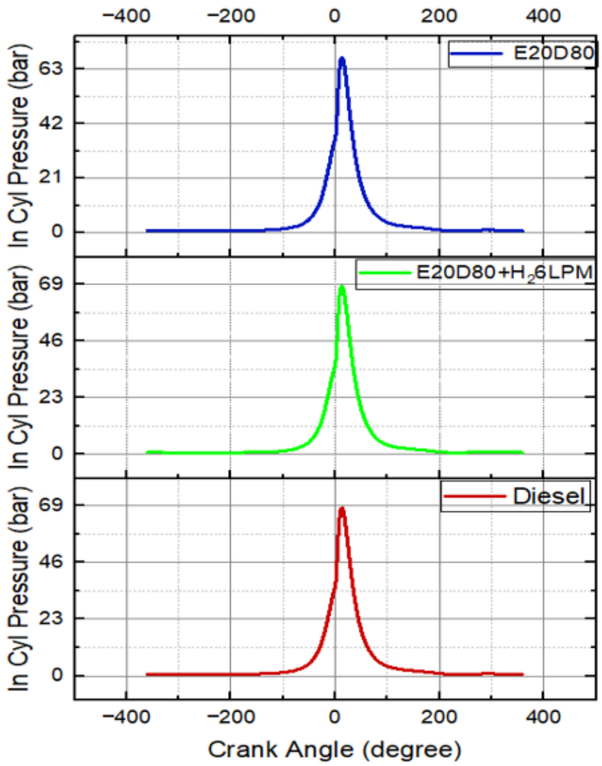

Figure 3: Crank angle versus cylinder pressure.

Table 2: Details of test engine.

S. No	Description	Specifications
1	Engine Model	Kirloskar & TV-1
2	No. of Cylinders	1
3	Strokes	4
4	Speed, Power	1500 rpm, 5.2 kW
5	Stoke length	110 mm
6	Cylinder Bore	87 mm
7	C R	17.5:1
8	Injection timing	23° bTDC
9	Injection Pressure	200 bar
10	Type of Loading	Eddy current

the E20D80+H26LPM blend was obtained 69 bar under full load condition. The rapid burning of hydrogen and higher calorific value and diffusivity properties of hydrogen enhance the cylinder pressure. The blend E20D80 shows 65 bar pressure which is 7.24% lower than the conventional diesel. This reduction is attributed to lesser calorific value of ethanol and maximum part of the fuel burnt after the post combustion stage.

The quantity of fuel burned in premixed phase and initiation of combustion and rate of fuel combustion is determined by the heat release rate. During ignition delay period, the fuel and air combine to form the premixed phase, the first stage of combustion. Mixing-controlled combustion is the name given to this stage of combustion. The post combustion phase extends until the power stroke is completed. During this phase, a slight but noticeable rate of heat release occurs. Figure 4 shows the variation of HRR at full load engine operation with test fuels such as diesel, E20D80 and E20D80+H26LPM. The higher heat release rates of E20D80, E20D80+H26LPM and diesel fuels were found to be 58 J/deg, 57 J/deg and 56 J/deg, respectively, at maximum load. The heat release rate for E20D80 and E20D80+H26LPM is more than diesel due to the inherent oxygen content of ethanol and higher calorific value of hydrogen.

3.2. Performance attributes

A) Brake Thermal Efficiency (BTE):

Brake thermal efficiency signifies the capability of an engine to transfer chemical energy of the fuel into brake power output. Figure 5 shows variation of BTE at different loads for diesel, blend E20D80 and E20D80+H26LPM. From Figure 5, it was found that the blend E20D80 shows relatively poor performance than the diesel and the blend E20D80+H26LPM by 7.38% and 14.98%, respectively. This reduction is attributed to lesser calorific value of ethanol relative to hydrogen

Table 3: Uncertainty analysis.

Instrument	Range	Accuracy	Percentage of uncertainty
Crank angle encoder	0–100 bar	±1	±0.1%
Load Indicator	0–100 kg	±0.1	±0.3%
Speed indicator	0–900 rpm	±10 rpm	±0.1%
Stop watch	–	±0.5	±0.1%
Manometer	–	±1 mm	±1%
Burette	–	±0.1 cc	±1%
EGT indicator	0–900°C	±1°C	±0.15%
Smoke meter	0–10 HSU	±0.2	±2%
Gas analyser	CO_2 0–20%	±0.02%	±0.2%
	CO 0–10%	±0.03%	±0.20%
	HC 0–10,000 ppm	±15 ppm	±0.1%
	NO_x 0–5000 ppm	±10 ppm	±0.2%

and diesel. However, induction of hydrogen to the air improves the combustion of blend E20D80 due to hydrogen's higher heat content and diffusivity, which helps to form a homogeneous fuel-air mixture and contributes to clear and complete combustion. Notably, the blend E20D80+H26LPM demonstrated an 8.94% increase in BTE relative to diesel fuel. This improvement is attributed to the higher oxygen content of ethanol and high flame speed; the high diffusivity of hydrogen promotes a more uniform mixture of air and fuel when mixed with the ethanol-diesel blend.

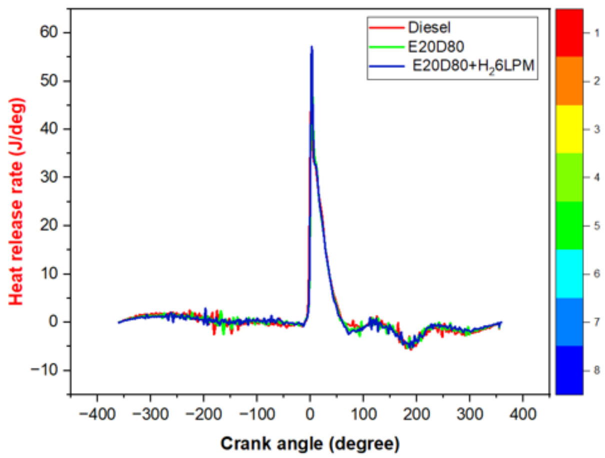

Figure 4: Heat release rate versus crank angle.

B) Brake Specific Fuel Consumption (BSFC):

BSFC is an important measure of capability of an engine to convert given fuel into useful work. Figure 6 demonstrates the brake specific fuel consumption of tested fuels with respect to the variation of load. From Figure 6, it is noticed that maximum fuel consumption takes place at lower loads for all test samples. This reduction is attributed to elevated heat and friction losses and incomplete combustion of fuel at lower loads. However, as the load raises, BSFC drops gradually. The blend E20D80 consumes more amount of fuel and shows higher BSFC values for all loads. At maximum load, BSFC for blend E20D80 was 16.67% higher than diesel. This is due to the lower heat content of ethanol. Introducing hydrogen at 6 LPM, together with air at the inlet manifold, resulted in a decreased BSFC which is closer to the diesel value at lower loads and meets the diesel value at higher loads, but no significant improvement was noticed with addition of hydrogen to blend E20D80 when compared to diesel fuel.

3.3. Emission characteristics

A) Carbon Monoxide (CO):

Carbon monoxide is one of the most harmful pollutants to both humans and the environment, emitted from the exhaust engine. More carbon monoxide reveals incomplete combustion of the fuel. Formation of carbon monoxide mainly relies on air-fuel ratio and temperature inside the cylinder. Figure 7 shows the plot between CO emission and load. Generally, CO formation occurs under conditions of fuel-rich mixtures, insufficient oxygen and incomplete combustion. From Figure 7, it was observed that at lower loads up to 50%, addition of ethanol to diesel (E20D80) increases the formation of CO emission compared to diesel due to the cooling effect of ethanol and low cylinder temperature, which reduces the vaporization of fuel. The induction of hydrogen at a flow rate of 6 LPM to the air leads to a slight reduction in CO emissions by 1.63% and 5.08% for blend E20D80+H26LPM compared to diesel and blend E20D80, respectively.

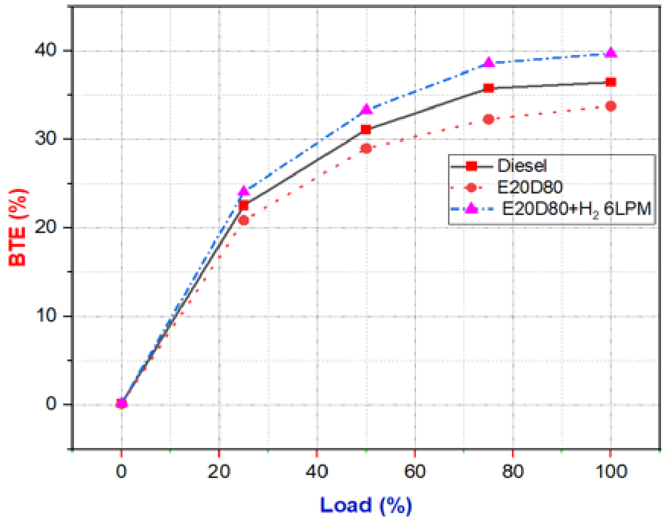

Figure 5: Brake Thermal Efficiency (BTE) with load.

This decline is attributed to hydrogen's catalytic action, which promotes the breakdown of the mixture's hydrocarbon molecules. Ethanol's improved hydrocarbon-excess oxygen interaction leads to more thorough burning, which drastically lowers carbon monoxide emissions.

B) Carbon Dioxide (CO_2):

Carbon dioxide (CO_2) is a colorless and non-combustible gas, formed primarily due to complete combustion of the fuel. Figure 8 illustrates the change of CO_2 with load. The minimum amount of CO_2 emission was found as 7.35% with E20D80+H26LPM at maximum load, which is lower by 6.13% compared to base diesel and 8.69% compared to E20D80 blend fuel.

C) Hydrocarbon (HC) emissions:

Hydrocarbon emissions arise from partial burning of hydrocarbon-based fuels. The fluctuation of HC emissions for E20D80, diesel and E20D80+H26LPM with load is shown in Figure **??**. The minimum HC emission was recorded as 28 ppm with the E20D80+H26LPM fuel blend at half load (50%). In contrast, higher hydrocarbon emissions were found with diesel and the ethanol-diesel blend E20D80, reaching approximately 56 ppm at peak load. A reduction in HC emission was observed with E20D80+H26LPM relative to all the test fuels at all engine loads. This reduction with hydrogen-enriched air and E20D80+H26LPM is due to the higher burning velocity and absence of carbon atoms in hydrogen.

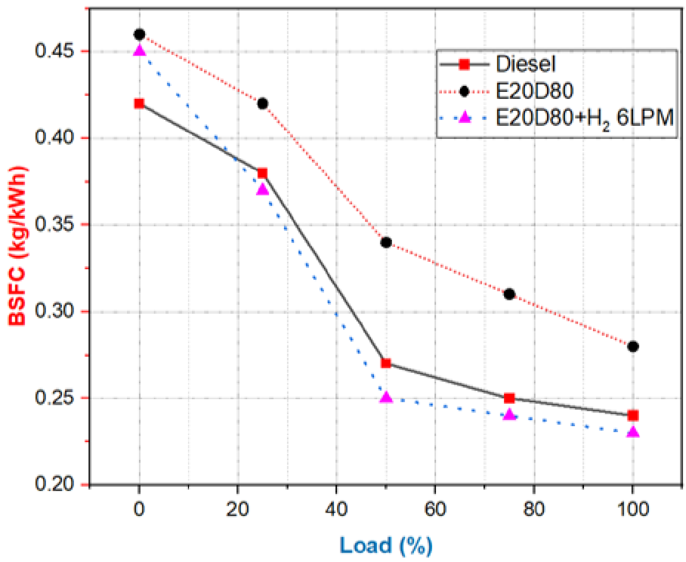

Figure 6: BSFC with load.

D) NO_x emissions:

The most harmful emissions from diesel engines are NO_x emissions. The formation of NO_x is primarily based on the availability of oxygen and temperature of the cylinder. NO_x emissions of diesel, the ethanol-diesel blend, and hydrogenated air with the ethanol-diesel blend at varying engine loads are presented in Figure 10.

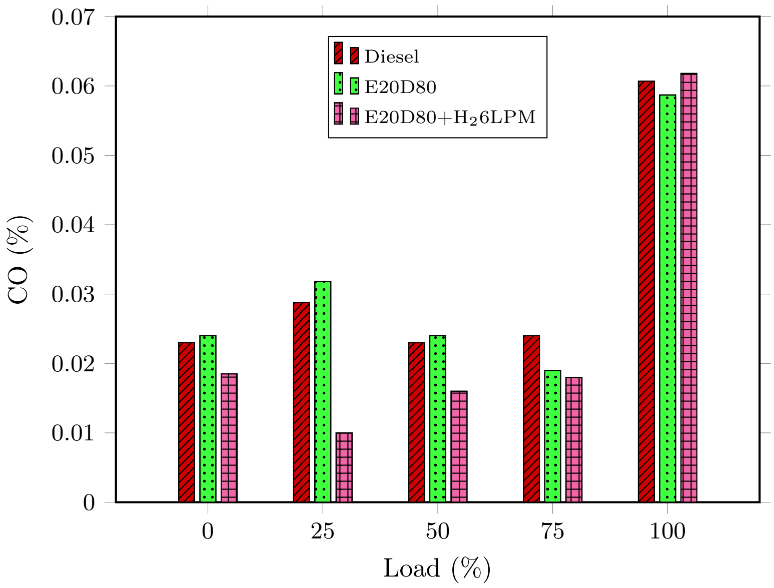

Figure 7: Load versus CO emissions.

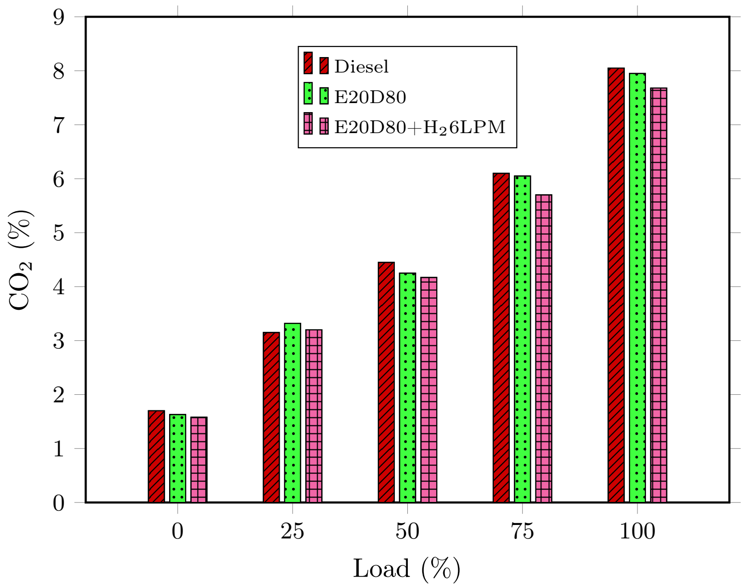

Figure 8: Load versus CO_2 emissions.

Nitrogen oxide (NO_x) emissions arise from the oxidation of nitrogen in the air when the internal temperature of the cylinder is higher than 1600 °C. From the results, it is witnessed that a lower amount of NO_x emissions is produced with the addition of ethanol to diesel, forming E20D80 fuel. At maximum load, the nitrogen oxide emissions produced by the engine for diesel, E20D80 and E20D80+H26LPM were 1803 ppm, 1023 ppm and 1775 ppm, respectively. At rated power, blend E20D80 exhibits a lower amount of NO_x emissions of 1023 ppm, which is lower by 43.26% and 43.37% than diesel and E20D80+H26LPM fuel, respectively. This is due to the addition of ethanol to diesel, which may create a leaner air-fuel mixture, while ethanol's high latent heat of vaporization creates a cooling effect that lowers the temperature of the cylinder during combustion and contributes to lower thermal NO_x production.

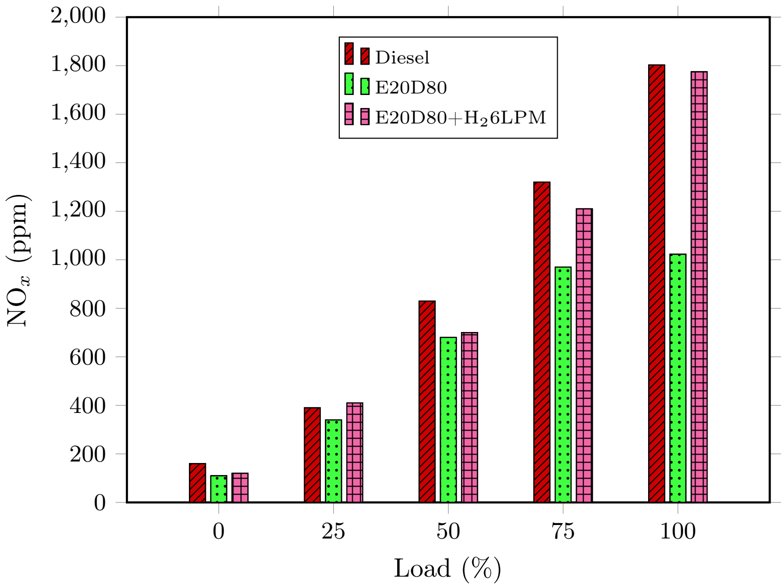

Figure 10: Load versus NO_x emissions.

E) Smoke opacity:

Figure 11 illustrates the variation in smoke opacity of test fuels at different load conditions. From Figure 11, it was noticed that smoke levels are enhanced by increasing the load, which varies from 0.7% to 33.8%. Among all test fuels, blend E20D80 shows less smoke opacity under all loading conditions. This is due to the oxygen content of ethanol, which increases the overall oxygen availability during combustion and promotes complete combustion of the fuel. However, the introduction of hydrogen-enriched air with E20D80 forms the E20D80+H26LPM blend, which shows a higher smoke value compared to diesel and blend E20D80.

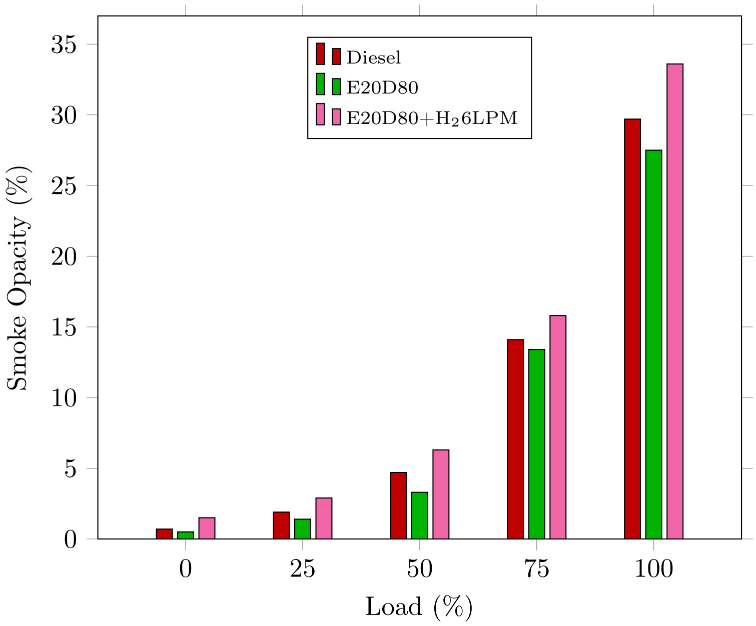

Figure 11: Load versus smoke opacity.

4. Conclusion

The study evaluated diesel, E20D80 (20% ethanol, 80% diesel), and E20D80+H26LPM in a compression ignition engine. The following observations are noticed when running the engine with the above tested fuels under different loads. Maximum cylinder pressure was observed for E20D80+H26LPM (69 bar), close to diesel, due to rapid hydrogen combustion. E20D80 showed lower peak pressure (65 bar) because of ethanol's low calorific value and delayed combustion. CO emissions were highest for E20D80 and reduced with hydrogen due to better combustion. CO_2 emissions were lowest with E20D80+H26LPM, showing cleaner fuel burning. HC emissions dropped significantly with hydrogen, reaching 28 ppm at 50% load. The absence of carbon in hydrogen and high flame speed reduced unburned hydrocarbons. NO_x emissions were lowest for E20D80 (1023 ppm) due to ethanol's cooling effect. Hydrogen addition slightly increased NO_x, but the emissions remained lower than diesel. Smoke opacity was lowest for E20D80 because of the additional oxygen aiding complete combustion. Hydrogen addition slightly increased smoke, but it remained within acceptable limits.

Overall, E20D80 alone showed weaker performance but lower NO_x and smoke. Hydrogen enrichment improved power output and combustion and reduced CO and HC. E20D80+H26LPM is a promising alternative fuel for cleaner and more efficient engine operation. The addition of hydrogen to an ethanol–diesel blend (E20D80+H26LPM) significantly enhances combustion and performance parameters while offering considerable improvements in emission characteristics over base diesel and E20D80. While E20D80 alone showed drawbacks in performance and certain emissions, hydrogen enrichment compensates for these, making E20D80+H26LPM a promising alternative fuel blend for cleaner and more efficient diesel engine operation.

Declarations and ethical statements

Conflict of interest: The author declares that there is no conflict of interest.

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Artificial Intelligence usage statement: During the preparation of this manuscript, the authors utilized ChatGPT solely for language refinement and grammatical corrections. The authors carefully reviewed and revised the generated content and take full responsibility for the accuracy, integrity, and originality of the final manuscript.

Availability of data and materials: The data and/or materials that support the findings of this study are available from the corresponding author upon reasonable request.

CRediT authorship contribution statement

Kadimisetti Uma Kiran Rama Sandeep: Conceptualization, Data curation, Methodology, Implementation. Kadupu Rakesh Varma Formal analysis, Writing– Original draft, Review & Editing. **Sundarapalli Ganapathi**: Formal Analyis, Validation & Visualization. **Devi Veera Venkata Satya Bhimeswar Reddy Saragada**: Conceptualization, Data curation, Formal analysis, Validation, Writing–Review & Editing. **Adduri S S M Sitaramamurty**: Validation & Visualization.

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