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Performance And Emissions Analysis Of Compression Ignition Engine With Exhaust Gas Recirculation System

Pagidipalli Saidulu[a*], Narsimhulu Sanke[b]
[a]*Research Scholar, Department of Mechanical Engineering, Osmania University, Hyderabad, Telangana, India.*
[b]*Professor, Department of Mechanical Engineering, Osmania University, Hyderabad, Telangana, India.*

Abstract:
The Extensive Utilisation Of Fossil Fuels In The Nineteenth Century Led To An Increase In Pollution Emissions, Which Caused Global Warming. The Largest Contributors To These Harmful Pollutants Are Developed And Emerging Countries With High Fuel Consumption. The Present Study Focuses On The Experimental Analysis Of Engine Performance Characteristics And Exhaust Gas Emissions With Different Exhaust Gas Recirculation (EGR) Percentages And Loads In Order To Reduce Exhaust Gas Emissions. The Experiments Have Been Carried Out With Different Load Conditions (5kgf, 10kgf, 15kgf, And 20kgf) And EGR Percentages Of 0%, 5%, 10%, 15%, And 20%. Mechanical Performance And Exhaust Gas Emissions Were Estimated Using The Modified CI Engine Setup. The Experimental Results Emphasise The Variations In Brake Thermal Efficiency, Brake Mean Effective Pressure (BMEP), Friction Power, Mechanical Efficiency, Exhaust Gas Temperatures, And Emissions Of Nox, CO, And UBHC. Larger EGR Percentages Reduce Brake Thermal Efficiency Due To Decreased Oxygen Availability, However Higher Loads Increase Efficiency. The BMEP Values Vary Based On The EGR Percentage And Load Conditions. Friction Power Reduces As EGR % Increases, Implying Lower Mechanical Losses. Mechanical Efficiency Decreases With Increasing EGR Percentages Above 5%, With The Maximum Efficiency Attained For All Load Conditions At A 5% EGR Opening. Exhaust Gas Temperatures Vary With Load And EGR Opening, With Higher Loads And Lower EGR Openings Leading To Higher Temperatures. The Study Provides Valuable Insights Into The Relationships Between EGR Percentages, Loads, And Engine Performance Parameters And Emission Parameters.

Keywords: *CI Engine, CO, EGRS, Nox, UBHC*

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I. Introduction:

Fossil fuels, as the primary energy source, play a significant role in global warming and air pollution [1]. Therefore, it is crucial to introduce and develop new technologies that can be integrated with existing compression-ignition (CI) engines. The emissions produced by CI engines often contain pollutants at high temperatures, presenting an opportunity to utilize these emissions for further reduction of exhaust gas emissions. The combustion process in biodiesel engines leads to increased NOx formation, posing a challenge for emission control. Strategies like EGR have been explored as effective techniques for reducing NOx emissions in compression ignition engines. EGR involves redirecting a portion of the exhaust gas back into the combustion chamber, which lowers the flame temperature and oxygen concentration, thus suppressing NOx formation. However, optimizing EGR rates is crucial, as higher levels of EGR can result in increased smoke and carbon monoxide emissions. Striking the right balance between emission reduction and maintaining overall combustion performance remains a critical area of research in the biodiesel and engine technology field. To address the issue of harmful emissions from CI engines, EGR systems have gained significant attention as an effective technique for reducing nitrogen oxide (NOx) emissions **[2]**. The EGR system involves redirecting a portion of exhaust gases back into the intake air, reducing the combustion temperature and oxygen concentration, thereby suppressing NOx formation. While the use of EGR in conjunction with conventional diesel fuel has been extensively studied, limited research has been conducted on its application with Karanja biodiesel.

Zheng Chen et al. **[3]** studied the combustion and emissions of a high n-butanol/diesel blend with EGR. B. Rajesh Kumar et al. **[4]**examined the effects of blending n-pentanol with diesel under EGR conditions. Erkan Ozturk et al. **[5]** investigated moderation techniques for a B10 biodiesel blend, including EGR. Samad Jafarmadar et al. **[6]** analyzed the effects of EGR in a dual-fuel hydrogen-diesel engine. Özer Can et al. **[7]**studied a soybean biodiesel blend with EGR. Ravikumar Jayabal et al. **[8]** explored sapota biodiesel blends with EGR and oxygenated additives. Erkan Öztürk et al. **[5]** investigated the moderation techniques for a B10 biodiesel blend, including EGR, injection retardation, and ethanol addition. The results show that EGR at 5% improved the combustion parameters. Vinod Singh Yadav et al. **[9]** used hydrogen-enriched air with EGR in a compression ignition engine. Pandey, A et al. **[10]**investigated a military diesel engine with EGR and turbocharging. Ashish Dubey et al. **[11]** studied waste soybean cooking oil biodiesel blends with EGR. Domenico De Serio et al. **[12]** tested B7 biodiesel with an adapted EGR system. Ramaswamy, N et al. **[13]** examined Karanja biodiesel blends with different EGR rates. Dronniou, N et al. **[14]** investigated high EGR rates and multiple injections on combustion and emissions. Pang, H et al. **[15]** explored engine cooling settings to reduce NOx emissions. Pandey, A et al. **[16]** evaluated gasoline, JP-8, and Karanja biodiesel fuels with EGR. Barman, J et al. **[17]**studied the effects of EGR and multiple injections on emissions and fuel consumption. Van Aken et al. **[18]** investigated high EGR rates with low NOx and PM emissions on a heavy-duty diesel engine.

Nevertheless, there have been numerous studies **[19] [20] [21] [22] [23]** on the use of EGRS to reduce exhaust gas emissions in CI engines, scantly research has focused on the integration of EGRS in the existing CI engines for further usage without replacing with new engines. Therefore, there is a need for further investigation to accurately assess the performance and exhaust gas emissions in this context. Therefore, the objective of this study is to analyze the performance and emissions characteristics of a compression ignition engine by introducing an EGR system. By investigating the exhaust gas emissions, and mechanical performance of the engine under various operating conditions, valuable insights can be gained regarding the potential of EGR system integration. This research aims to contribute to the understanding of the performance and environmental impact of EGRS in compression ignition engines.

II. Methodology:

Design and installation of EGRS for CI engine

The design and installation of an EGR system for a Compression Ignition (CI) engine involve several components. These include a GI pipe with a diameter of 1 inch, which serves as the conduit for recirculating the exhaust gases. Additionally, an orifice meter with a 15mm diameter is utilized to accurately measure the discharge of the gases. To control the flow and regulate the opening of the system, a non-return control valve is incorporated, allowing for the desired amount of exhaust gases to be reintroduced into the engine. Careful consideration and proper installation of these components are crucial for the effective implementation of the EGRS, optimizing engine performance and reducing emissions. The temperature of the exhaust gases is measured by using a K-type thermos couple.

Experimental setup:

The experimental investigation was conducted on a conventional vertical water-cooled four-stroke compression ignition diesel engine. The engine used in the study was supplied by Kirloskar Oil Engines Ltd., India, and underwent modifications to incorporate an EGR system. The EGR system was carefully designed and implemented with precise flow measurement and control using an orifice meter and gate opening mechanism. By utilizing the controlled EGR system, a series of experiments were performed with varying EGR valve opening percentages to assess its impact on engine performance and emissions. To measure the developed torque, a rope brake dynamometer was employed, providing a reliable means of applying load to the engine. The engine's valve timing was set as follows: the inlet valve opens 5.0° before Top Dead Center (TDC), the inlet valve closes 35° after Bottom Dead Center (BDC), fuel injection commences 23° before TDC, the exhaust valve opens 35° before BDC, and the exhaust valve closes 5.0° after TDC. These specific valve timing settings were chosen to ensure optimal engine operation during the experiments.

The detailed specifications of the experimental setup, including the engine model, EGR system configuration, measurement devices, and valve timing, are provided in Table 1. This comprehensive experimental setup allowed for accurate data collection and analysis, enabling a thorough investigation into the effects of EGR on the engine's performance and emissions.

Table 1: Specifications of the experimental setup

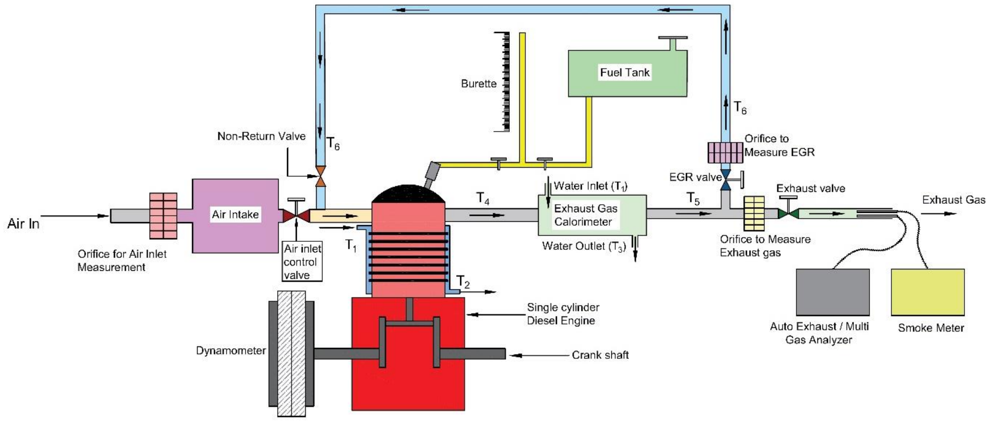
Specifications of the CI engine with EGRS	
Engine Make	Kirloskar Oil Engines Ltd., India
Engine Type	Vertical cylinder, water-cooled
Engine rated power	5Hp at 1500 rpm
Number of Cylinders	01
Bore/ Stroke (mm)	87.5/80
Cubic Capacity in Liters	0.553 (553 CC)
Compression Ratio	17.5
Engine Weight (kg)	130

Type of Fuel Injection	Direct Injection
Injection Pressure	200 Bar
Type of Dynamometer	Rope Brake Dynamometer
Diameter of the Brake Drum	330 mm
EGR Gas Measurement	Orifice and U-tube Manometer. Manometer fluid: Mercury

Experiments were carried out by adjusting the load on a dynamometer, starting from a no-load situation and progressing to 5, 10, 15, and 20 kgf at a rated speed of 1500rpm, known as the economic speed test. Various parameters were measured during these tests, including fuel consumption, air intake flow, inlet coolant water temperature, outlet water temperature, exhaust gas temperature at the engine outlet, exhaust gas temperature at the calorimeter outlet, and mass flow rate of the exhaust gas. Exhaust gas analysis was performed using an exhaust gas analyser (NPM-MGA-2, NETEL (I) Ltd.) and a smoke meter (Smoke meter 437C, AVL (I) Ltd.). The exhaust gas analyser provided measurements of CO2, CO, NOx, HC, and O2. The experimental setup depicted in Figure 1 featured a modified compression ignition (CI) engine equipped with an EGR system. The tests encompassed a range of load conditions on the dynamometer, from no load to 5, 10, 15, and 20 kgf, while maintaining a constant speed. Furthermore, controlled levels of EGR were implemented at 0%, 5%, 10%, 15%, and 20%.

During the experiments, several parameters were measured to assess the engine's performance and emissions. These parameters included fuel consumption, air flow intake, inlet coolant water temperature, outlet water temperature, exhaust gas temperature at the engine outlet, exhaust gas temperature at the calorimeter outlet, and mass flow rate of exhaust gas. Various instrumentation and equipment, such as flow control valves, fuel measurement devices, and thermocouples, were strategically placed at various positions to enable operation and data collecting, as shown in Figure 1.

Figure 1: Schematic diagram of the experimental setup with EGRS



By systematically varying the load, and EGR valve openings, a comprehensive set of data was gathered to evaluate the engine's performance characteristics and exhaust emissions. This experimental procedure provided valuable insights into the impact of load, fuel type, and EGR levels on the CI engine's operational parameters, facilitating a thorough analysis of the engine's behavior under various operating conditions.

III. Results and discussions

Performance characteristics:

Brake thermal efficiency is a crucial metric that quantifies the efficiency of an engine in converting fuel energy into useful work. In Figure 2, experimental data presents the brake thermal efficiency values for different EGR percentages (ranging from 0% to 20%) and various loads (5kg, 10kg, 15kg, and 20kg). At 0% EGR and a load of 5kg, the brake thermal efficiency is measured to be 19.9%. As the EGR percentage and load conditions change, the brake thermal efficiency values also exhibit variations. Typically, higher EGR percentages result in lower brake thermal efficiency due to the reduced availability of oxygen for combustion caused by recirculating exhaust gas. Conversely, higher loads tend to yield higher brake thermal efficiency by enhancing combustion efficiency and fuel utilization. Meanwhile, Figure 3 showcases the brake mean effective pressure (BMEP), which reflects the average pressure applied to the piston during the power stroke. At 0% EGR and a load of 5kg, the BMEP is recorded as 1.3453 bar. The values of BMEP also demonstrate fluctuations depending on the EGR percentage and load conditions. Increasing EGR percentages can lead to a slight decrease or relatively constant values of BMEP due to the influence of EGR on oxygen concentration, combustion temperature, and flame propagation characteristics. These factors affect the peak pressure and mean effective pressure during the power stroke of the engine.

Figure 3: Brake thermal efficiency vs EGR opening %ge.

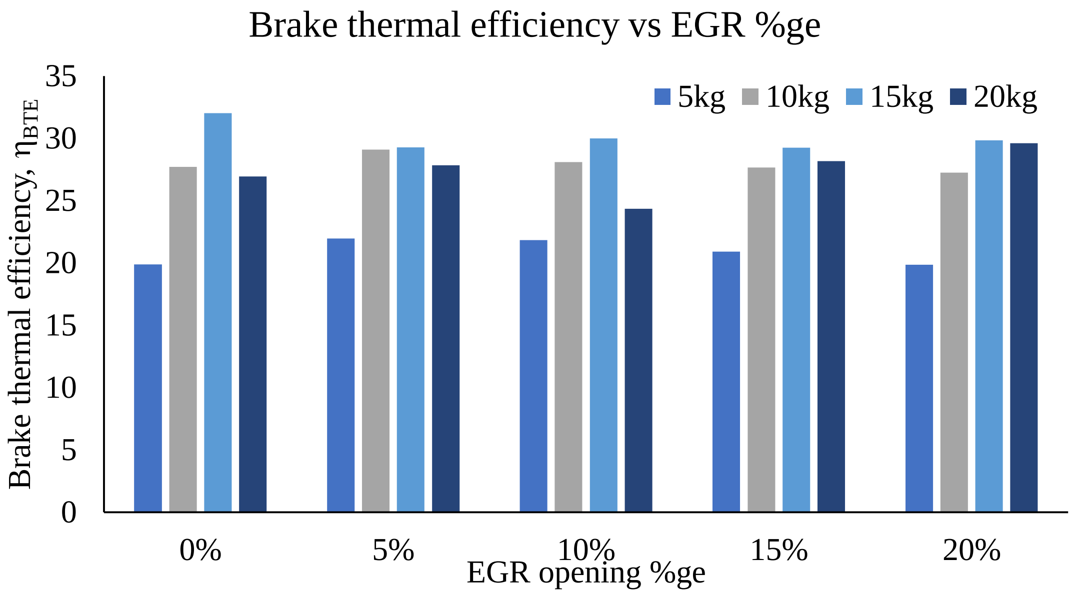
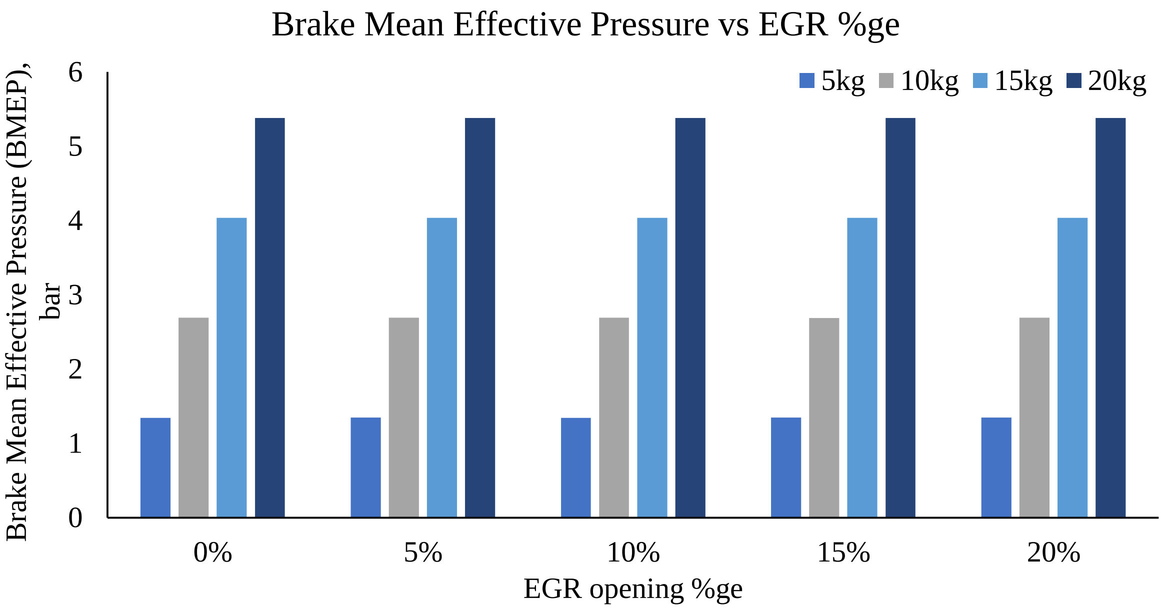


Figure 4: Brake Mean Effective Pressure vs EGR opening %ge.



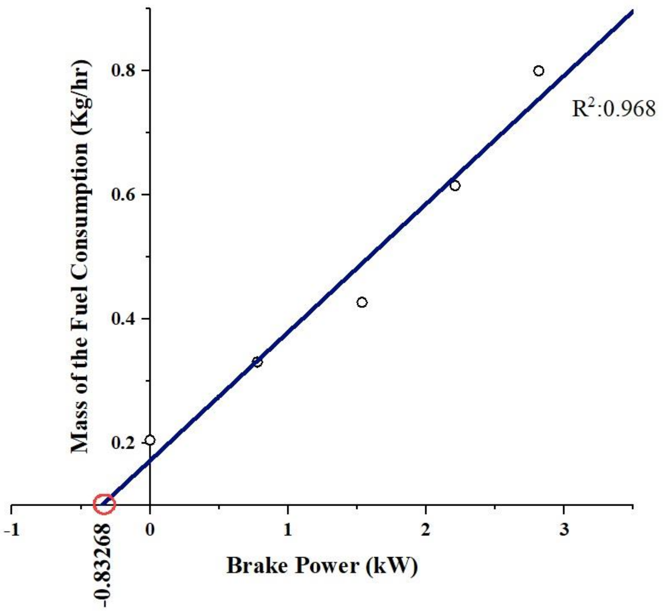


Figure 5: Friction power by William's line method

The friction power for the CI (Compression Ignition) engine is determined using the Williams line method for a 0% EGR (Exhaust Gas Recirculation) opening across all loading conditions. Experimental data is fitted to a linear curve using linear regression techniques, resulting in R^2 values greater than 0.95, indicating a good fit. The analysis reveals a friction loss of 0.8326 kW at 0% EGR. The same method is employed to estimate the friction power loss at 5%, 10%, 15%, and 20% EGR, and all corresponding R^2 values exceed 0.95. Thus, it is recommended to utilize linear regression for fitting all experimental data. Table 2 displays the friction power values for various EGR percentage openings. These friction power values are utilized to calculate the indicated power, which in turn provides the determination of the mechanical efficiency. The relationships between the indicated power, mechanical efficiency, and EGR percentage are depicted in Figure 6.

Table 2: Friction power at different EGR percentage openings

S.No	EGR %ge opening	Friction power, kW
1	0%	0.83268
2	5%	0.46938
3	10%	0.49599
4	15%	0.56976
5	20%	0.6602

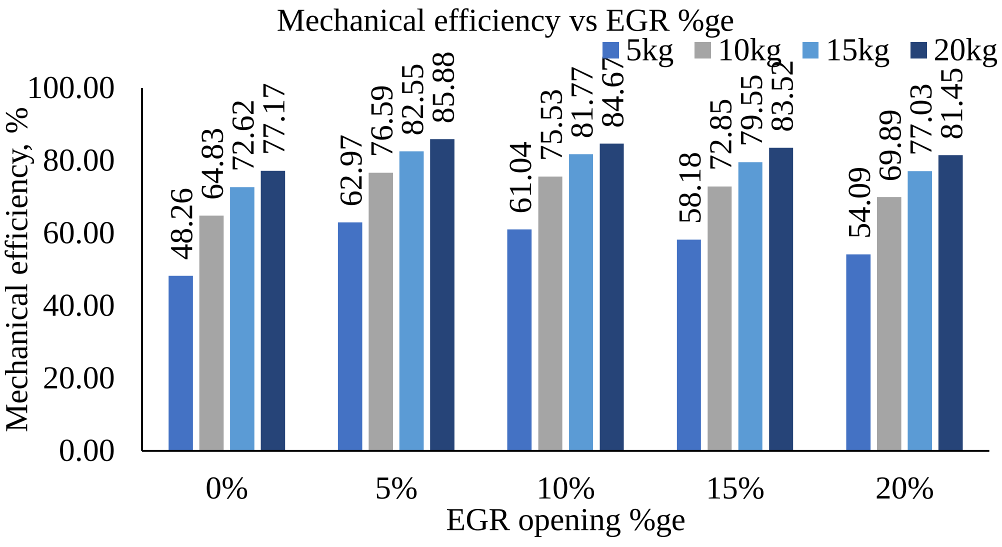


Figure 6: Mechanical efficiency vs EGR %ge opening.

Figure 6 illustrates the mechanical efficiency values corresponding to different EGR percentage openings and loads. It is evident that as the EGR percentage increases beyond 5%, the mechanical efficiency tends to decrease at each load. Notably, there is an initial increase in mechanical efficiency from zero EGR opening to 5% EGR opening for all loading conditions. At a 5kg load, the highest mechanical efficiency is achieved as 62.97% at 5% EGR opening, while at a 10kg load, the highest efficiency is recorded as 76.59% with the same 5% EGR opening. Similarly, at a 15kg load, the highest efficiency is observed as 82.55% with a 5% EGR opening, and at a 20kg load, the highest efficiency reaches 85.88% with the same 5% EGR opening. These findings suggest that employing a 5% EGR opening across various loads (5kg, 10kg, 15kg, and 20kg) yields the highest mechanical efficiency.

Figure 7 shows the exhaust gas temperatures in degrees Celsius at different loads and various EGR percentage openings. At a load of 5kg, the exhaust gas temperatures remain relatively consistent across different EGR openings, ranging from 127°C to 137°C. For a load of 10kg, the temperatures vary between 166°C and 182°C, with the highest temperature recorded at 182°C for both 10% and 15% EGR openings. At a load of 15kg, the temperatures gradually increase from 222°C to 282°C as the EGR opening percentage increases from 0% to 20%. Finally, at a load of 20kg, there is a significant variation in temperatures, with the highest temperature recorded at 521°C for 0% EGR opening and the lowest temperature of 316°C for 20% EGR opening. Overall, the experimental results shows the changes in exhaust gas temperatures at different loads and EGR openings, indicating the impact of these factors on the combustion process.

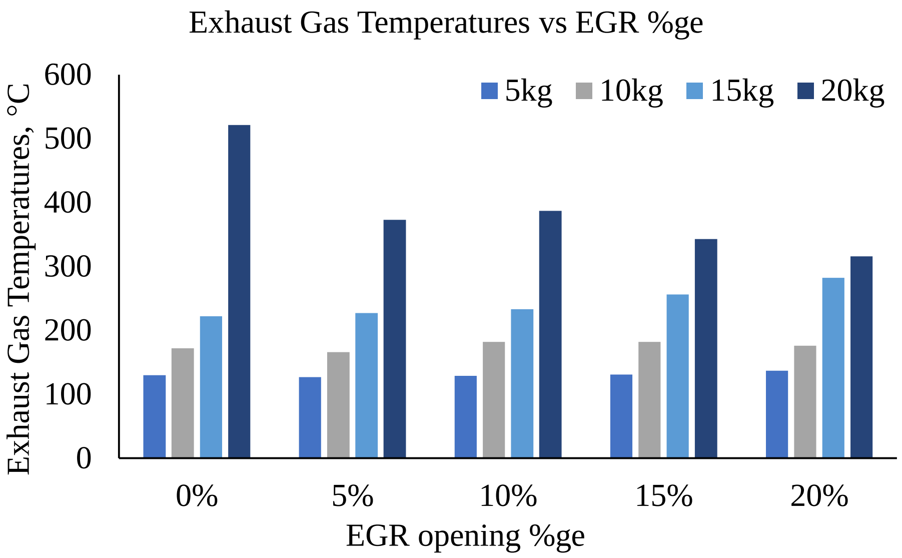


Figure 7: Exhaust Gas Temperatures vs EGR %ge

Based on the experimental data, the best combination would be to use a 5% EGR opening at various loads (5kg, 10kg, 15kg, and 20kg) to achieve the highest mechanical efficiency. This combination consistently yields the highest mechanical efficiency values across different loads. As for the exhaust gas temperatures, there are variations depending on the load and EGR opening. However, the specific combination that provides the best overall performance would depend on the specific requirements in terms of mechanical efficiency and exhaust gas temperatures in the given context.

Exhaust gas emissions:

Exhaust gas emissions were evaluated through a smoke meter and exhaust gas analyzer. The exhaust gas analyzer and smoke meter were used to measure NOx, CO, Unburnt Hydrocarbons (UBHC) and smoke opacity. Figures 8 to 11 illustrate the relationship between these exhaust emissions and the EGR opening under various loading conditions. At each load condition (5kg, 10kg, 15kg, 20kg), the emissions are measured at various EGR opening %ge. As the load increases from 5kg to 20kg, the emissions of NOx, CO, and HC generally increase. At 0% EGR opening, the NOx emissions increase from 7.46 g/kW-hr at 5kg load to 12.20 g/kW-hr at 20kg load. Similarly, CO emissions decrease from 9.87 g/kW-hr at 5kg load to 6.93 g/kW-hr at 20kg load, indicating better combustion efficiency. HC emissions show a slight decrease from 19.05 g/kW-hr at 5kg load to 17.00 g/kW-hr at 20kg load.

However, with increasing the EGR opening leads to reduced emissions of NOx and CO. at 15% EGR opening, the NOx emissions decrease from 7.73 g/kW-hr at 5kg load to 10.75 g/kW-hr at 20kg load. CO emissions also decrease, such as from 7.21 g/kW-hr at 5kg load to 6.60 g/kW-hr at 20kg load. However, HC emissions show relatively minor variations across different EGR openings.

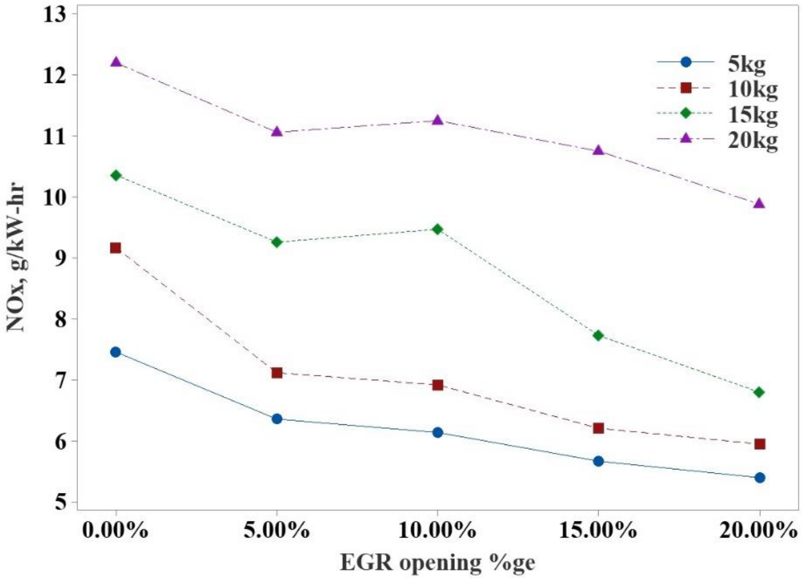


Figure 8: NOx emissions vs EGR opening %ge

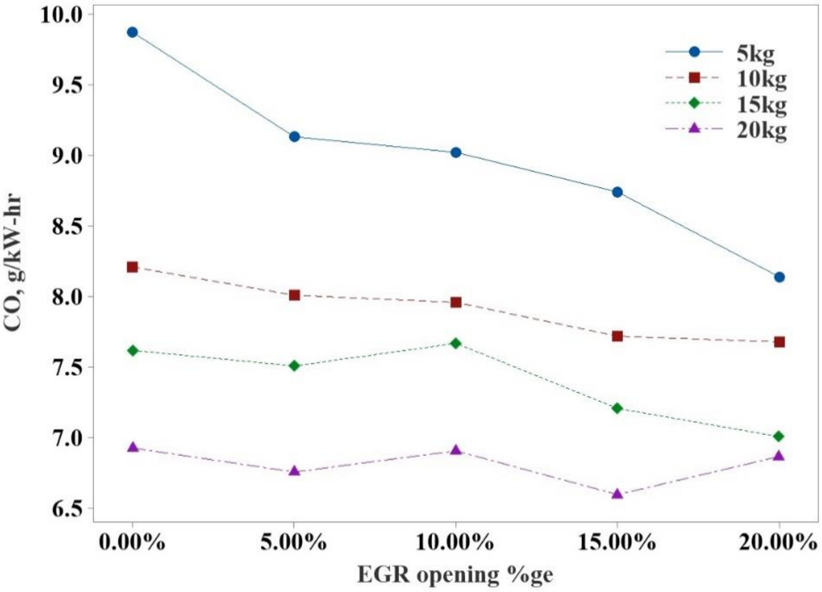


Figure 9: CO emissions vs EGR opening %ge

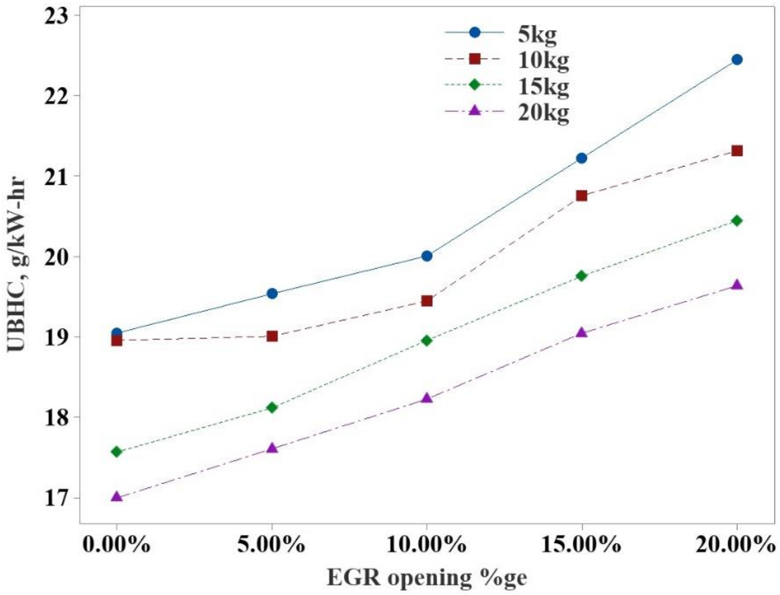


Figure 10: UBHC emissions vs EGR opening %ge

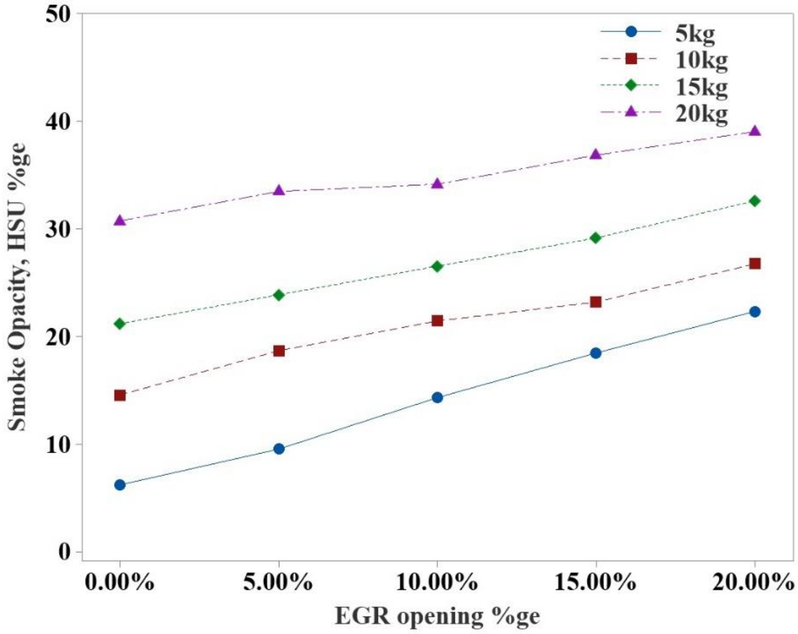


Figure 9: smoke opacity vs EGR opening %ge

These variations demonstrate the impact of both load conditions and EGR openings on exhaust gas emissions. Higher loads generally result in increased emissions, while higher EGR openings tend to reduce NOx and CO emissions.

IV. Conclusions:

Based on the experimental results on modified CI engine with EGRS, the following conclusions are drawn.

- The brake thermal efficiency values vary with different EGR percentages and loads. Higher EGR percentages generally result in lower brake thermal efficiency due to reduced oxygen availability for combustion. On the other hand, higher loads tend to yield higher brake thermal efficiency by enhancing combustion efficiency and fuel utilization.
- The BMEP values exhibit fluctuations depending on the EGR percentage and load conditions. Increasing EGR percentages can lead to a slight decrease or relatively constant BMEP values due to the influence of EGR on oxygen concentration, combustion temperature, and flame propagation characteristics.

- Friction power is determined using the Williams line method, and the experimental data is fitted to a linear curve. Friction power values decrease with increasing EGR percentages, indicating reduced mechanical losses.
- Exhaust gas temperatures vary with load and EGR opening. Higher loads and lower EGR openings generally result in higher temperatures, while higher EGR openings can lead to lower temperatures depending on the specific conditions.
- The emissions of NOx and CO generally increase with increasing load, while higher EGR openings contribute to reduced NOx and CO emissions. HC emissions show relatively minor variations across different EGR openings.
- Mechanical efficiency values tend to decrease with higher EGR percentages beyond 5%. The highest mechanical efficiency is achieved at a 5% EGR opening for all load conditions, indicating the optimal EGR percentage for maximizing efficiency.

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Conflicts of interest or competing interests: -NIL-

Data and code availability: -NA-

Supplementary information: -NA-

Ethical approval: The present work doesn't involve any human samples or tissues or any biological samples.

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