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Optimizing Combustion Processes in Diesel Engines Using Variable Compression Ratio Technology

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Abstract: Diesel engines are essential in the transportation and industrial sectors due to their notable efficiency and ability to deliver power. Optimizing combustion processes in diesel engines improves performance, increases fuel efficiency, and minimizes pollutants. Through a comprehensive analysis of existing research studies, experimental data, and computational simulations, this review aims to provide insights into the effectiveness of variable compression ratio (VCR) technology in achieving optimized combustion processes in diesel engines. It explores the fundamental principles (fuel efficiency, combustion stability, emission measurement, dynamic response, and heat release) of optimizing combustion in diesel engines, the operational advantages of VCR technology, and the possible improvements in engine economy. The review concludes that adjusting the CR based on operating conditions can assist in fine-tuning combustion parameters to achieve more complete and efficient fuel combustion, resulting in higher thermal efficiency and reduced fuel consumption.

***Keywords*:** Diesel engines, fuel efficiency, combustion process, variable compression ratio, emission measurement.

Nomenclature

VCR	Variable compression ratio	HCCI	Homogeneous charge compression ignition
CR	Compression ratio	RON	Research octane number
CI	Compression ignition	DI	Direct injection
A/F	Air-fuel	SFC	Specific fuel consumption
IC	Internal combustion	BTE	Brake thermal efficiency
NOx	Nitrogen oxides	BSFC	Brake-specific fuel consumption
PM	Particulate matter	WHTC	World harmonized transient cycle
CO	Carbon monoxide	ESC	European stationary cycle
HC	Hydrocarbon		

1 Introduction

Diesel engines have long been a cornerstone of transportation and industry, known for their efficiency and reliability. However, the quest for greater performance, reduced emissions, and improved fuel efficiency has prompted a closer examination of the combustion processes within these engines. One promising avenue for enhancing combustion efficiency is integrating variable compression ratio (VCR) technology [1]. VCR technology offers a dynamic approach to optimizing combustion processes in diesel engines, allowing for adjustments to be made based on operating conditions and performance requirements [2]. Engineers can achieve maximum efficiency and regulate emissions by managing the combustion process with the CR adjustment.

This review paper explores the advances, challenges, and opportunities associated with utilizing VCR technology to optimize combustion processes in diesel engines. Through a comprehensive analysis of existing research, experimental data, and computational studies, the study seeks to provide insights into the potential benefits of this technology and its implications for the future of engine design and performance. Furthermore, this study intends to contribute to the wider discussion around sustainable transport and the development of cleaner, more efficient diesel engines by exploring the complexities of combustion optimization using VCR technology.

2 Diesel engine combustion processes

Combustion in diesel engines is a complex process that relies on a combination of thermodynamic principles to efficiently convert chemical energy into mechanical work. Many studies have shown that to thoroughly understand the fundamentals of combustion in diesel engines, factors such as compression ignition (CI), air-fuel (A/F) mixture formation, combustion phasing, and heat release dynamics are critical (Figure 1) [3, 4, 5]. These concepts are discussed and their fundamentals are carefully examined.

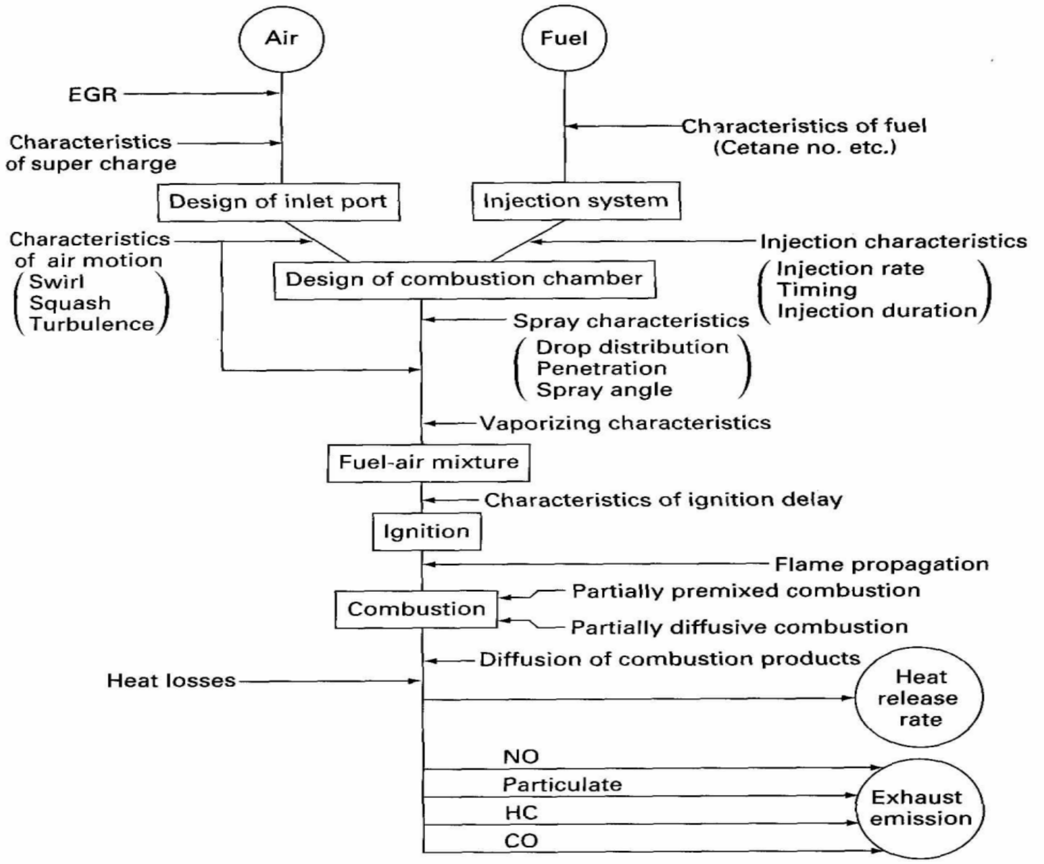

Figure 1: Important processes involved in the consumption of the liquid fuel in a typical CI diesel engine [4, 5].

2.1 Compression ignition (CI)

Unlike gasoline engines, which use spark plugs to ignite an A/F mixture, diesel engines rely on CI. This process compresses the air in the cylinder to a high temperature and pressure, leading to the spontaneous ignition of the injected fuel [6]. The engine's CR plays a critical role in achieving the high temperatures and pressures required for combustion.

2.2 Air-fuel (A/F) mixture formation

In a diesel engine, fuel is injected directly into the combustion chamber during the compression stroke. The injected fuel atomizes and mixes with the high-pressure air in the cylinder [7]. The quality of A/F mixture formation, which includes factors such as spray pattern, injection timing, and fuel atomization, influences the engine's combustion efficiency and emissions [8].

2.3 Combustion phasing

Combustion phasing is defined as the timing of fuel ignition and combustion relative to the position of the piston in the cylinder [7, 9]. Proper combustion phasing is essential for maximizing engine efficiency and minimizing emissions. It is influenced by factors such as injection timing, A/F mixture quality, and engine speed.

2.4 Heat release dynamics

The combustion process releases the chemical energy from the fuel as heat, leading to an increase in temperature and pressure within the combustion chamber. The rate and magnitude of heat release during combustion dictate engine performance parameters such as power output, torque, and thermal efficiency [10, 11].

Several studies have looked into the fundamentals of combustion in diesel engines, exploring the underlying thermodynamic principles that govern the efficiency and performance of these power plants [12, 13]. For instance, Wang et al. [14] investigated the combustion characteristics of a dual-fuel diesel engine operating with a mixture of hydrogen and methane. The research explores the thermodynamic aspects of combustion, including ignition delay, heat release rates, and combustion efficiency. Li et al. [15] analyzed the impact of injection pressure on the combustion process in a common-rail diesel engine. The study examines how variations in injection pressure influence combustion phasing, heat release profiles, and engine performance, with a focus on thermodynamic principles. A contribution by Yan et al. [16] focused on in-cylinder mixture distribution and combustion characteristics in direct-injection diesel engines. The research pinpointed the significance of A/F mixing, combustion phasing, and heat release dynamics, providing insights into the thermodynamic principles governing combustion efficiency.

A recent study was conducted by Liu et al. [17] when they presented a computational model for simulating diesel spray combustion in a pre-chamber homogeneous charge CI engine. This study incorporated thermodynamic principles to analyze combustion processes, A/F mixing, and heat release mechanisms in the engine. These studies, among others, contribute to the body of knowledge surrounding the fundamentals of combustion in diesel engines and the application of thermodynamic principles to optimize engine performance, emissions, and efficiency. Moreover, there is evidence that considering the fundamental aspects of combustion in diesel engines can greatly assist in optimizing the combustion processes to improve engine performance, fuel efficiency, and emission characteristics [18, 19]. Understanding the interplay between these factors is essential for developing advanced combustion strategies and technologies, such as VCR systems, to enhance the overall efficiency and sustainability of diesel engines.

3 Variable compression ratio (VCR) technology

VCR technology is a ground-breaking innovation in internal combustion (IC) engines that allows for CR adjustment during operation. The CR, which is the ratio of the maximum to minimum volume in the engine's combustion chamber, plays a critical role in engine efficiency, performance, and emissions [20, 21]. By enabling the CR to vary, VCR technology offers several key benefits and advancements in engine design and operation. Additionally, previous research has shown that the concept of VCR has the potential to reduce fuel consumption [20, 22]. The reduction in consumption leads to an improvement in positive mechanical work (engine efficiency) and a reduction in negative mechanical work (mechanical losses through friction). Table 1 presents some technologies for reducing fuel consumption using the VCR strategy.

Table 1: Various technologies for reducing fuel consumption using the VCR strategy [23]

Technical strategy	Technologies
Variable Compression Ratio	• Articulated cylinder head • Slide-mounted engine block. • Additional piston in the cylinder head • Multilinks rod crank mechanism • Eccentrics on bearings • Hydraulic pistons • Gear-based mechanism

3.1 Optimized combustion efficiency

One of the primary advantages of VCR technology is its ability to optimize combustion efficiency. By adjusting the CR based on operating conditions such as load, speed, and fuel quality, VCR engines can achieve more complete and efficient combustion, leading to improved fuel efficiency and reduced emissions [24, 25].

3.2 Enhanced performance

Varying the CR allows for better control over the combustion process, resulting in enhanced engine performance. Previous studies have shown that higher CRs can increase power output and torque, while lower CRs can improve engine response and reduce knocking tendencies [26, 27].

3.3 Emission reduction

VCR technology can contribute to lower emissions by facilitating cleaner and more efficient combustion. Through the process of fine-tuning the CR, VCR engines can achieve optimal air-fuel mixing, combustion phasing, and heat release characteristics, leading to reduced levels of harmful pollutants such as nitrogen oxides (NOx) and particulate matter (PM) [28].

3.4 Flexibility and adaptability

VCR technology offers flexibility and adaptability to varying operating conditions and fuel types. Engine control systems can dynamically adjust the CR in response to real-time demands, optimizing engine performance while maintaining fuel economy and emissions compliance [27, 28, 29].

3.5 Engine downsizing and turbocharging

Few studies have demonstrated that VCR technology can also complement engine downsizing and turbocharging strategies, allowing downsized engines to maintain performance levels while improving efficiency [30, 31]. Moreover, the ability to adjust the CR can compensate for the reduced displacement of downsized engines and enhance their overall performance capabilities.

Numerous previous studies have explored the benefits of VCR engines have been the subject of numerous previous studies. Sharma, Duraisamy, and Arumugum [32] conducted the experimental analysis of a diesel engine equipped with a VCR mechanism. The research evaluated the engine's performance, emissions, and combustion characteristics under different CR settings, providing insights into the benefits and challenges of implementing VCR technology in diesel engines. Zareei, Aghkhani, and Ahmadipour [33] conducted a numerical investigation of the variation of CR on a turbo-diesel engine's performance and exhaust emission.

Their findings showed that as the CR increased, carbon monoxide (CO) and hydrocarbon (HC) emissions increased and NOX emissions decreased in the turbocharged engine, but in the naturally aspirated engine, emission levels increased. Calam et al. [34] investigated experimentally the effect of the CR on the combustion process and pollutants in a homogeneous charge compression ignition (HCCI) engine. Their studies were conducted at different A/F ratios, with a fixed intake air temperature of 353 K, and by utilizing RON20 and RON40 fuel. They demonstrated that the combustion duration decreased along with the increase in CR. Additionally, they observed higher CO and HC emissions and lower NOx emissions at lower CRs. Some scholars have shown that using higher CRs can increase output power and engine efficiency, mainly due to the A/F mixture's higher heat release rate [35, 36].

In the open literature, little work is available on the study of the combustion characteristics of a VCR engine using a mixture of two biodiesel blends with diesel as fuel. Consequently, recent studies have focused on the effect of varying the CR in engines fuelled with biodiesel blends. In this regard, Hussain et al. [37] evaluated the performance and emissions by examining the variations in the CR in an SI engine fuelled by gasoline and n-butanol blends at different loads. They found that the use of alcoholic fuels like n-butanol indeed improved the engine performance at higher CRs. In addition, thermal efficiency increased with the increase in CRs at all loads. Similarly, Hosamani and Katti [38] conducted an experimental analysis of the combustion characteristics of a compression ignition (CI) and direct injection (DI) VCR engine using a mixture of two biodiesel blends with diesel. The results revealed that increasing CR increases peak cylinder pressure, heat release and the rate of pressure rise for a mixture of two biodiesels with a diesel blend. Moreover, an increase in CR improves the combustion characteristics of the engine for all fuels.

Previous studies have offered valuable insights into VCR technology and its potential to enhance the performance of diesel engines [39, 40]. As research and development in VCR technology progress, the prospects for diesel engines equipped with VCR mechanisms look promising. Future research shows that continued innovation in materials, control systems, and design features is expected to further enhance the efficiency, sustainability, and performance capabilities of diesel engines, paving the way for more advanced and environmentally friendly diesel engines [41, 42].

4 Performance and emission analysis

When optimizing the combustion process in diesel engines, a comprehensive evaluation of performance and emissions is essential. Generally, the analysis involves assessing essential parameters of engine performance, including power output, fuel efficiency, combustion stability, and emissions levels. That being said, researchers can assess the effects of VCR technology on the efficiency and environmental impact of diesel engines by analyzing performance indicators across different CR configurations and operating conditions. Through detailed performance and emission analysis, insights can be gained into the effectiveness of optimizing combustion processes using VCR technology to achieve higher efficiency and lower emissions in diesel engines.

4.1 Power output analysis

Assessment of the engine's power delivery characteristics under different CR settings is essential. This type of analysis aims to understand how variations in CR, facilitated by VCR technology, influence the engine's power output and performance. To better understand this correlation, Pathak et al. [43] experimentally analyzed the power output variation in a diesel engine with a VCR mechanism. They investigated the impact of adjusting the CR on power output characteristics in a diesel engine. They observed that higher CRs lead to increased power output. In essence, higher CRs result in more efficient combustion, generating greater pressure on the piston during the power stroke and thus producing more mechanical work.

Other researchers have been interested in the numerical simulation of power output. For instance, Kim et al. [44] used computational simulations to study the optimization of power output in a VCR diesel engine. They simulated the effects of CR adjustments on engine power and efficiency and found that increasing the CR typically leads to an increase in engine power output. These results correlate with the findings of Alahmer et al. [45]. With regards to efficiency, recent reports have suggested that adjusting the CR can have a dual impact.

Other studies have shown that higher CRs typically lead to improved thermal efficiency. The engine extracts more work from each unit of fuel, resulting in better overall efficiency. While some studies have demonstrated that excessively high CRs can lead to increased heat losses and higher pumping losses, which can reduce overall efficiency. This is evidence that the CR can either have a positive or negative impact on the power output, depending on the value of compression.

4.2 Fuel efficiency assessment

The assessment of fuel efficiency involves investigating the engine's capacity to extract energy from fuel while minimizing consumption. Several studies have demonstrated that VCR technology is essential for improving fuel efficiency by optimizing the combustion process at various CRs [46, 47, 48]. VCR technology can enhance combustion efficiency, thermal efficiency, and fuel conservation by modifying the CR according to operating conditions. Consequently, these results in improved fuel efficiency, reduced fuel expenses, and reduced environmental harm due to lowered emissions [49]. An extensive evaluation of fuel economy across different CRs provides useful insights into the effectiveness of optimizing combustion processes using VCR technology, which contributes to the advancement of more efficient and environmentally friendly diesel engines.

The CR is a critical design parameter that has the most significant impact on fuel efficiency, emissions, and engine performance. Utilizing various methods expands the engine's optimal operating conditions to meet primary criteria such as consumption, power, emission, and noise [50]. Furthermore, this extends the engine's capacity to run on diverse fuel types. There is substantial research on fuel efficiency assessment in diesel engines utilizing VCR technology for optimizing combustion processes. Previous studies investigated the impact of CR adjustments on fuel efficiency, taking into account factors such as combustion stability, thermal efficiency, and emissions levels. For example, Baranitharan, Ramesh, and Sakthivel [51] experimentally predicted the dependence between the specific fuel consumption (SFC) and the CR for optimal injection and various loads. As seen in Figure 2, they reported that at high loads, the fuel consumption first decreases and reaches the minimal value for CR near 15, in order to start growing again with further increases in CR.

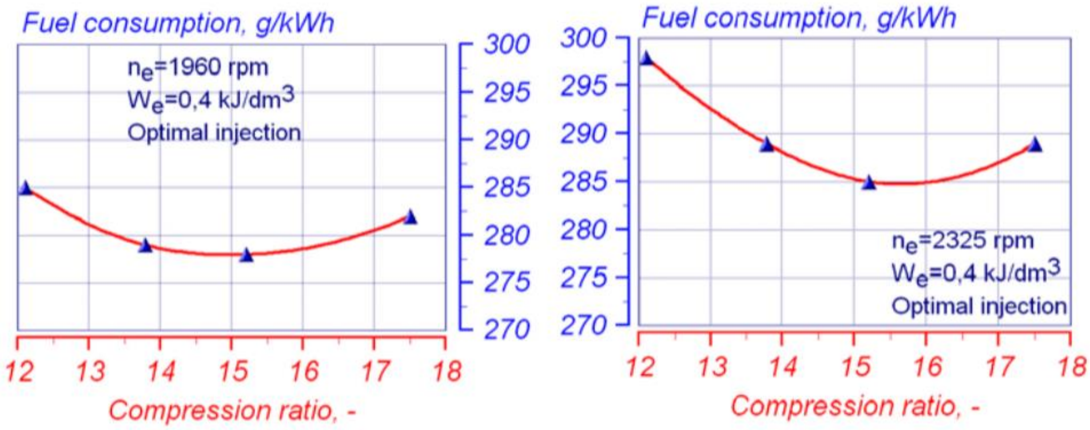

Figure 2: The influence of the CR on the fuel consumption [51].

Other studies have shown that using other diesel blends could improve fuel efficiency without relying on the CR. Vohra et al. [52] reported that their analysis of simulation results shows that brake thermal efficiency (BTE) decreases and brake specific fuel consumption (BSFC) increases with the use of palm biodiesel instead of diesel. Kassaby and Allah [53] studied the effect of CR on an engine fuelled with waste oil-produced biodiesel or diesel fuel. The results showed that biodiesel could be safely blended with diesel fuel up to 20% at any of the CRs and speeds tested, getting almost the same performance and emissions as that with diesel fuel. This is due to the physical and chemical properties of waste oil-produced biodiesel compared to pure diesel, as seen in Table 2. In general, increasing the CR improved the performance and cylinder pressure of the engine and had more benefits with biodiesel than with high pure diesel.

Table 1: Physical and chemical properties of waste oil biodiesel and pure diesel [53].

Fuel properties	Diesel	Waste oil biodiesel (B100)
Chemical formula	C8–C20	CH3(CH2)nCOOCH3
Density (kg/m3)	840	880.4
Temperature on auto-ignition n (◦C)	257	430
Stoichiometric A/F proportion (kJ/kg)	14.5	12.5
Combustibility Limits (Volume %)	0.6-5.5	1.9–6.0
Lower calorific value (kJ/kg)	42700	37500
Max deflagration speed (m/s)	0.3	0.4
Lower heating value of Stoichiometric blend (kJ/kg)	2930	4213

4.3 Combustion stability examination

In diesel engines, combustion stability examination is a critical aspect that directly impacts engine performance, efficiency, and emissions. Combustion stability refers to the engine's ability to consistently ignite and burn the A/F mixture in a controlled manner without disruptions or irregularities [54]. Achieving and maintaining stable combustion is essential for maximizing power output, improving fuel efficiency, and reducing harmful emissions. Factors that influence combustion stability in diesel engines include injection timing, A/F ratio, CR, and the design of the combustion chamber [55, 56]. When optimizing combustion processes in diesel engines using VCR technology, combustion stability examination becomes even more crucial. The ability to adjust the CR introduces an additional variable that can impact combustion characteristics. Reports have suggested that varying the CR can influence parameters such as ignition delay, combustion phasing, and flame propagation speed [55, 57]. It is essential to ensure that changes in CR do not compromise combustion stability, leading to issues like engine knock, rough idle, or incomplete combustion.

Recent reports show that researchers commonly evaluate combustion stability in diesel engines by a combination of tests, numerical simulations, and data analysis [58, 59]. Through the analysis of factors like cylinder pressure profiles, heat release rates, and combustion duration, researchers may assess the uniformity and effectiveness of combustion across various CR configurations. Other studies have recommended that advanced engine diagnostics, such as in-cylinder pressure sensors and optical combustion visualization techniques, can provide vital insights into the characteristics of combustion stability [60, 61].

4.4 Emissions measurement

Emissions measurement in diesel engines plays a vital role in assessing and controlling the environmental impact of combustion processes. Diesel engines are known for producing emissions such as NOx, PM, HC, and CO, which can have adverse effects on air quality and human health. Monitoring and quantifying these emissions are essential for regulatory compliance, emission reduction strategies, and overall environmental management.

To measure emissions in diesel engines, researchers utilize a variety of techniques and instruments. This includes exhaust gas analyzers, particulate matter sensors, smoke meters, and other analytical tools that quantify the concentration of pollutants in the exhaust gases. Soudagar et al. [62] discussed effective strategies to reduce emissions, which include; combustion management, fuel additives, and after-treatment technology. They reported that it is almost impossible to reduce all the emissions of diesel engines using only one strategy. Dhanarasu, Ramesh, and Maadeswaran [63] suggested that the best-proposed solution for the reduction of diesel engine pollutants is using biofuels, which consist of a combination of diesel, biodiesel, and ethanol.

Generally, emissions measurements are typically conducted under standardized test cycles, such as the World Harmonized Transient Cycle (WHTC) or the European Stationary Cycle (ESC), to provide consistent and comparable results across different engine setups and operating conditions [64]. Emissions measurement becomes especially significant in the context of VCR technology. Mencarelli et al. [65] reported that by adjusting the CR, it is possible to improve combustion efficiency and reduce emissions of harmful pollutants. Some researchers, such as Puškár and Kopas [66], Lyu et al. [67], and Hora and Agarwal, [68], have previously analysed emission levels under varying CRs to evaluate the effectiveness of combustion optimization strategies. Their findings indicate that increasing the CR reduces some emissions but also increases others. Therefore, it is concluded that adjusting the CR in diesel engines has both advantages and disadvantages. These studies have provided direction for future research. Consequently, lowering NOx and PM emissions while maintaining or improving engine performance is a key focus when utilizing VCR technology to enhance combustion processes in diesel engines.

4.5 Dynamic response testing

Dynamic response testing in diesel engines is essential for evaluating the engine's response to variations in operating conditions, such as fluctuations in loads, speeds, or CRs. In general, an engine's dynamic response refers to its ability to quickly and effectively adapt to fluctuations in demand while maintaining stable and efficient operation. This testing is essential for evaluating the engine's responsiveness, performance characteristics, and overall reliability in real-world driving conditions. A study by Norouzi et al. [69] suggested that shorter response times indicate faster engine reactions and better adaptability to dynamic conditions.

During dynamic response testing, VCR diesel engines undergo rapid adjustments in CRs to simulate transitory situations. Through the examination of factors like throttle response, torque delivery, and power production in dynamic scenarios, researchers can assess the engine's ability to adjust to different CRs. This testing provides insights into the engine's flexibility, responsiveness, and ability to meet sudden changes in power requirements. According to Duan et al. [70], the ability to dynamically adjust the CR allows for better optimization of combustion processes under different operating conditions. Assessing the engine's dynamic response to CR changes makes it uncomplicated to fine-tune combustion characteristics, enhance efficiency, and improve overall engine performance in real-time.

4.6 Heat release analysis

One of the fundamental aspects of understanding combustion processes and optimizing engine performance in diesel engines is performing heat release analysis. Typically, the heat release profile represents the rate at which heat is released during the combustion process within the engine cylinder [71]. In diesel engines, heat release analysis is crucial for evaluating the combustion characteristics under different CRs or operating conditions. By studying parameters such as ignition delay, combustion duration, and peak heat release rate, researchers can determine the combustion efficiency and stability of the engine. This analysis provides valuable information on the combustion process's energy conversion efficiency and its impact on overall engine performance. One of the key benefits of conducting heat release analysis in diesel engines is the ability to optimize combustion processes for improved efficiency and reduced emissions [72, 73].

Several studies have shown that analyzing this profile can immensely assist in gaining insights into the timing, intensity, and efficiency of combustion, allowing for precise control and optimization of the combustion process. For instance, Renish et al. [74] reported that adjusting the CR in VCR diesel engines optimizes the heat release profile, leading to more efficient and complete combustion. However, the challenge is finding the precise CR that fully optimizes engine combustion. Thus, researchers are tasked with conducting further investigations that involve the accurate values of CR. Other researchers, such as Bhowmik et al. [75], Chen, He, and Zhong [76], and Krishnamoorthi et al. [77] have demonstrated how changes in CR affect the timing and duration of heat release during the combustion process. Subsequently, future studies are directed towards fine-tuning parameters such as fuel injection timing, air-fuel mixing, and CR to achieve more complete combustion, leading to increased thermal efficiency and lower pollutant emissions. However, this is only possible through a thorough understanding of heat release dynamics and its algorithms.

5 Concluding remarks

Through combining the existing research results on the optimization of combustion processes, it was found that closer examination of combustion processes within these engines has become an important consideration for greater performance, reduced emissions, and improved fuel efficiency. The research findings in this review paper highlight the considerable potential of VCR technology in optimizing combustion processes in diesel engines. Moreover, they demonstrate that engineers can optimize combustion characteristics, enhance engine performance, and maximize fuel efficiency by utilizing the capability to dynamically modify the CR.

The findings highlight the efficiency of VCR technology in achieving enhanced and consistent combustion, resulting in increased power output, torque delivery, and overall engine effectiveness. Furthermore, heat release analysis, emissions monitoring, and dynamic response testing reveal the diverse advantages of deploying VCR technology for optimizing diesel engines. Although previous research has offered theoretical insights into the advantages and possible enhancements of combustion optimization using VCR technology, there appears to be a lack of practical demonstrations and validation of these principles in real-world diesel engines. Conducting thorough experimental validation and field testing to evaluate the real-world performance, efficiency improvements, and emissions reduction achieved through VCR technology could offer valuable insights and enhance the general comprehension of the technology's impact on engine optimization. With that being said, the insights provided in this review paper offer a clear direction for the development of cleaner and more efficient diesel engines in the automobile sector.

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