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THE INFLUENCE OF EXHAUST GAS RECIRCULATION ON A CRDI DIESEL ENGINE OPERATING ON BIODIESEL ANALYSED USING A FUZZY LOGIC MODEL

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Narayanan Th.[1], Dhamodaran R.[2], Pandian B.[3]

Author for correspondence: Pandian Balu,
e-mail: balumitauto@gmail.com

[1] Research Scholar
https://orcid.org/0009-0007-7062-7860

[2] Researcher
http://orcid.org/0000-0002-1477-4774

[3] Researcher
http://orcid.org/0000-0003-3480-1116

[1, 2, 3] Bharath Institute of Higher Education and Research, Chennai, Tamil Nadu, India

Abstract. *This study explores the impact of Exhaust Gas Recirculation (EGR) on the performance and emission characteristics of a Common Rail Direct Injection (CRDI) diesel engine operating on biodiesel. Biodiesel blends were tested under various EGR rates (5%, 10%, and 15%) to analyze key performance parameters such as brake thermal efficiency (BTE), brake specific fuel consumption (BSFC), and emissions including nitrogen oxides (NOx), carbon monoxide (CO), unburned hydrocarbons (HC), and particulate matter. To effectively model the nonlinear behavior of the engine system, a fuzzy logic-based approach was employed. The fuzzy logic model (FLM) was developed using inputs such as engine load, EGR rate, and biodiesel blend ratio, with outputs being engine performance and emission indices. Experimental results indicated that moderate EGR rates significantly reduced NOx emissions, though with slight reductions in thermal efficiency and increases in BSFC. The fuzzy model accurately predicted engine responses, demonstrating its suitability for decision-making and optimization in dual-fuel, EGR-assisted diesel engine systems. The integration of biodiesel and fuzzy-controlled EGR offers a promising approach to achieving cleaner combustion while maintaining acceptable engine performance.*

Keywords: *Fuzzy Logic Model, exhaust gas recirculation, CRDI engine, Biodiesel, Emissions.*

Abbreviations

CRDI – Common Rail Direct Injection
EGR – Exhaust Gas Recirculation
BP – Brake Power
BSFC – Brake Specific Fuel Consumption
BTE – Brake Thermal Efficiency
HC – Hydro carbon
CO – Carbon monoxide
CO_2 – Carbon dioxide
HRR – Heat Release Rate
CP – Cylinder pressure
NOx – Nitrogen Oxides
DOE – Design of Experiments
CI – Compression Ignition
EGT – Exhaust Gas Temperature
TMF – triangle membership function
MSE – Mean Squared Error
MAPE – Mean Absolute Percentage Error

1. Introduction

Growing interest in improved engine technology and alternative fuels has resulted from the increased focus on reducing the environmental effect of transportation in recent years. Because it produces less greenhouse gas emissions than petroleum diesel and can be produced domestically, biodiesel which is made from renewable sources like vegetable and animal fats has shown great promise as an alternative [1]. The performance, emissions, and combustion characteristics of engines, particularly those of contemporary engines like Common Rail Direct Injection (CRDI) engines, provide obstacles to the broad use of biodiesel. Among all the many alternative fuels, biodiesel is the fuel that experts have determined is most ideal since it can run the CI engine at a high capacity and therefore meet the global need for energy [2]. In addition, it will lessen the toxic emissions that are bad for human health. Exhaust Gas Recirculation (EGR) is a crucial tactic used to reduce emissions, especially nitrogen oxide (NOx), in internal combustion engines. In order to lower peak combustion temperatures and lessen the generation of NOx, exhaust gases are partially reintroduced into the engine's intake air through the use of EGR. The relationship between EGR and biodiesel in CRDI engines provides a complicated and diverse scenario that calls for more exploration, despite having been thoroughly explored in conventional diesel engines [3]. The purpose of this research is to investigate how exhaust gas recirculation affects biodiesel combustion parameters, emissions, and engine performance in CRDI engines. A thorough analysis of how EGR affects engine performance when running on biodiesel can provide important insights into how to improve emissions control, maximise engine performance, and encourage the long-term usage of alternative fuels [4]. This study intends to forward the objective of environmentally conscious and sustainable transportation by methodically examining these variables in order to optimise the performance of CRDI engines running on biodiesel [5]. JME (jojoba methyl ester) was used in an experiment by H E Saleh20 on a diesel engine with two cylinders. It was discovered that the EGR approach greatly decreased NOx emissions at the expense of somewhat higher fuel usage [6]. Yilbasi et al. (2022) examined the combustion and emission characteristics of this biodiesel and diesel blend after producing biodiesel from industrial hemp seed oil using a single-stage homogeneous catalytic transesterification method [7]. The findings demonstrated that while biodiesel and its blends had marginally lower CO, HC, and soot emissions under load than diesel, their thermal efficiency was still higher. In order to investigate the impact of linseed biodiesel/diesel blend on engine performance and combustion, [8] conducted experiments on a CI engine. It was observed that the NOx emissions from soy-bean biodiesel under 100% load state were lower than those from diesel. The emission characteristics of diesel and biodiesel compression ignition engines with various injector orifices and EGR settings were studied by [9]. The findings demonstrated that when the combination of biodiesel and pure diesel was 20%, the NOx emissions of the diesel engine with EGR were 50% of those of the diesel engine without EGR, while the emissions of CO and CO2 were not significantly affected. In a common rail diesel engine, [10] investigated the combustion and emission characteristics of a combination of ethanol, biodiesel, and diesel. Ethanol's increased oxygen content accelerated burning and increased thermal efficiency. The inclusion of ethanol resulted in a 50% reduction in soot emissions. [11] looked into how Canola biodiesel mix performance was affected by ethanol addition, injection delay, and EGR. The experimental findings shown that delayed injection may successfully enhance the emission characteristics and 5% EGR can effectively ameliorate the combustion parameters of B10 biodiesel blends. Furthermore, NOx emissions may be successfully decreased using all three techniques. In an experiment using diesel-used palm oil-butanol blends in a DI air-cooled diesel engine, Sharon et al. [12] observed that the blends' BSFC and BTE were lower than those of diesel fuel. The mixes had decreased emissions of CO, NOx, and smoke, but greater emissions of HC. The mix that contained 15% butanol, 35% used palm oil, and 50% diesel fuel performed better in terms of emissions and combustion. How et al.'s study [13] examined the effects of injection timing and split injection strategies on the operation, emissions, and combustion characteristics of a CRDI diesel engine running on blended biodiesel fuels. The researchers came to the conclusion that split injections was a workable way to reduce smoke and NOx emissions at the same time. [14] examined the combustion and emission characteristics of this biodiesel and diesel blend after producing biodiesel from industrial hemp seed oil using a single-stage homogeneous catalytic transesterification method. The findings demonstrated that while biodiesel and its blends had reduced emissions of CO, HC, and soot, their thermal efficiency under load was marginally lower than that of diesel. It was noted from the thorough literature review of CRDI engines that there hasn't been much information published on how performance, emissions, and combustion affect engine performance. Therefore, the primary goal of the current study is to determine if biodiesel blends made from non-edible oil are suitable for use in CRDI engines. The current effort also aims to optimise the CRDI engine's NOx emissions within allowable bounds by utilising fuzzy logic prediction. In the current experimental studies, the fuzzy logic model has been suggested to establish the connection between the selected parameters and the characteristic(s), and the minimal experiments have been prepared in accordance with DOE. The outcomes were contrasted with a clean biodiesel-powered CI engine running mode. Ultimately, the inquiry led to the formulation of important findings.

2. Materials and Methods

2.1 Momordica charantia–biodiesel

One species of plant in the Momordica genus is Momordica charantia. It is grown naturally in tropical settings all over the world and is cultivated for medical and agricultural purposes. Also used as a diabetic medicine is Momordica charantia seed oil (Fig. 1). Momordica charantia seed oil is split into glycerol and biodiesel to extract free fatty acids. The separated biodiesel is maintained well away from the glycerol. One of the most often used methods in the biodiesel industry to lower oil viscosity is transesterification, which happens when a vegetable oil and an alcohol are mixed with a catalyst. Transesterification is essentially a reaction to time. Triglycerides are first converted to diglycerides. Next, the diglycerides are reduced to create the monoglycerides. Lastly, the monoglycerides are converted to fatty acid esters.

Fig. 1. Momordica charantia

Table 1 shows the physical and chemical properties of biodiesel that were determined using recognised methods. To evaluate the quality of the biodiesel and blends, the following test methods were used. Density is a key factor in biodiesel.

Table 1. Momordica charantia seed biodiesel properties

S.no	Properties	Values
1	Density	0.897 g/c
2	Moisture content	0.82%
3	Pour point	6°C
4	Cloud point	8°C
5	Kinematic viscosity @ 40°C	6.023 cSt
6	Calorific value	74.43 MJ/kg
7	Acid value	0.130 mg NaOH/g of Oil
8	Flash point	265°C
9	Fire point	275°C

3. Experimental set up

The experimental investigation uses a modern Common Rail Direct Injection (CRDI) engine as its test bed. The engine is chosen based on how well it fits into contemporary automobile applications and how well it can run on alternative fuels like biodiesel. It has enhanced combustion monitoring capabilities, computerised controls, and a high-pressure common rail fuel injection system. A combination of diesel and biodiesel in different quantities is used as test fuel for the engine. To precisely regulate the blend ratio and create the necessary biodiesel-diesel mixtures, a fuel blending system is employed. In order to precisely transport the fuel mixtures to the engine's combustion chamber, fuel flow meters and injectors are fitted. To enable the recirculation of exhaust gases, an Exhaust Gas Recirculation (EGR) system is added into the engine configuration. To lower the temperature of the recirculated gases before reintroducing them into the intake manifold, the EGR system has a high-temperature EGR cooler. EGR flow control valves and sensors allow the EGR rate to be precisely adjusted so that the effects on emissions and engine performance can be studied (Fig. 2).

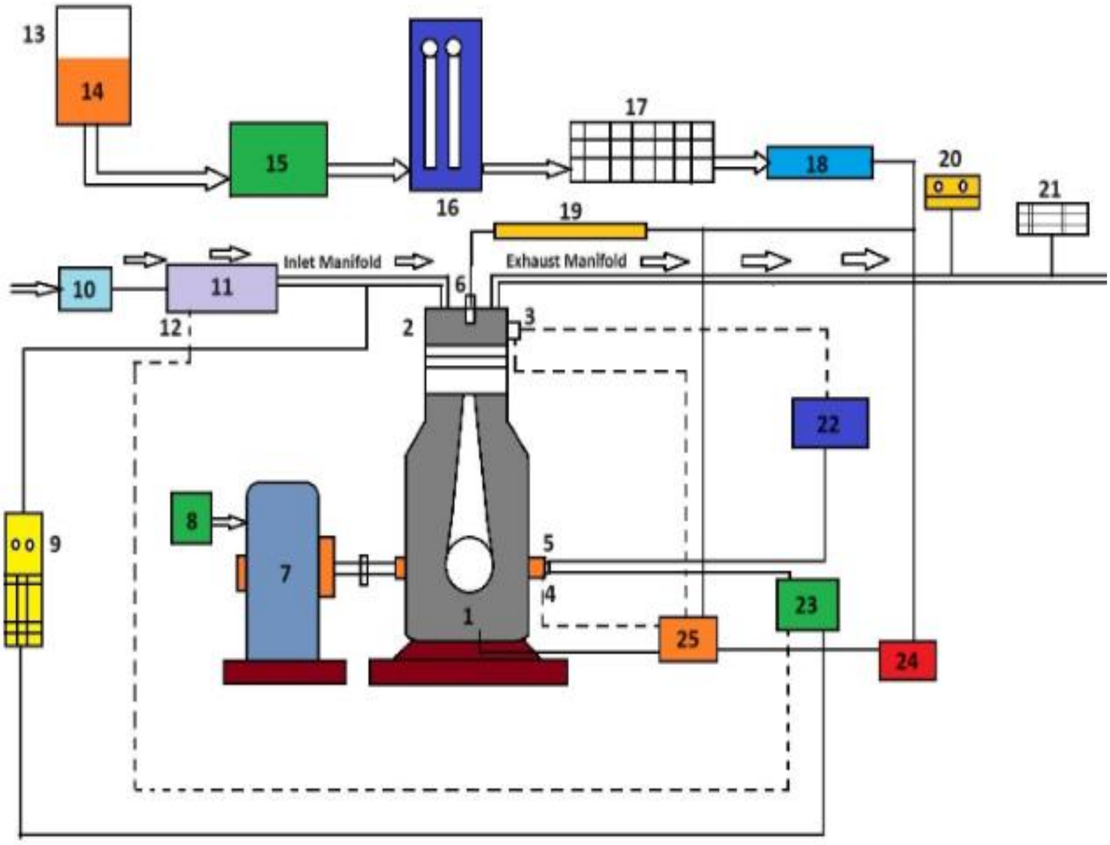


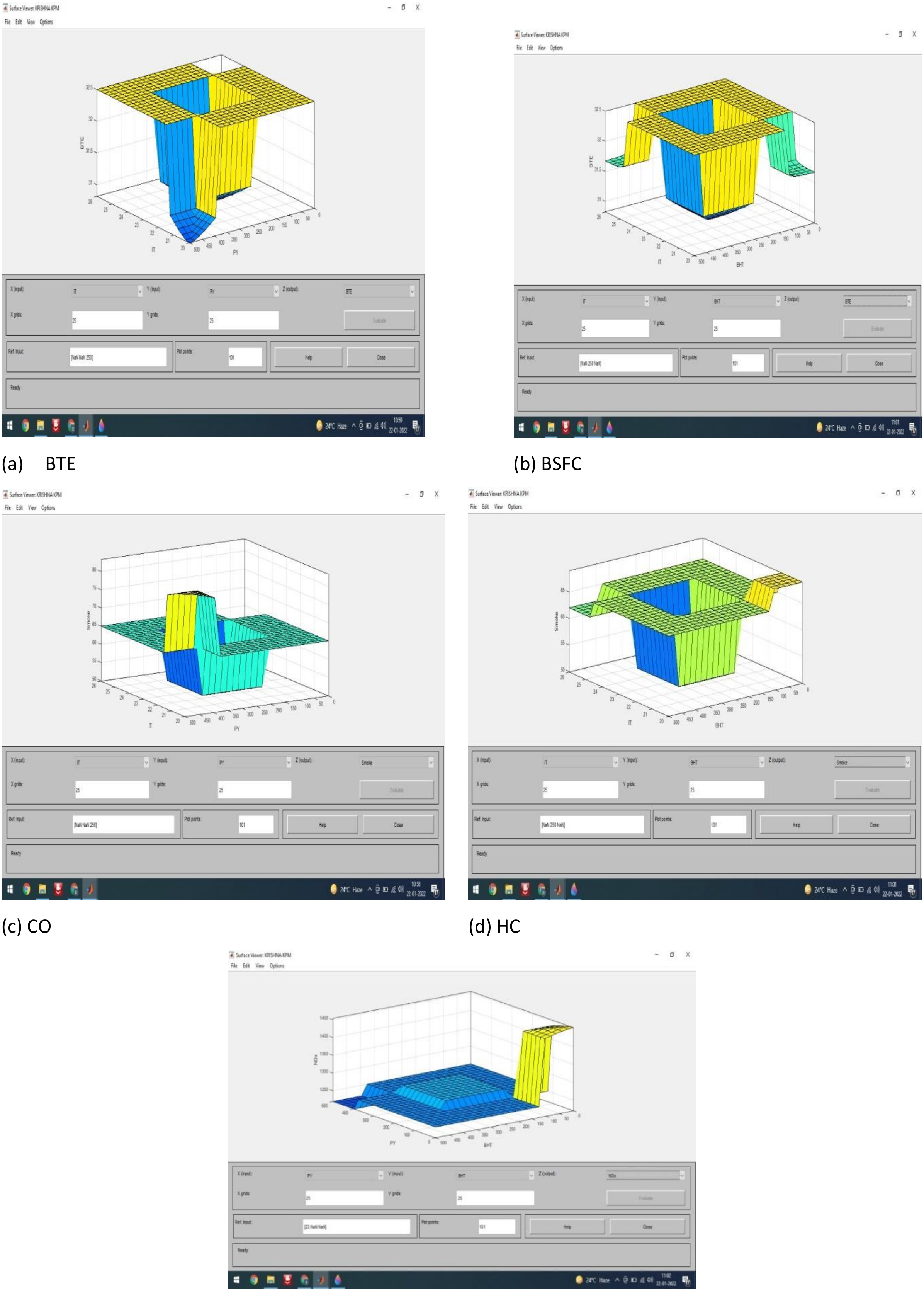
Fig. 2. Schematic diagram of CRDI engine

1. CRDI Engine; 2. Pressure Sensor; 3. Coolant Temperature Sensor ; 4. Cam Sensor ; 5. Crank Angle Sensor ; 6. Solenoid Injector; 7. Eddy Current Dynamometer; 8. Dynamometer Controller; 9. Charge Amplifier; 10. Surge Tank; 11. Air Flow Meter; 12. Air Flow Sensor; 13. Diesel Tank; 14. Biodiesel; 15. Fuel pump; 16. Fuel Measuring Unit; 17. Fuel Filter; 18. High pressure fuel pump; 19. Common rail; 20. Exhaust gas analyser; 21. Smoke meter; 22. Combustion analyser; 23. Data Acquisition system; 24. Programmable ECU controller; 25. A-D Converter;

4. Results and discussions

4.1 Development of a mathematical model of fuzzy logic

The Fuzzy Logic Toolbox is used to develop the fuzzy logic model in the LABVIEW V12 environment. The inputs are NOX, Smoke, BTE, HC, CO, EGT, and MRPR; the outputs are NOX, Smoke, BTE, HC, CO, EGT, and MRPR. Output values are normalised in order to improve performance. Six fuzzy sets reflect the load for each injection time (23°bTDC), whereas five fuzzy sets (lowest, medium, high, and highest) express the mixes.



(a) BTE (b) BSFC

(c) CO (d) HC

(e) NOx

Fig. 3. All performance and emission metrics are surface plotted using three factors: load, mix, and one output. BTE (a) and BSFC (b) (c) (d) CO, (e) HC, (f) NOx

The surfaces plots for braking power, torque, BSFC, and BTE are shown in Fig. 3 (a) through (b). The surface plots for CO, HC, and NOx pollutants are shown in Fig. 3(c)–(e), respectively. Eleven data sets were utilised to assess the model. The statistical significance showed that there was a high degree of agreement between the engine test results and the planned model's expected results. The efficiency of the fuzzy logic model is significantly influenced by the type and quantity of membership functions. The triangle membership function (TMF) outperformed other membership functions during this investigation. Triangle membership functions were chosen for this study due to their greater suitability for real-time applications, lower computing cost, and more economy. The membership function and the number of training epochs have a major impact on how effective a fuzzy logic model is. There was no improvement after the 210 training sessions, but the fuzzy logic model did better. Therefore, the ideal values for the training period and membership function are 210 and 8, respectively.

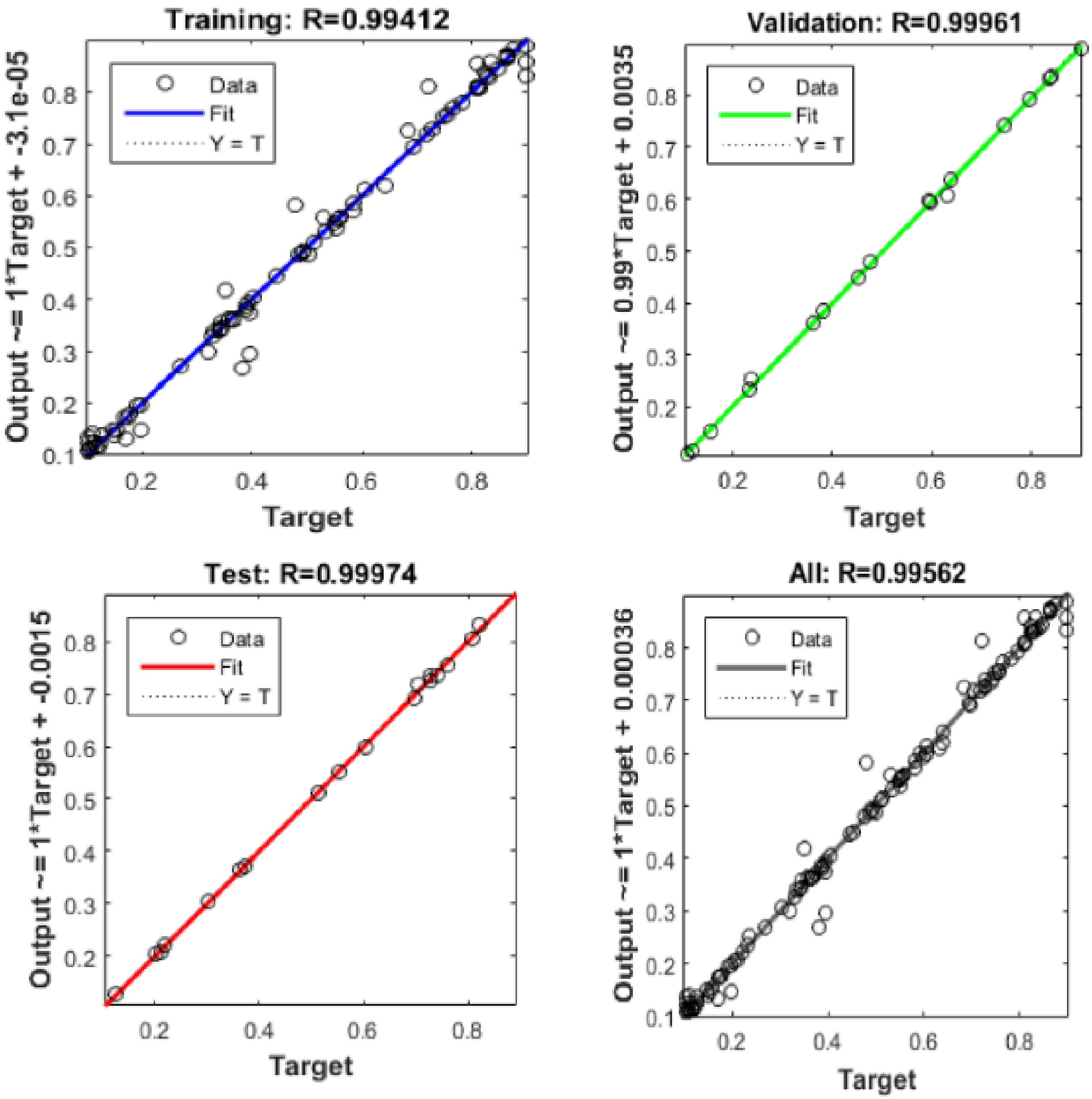


Fig. 4. The fuzzy logic model's overall correlation coefficient

The regression coefficients are higher than the determined critical value in training, testing, validation, and every other scenario (Fig. 4). Following network training, each predicted response's MSE and MAPE values are also determined. The measured BTE, BSEC, and NOx prediction MSE and MAPE values were 0.000214389, 0.000358127, and 0.000417895; these were 4.12, 5.36, and 5.12%, respectively. These exceptionally low MSE and MAPE values are only possible due to the model's high degree of accuracy and intrinsic sensitivity. For BTE, BSEC, and NOx, the fuzzy logic model produced correlation coefficients of 0.99973, 0.99962, and 0.99958, respectively, which are very close to one.

4.2 Brake thermal efficiency

The BTE provides evidence of the engine's economy. The trend of BTE for diesel engines at various EGR rates is seen in Fig. 5. It is evident that under all loads, the BTE exhibits a declining pattern as the EGR increases. At 0% EGR, the maximum BTE is noted. The BTE falls by 1.26%, 2.62%, and 3.75%, respectively, as the EGR rises to 5%, 10%, and 15%. This pattern is caused by a fall in combustion temperature and oxygen concentration brought on by a rise in EGR rate, which seriously impairs combustion. Moreover, the reduction in combustion time brought about by the rise in EGR rate also resulted in a drop in combustion rate and, ultimately, a loss of thermal efficiency [16].

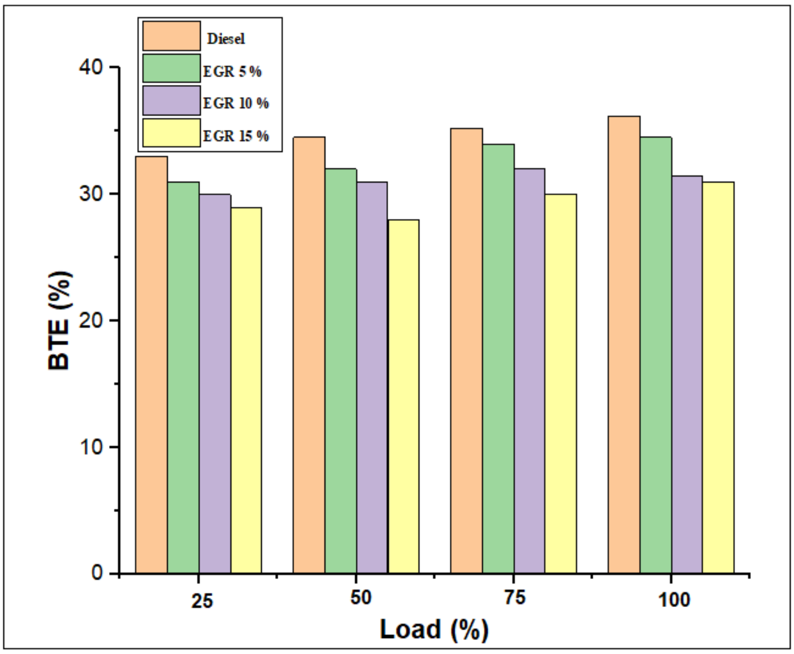


Fig. 5. *Brake thermal efficiency with load*

4.3 Brake specific fuel consumption

The positive correlation between the engine's EGR rate and the quantity of BSFC is seen in Fig. 6. For instance, increasing the EGR rate to 5%, 10%, 15%, and 20%, respectively, at 50% load results in increases in the BSFC of 0.83%, 1.72%, 2.43%, and 3.31%. This is due to the fact that raising the EGR rate allows additional exhaust gases to enter the cylinders, and lowering the oxygen concentration deteriorates the combustion process, requiring more fuel to keep the engine operating at peak efficiency.

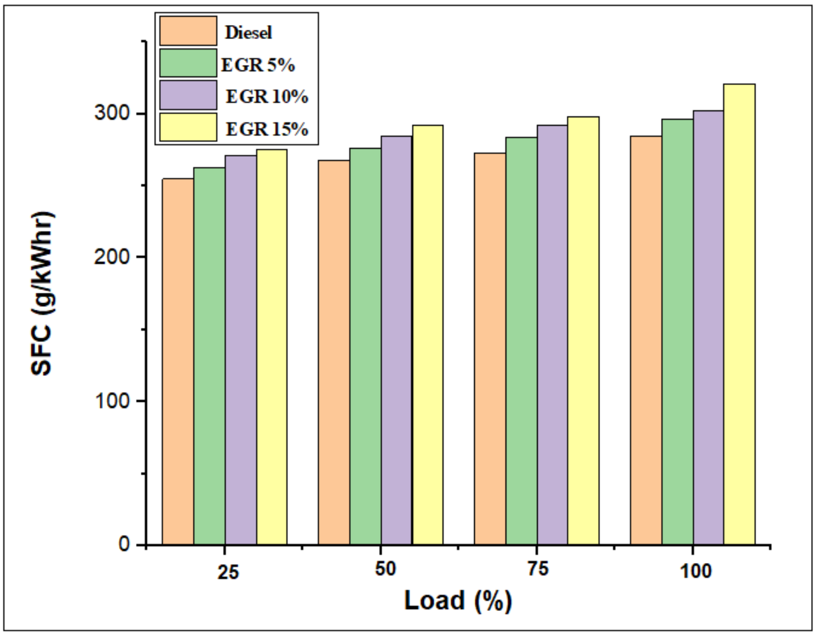


Fig. 6. Brake specific fuel consumption with load

4.4 NOx emissions

Blends of biodiesel and diesel produce greater NOx emissions than pure diesel, thus EGR is a useful tool for reducing NOx emissions. According to the study results, as indicated in Fig. 7, when EGR was increased to 5%, 10%, 15%, and 20%, respectively, at 100% load, NOx emissions were decreased by 49.9%, 64.3%, 73.9%, and 84.3%. This is because, while the addition of EGR lowers intake air flow, the real surplus air coefficient lowers the in-cylinder oxygen concentration, destroying the circumstances necessary for NOx formation and resulting in a drop in NOx emission. In contrast, tri-atomic molecules like CO_2 and water vapour enter the cylinder during EGR. This raises the in-cylinder mass's specific heat capacity and lowers the cylinder's maximum combustion temperature and pressure, which lowers NOx generation and, consequently, NOx emission [17].

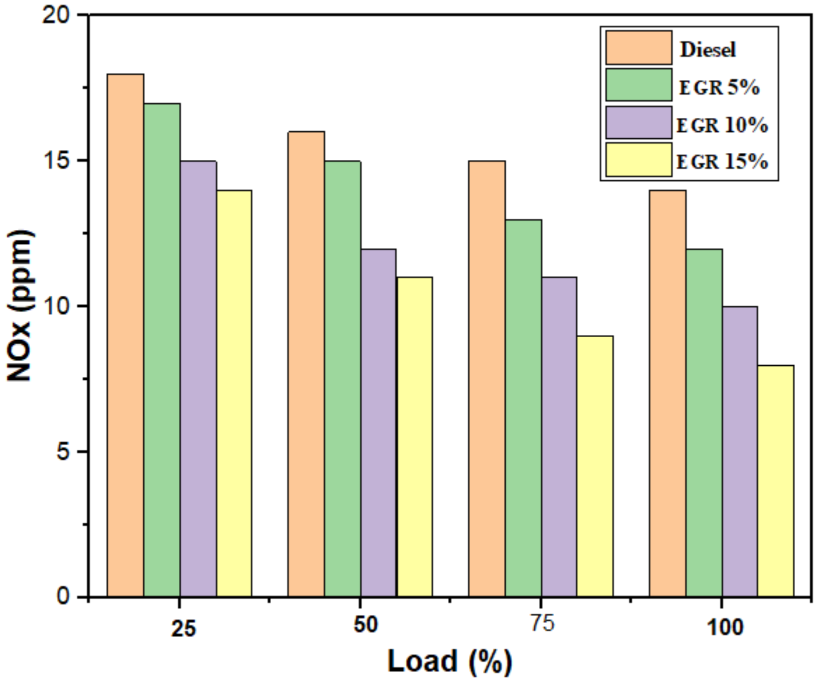


Figure 7. NOx emission with load

4.5 CO emission

The pattern of fluctuation of CO emissions with the EGR rate is seen in Fig. 8. It is evident that CO emissions increase with increasing EGR rates. For instance, at 100% load, the CO emission is 12.16% greater with 20% EGR than it is at 0% EGR. This is a result of the inert gas in the exhaust gas diluting the oxygen concentration and the increased area of the cylinder that lacks oxygen increasing the amount of CO produced. Furthermore, the exhaust gas's high specific heat capacity gases, such CO_2 and H_2O, raise the mixture's specific heat capacity, inhibiting the combustion process and lowering the cylinder's maximum temperature. It is more difficult to oxidise the produced CO to CO2 due to the cylinder's lower oxygen concentration and temperature, which ultimately causes CO emissions to rise.

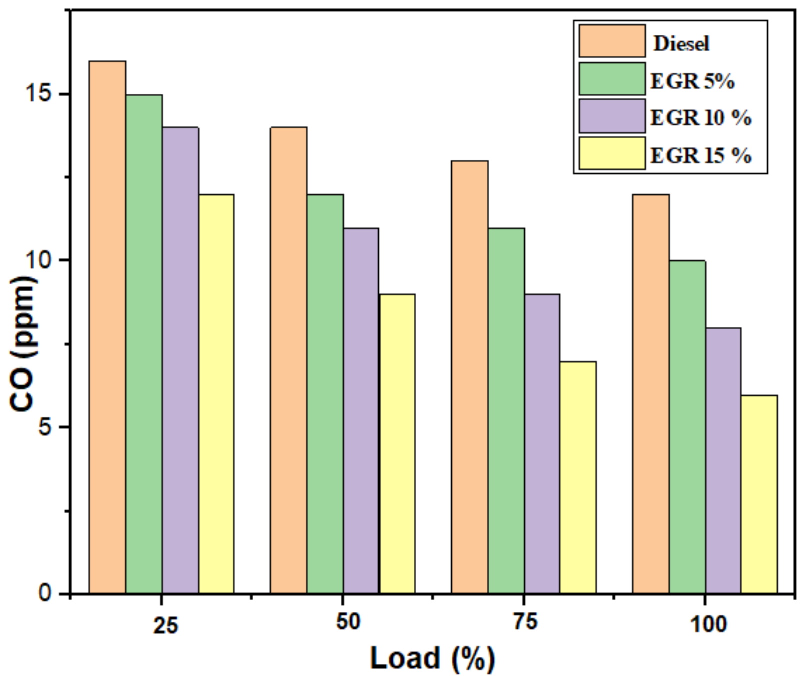


Fig. 8. CO emission with load

4.6 HC emissions

The connection graph between HC emissions and EGR rate is displayed in Fig. 9. It is evident that when the EGR rate increases, so do the HC emissions. Maximum HC emissions occur at an EGR rate of 20%. This is caused by the EGR rate increasing, which lowers the oxygen content in the cylinder, much like soot does. Higher HC emissions are the result of the fuel not burning all the way through and the inhibition of HC oxidation. Furthermore, the cylinder's combustion temperature decreases as a result of the ongoing increase in the EGR rate. Because of the greater quenching phenomena in the cylinder, there is an additional rise in HC emissions.

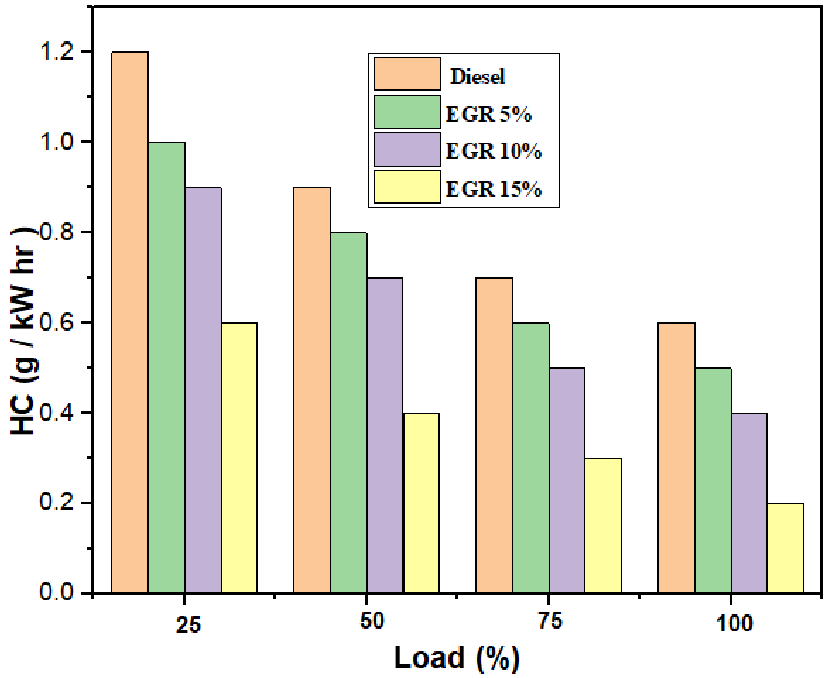


Fig. 9. HC emission with load

Conclusion

This document offers special benefits for minimising pollutant emissions and improving the combustion performance of diesel engines. Some data support this study's particular results, which may be applied to other EGR control studies:

1. All created fuzzy logic response models were deemed statistically significant at a 93.55% confidence level.

2. At 50% load, the values of BTE reduced by 1.26%, 2.62%, 3.75%, and 4.87%, while the values of BSFC rose by 0.83%, 1.72%, 2.43%, and 3.31%, respectively, when EGR increased from 0% to 20% in 5% increments each time.

3. NOx emissions may be successfully decreased using EGR; at a 20% EGR rate, they are reduced by 84.3%. This is because NOx generation is suppressed by the cylinder temperature and decreased oxygen concentration. Instead, very high EGR rates raise emissions of CO_2, HC, and soot. Therefore, an EGR rate of around 15% is ideal for the economic model.

The aforementioned result demonstrates that the low oxygen concentration brought on by a high EGR rate is the primary source of the effect of EGR rate on diesel engines. Additionally, alcohol has high oxygen content, therefore attempting to improve combustion and emission performance by including alcohol into the fuel mixture may be one approach to lower emissions from diesel engines. Furthermore, for practical applications in the future, the development of new materials and technologies to increase the robustness and longevity of EGR systems would be required.

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