

Advanced Optimization of Compression Ratio in Diesel-Fueled Compression Ignition Engines for Enhanced Performance and Emission Control

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Abstract

This study presents a comprehensive experimental investigation to determine the optimal compression ratio (CR) for a diesel-fueled compression ignition (C.I.) engine under controlled operating conditions. Experiments were conducted on a single-cylinder, four-stroke variable compression ratio engine across a wide range of compression ratios (13.2–20.2) at constant speed and varying load. Key performance and emission parameters, including brake thermal efficiency (BTE), specific fuel consumption (SFC), exhaust gas temperature (EGT), and smoke density, were systematically evaluated.

The results indicate that engine performance is strongly dependent on compression ratio, with an optimal value identified at $CR = 14.8$. At this condition, the engine exhibits maximum thermal efficiency, minimum fuel consumption, and reduced smoke emissions, reflecting improved combustion efficiency and enhanced air–fuel mixing. In contrast, lower compression ratios lead to incomplete combustion, while higher compression ratios result in increased heat losses and reduced net work output, causing a decline in overall performance.

The findings demonstrate that compression ratio optimization is essential for achieving a balance between engine efficiency and emission control. This study provides valuable insights into the role of compression ratio as a key design and operating parameter, contributing to the development of more efficient and environmentally sustainable diesel engines.

Keywords: Compression ratio optimization, diesel engine, thermal efficiency, fuel consumption, emissions, combustion.

1. Introduction

The increasing global demand for petroleum-based fuels, coupled with their limited availability, has driven extensive research toward improving the performance and efficiency of diesel-fueled compression ignition (C.I.) engines. Enhancing engine design and operating parameters plays a critical role in improving combustion quality, thereby increasing brake thermal efficiency and reducing fuel consumption.

Early studies on energy utilization highlighted the growing dependency on fossil fuels and the economic burden associated with energy imports, particularly in developing economies with limited

hydrocarbon reserves (Sarma, 2003; Raman & Ghosh, 2003). Foundational research in internal combustion engines established that thermodynamic parameters, especially compression ratio, significantly influence engine performance, combustion efficiency, and fuel economy (Heywood, 1988; Ganesan, 1998).

Subsequent experimental investigations explored alternative fuels such as vegetable oils and hydrogen in diesel engines, demonstrating their potential to improve sustainability while introducing new challenges related to combustion characteristics and engine performance (Prabhu Kumar, 1985; Ramesh, 2001). Studies on dual-fuel engines further emphasized the importance of optimizing operating parameters, including compression ratio, to achieve efficient combustion and reduced emissions (Karim, 1987; Samaga, 1983; Smith & Aceves, 1995).

In recent years, research has advanced toward integrating alternative fuels and optimizing combustion processes using modern techniques. For instance, dual-fuel strategies involving ethanol, diesel, and compressed natural gas have demonstrated significant impacts on engine performance and emissions, although they require careful balancing of efficiency and environmental outcomes (Bhowmik et al., 2022). Similarly, methanol-based fuel systems have shown promising potential for enhancing combustion efficiency while reducing emissions in C.I. engines (Farooq et al., 2025).

Moreover, optimization of fuel injection timing and quantity has been shown to significantly improve engine efficiency and emission characteristics (Aldarwish et al., 2024). Engine design parameters, including piston bowl geometry and compression ratio, also play a crucial role in reducing NO_x and soot emissions while maintaining acceptable performance levels (Vikraman et al., 2023). Additionally, experimental studies using biodiesel blends under variable compression ratio conditions have confirmed that compression ratio remains a dominant factor influencing engine performance, combustion quality, and emission characteristics (Equbal et al., 2025).

Among all influencing parameters, the compression ratio is considered one of the most critical factors governing engine thermodynamic performance. While higher compression ratios generally enhance thermal efficiency, they may also lead to increased emissions and mechanical stresses. Conversely, lower compression ratios tend to result in incomplete combustion and higher fuel consumption.

Therefore, determining the optimal compression ratio is essential to achieve a balance between engine performance, fuel efficiency, and emission control. In this context, the present study aims to experimentally investigate the effect of varying compression ratios on the performance and emission characteristics of a diesel-fueled C.I. engine operating under variable load and constant speed conditions.

2. EXPERIMENTAL SETUP AND METHODOLOGY

The experimental investigation was carried out on a single-cylinder, four-stroke, direct injection compression ignition (C.I.) diesel engine equipped with a variable compression ratio (VCR) system. The study aims to evaluate the influence of compression ratio on engine performance, combustion characteristics, and emission behavior under controlled and repeatable conditions.

The compression ratio was varied systematically from 13.2 to 20.2, while the engine speed was maintained constant throughout the experimental campaign. Engine loading was applied using an eddy current dynamometer, ensuring precise control and stability across all test conditions.

2.1 Engine Specifications

- Engine type: Single-cylinder, four-stroke, direct injection diesel engine

- Manufacturer: Kirloskar
- Compression ratio range: 13.2–20.2
- Bore × Stroke: 70 mm × 110 mm
- Rated power: 3.75 kW
- Loading system: Eddy current dynamometer

2.2 Experimental Procedure

The engine was operated under steady-state conditions for all experiments. Prior to data acquisition, sufficient time was allowed for the engine to reach thermal equilibrium. The cooling water temperature was maintained at $70 \pm 2^\circ\text{C}$ to ensure consistent thermal boundary conditions.

At each compression ratio, the engine was tested under varying load conditions. The following parameters were recorded:

- Brake thermal efficiency (BTE)
- Specific fuel consumption (SFC)
- Exhaust gas temperature (EGT)
- Smoke density

Each experiment was repeated three times, and the average values were used to ensure data reliability and minimize random errors.

2.3 Instrumentation and Measurement Accuracy

All measurements were performed using calibrated instruments with known accuracy limits, as summarized below:

Parameter	Instrument Used	Accuracy
Engine load	Eddy current dynamometer	$\pm 1\%$
Fuel consumption	Burette method	$\pm 0.5\%$
Temperature	Thermocouple (K-type)	$\pm 1^\circ\text{C}$
Smoke density	Smoke meter	± 1 HSU

2.4 Fuel Properties

The experiments were conducted using conventional diesel fuel. The key physicochemical properties are presented in Table below:

Property	Value
Density (kg/m^3)	~830
Calorific value (MJ/kg)	~42–45
Cetane number	45–55
Viscosity (cSt @ 40°C)	2–4

2.5 Experimental Matrix

The experimental conditions investigated in this study are summarized as follows:

Parameter	Range/Condition
Compression ratio	13.2 – 20.2
Engine speed	Constant
Load conditions	Variable
Cooling temperature	70 ± 2°C

2.6 Uncertainty Analysis

To ensure the reliability and accuracy of the experimental data, an uncertainty analysis was conducted based on the accuracy of the measuring instruments. The overall uncertainty in calculated parameters such as brake thermal efficiency and fuel consumption was estimated using standard error propagation methods.

The maximum uncertainty in the measured parameters was found to be within acceptable limits (typically less than ±3%), indicating good experimental precision and repeatability.

2.7 Experimental Control and Repeatability

To minimize systematic and random errors, the following control measures were implemented:

- Maintaining constant engine speed throughout experiments
- Stabilizing cooling water temperature
- Ensuring consistent fuel supply conditions
- Performing repeated measurements and averaging results
- Conducting tests under similar ambient conditions

3.0 RESULTS AND DISCUSSION

The variation of engine performance and emission characteristics with compression ratio provides a comprehensive understanding of the combustion behavior in the tested diesel engine. The experimental results demonstrate that brake thermal efficiency (BTE) increases progressively with increasing engine load for all tested compression ratios, which is attributed to improved combustion efficiency and reduced relative heat losses at higher loads. Among the investigated conditions, the maximum BTE is achieved at a compression ratio of 14.8, indicating the presence of an optimal compression condition for the tested engine.

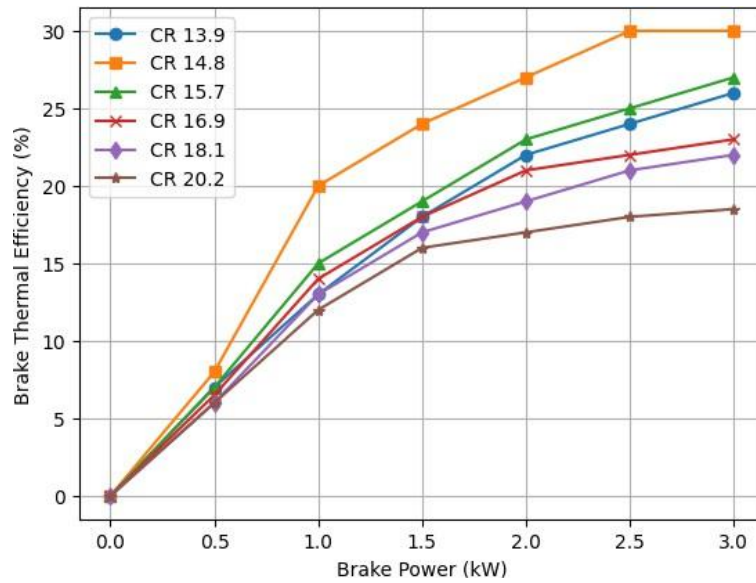


Figure 1. Effect of compression ratio on brake thermal efficiency as a function of brake power. The results demonstrate a consistent increase in efficiency with load, with a peak observed at a compression ratio of 14.8. This behavior indicates enhanced combustion efficiency and optimal air–fuel mixing at intermediate compression ratios, while deviations at higher compression ratios are attributed to increased heat losses and reduced net work output.

This optimal performance can be explained by enhanced combustion characteristics at this compression ratio, where improved atomization and more effective air–fuel mixing promote efficient heat release. Similar observations have been reported in classical and recent studies, where optimal compression ratios were found to enhance combustion phasing and energy conversion efficiency (Heywood, 1988; Ganesan, 1998; Vikraman et al., 2023). Although thermodynamic theory suggests that increasing the compression ratio should lead to higher thermal efficiency, the experimental results reveal a decline in BTE at higher compression ratios (18.1 and 20.2). This deviation from ideal behavior is primarily attributed to increased convective heat transfer losses, elevated mechanical stresses, and possible charge dilution effects, which reduce the net useful work output, as also highlighted in recent experimental investigations (Equbal et al., 2025).

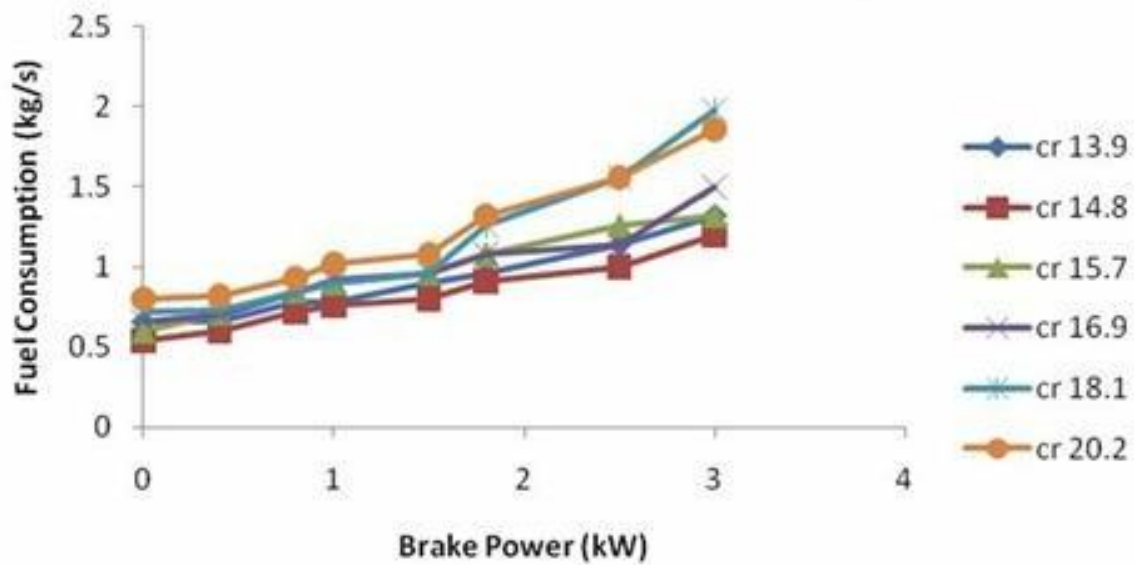


Figure 2. Variation of fuel consumption with brake power at different compression ratios. The minimum fuel consumption is observed at a compression ratio of 14.8, confirming optimal combustion efficiency.

A similar trend is observed in fuel consumption characteristics, where the minimum fuel consumption is recorded at the same optimal compression ratio of 14.8. At lower compression ratios, inefficient combustion due to insufficient in-cylinder temperature leads to higher fuel consumption. Conversely, at higher compression ratios, fuel consumption increases again despite improved compression, which can be attributed to excessive heat losses to the cylinder walls and reduced combustion efficiency under over-compressed conditions. This non-linear relationship has been widely discussed in modern combustion studies, particularly in dual-fuel and alternative fuel engines, where optimal performance is achieved within a narrow compression ratio range (Bhowmik et al., 2022; Farooq et al., 2025).

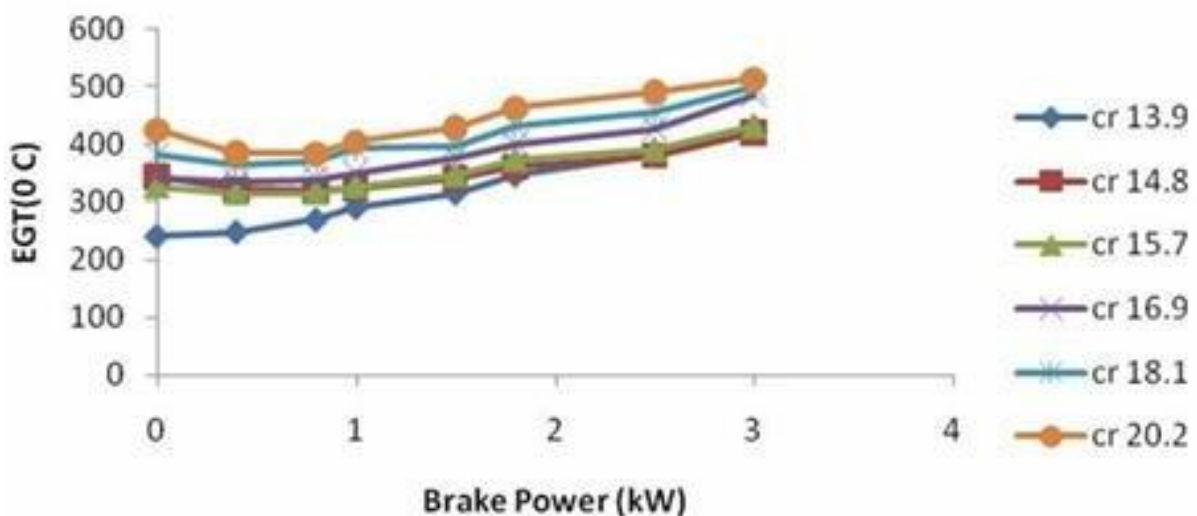


Figure 3. Effect of compression ratio on exhaust gas temperature at varying brake power. Exhaust gas temperature increases with both load and compression ratio due to elevated combustion temperatures.

The exhaust gas temperature (EGT) results further support this interpretation, as EGT is found to increase with both engine load and compression ratio. The highest exhaust temperatures are observed at the maximum compression ratio of 20.2, while the lowest are recorded at 13.2. The increase in EGT at higher compression ratios is associated with elevated peak combustion temperatures and longer residence time of high-temperature gases. However, excessively high exhaust temperatures indicate greater energy loss through exhaust gases rather than effective conversion into useful work. This behavior is consistent with findings reported in combustion optimization studies, where excessive thermal loading reduces overall engine efficiency (Aldarwish et al., 2024).

The emission characteristics, particularly smoke density, also exhibit a strong dependence on compression ratio. Smoke density increases with engine load due to higher fuel injection rates and the formation of locally rich combustion zones. However, the lowest smoke emissions are consistently observed at a compression ratio of 14.8, indicating more complete combustion and improved oxidation of soot precursors. At lower compression ratios, insufficient combustion temperature leads to incomplete oxidation and higher soot formation, whereas at higher compression ratios, rapid combustion and localized fuel-rich regions may contribute to increased particulate emissions. Similar emission trade-offs between soot formation and combustion conditions have been extensively discussed in recent engine studies (Vikraman et al., 2023; Aldarwish et al., 2024).

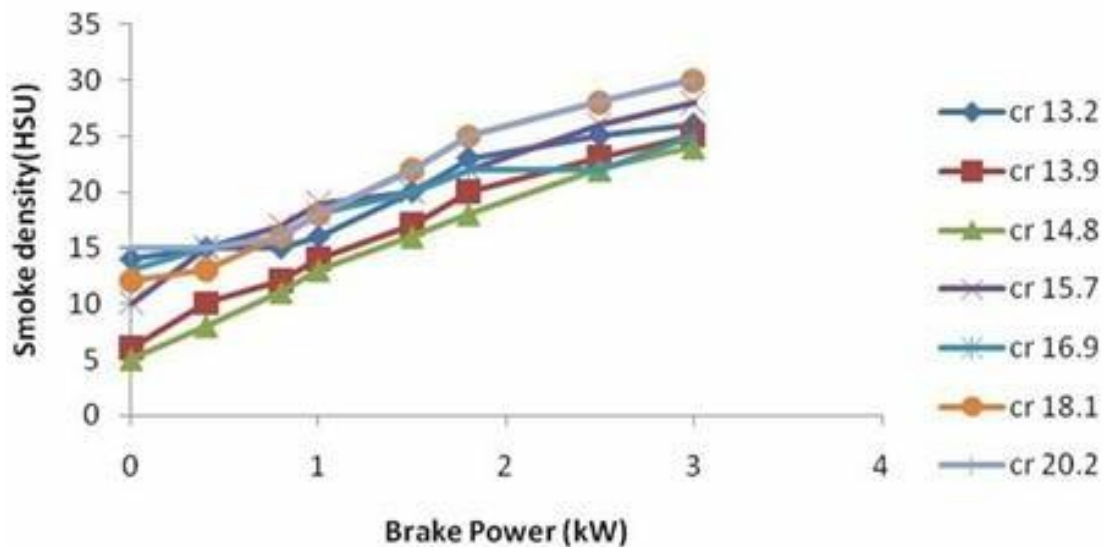


Figure 4. Variation of smoke density with brake power for different compression ratios. The lowest smoke emissions are observed at a compression ratio of 14.8, indicating more complete combustion.

Overall, the experimental findings clearly demonstrate that the compression ratio plays a crucial role in governing both performance and emission characteristics of diesel engines. The results highlight the existence of an optimal compression ratio, beyond which further increases lead to diminishing returns or even performance deterioration. The compression ratio of 14.8 is identified as the most suitable operating condition for the tested engine, providing the best compromise between thermal

efficiency, fuel consumption, exhaust temperature, and emission characteristics. This outcome aligns well with both classical engine theory and contemporary research trends, emphasizing the importance of multi-objective optimization in modern engine design (Heywood, 1988; Farooq et al., 2025).

4.0 CONCLUSION

The present study experimentally investigated the effect of compression ratio on the performance and emission characteristics of a diesel-fueled compression ignition engine operating under variable load and constant speed conditions. The results clearly demonstrate that the compression ratio plays a critical role in governing combustion efficiency, fuel consumption, and emission behavior.

It was observed that brake thermal efficiency increases with engine load for all tested compression ratios, with a maximum value achieved at a compression ratio of 14.8. This optimal condition is attributed to improved air–fuel mixing, enhanced combustion phasing, and more effective heat release. Although higher compression ratios are theoretically expected to improve thermal efficiency, the experimental findings reveal a decline in performance beyond the optimal point due to increased heat transfer losses, mechanical stresses, and non-ideal combustion effects.

Fuel consumption analysis further supports these findings, as the minimum fuel consumption was also recorded at the same compression ratio of 14.8. Both lower and higher compression ratios exhibited increased fuel consumption, highlighting the existence of an optimal operating window for efficient fuel utilization. Similarly, exhaust gas temperature was found to increase with both load and compression ratio, with excessively high values at higher compression ratios indicating greater thermal losses rather than improved energy conversion.

In terms of emission characteristics, smoke density was significantly influenced by compression ratio, with the lowest emissions observed at the optimal compression ratio. This indicates more complete combustion and improved oxidation of soot-forming species under balanced thermodynamic conditions.

Overall, the study confirms that a compression ratio of 14.8 provides the best compromise between performance and emission characteristics for the tested engine configuration. The findings emphasize the importance of optimizing compression ratio as part of a multi-objective approach in engine design, where efficiency, fuel economy, and environmental impact must be simultaneously considered.

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