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Investigation of Performance and Emission Characteristics of Diesel-Ethanol PCCI Engine

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***Abstract:** Using numerical analysis and the ANSYS Forte 19.2 package, this study investigates the performance, combustion, and emission characteristics of dual-fuel operation using ethanol as a partial substitute for diesel in a direct injection compression ignition engine. The study discovered that adding ethanol to diesel engines reduces peak cylinder pressure and temperature due to its evaporative cooling qualities, with a maximum error of only 2.5%, exhibiting remarkable alignment between simulation and experimental data. The experiment was conducted on a modified single cylinder direct injection CI engine with an ethanol port injector controlled purely by Arduino software. The tests were carried out with different Ethanol substitutions at varied engine loads (0, 20%, 40%, 60%, 80%, and 100%). The study looked at the performance and emissions of a DI CI engine with ethanol substitutes of 10%, 20%, and 30%, with E10 outperforming and E30 outperforming, but caution is urged due to increased energy degradation. E10 and E20 ethanol replacements dramatically cut CO, HC, and NO emissions in diesel engines, improving environmental performance with modest changes.*

***Keyword:** Direct-Injection, Dual-Fuel, Premixed Charge, Compression Ignition Engine, Ethanol-Port Injection, Engine Performance.*

1. INTRODUCTION

1.1 Background of the Study

Diesel engines are indispensable in transportation, industry, and industrial uses, but their emissions pose health and environmental problems. Governments are implementing severe pollution rules, encouraging experts to investigate alternate energy sources .Variable valve timing, turbochargers, and fuel injection systems are among the novel solutions being investigated for greater engine efficiency and lower particulate matter emissions. [1].As fossil fuel substitutes, primary alcohols such as methanol and ethanol generated from biomass, natural gas, or coal provide advantages. Because of their low cetane numbers and viscosity, they are suitable for spark ignition engines but difficult for diesel engines due to efficient soot oxidation and reduced opacity [2].

Alternative fuels and combustion techniques for diesel engines are being investigated in order to reduce pollution. Because of its clean, colorless, and flammable qualities, ethanol, a common secondary fuel, is utilized to reduce NOx and PM emissions. Its availability from fermentable sources and agricultural feedstock adds to its advantages [3].The research looks into a dual-fuel combustion system that combines ethanol injection in the intake manifold with direct diesel injection into the combustion chamber, promoting efficient combustion in various engine zones dependent on fuel characteristics and timing [4]

2. METHODOLOGY AND MATERIALS

Engine Fuel System Modifications

The engine was modified to achieve a premixed dual-fuel combustion mode, improving volumetric efficiency and taking use of ethanol's better latent heat of vaporization. Installing a precise fuel injection system and regulating numerous components was required using MATLAB Simulink Model.

Overview of Port Fuel Injection and Its Components

The port fuel injection technology combines gasoline and air at the intake port to deliver a homogenous charge for auto-ignition near top dead center. For best engine performance, a well-coordinated fuel delivery system, which includes a fuel tank, injector, pump, transducers, and other vital components, is required.

Intake air-fuel Dynamics Modeling

By managing airflow and control, the intake manifold, a dynamic system controlled by the accelerator pedal and intake valves, increases engine performance and fuel efficiency.

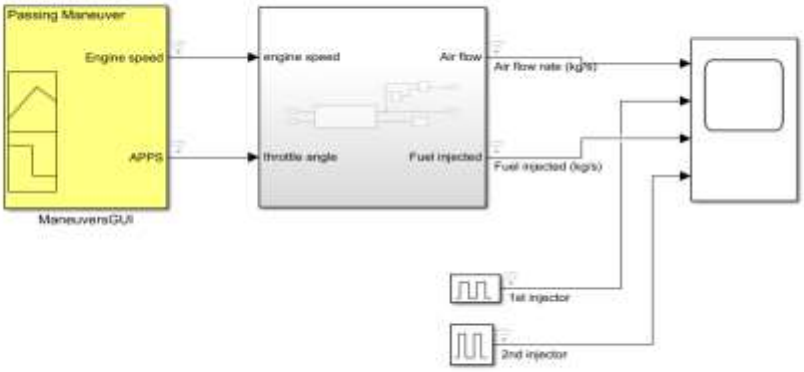


Figure 1 Simulink model for engine control algorithm

The Simulink model analyzes intake air-fuel interactions, modifying input parameters to maintain target output and optimize fuel injection while being led by the vehicle's power control module [38][39].

Experimental Test rig

The experimental tests made use of a single-cylinder, four-stroke DI engine with a power rating of 5.67 kW and a hydraulic dynamometer for precise torque and load management. The system featured thermocouples, measurements of fuel and air flow rates, pollutants, and speed. The program developed using Arduino software controls Ethanol port fuel injector (PFI) to control the amount of fuel injected to the engine as shown Fig 3.8.

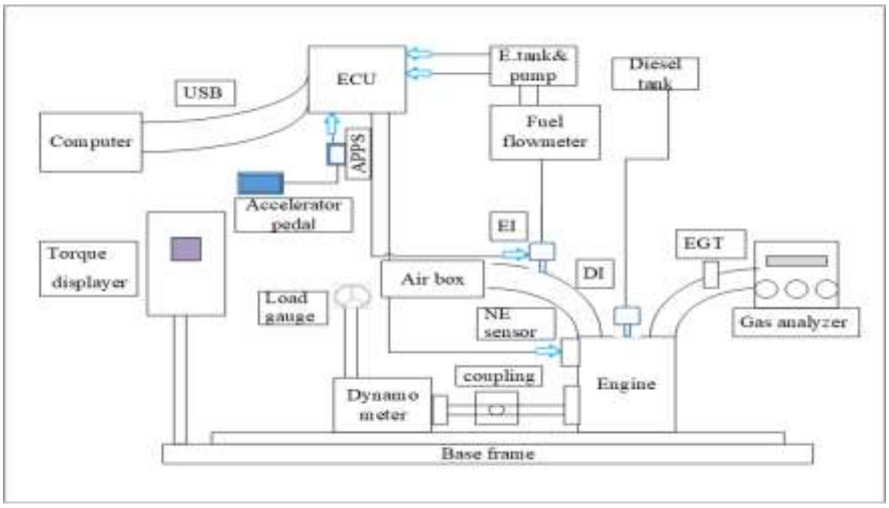


Figure 2.1 Schematic experimental setup

Figure 2.2 Modified expermental setup photographic view

1. Diesel engine
2. Hydraulic dynamometer
3. Port fuel injector (PFI)
4. Arduino Uno
5. Computer
6. The rmocouple
7. Air Box
8. Exhaust gas analyzer
9. Ethanol fuel tank &pump
10. Torque load cell
11. Intake manifold
12. Exahust manifold
13. Battery
14. Air and fuel flow meter
15. crank shaft speed sensor

Experimental Uncertainty

For accuracy, this study uses single sample measurements, ensuring that uncertainties match the instrument's last count. Errors are derived from credible sources, and uncertainty in measured values is calculated using method proposed by Holman(2007).The uncertainties in the measured values like airflow, fuel flow, engine power and pressure are calculated and the results are presented in Table 4.4.

Table 2.1 Experimental uncertainties

Variable	Uncertainties
Engine power, kW	±0.00286
Brake specific fuel consumption	±0.00224
Brake thermal Efficiency, %	±0.01236
HC,ppm	±0.05
CO,%	±1.5023
NO, ppm	±0.02

Except for emission measurement, the errors in parameters in Table 4.4 are less than 1%. However, the 1.5% uncertainty may impair the accuracy of the results because it comprises exhaust mass flow, temperature, power, and emission level.

3. RESULT AND DISCUSSIONS

The paper uses numerical and experimental approaches to explore the direct injection compression ignition dual fuel engine with ethanol port injection, investigating pulse width fluctuations and combustion parameters.

3.1 MATLAB Simulink Result

Through simulated experiments using MATLAB, this part investigates the link between air and fuel flow rates and ethanol injection ratios, providing insights into system behavior and performance.

Air Flow Rate

The ECU regulates engine air injection to ensure proper combustion. Airflow rate drops with incremental pedal push but increases with full depressure, ensuring optimal performance, according to Simulink research. The variation of air flow rate with time as shown in Fig 4.1.

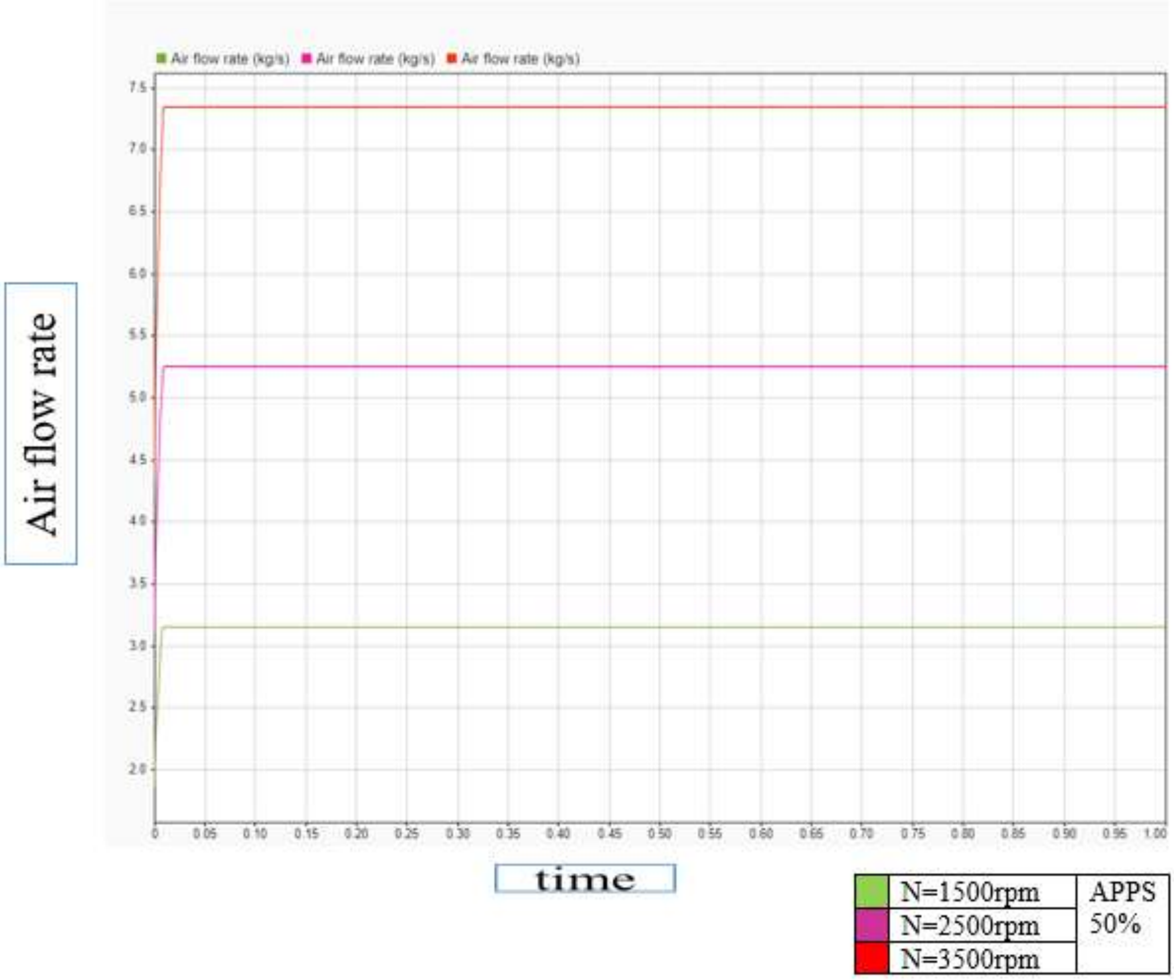


Figure 3.1 Variation of air flow rate vs time

Fuel Flow Rate

The driver's accelerator pedal input controls fuel supply and injection in engine cylinders, with the ECU controlling flow rate depending on sensor readings. The variation of fuel flow with time is shown below Fig 4.2.

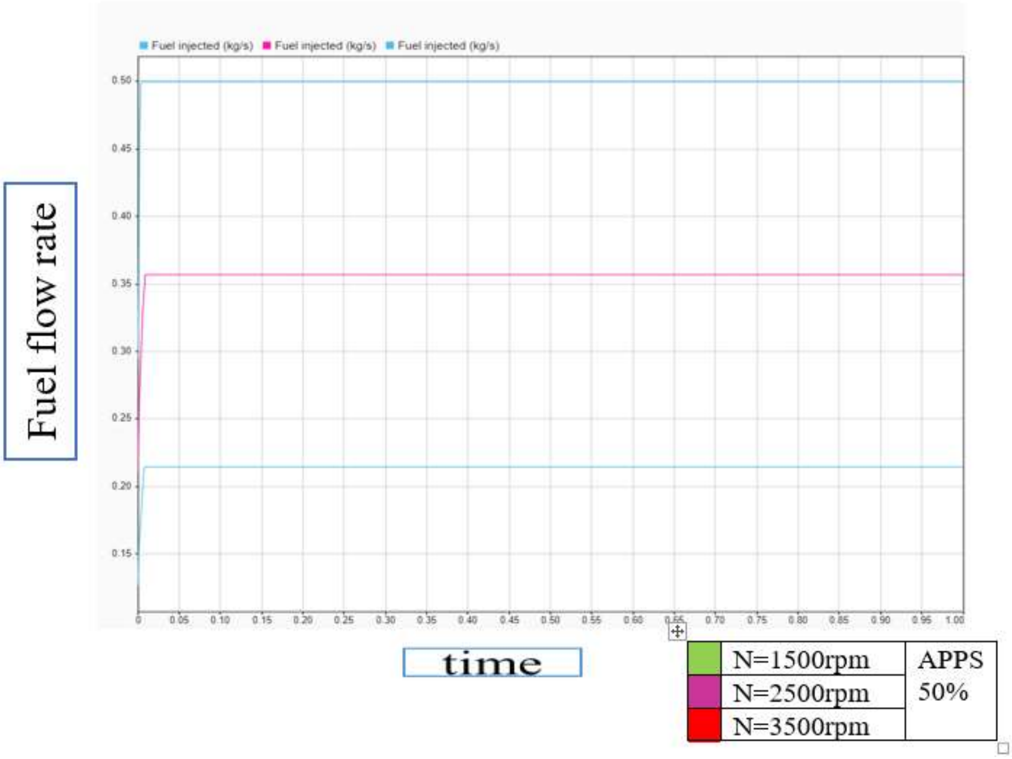


Figure 3.2 Variation of fuel flow rate vs time

Duration of Injection

The study looks at how the ethanol injection ratio affects the injection length of diesel and ethanol fuels. The results reveal that raising the proportion of ethanol results in longer pulse width and better combustion. As observed from the graph the pulse width of E30 is greater than E20 this indicated that the duration of injection is increased.

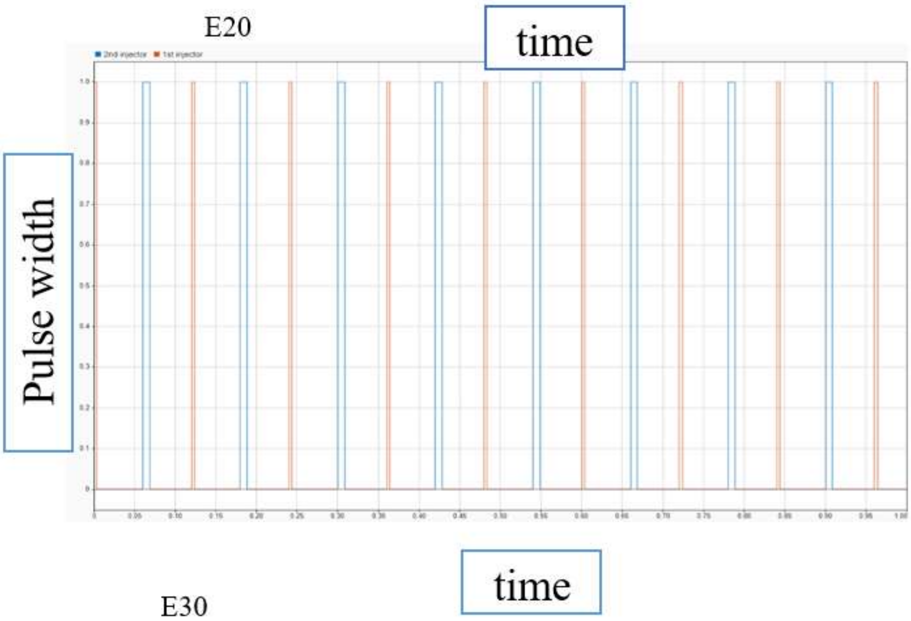


Figure 3.3 Duration of injection vs time

3.2 CFD Results

A CFD simulation utilizing ANSYS FORTE software examines the effect of ethanol port injection on dual fuel engine combustion parameters such as cylinder pressure and temperature. In the following part, the combustion properties such as cylinder pressure and temperature analyzed in depth.

In cylinder Pressure

Because of its vaporization cooling effect, ethanol in diesel-ethanol mixes reduces peak cylinder pressure. Higher ethanol substitution rates reduce cylinder pressure, owing to lower cetane values, longer ignition delays, and higher premixed burning stage fuel consumption.

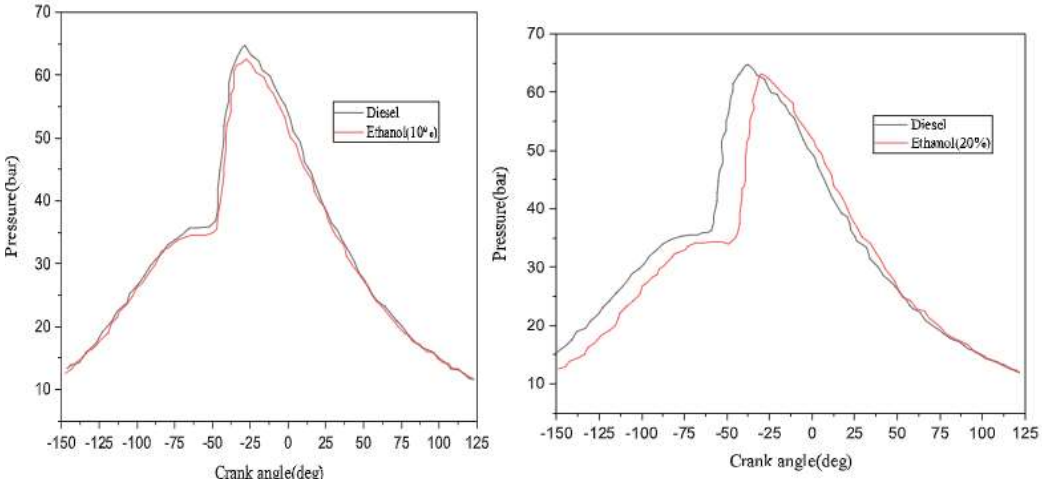


Figure 3.4 Variation of cylinder pressure vs crank angle

In Cylinder Temperature

Because of ethanol's greater latent heat of vaporization and longer ignition delay, pure diesel has higher cylinder temperatures than diesel-ethanol fuel (see Figure 4.5). However, because of its lower heating value and higher latent heat of vaporization, ethanol lowers combustion temperature.

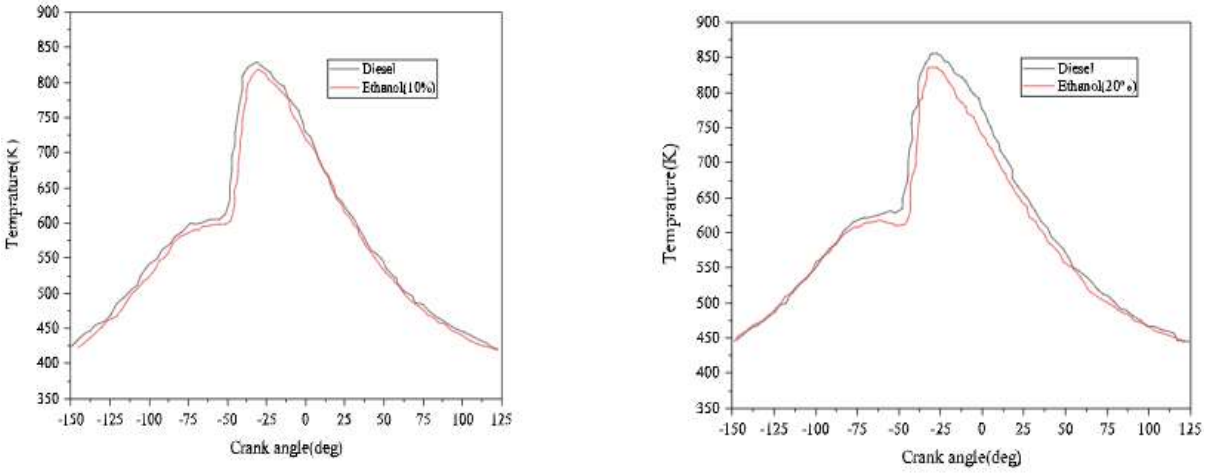
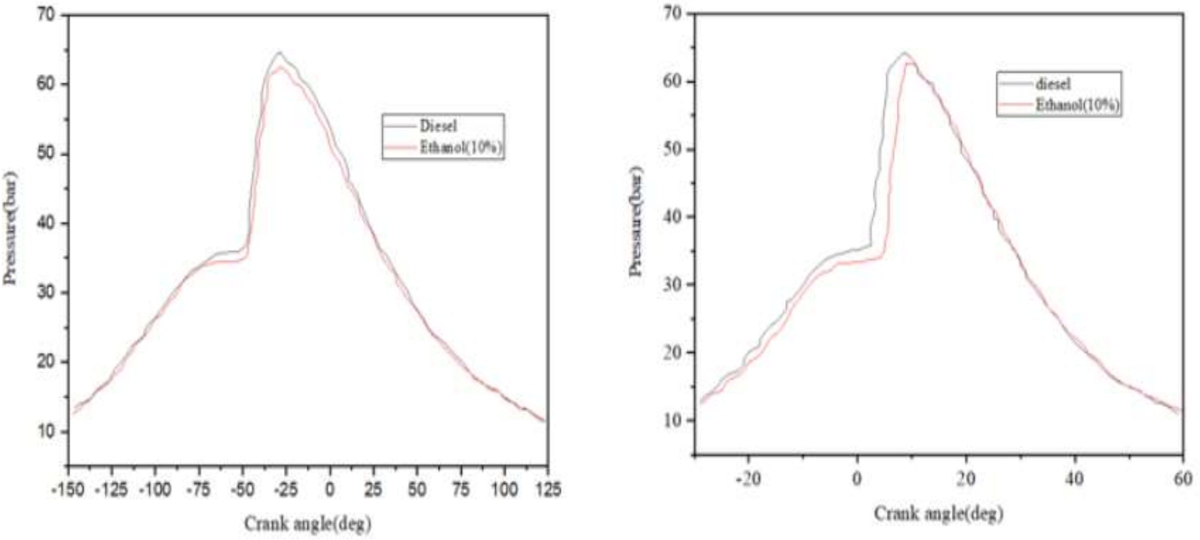


Figure 3.5 Variation fo incylinder temprature with crank angle

Validation of CFD Results

The correctness of the model was evaluated by comparing simulation results to experimental data. With a maximum error of 2.5%, the simulated peak cylinder pressure closely matched the experimental value, confirming the model's ability to reliably predict engine combustion characteristics.



a) Simulation result b) experimental result

Figure 3.6 Validation results for Peak cylinder pressure

3.3 Experimental Investigations

The study investigated the performance and emission characteristics of a direct injection compression ignition engine under varied engine loads and ethanol replacement rates, yielding detailed results.

Engine Performance Analysis

At various engine loads and speeds, experiments were conducted to assess braking power, brake specific fuel consumption, and brake thermal efficiency in diesel and ethanol dual-fuel engines. Across all fuels, the results showed similar patterns, with reduced braking power and thermal efficiency at lower loads and higher brake specific fuel consumption.

Brake Power

Diesel fuel brake power is frequently lower than claimed, however E30 at 80% engine load can raise it by 2.1% due to improved combustion and volumetric efficiency.

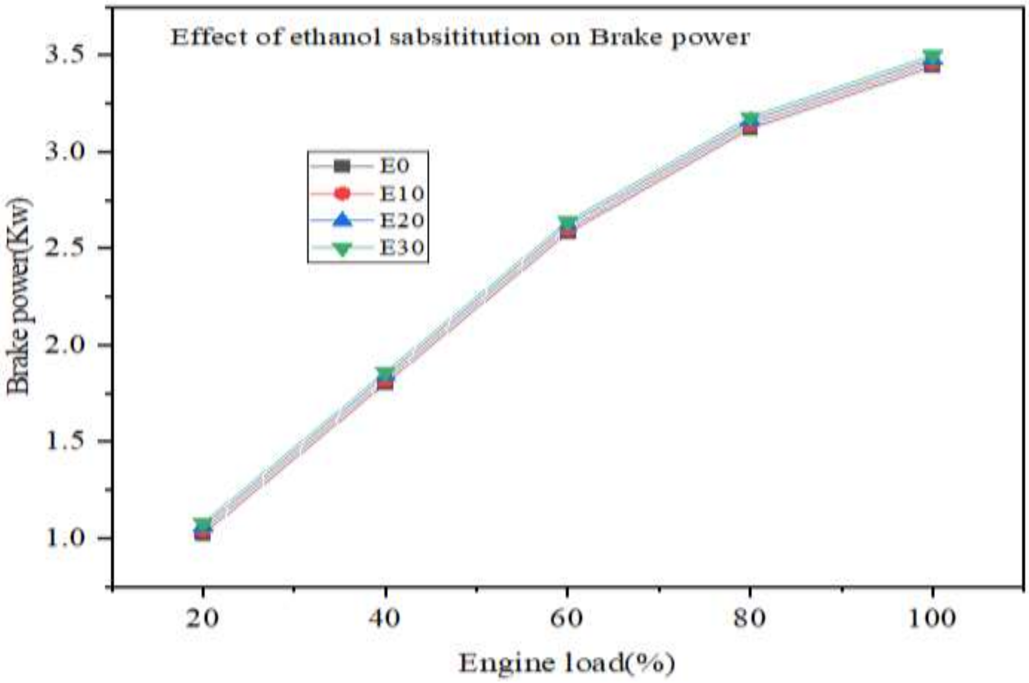


Figure 3.7 Variation of brake power with engine load

A smaller injection of diesel fuel ignites ignition during the compression stroke, minimizing diffusion combustion and enhancing kinetic combustion. This enables fine ignition control and fuel mix changes. The duration of kinetic combustion rises as the alcohol content increases.

Brake Thermal Efficiency

When compared to pure diesel, E30 ethanol substitutes had worse brake thermal efficiency, with a maximum energy decline of 24.8% at 80% engine load. The lower heating value of ethanol reduced efficiency.

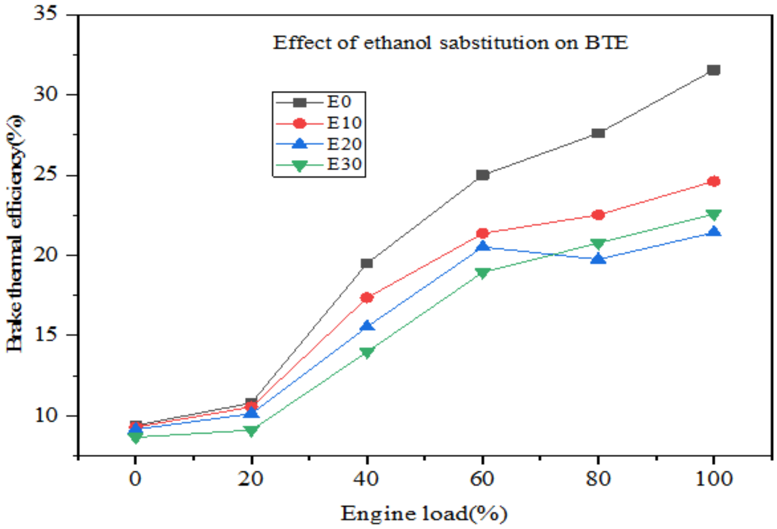


Figure 3.8 Variation of brake thermal efficiency with engine load

The use of ethanol in diesel has a major impact on brake thermal efficiency. It cools the gas in the cylinder, preventing optimal air-fuel mixture formation and lowering efficiency. The lean air-fuel mixture prevents complete combustion, which reduces thermal efficiency. As load grows, more fuel is used, raising the temperature of the cylinder gas. Peak pressure and heat release rate are lowered at lower loads, whereas they are increased at larger loads.

Brake Specific Fuel Consumption

According to Fig. 4.8, diesel fuel has the lowest fuel consumption among ethanol-diesel blends, particularly at high engine loads, whereas E30 substitution has the highest fuel consumption at low load situations.

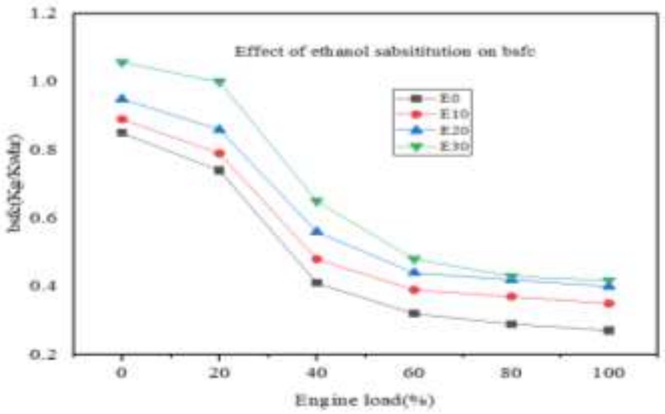


Figure 3.9 Variation of bsfc with engine load

Due to ethanol's lower calorific value and cetane number, dual-fuel compression ignition engines burn more gasoline, especially with increased substitutions. At maximum load, fuel fumigation is particularly efficient due to its rapid evaporation rate.

Engine Emission Analysis

This study compares exhaust emissions from autos and diesel fuel with various ethanol replacements, emphasizing the need of emission standards in minimizing environmental pollution.

Carbon Mono Oxide Emissions (CO)

Incomplete combustion produces carbon monoxide (CO) in diesel fuel. CO emissions rise in direct proportion to engine load. Due to a lack of oxygen, diesel fuel emits more CO at lower loads. Higher cylinder temperatures hasten the conversion rate of CO gas to CO2.

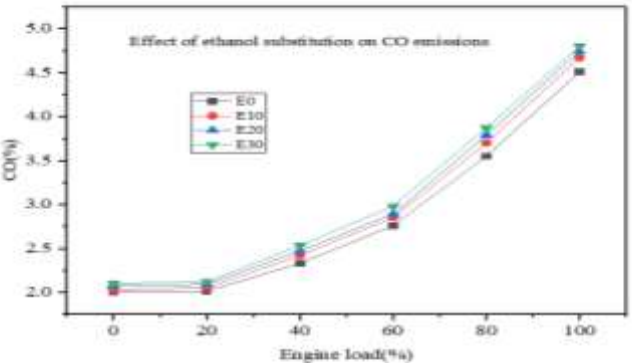


Figure 3.10 Variation of CO emissions vs engine load

Ethanol in gasoline mixes helps to eliminate extra air, which lowers CO emissions. Higher loads minimize the effect of vaporization on gas temperature. Because of their lower cetane number and higher oxygen content, E10, E20, and E30 ethanol substitutes cut CO emissions by 5%, 7.8%, and 21%, respectively.

Carbon dioxide Emissions (CO_2)

Regardless of fuel type, higher combustion chamber temperatures and oxygen availability increase carbon dioxide emissions. As the combustion process progresses, cylinder temperatures rise, increasing vaporization and ignition.

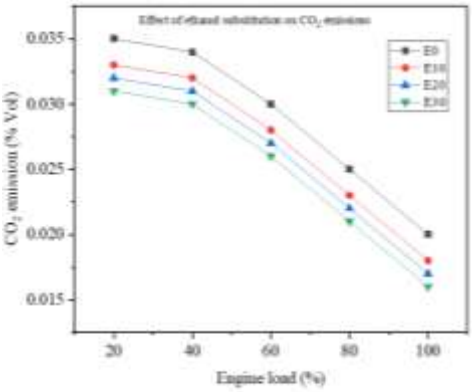


Figure 3.11 Variation of CO_2 emissions with engine load

When ethanol fuel is fumigated with E30 substitution, CO2 emissions in dual-fuel vehicles are much higher than in pure diesel vehicles. This is because bioethanol contains more oxygen, which accelerates internal oxidation.

Unburned Hydrocarbons (UHC) Emissions

In engines with ethanol substitution, unburned hydrocarbon emissions are influenced by incomplete combustion and a rich air-fuel mixture. Reduced gas temperature, insufficient fuel distribution, excessive air, low exhaust temperature, and lean air-fuel mixes all contribute to higher HC emissions.

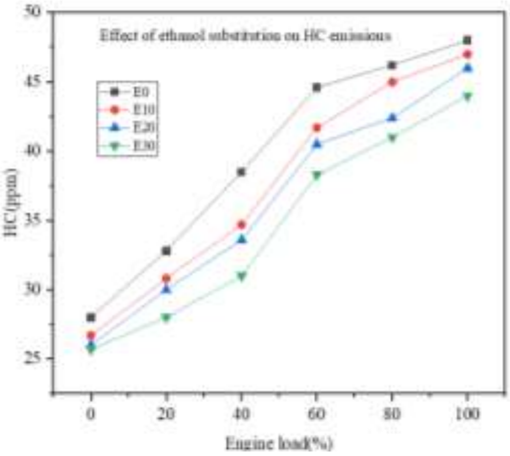


Figure 3.12 Variation of HC emissions with engine load

A mixture of air and ethanol is used in the combustion process, which raises pressure and oxidizes during the expansion and exhaust strokes. This connection improves combustion quality and decreases HC emissions under heavy loads.

Nitrogen Oxide Emissions (NO_x)

Figure 4.13 depicts the variations in NO emissions caused by ethanol substitutes and diesel fuels. Ethanol substitutes emit less NO than pure diesel, demonstrating a complicated link between NO generation and emissions in diesel engines.

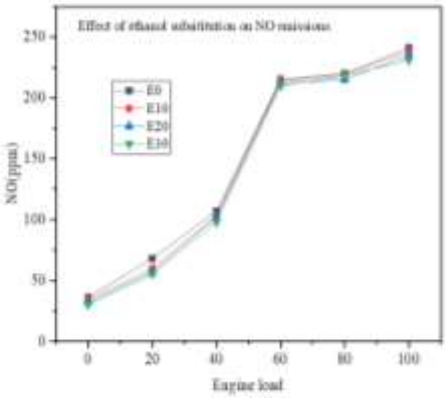


Figure 3.13 Variation of NO emissions with engine load

NO_2 emissions have risen dramatically, reaching 40% and 60% respectively. The higher-octane rating of ethanol, on the other hand, decreases these emissions across all loads by taming autoignition flames and moderating exhaust temperatures. This transition helps to clean the air and reduce NO_2 emissions in a balanced manner.

Exhaust Gas Temperature (EGT)

The study investigates the use of ethanol to change engine exhaust, revealing a dramatic transformation. The magnificence of ethanol, a higher latent heat of vaporization, results in a plunging EGT at high engine loads, with the most spectacular drop recorded in E30.

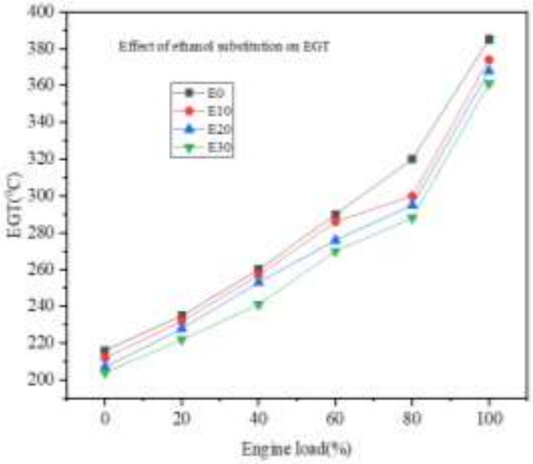


Figure 3.14 Variation EGT with engine load

4. CONCLUSIONS

The study examined the performance, combustion, and emissions of a dual fuel DI CI engine using ethanol port injection. A 3D computational fluid dynamics model was used to predict combustion characteristics. Experimental work evaluated engine performance under different ethanol substitution levels. From the study the following key conclusions were drawn.

- The study found that neat diesel fuel had higher in-cylinder pressure and temperatures compared to ethanol substitution due to its cooling effect and lower cetane number, resulting in decreased cylinder pressure and temperature.
- . Increasing the ethanol energy ratio led to an increase in pulse width and injection duration. The engine control unit (ECU) regulated the fuel injection amount based on signals from the accelerator pedal position sensor (APPS).
- E30 engines showed higher brake power than pure diesel due to improved combustion and volumetric efficiency. However, brake thermal efficiency was lower for all ethanol substitutions due to poor air-fuel mixing and higher brake-specific fuel consumption.
- Because of their lower cetane number and higher oxygen content, ethanol fuel substitutes lessen carbon monoxide and hydrocarbon emissions. However, because to better combustion quality, HC emissions rise at low load and fall at high load.

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