Tuijin Jishu/Journal of Propulsion Technology
ISSN: 1001-4055
Vol. 45 No. 2 (2024)

Performance, Design and Operational Parameters of Variable Compression Ratio Diesel Engine

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Abstract

The development and implementation of Variable Compression Ratio technology in diesel engines has garnered significant attention due to its potential to revolutionize engine performance and efficiency. Understanding how the design of Variable Compression Ratio diesel engines influences performance parameters, such as brake thermal efficiency, brake specific fuel consumption, brake power, and exhaust gas temperature, could prove vital for engineers and designers, as it directly contributes to optimizing performance. Several studies have reported the key design considerations and engineering challenges associated with Variable Compression Ratio diesel engines, along with their impact on overall performance and durability. However, this work critically discusses design factors, parameters, and governing equations and evaluates how they influence the operational parameters. Through a systematic review of existing literature and technical insights, this work aims to clarify the potential and limitations of Variable Compression Ratio technology in diesel engines, offering valuable guidance for future research and development in this crucial field of automotive engineering.

Keywords: Variable Compression Ratio, diesel engines, brake thermal efficiency, brake specific fuel consumption, brake power, exhaust gas temperature.

Nomenclature

VCR	Variable compression ratio	BL80	80% RM + 20% diesel
BTE	Brake thermal efficiency	CO	Carbon monoxide
BSFC	Brake specific fuel consumption	HC	Hydrocarbon
BP	Brake power	NOx	Nitrogen oxides
EGT	Exhaust gas temperature	CO_2	Carbon dioxide
CR	Compression ratio	MEP	Mean effective pressure
IC	Internal combustion	EGR	Exhaust gas recirculation
VVT	Variable valve timing	ECU	Electronic control units
RA	Rapeseed biodiesel	MOME	Mahua oil methyl ester
MU	Mahua biodiesel	BMEP	Brake mean effective pressure
RM	Dual biodiesel	HCCI	Homogeneous charge compression ignition
BL20	20% RM + 80% diesel	SCR	Selective catalytic reduction
BL40	40% RM + 60% diesel	DPF	Particularly diesel particulate filters
BL60	60% RM + 40% diesel	IP	Indicated power
PG	Producer gas	ITE	Indicated thermal efficiency
F/A	Fuel air ratio	A/F	Air fuel ratio

1 Introduction

Today, diesel engines are widely used in various vehicles such as trucks, buses, trains, ships, power generators, and heavy machinery, playing a significant role in global transportation and industries. The rising cost of fuel and stricter emission laws have created a significant need for the development of new engines that offer both high fuel efficiency and low emissions. Consequently, in the past few decades, diesel engines have been equipped with a VCR system, enabling them to operate at different CRs based on the specific requirements of the vehicle's performance. This is accomplished by adjusting the combustion chamber volume to meet the needs of the most suitable operating conditions [1, 2]. The VCR diesel engine is an innovative type of IC engine that is designed to vary the engine's CR of the engine, resulting in improved fuel efficiency and reduced emissions [3]. By adjusting the CR based on driving conditions, the VCR diesel engine aims to optimize performance while meeting increasingly stringent environmental regulations. This technology represents a significant advancement in the quest for cleaner and more efficient diesel engines.

In the realm of combustion engines, the VCR diesel engine stands out as a marvel of modern engineering. For many, the performance of such an engine is undoubtedly a primary concern, as it provides the possibility of improved power delivery, torque characteristics, and overall driving experience [4]. Simultaneously, it is critical to devote special consideration to the design and operational characteristics to ensure that the engine functions smoothly under various conditions and complies with strict regulatory criteria. Successfully creating and improving a diesel engine with VCR requires a thorough comprehension of its design principles, operational complexities, and performance measurements. By examining this complicated interaction of elements, a significant understanding of the future of automobile propulsion and the utilization of renewable energy can be acquired.

2 Design concept

The design of a VCR diesel engine is crucial to optimizing its performance. Usually, this is accomplished by utilising inventive piston and crankshaft configurations, which allow for adjustments to the piston's location at the top of its stroke [5]. Through the integration of these systems, the engine can adaptively optimise its CR according to the prevailing operating conditions, maximising both performance and efficiency. Moreover, the design incorporates advanced electronic control systems that dynamically regulate the CR adjustments, frequently under variables such as engine load, velocity, and fuel quality [6, 7]. The integration of mechanical and electronic systems is essential for guaranteeing the accurate and dependable functioning of the VCR diesel engine. The primary focus of the structural design should be on ensuring long-lasting strength and optimal heat insulation to handle the different pressures caused by the dynamic CR modifications [8]. Within the domain of VCR diesel engine design, achieving the maximum capabilities of this innovative technology requires careful equilibrium between mechanical robustness, advanced electronics, and efficient thermal management.

2.1 Effect of VVT and VCR strategy on the combustion process

VCR and variable valve timing (VVT) are two effective methods for adjusting the effective CR, and these tactics are excellent for managing the combustion process in advanced combustion modes [9]. Like any new technology, there may be challenges or adjustments to be made in the implementation and fine-tuning of VCR diesel engines. Consequently, recent reports have shown that VCR diesel engines are sometimes unable to perform as anticipated. For instance, Zang et al. [10] indicated that CRs lower than 19.0 result in a drop in BTE and a rise in fuel consumption. Sharma [11] conducted a simulation for three CRs of 16, 17, and 18 at a constant speed of 1500 rpm. The simulation results showed that thermal efficiency increases and BSFC decreases with the increase in CR. In contrast, Tamilselvan and Periyasamy [12] conducted a study that demonstrated that at a CR of 18, the B20 biofuel blend improves the BTE performance. Similarly, Saravanan et al. [13] compared conventional diesel with different biodiesels, namely Rapeseed biodiesel (RA), Mahua biodiesel (MU), Dual biodiesel (RM), and its different blends with diesel (BL20, BL40, BL60, and BL80). Among all tested biodiesel blends, the BL20 showed a BSFC that is 8.18% higher than conventional diesel. Moreover, for all tested biodiesels and blends, the CO and HC emissions were observed to be lower than conventional diesel. Other scholars have demonstrated that NOx and CO_2 emissions increase at higher CR due to the higher pressure and temperature [14, 15, 16]. This serves as evidence that while the VCR system is a milestone achievement within the IC engine community, it does have its challenges and limitations.

2.2 Low-Friction Technology

Friction losses in engines refer to the transformation of energy into heat as a result of the internal friction occurring within the engine's components, including the pistons, cylinders, and bearings [17]. It is essential to minimize these losses to enhance the overall efficiency of the engine. Currently, there are many methods for reducing the friction losses of the main components of an IC piston engine. Common techniques include employing quality lubricants, optimizing the design of engine parts, and incorporating advanced materials such as low-friction coatings and high-strength metals [18]. Furthermore, the implementation of technologies such as variable valve timing and cylinder deactivation can effectively minimize friction losses in engines. Several researchers have been interested in understanding the components that largely contribute to the friction losses in IC engines.

Figure 1 depicts a comprehensive analysis of mechanical friction loss for IC engines [19]. It reveals that the piston and ring assembly contribute significantly to the overall friction losses, whereas the friction ratio resulting from the valve train and crank bearings is approximately 20%. Tribological technology facilitates the examination of different lubrication and friction phenomena in moving parts. It accomplishes this by enhancing the structural design, material composition, and surface conditions [20, 21]. The goal is to achieve a decrease in the friction coefficient and enhance resistance to seizure in both fluid lubrication and boundary lubrication scenarios. As a result, future research should focus on assessing the friction reduction performance of each solution on components such as low-friction pistons, low-friction engine bearings, valves, and lubricating fluid design of lubricating fluids. In this way, optimization of IC engines focusing on friction losses will be an uncomplicated and viable alternative.

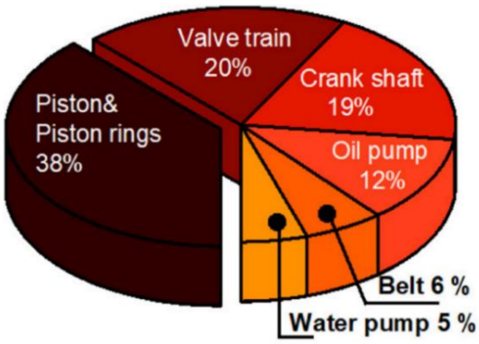

Figure 1: Breakdown of mechanical friction loss [19]

Modelling the mechanical losses that occur in the engine is a useful task as the first step to reducing friction losses, as it helps quantify the friction and understand the different contributions of each rubbing pair in IC engines. Tormos et al. [22] proposed a 1D model to predict the friction losses in engines. Abril, Rojas, and Flórez [23] used the Mobility Approach to calculate the friction losses produced in the journal bearing. The authors estimated the load in engine bearings utilizing the Dubois and Ocvirk short bearing approximation, which provides a good approximation to the full solution and used the Reynolds equation to predict the friction losses in the piston assembly. To provide designers with tools for the effective estimation of friction losses from the earliest stages of design, Delprete, Gastaldi, and Giorio [24] presented a code for the estimation of friction losses in the piston assembly that uses semi-analytical models requiring only strictly necessary geometric and functional inputs for the representation of components. This feature renders the code particularly suitable for the preliminary design phase.

Other scholars have been interested in developing innovations that can potentially be applied to reduce friction losses, thus increasing the efficiency of IC engines. Ahmed Ali et al. [25] conducted an analytical investigation on the dynamics of piston rings concerning the tribological characteristics of piston and ring assemblies, as well as the performance of engine combustion. The interaction between the roughness-induced friction at the boundary and the friction caused by the movement of fluid was altered due to the dynamics of the piston ring, resulting in an overall loss of power due to friction [25, 26]. Therefore, it is necessary to optimize the flow of lubricant to enhance the thermal efficiency of the engine. In contrast, several studies have focused on the influence of selected anti-wear coatings on the friction coefficients when using various lubricants, measured via tribometers [26, 27, 28].

A more recent study was conducted by Wróblewski and Rogólski [29], where they experimentally analysed the influence of the application of TiN, TiAlN, CrN, and DLC1 coatings on the friction losses of IC engines. Their results, shown in Figure 2, indicate that DLC1 coatings, in comparison to other anti-wear coatings, have the best ability to reduce friction losses of the sealing rings above 2000 rpm. This results in a significant reduction in the engine resistance torque in the most commonly used crankshaft rotational speed range of 3200 to 3600 rpm. Other researchers, such as Jia et al. [30], have proposed a model to mitigate friction losses based on the Stricbeck diagram. More focused studies are found in [31, 32, 33], in which the authors propose a model for the piston ring assembly that includes different effects such as bore distortion, cavitation, and surface texture.

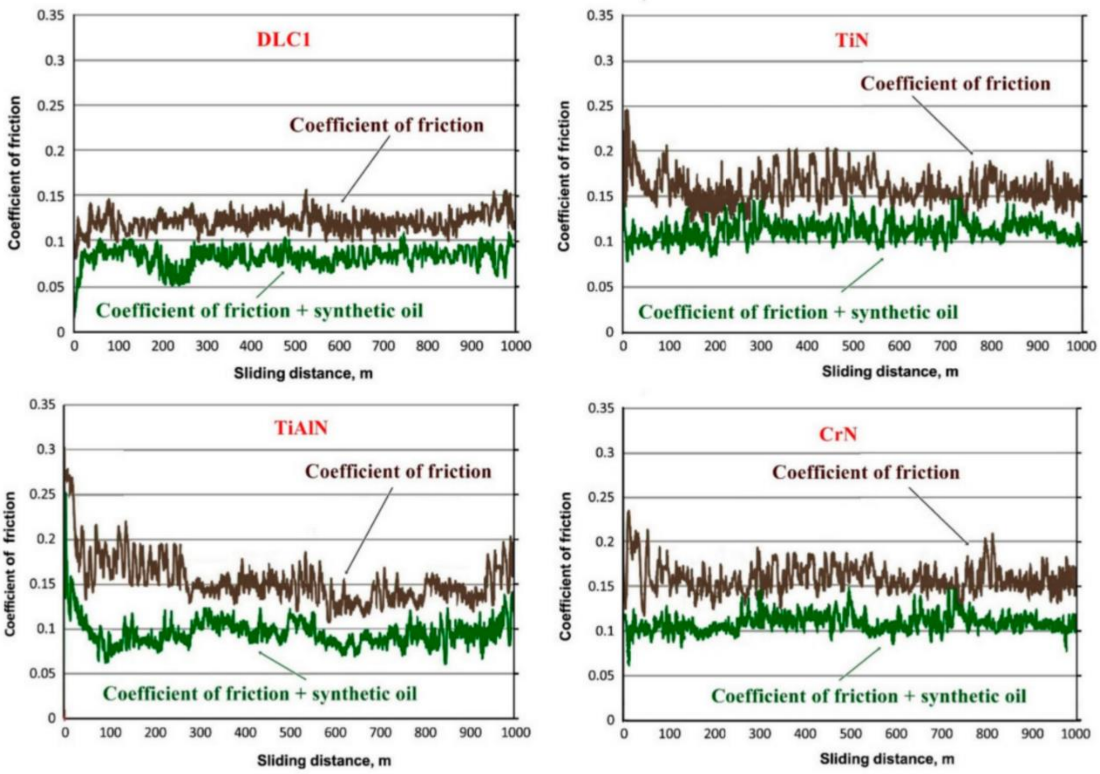

Figure 2: Coefficients of friction and wear recorded in dry friction conditions for various coatings [29].

2.3 Governing equations

The governing equations play a pivotal role in the design of diesel engines, providing engineers with the tools to comprehend the complex interactions within the engine. These equations enable accurate predictions of performance characteristics such as power output, fuel efficiency, and emissions, allowing for the optimization of design parameters such as fuel injection timing, combustion chamber geometry, and turbocharging [34, 35]. Furthermore, these equations are crucial for mitigating environmental impacts by aiding in the control of emissions. They also drive advancements in efficiency, helping to minimize heat losses and enhance combustion processes. Ultimately, the governing equations serve as the cornerstone for informed decision-making, enabling the creation of diesel engines that are both powerful and efficient while meeting stringent regulatory standards [36].

Engine efficiency is typically defined by the ratio of the useful work output to the energy input [37]. In the context of diesel engines, efficiency is commonly expressed as the ratio of the mechanical work produced by the engine to the energy content of the fuel consumed and is given by:

$$\eta f = \frac{W_C}{m_f Q_{HV}} = \frac{\left({}^{Pn_R}/_N\right)}{\left({}^{m_f n_R}/_N\right) Q_{HV}} = \frac{P}{m_f Q_{HV}} \quad (1)$$

The IPE (η_{ith}) of a diesel engine is a measure of how effectively it converts the energy in fuel into mechanical work. It is typically expressed as a percentage using the ratio of IP to the input fuel power as shown in equation (2). It can vary depending on factors such as engine design, operating conditions, and maintenance.

$$\eta_{ith} = \frac{IP}{m_f \times CV} \quad (2)$$

BTE is the ratio of the BP obtained from the engine to the fuel energy supplied to the engine, and given by the following basic equation:

$$BTE = \frac{P(kW)}{CV\left({}^{kJ}/_{kg}\right) \times \dot{m}\left({}^{kg}/_{s}\right)} \quad (3)$$

Mechanical efficiency (n_m) is defined as the ratio of BP or delivered power to the IP or power provided to the piston and it can also be defined as the ratio of BTE to the ITE (n_{ith}).

$$\eta_m = \frac{BP}{IP} \quad (4)$$

Relative efficiency or efficiency ratio (η_{rel}) is the ratio of the thermal efficiency of an actual cycle to that of the ideal cycle, the efficiency ratio is a very useful criterion that indicates the degree of development of the engine [36, 37]. The actual thermal efficiency takes into account factors such as heat losses, friction, and incomplete combustion, while the ideal thermal efficiency assumes perfect and complete combustion under ideal conditions. By comparing these two efficiencies, it's possible to assess how effectively an engine is converting fuel into useful work.

$$\eta_{rel} = \frac{Actual\ thermal\ efficiency}{ideal\ thermal\ efficiency} \quad (5)$$

One of the very important parameters which decide the performance of four-stroke IC engines is volumetric efficiency (η_v), where four-stroke engines have a distinct suction stroke and therefore the volumetric efficiency indicates the breathing ability of the engine. The volumetric efficiency is the volume flow rate of air into the intake system divided by the rate at which the volume is displaced by the system [37]. Generally, the volumetric efficiency for modern VCR diesel engines can range from around 85% to 95%. However, it is important to note that these figures are approximate and can vary based on factors such as turbocharging, valve timing, and intake/exhaust system design.

$$\eta_v = \frac{\dot{m}_a}{\rho_a V_{disp} {}^N/_2} \quad (6)$$

MEP and is a key performance indicator for diesel engines. It represents the average pressure in the engine cylinder during the power stroke. MEP is a critical parameter because it directly correlates to the engine's IP output. Additionally, it is a measure of pressure that is not influenced by the engine's size [37, 38]. This facilitates the comparison of various engine designs and provides an initial estimation of the engine size necessary for a particular task, as the usual brake BMEP values are widely recognised for different engine types [38].

$$MEP = \frac{P n_R}{V_d N} \tag{7}$$

However, MEP can further be defined in terms of torque as:

$$MEP = \frac{2\pi n_R T}{V_d} \tag{8}$$

BSFC is a measure of the fuel efficiency of an engine. It is defined as the amount of fuel consumed (in mass or volume) per unit of power produced. BSFC can vary based on engine design, load, and operating conditions. It is an important factor to consider when evaluating the overall efficiency and performance of an engine.

$$BSFC = \frac{m\left({}^{kg}/_{hr}\right)}{BP(kW)} \tag{9}$$

In engine testing, both the air mass flow rate ($\dot{m}_a$) and the fuel mass flow rate($\dot{m}_f$) are normally measured. The ratio of these flow rates is useful in defining engine operating conditions which are air/fuel ratio (A/F) and fuel/air ratio (F/A). Consequently, the following relationships between diesel engine performance parameters can be developed.

For power P:

$$P = \frac{\eta_f \dot{m}_a N Q_{HV} \left({}^{F}/_{A}\right)}{n_R} \tag{10}$$

$$P = \frac{\eta_f \eta_v N V_d Q_{HV} \rho_{a,i} \left({}^{F}/_{A}\right)}{2} \tag{11}$$

For Torque

$$T = \frac{\eta_f \eta_v V_d Q_{HV} \rho_{a,i} \left({}^{F}/_{A}\right)}{4\pi} \tag{12}$$

For mean effective pressure:

$$MEP = \eta_f \eta_v Q_{HV} \rho_{a,i} \left({}^{F}/_{A}\right) \tag{13}$$

The specific power or the power per unit piston area shown in Equation (7) is a measure of the engine designer's success in using the available piston area regardless of cylinder size.

$$\frac{P}{A_p} = \frac{\eta_f \eta_v N L Q_{HV} \rho_{a,i} \left({}^{F}/_{A}\right)}{2} \tag{14}$$

Mean piston speed:

$$\frac{P}{A_p} = \frac{\eta_f \eta_v N S_p Q_{HV} \rho_{a,i} \left({}^{F}/_{A}\right)}{4} \tag{15}$$

The specific power is thus proportional to the product of MEP and mean piston speed. These relationships illustrate the direct importance to engine performance of high fuel conversion efficiency, high volumetric efficiency, increasing the output of a given displacement engine by increasing the inlet air density, maximum fuel/air ratio that can be useful burned in the engine and high mean piston speed [39]. Comparing the CO_2 concentrations in the engine exhaust (CO_2 exh) and intake (CO_2 EGR) is a practical way to determine the EGR rate (Equation 8). It is an effective strategy to control NOx emissions from the diesel engine.

$$EGR = \frac{CO_{2-EGR} - CO_{2-atm}}{CO_{2-exh} - CO_{2-atm}} \tag{16}$$

The governing equations in diesel engine design are essential tools for comprehending the physics and behaviour of the engine. Nevertheless, there are still some constraints and difficulties that remain to these equations. One of the main challenges is adequately simulating the complex processes of ignition and combustion, which play a vital role in engine performance and emissions. The modelling of turbulence presents an additional complexity obstacle, as the ability to forecast and measure the turbulent properties inside the engine cylinder remains a subject of ongoing research. Moreover, modelling heat transfer and friction also presents considerable challenges, as accurately predicting these losses is crucial for optimising engine performance. The fundamental simplifications in traditional governing equations typically face difficulties in accurately representing the three-dimensional, unstable, and turbulent characteristics of flows within the diesel engine. To overcome these deficiencies and obstacles, more studies should be carried out focusing on continuous advancement and enhancement in modelling approaches. These studies are necessary to improve the precision of diesel engine design and simulation.

3 Performance parameters

Currently, there is a significant increase in the utilisation of fossil fuels, resulting in a subsequent rise in air pollution emissions. Due to all these environmental issues, there is a need for some innovative, cleaner, and environmentally feasible fuels. Considering all these factors, it is necessary to find an alternative solution to address this deficiency. Parameters such as BP, IP, BSFC, BTE, ITE, and mechanical efficiency are all used to measure the performance of any IC engine [40, 41]. One crucial factor in this optimization is the management of the combustion process, including fuel injection timing, pressure, and air-fuel ratio. Typically, turbocharging or supercharging can be employed to increase air density and improve combustion efficiency [42]. Moreover, technological advances in engine control systems, such as electronic control units (ECUs), have a substantial impact on optimising performance characteristics. These technologies continuously monitor and regulate many engine functions in real-time, guaranteeing optimal performance in various driving situations. Enhancing the mechanical components of the engine, such as the design of the pistons, the dynamics of the crankshaft, and the layouts of the intake and exhaust systems, could prove to be a milestone in the engine's performance and efficiency.

3.1 Brake Thermal Efficiency

BTE is a measure of how effectively an engine converts the energy available in fuel into useful work output. It is expressed as a percentage and represents the ratio of the engine's BP output to the fuel's input energy from the fuel. This efficiency is an important factor in evaluating the overall performance and fuel consumption of an engine. Previous work has demonstrated that incorporating exhaust gas recirculation (EGR) into a diesel pilot-ignited natural gas engine can enhance both BTE and emissions [43, 44, 45]. Furthermore, other researchers have demonstrated that intake throttling can also increase BTE while reducing THC and CO emissions [43, 46, 47]. High BTE generally means that the engine is operating more effectively and wasting less energy as heat. Consequently, a strong desire to improve engine thermal efficiency and reduce energy waste has motivated the advancement of dependable methodologies and modelling techniques to comprehensively understand the fundamental mechanics involved. As a result, Wang et al. [48] conducted a literature review of energy loss reduction technologies for IC engines to improve BTE. In their paper, they investigated the relative advantages of technologies mainly focused on minimizing energy loss in engine assemblies, including pistons and rings, bearings and valves, water and oil pumps, and cooling systems. Güler and Ozkan [49] experimentally studied the effects of timing and quantity parameters of multiple pilot injection strategies on the BTE, total exhaust energy, in-cylinder heat transfer, and friction with the help of a well-calibrated engine model. In their results (Figure 3), they discovered that increasing the pilot injection quantity and advancing slightly reduced the BTE.

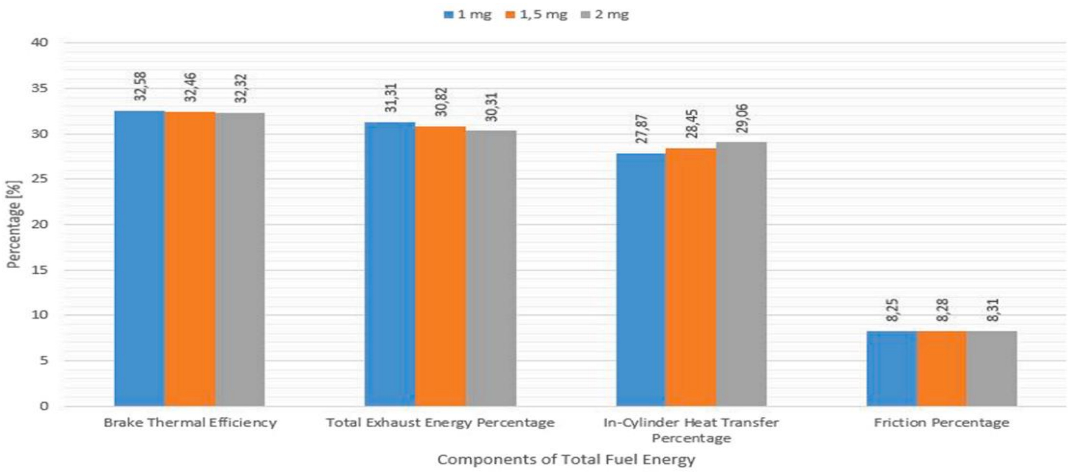

Figure 3: Variation of total fuel energy distribution depending on 1st pilot injection quantity [49].

On the other hand, Uchida and Watanabe [50] conducted a study to investigate the new combustion control concept for further improvement in BTE using multiple injectors combined with the soup-plate type piston cavity. The concept was initially intended to confirm the optimum heat release rate profile through both the zero-dimensional thermodynamic model and the single-cylinder engine experiments. However, it has also been established that there is much more potential for BTE improvement through the new temporal and spatial combustion control system utilizing this system. Yu et al., 2021 [51] studied the approach to achieving improved BTE for a heavy-duty diesel engine by experiment analysis. They showed that an engine designed based on a two-stage turbocharger system has the potential to maximize the BTE.

A contribution towards improving the BTE and reducing emissions was made by You et al., 2021 [52]. They conducted a detailed study on EGR coupled with intake throttling on a 6-cylinder turbocharged intercooler diesel/natural gas dual fuel heavy-duty engine at low load operations. Their results (Figure 4, right) suggest that EGR with intake throttling (throttling opening degree = 30.11%) will continue to increase BTE and reduce THC, NOx, and CO emissions as the EGR rate increases. Similarly, Figure 4 (left) shows the effect of EGR without intake throttling on BTE. As the EGR rate rises, the BTE increases. When the EGR rate changes from zero to maximum, BTE increases from 17.31% to 26.29%.

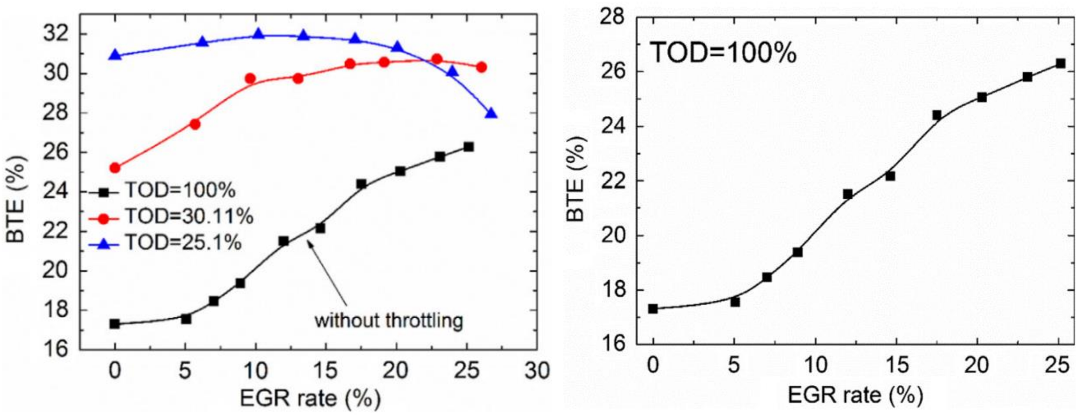

Figure 4: The effect of EGR with throttling (right) and without intake throttling (left) on BTE [52].

Research has shown that BTE is increased in blend B10 compared to B20, and a higher CR gives better BTE because, while compressing more, it has more power to burn the fuel, thus producing higher BTE than lower [53, 54, 55]. Increasing the load in a higher blend of B20 produces better BTE because of the proper air-fuel mixture in the combustion chamber. BTE tends to be lower in higher blends of B20 because of the increase in aromatic compounds that require more energy to break. A few other scholars have demonstrated that the CR of any diesel engine influences the effect of BTE. For example, Vijayakumar et al. [56] carried out a comprehensive analysis of the variation between BTE and BP for MOME proportions at different CRs of 17, 17.5, and 18. They demonstrated in Figure 5 that the increase in BTE is inferred from the increase in CR.

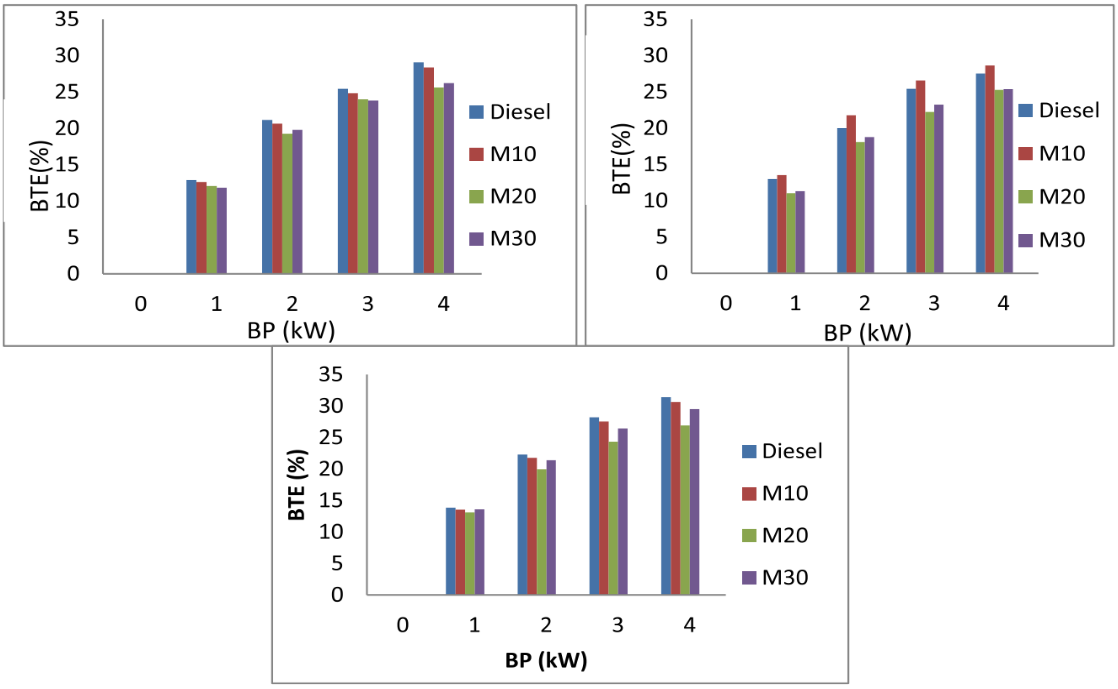

Figure 5: BP Vs BTE at CR 17, 17.5, and 18. [56]

Nabi, Rasul, and Gudimetla [57] developed a model for parametric characterisation using GT-Power software. They reported that the optimum BTE, BT and BMEP were found at an engine speed of 1700 rpm and a CR of 20. All of these studies demonstrate that improving BTE is an ongoing area of research and development in the field of engine and power generation technologies. However, there is a notable gap in the development of advanced combustion techniques. For instance, more studies should focus on developing new combustion methods, such as homogeneous charge compression ignition (HCCI) and stratified charge combustion, to improve fuel efficiency. Additionally, implementing improved engine cooling and waste heat recovery systems to better utilize thermal energy and reduce energy loss could prove to be a milestone achievement.

3.2 Brake Specific Fuel Consumption

BSFC is a measure of an engine's fuel efficiency in terms of burning fuel and producing mechanical power [38]. It is typically expressed in terms of fuel consumption per unit of power produced. BSFC is an important parameter in the evaluation of engine performance and efficiency, particularly in the automotive and aerospace industries. It helps engineers and designers understand how effectively an engine converts fuel into useful work, and it can be useful when comparing different engines or making decisions about improvements and optimizations.

Since BSFC is a vital parameter that reflects the efficiency of a combustion engine, it is significant to continuously evaluate innovations that can be implemented to improve it. Thus, this will result in improving the efficiency of an engine. The BSFC of a VCR diesel engine is influenced by several parameters, including the load, CR, injection pressure, and fuel quality [57]. Research has shown that as the amount of biodiesel in the fuel is increased, the fuel consumption also increases. This is because B80, which has poor atomization, is responsible for this effect under all situations [58, 59]. Some scholars have suggested that this challenge can be resolved by increasing the CR, maximising the load at full capacity, and elevating the injection pressure. However, the reduced ignition delay of biodiesel leads to an elevation in in-cylinder temperature during high CR and full-load operation [60]. Patel et al. [61], evaluated the predicted values for the corrected BP and corrected BSFC of single cylinder VCR diesel engine operated on diesel and jatropha biodiesel blend (0%, 25%, 50%, 75%, 100%) derived from jatropha curcas oil. Their results shown in Figure 6, suggested that 100% blend and 10 kg of engine load are the optimum parameters for maximum BP, while the optimized set of parameters for BSFC is 0% blend and 10 kg engine load. These results demonstrate that significant improvements in performance characteristics (BSFC and BTE) are obtained with the help of supercharging.

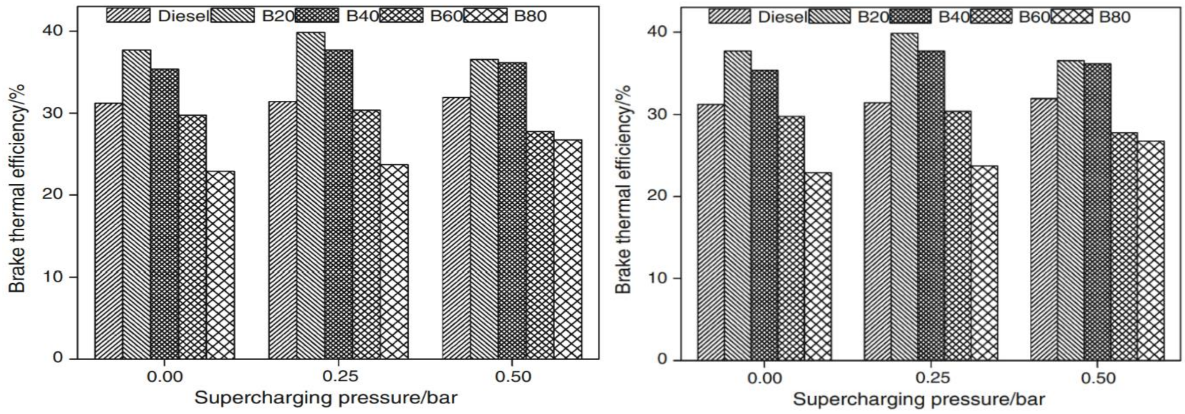

Figure 6: Variations in BSFC and BTE with supercharging for different blends at CR 20 [61].

Mohamed et al. [62] demonstrated that the BSFC increases with increase in blend B20 and slightly decreased while increasing the CR to 17. This is because of higher blends have higher oxygen content. While in higher percentage of blend in diesel the oxygen content tends to burn the fuel completely to produce better BSFC. By increasing the load BSFC tends to lower slightly in higher levels. Thence, for better BSFC the engine has to be run with low CR, load with higher in blend percent of diesel. Similarity, Koli and Rao [63] experimentally proved that BSFC and required cost to operate the engine, in case of duel fuel mode operation will be less for the CR of 17. Vijayakumar et al. [56] demonstrated the effect of different CRs on BSFC as a function of BP with the comparison of diesel and mahua biodiesel blends with blend ratios of (M10, M20 and M30). Their results shown in Figure 7, strongly suggest that the decrease of BSFC is inferred with CR increase, which validates the results of [62] and [63]. Other studies have shown that with duel fuel mode and decreased CR the brake power (BP) increases with approximately 6% with an increase in BTE. All these contributions are evidence that in future, as the cost of diesel rises, the use of duel fuel mode will become a viable option as an alternate fuel for diesel engines to generate power.

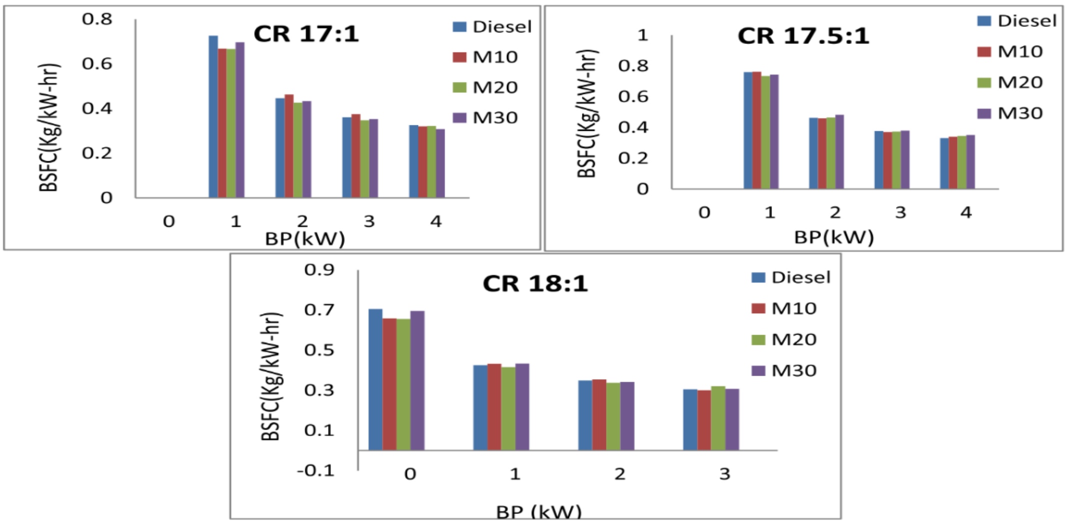

Figure 7: BSFC Vs BP at CRs of 17, 17.5, and 18. [56]

A more recent study was conducted by Sri, Murthy, and Rao [64]. Their results were obtained by using the Python module, and the best-suited code was derived. It was found that the combined increase of CR and injecting timing increases the BTE and reduces the BSFC. This module helps reduce load variations and performances compared to the experimental. Diesel (25%) will greatly meet the demand for fuel in automobiles. Taneja and Singh [65] reported that BSFC is at a minimum of 0.21 Kg/kWh at 7 kg and CR16 through a mathematical model. Similarly, Kadam et al. [66] demonstrated that BSFC is minimal for CR 16 and load 7 kg and maximum for CR 14 and load 1 kg. As per the graphical results in Figure 8, it is observed that as load increases, BSFC decreases, and as CR decreases, BSFC increases. This further validates the results obtained by [64] and [65].

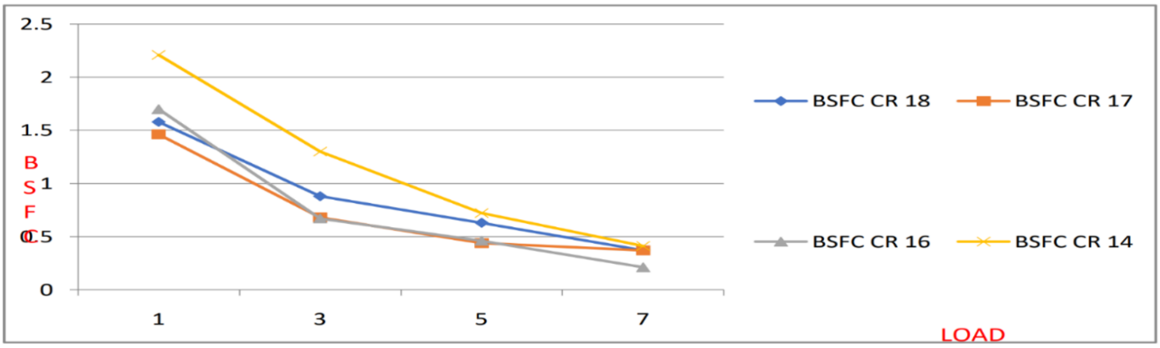

Figure 8: Relationship of BSFC and the load [66].

Typically, the average efficiency of IC engines operating under optimum conditions is approximately 30% in automobile applications and roughly 45% for watercraft [67, 68]. Hence, there exist numerous prospects for enhancing fuel efficiency and optimising IC engines. The implementation of optimisation technologies on the engine and gearbox, the introduction of the start-stop system, the reduction of vehicle resistance to movement, and the application of variable drive for peripheral equipment on the engine and vehicle have the greatest impact on reducing fuel consumption [67, 69]. Figure 9 illustrates a detailed analysis of the equipment that has a role in reducing fuel consumption. These components are crucial as they enable designers to comprehend the essential elements for optimising and achieving higher BSFC.

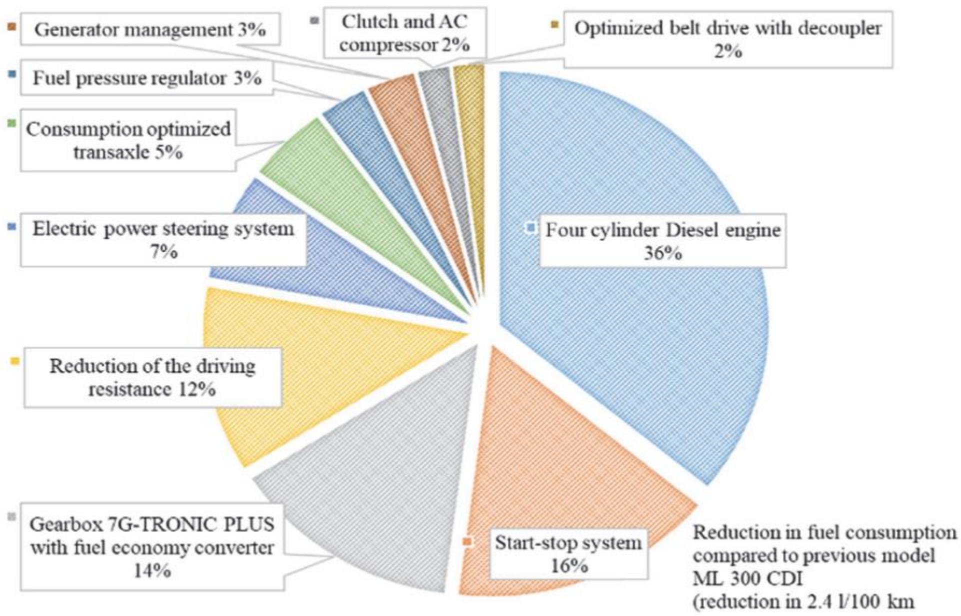

Figure 9: Share of equipment in fuel consumption reduction of optimized vehicle Mercedes-Benz ML 250 BlueTEC [MILOJEVIĆ, SAVIĆ et al., [70].

3.3 Brake power

BP in IC engines denotes the maximum power output that the engine can transmit to the crankshaft [71]. The measurement of this power is conducted using a dynamometer and represents the practical power generated by the engine, usually expressed in kilowatts (kW). It serves as a crucial measure of the engine's performance and efficiency. Various elements, including the CR, fuel injection system, turbocharging, and general engine architecture, might influence the BP output [72]. Several innovations, such as tuning the fuel injection system, enhancing air intake, and adjusting CR, have been developed to optimize the BP. However, there are still gaps in the optimization methods. Notably, few studies have focused on investigating how the optimal piston and cylinder head design, as well as reducing internal friction, can contribute to better power output. In addition, relatively few reports have focused on optimizing the exhaust system in such a way that back pressure is reduced.

BP is a vital parameter within the IC engine as it can be used to predict other brake performance parameters such as BTE, BMEP, and BSFC [72, 73]. Recent reports have suggested that poor atomization, vaporisation, and mixing of the fuel droplet with air during combustion performance due to the low engine loading range cause BP reduction [74]. In addition, the low load range operation causes poor combustion performance, which results in a lower value of BP [72, 74]. Similarly, Hasan et al. [75] demonstrated in Figure 10 that BP is increased by increasing engine load when using methanol/diesel blends. However, less engine power was achieved compared to pure diesel fuel. This is attributed to a decrease in the cylinder pressure peak found in the cylinder. The maximum engine BP was achieved when using pure diesel at a higher load condition. Moreover, Emaish et al. [76] reported that increasing the engine load results in decreased engine speed and increased BP, which validated the results of [72, 74, 75]. These reports are evidence that engine loads significantly impact the BP of the diesel engine.

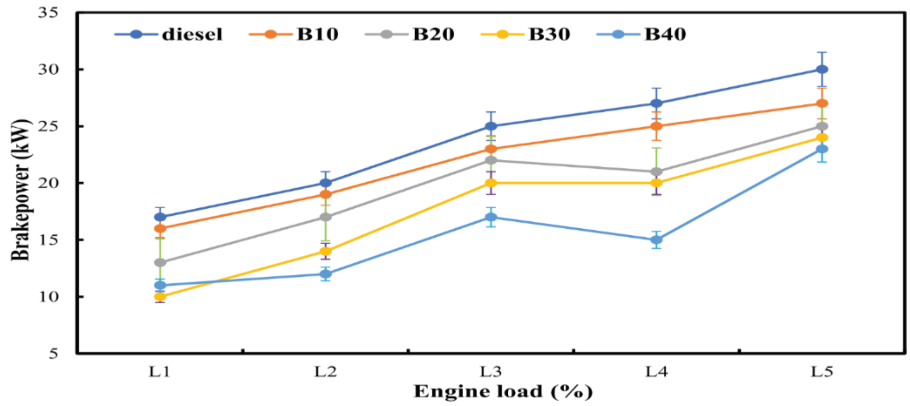

Figure 10: Engine BP of the methanol/diesel blends [75].

A more novelty study was conducted by Ahmadipour, Aghkhani, and Zareei [77], where they used the GT-POWER software to predict the effect of CR and alternative fuels on the performance of turbocharged diesel engines. Their results suggested that increasing the CR and BP would also increase BTE. Among the fuels used in this engine, the maximum BP and BT in the CR of 19 with the fuel were 3.86% higher than that of the base fuel, and the lowest value was awarded in the CR of 15 with methanol fuel, and it was equal to 56.04%. In a review, Ellappan and Rajendran [78] discussed that biodiesel blends demonstrate a lower level of BP than that of pure diesel (0.9–12.5% less than diesel fuel). According to the trend, the proportion of biodiesel used in the blends has an effect on the amount of BT that is produced.

To improve the BP of diesel engines, several innovations can be implemented. Recent studies have shown that utilization of alternative fuels, such as biodiesel or synthetic diesel, can immensely enhance combustion and power output, thus improving the BP. Further research work should focus on materials science and engineering, which may lead to the development of lighter and more durable engine components, contributing to improved overall performance and BP. By integrating these innovations, diesel engines can achieve higher levels of efficiency and power output while reducing their environmental impact.

3.4 Exhaust emission

Ongoing improvements to the combustion process in IC engines are critical for reducing fuel consumption, emissions, and criteria emissions in global vehicle transportation. For instance, Sharma and Kaushal [79] conducted an experimental study that determined the performance and emission characteristics of a VCR engine operating with Producer Gas (PG). During experimentation, results were acquired by altering CR and BP and then compared with standard diesel run results. A contribution by Uchida and Watanabe [50] demonstrated that the exhaust emission characteristics of the swirl-against injection result in a slight deterioration in the NOx-soot emissions trade-off, whereas it reduces the CO and total hydrocarbon (THC) emissions (Figure 11). Their study suggested that combustion efficiency can certainly be improved by the spatial control of the flame in the cylinder, but there is still room for optimizing the mixture formation.

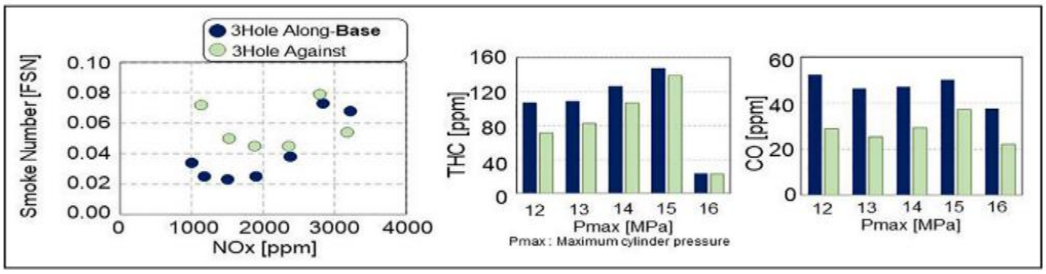

Figure 11: Experimental results of emission characteristics [50].

3.4.1 Exhaust gas temperature

EGT in diesel engines is of utmost importance for both engine performance and emissions regulation. Monitoring and controlling EGT emissions is crucial for ensuring optimal efficiency and adherence to environmental regulations. Excessive EGT can be advantageous for some procedures, such as after-treatment systems, particularly diesel particulate filters (DPF) and selective catalytic reduction (SCR) systems [80, 81]. These systems necessitate a specific threshold of heat in order to efficiently filter and process exhaust gases, thereby minimising harmful emissions. However, excessively high exhaust temperatures can result in issues such as overheating, which may lead to engine damage or reduced component lifespan. Furthermore, EGT also has an impact on the energy balance of the engine system, influencing the energy available for waste heat recovery systems, which can improve overall engine efficiency [81]. Therefore, future studies should focus on the optimization and design of exhaust systems, aiming to effectively control the EGT. This will serve as a key parameter in optimizing diesel engine performance, emissions, and thermal management.

In a recent study, Singh et al. [82] showed that the increase in biodiesel content leads to a decrease in EGT due to its viscosity, as depicted in Figure 12. At greater CRs of blends, the EGT drops as the air flow variation increases. However, the EGT remains higher than that of diesel due to the reduced calorific value of biodiesel. These results show that heat dissipated through the exhaust is directly related to the engine's performance at greater CRs. Muralidharan and Vasudevan [83] compared the performance, emission, and combustion characteristics of a variable CR engine using methyl esters of waste cooking oil and diesel blends. The experiments were conducted with different CRs of 18:1 to 22:1 at 1500 rpm. The test results proved that the BTE, EGT, and BP are dependent on CR and the biodiesel blend. Jindal [84] investigated the effect of CR and IP in a diesel engine with Karanja methyl ester. It was demonstrated that an increase in CR and IP improves the performance of the engine. HC, NOx, smoke emissions, and EGT were lower with biodiesel compared to diesel. In the past decade, Raheman and Ghadge [85] studied the performance of the engine (Ricardo E6) by using diesel and biodiesel from mahua oil blends at different CR, injection timing, and engine loads. They found that

BSFC and EGT are enhanced for all injection timings and CR ratios when the biodiesel percentage in the fuel mixture increases. This study served as a benchmark for most modern studies.

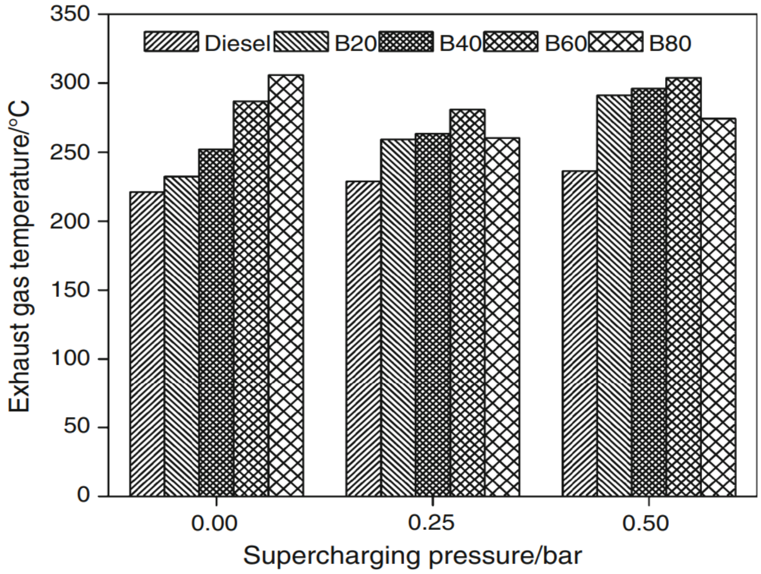

Figure 12: Variations in EGT with supercharging for different blends at CR 20 [82].

The effect of variation of the CR on the performance, emission, and combustion parameters of a CI engine was evaluated at different engine loads by Hariram and Vagesh Shangar [86]. The results of the research indicated that EGT and BSFC were enhanced and BTE decreased when the CRs decreased. Figure 13 illustrates that when the CR increases, the EGT lowers when various biodiesel fuels and their blends are used [87, 88]. In essence, this is due to the fact that when the CR increases, so does the burning velocity, resulting in a shorter period for complete combustion and lower EGT. Similarly, Figure 14 depicts the difference in EGT between diesel and biodiesel-diesel blends with relation to load at CR 18:1. At maximum load, the EGT for mixed fuels was greater than that of diesel. This is because delayed combustion shortens the time required by the engine to generate power from the fuel, which validates the work done by Hojati and Shirneshan [89]. Even though biodiesel blends have a higher cetane number, poor atomization due to the high viscosity of such fuels allows unburnt fuels to occur during the pre-mixed combustion phase. Later, during the diffusion combustion phase, the unburnt fuels continue to burn, resulting in increased EGT.

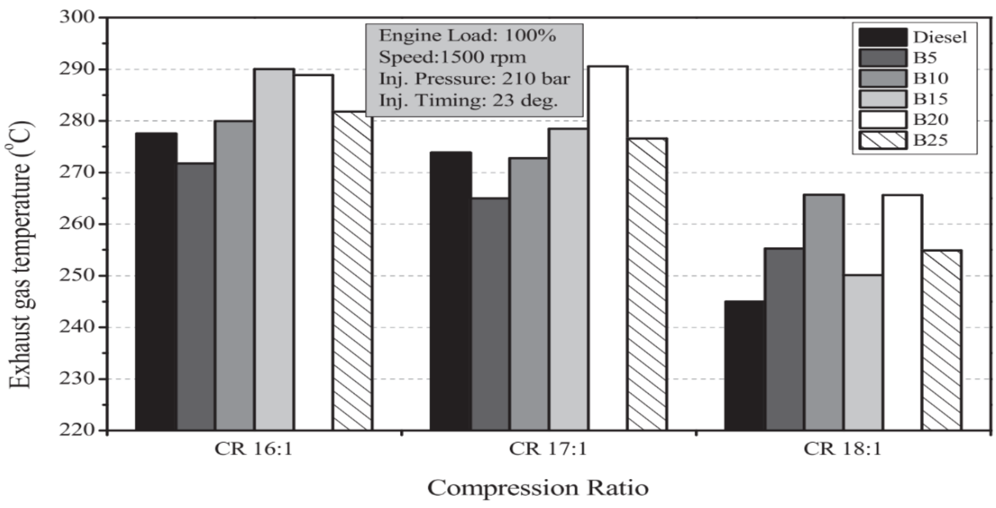

Figure 13: EGT at different CRs [88].

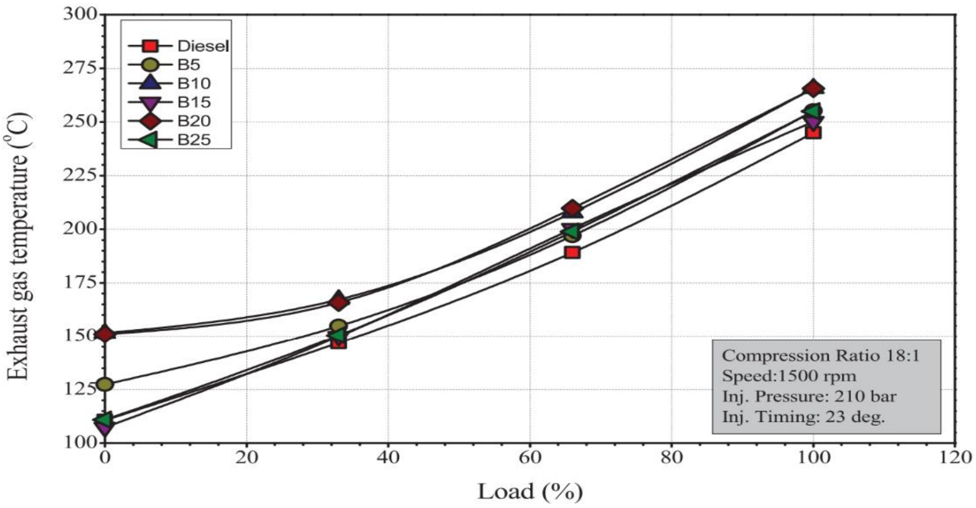

Figure 14: EGT vs load for CR of 18 for diesel and biodiesel-diesel blends [89]

BP is one factor that can be used to predict the EGT is BP. Literature survey has suggested that higher BP usually correlates with higher energy release during the combustion process, which in turn leads to higher EGT. This is particularly evident in diesel engines, where higher BP often corresponds to higher EGT due to the inherent nature of diesel combustion. Through experimental work, Vijayakumar et al. [90] studied the impact of CR and the effect of biodiesel blends on the performance of a VCR diesel engine. In their results, they depicted the variation between EGT and BP for MOME proportions at CR 17, 17.5, and 18, as seen in Figure 15. The increase in EGT is inferred from the increase in CR. The EGT of M10 at CR 18 is lower by 19.6% than diesel. It is due to the advance of combustion and more BP developed at higher CR, which leads to a decrease in EGT.

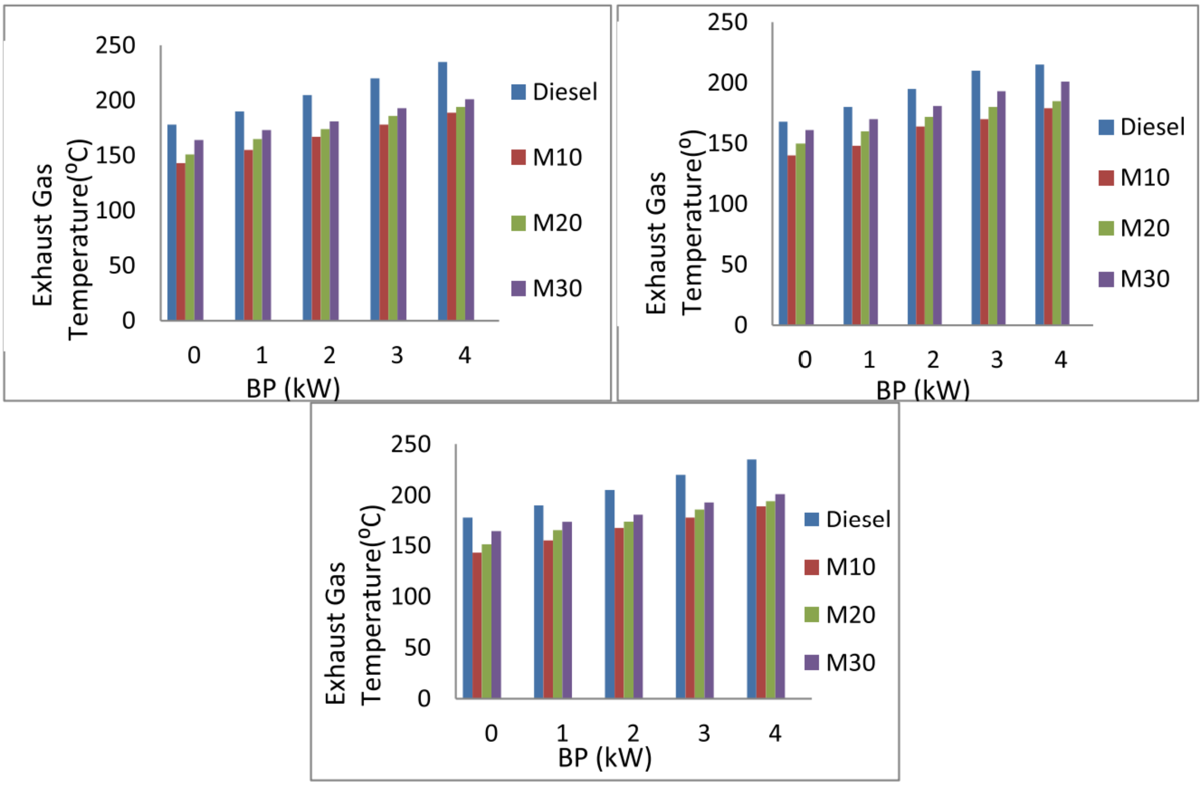

Figure 15: EGT Vs BP at CRs of 17, 17.5, and 18 [90]

There are several potential innovations that can be implemented to reduce EGT. Recent reports have proved that one approach is the use of EGR systems, which involves redirecting a portion of the exhaust gas back into the engine's cylinders. This helps to lower combustion temperatures and reduce the formation of nitrogen oxides (NOx). Additionally, the integration of selective catalytic reduction (SCR) systems can further reduce NOx emissions by using a catalyst to convert them into harmless nitrogen and water. Although these reports suggest that researchers have made a significant contribution to reducing the EGT, there are still research gaps that should be filled. Notably, these gaps exist within the implementation of advanced engine design and improved fuel injection systems to optimize combustion efficiency, which can immensely assist in lowering overall EGT. Finally, other studies should also divert toward the use of heat recovery systems, such as waste heat recovery units (WHRUs). These systems have the potential to capture and utilize thermal energy from the exhaust gases to improve overall efficiency and reduce temperature. These innovations, when integrated effectively, can contribute to lowering EGT and improving the environmental impact of combustion processes.

4 Conclusions

The review of performance, design, and operational parameters of VCR diesel engines has provided clarity on the significant potential and challenges of this innovative technology. Several studies have made efforts to propose the possible innovations that can be implemented to adjust the performance parameters, thus improving the efficiency of a VCR diesel engine. The current literature survey has critically discussed the impact of vital operational parameters such as BTE, BSFC, BT and EGT. A thorough understanding of how the design of diesel engine can be potentially enhanced in order to optimize the aforementioned parameters. This work further examines the concept of low friction technology including the strategies that are used to reduce friction including improved lubrication, using advance materials, optimizing the design of engine parts, and applying anti-wear coatings. The examination of the innovations has provided valuable insights into strategies for enhancing engine performance.

Modern studies have focused on the relationship between fuel blends, CR, and operational parameters, as these have shown promising avenues for optimizing overall engine operation. According to the reviewed literature, BTE is increased in blend B10 compared to B20, and a higher CR gives better BTE because, while compressing more, it has more power to burn the fuel, thus producing higher BTE than lower. Moreover, other studies have demonstrated that the optimum BTE, BT, and BMEP are found at an engine speed of 1700 rpm and a CR of 20. On the other hand, it is reported that DLC1 coatings, in comparison to other anti-wear coatings, have the best ability to reduce friction losses of the sealing rings above 2000 rpm. Research on the combined effects of fuel blends and CRs on diesel engine performance at different speeds and conditions is essential for improving engine design. Future studies should prioritize thorough tribological investigations to evaluate durability, wear, and friction characteristics under various operating conditions. Developing advanced modelling and simulation methods will facilitate accurate predictions and optimizations for efficient engine operation.

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