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Exploring the Impact of Exhaust Back Pressure on Variable Compression Ratio Diesel Engines: A Critical Review

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Abstract

There is a growing need to thoroughly understand the influence of exhaust back pressure (EBP) in Variable Compression Ratio (VCR) engines, as it directly affects the performance and emissions of the engine. Understanding how EBP is influenced by factors such as the VCR can lead to more efficient engine designs and operations. It can also help in optimizing combustion and emissions control strategies, ultimately leading to improved overall engine performance. Several studies have investigated the impact of EBP on the performance of internal combustion (IC) engines. However, this review paper presents several vital factors that contribute to the increase in EBP in IC engines. Factors such as exhaust system design (emission considerations, energy recovery, manifolds, and pipes), Exhaust Gas Recirculation (EGR) system (enhancement methods), and VCR system (design technological advancements) are all critically evaluated. The review further discusses methods to enhance or design these factors in a way that reduces EBP, improves engine performance, and reduces emissions.

Keywords: Exhaust back pressure, Variable Compression ratio, Internal Combustion engines, Exhaust system, Exhaust Gas Recirculation.

1 Introduction

The diesel engine is the most effective propulsion system currently available. Diesel engines transport most of the world's goods, operate most of the world's machinery, and generate electricity more efficiently than any other device in their size range. Diesel is one of the largest contributors to global environmental pollution concerns and will continue to be so as vehicle population and vehicle miles travelled (VMT) increase, resulting in ever-increasing global emissions [1]. On the contrary, Variable Compression Ratio (VCR) provides diesel engines with several benefits. It enhances the fuel economy and emission performance of diesel engines. Consequently, research on VCR diesel engines has gained popularity in recent years. While the concept has been investigated for many years, it has been difficult to justify the added cost and complexity in many applications. The use of connecting rods of variable length, which has simplified the mechanism, appears to make this a viable option for volume production [2].

Concerns arise when the variable compression ratio (VCR) diesel engine is unable to perform as anticipated. This is normally noticed by the high fuel consumption and unfavourable emission characteristics that often occur unexpectedly. This may be caused by several factors, including the effect of exhaust backpressure (EBP). EBP refers to the pressure build-up within the vehicle's or system's exhaust caused by the restriction of exhaust gas passage [3, 4]. Several components in the exhaust system prevent the direct passage of exhaust gases, resulting in a flow restriction. The resulting pressure build-up affects the piston's movement during the exhaust stroke phase and may cause several issues, such as crankshaft power loss, increased pumping work, turbocharger problems, thermal efficiency, increased fuel consumption, cylinder scavenging and combustion effects, etc. [5]. However, it is worth noting that the backpressure can only be detrimental at certain high magnitudes.

Considering the expensive nature and intricate experimental apparatus required for diesel engine tests, the existing tests on EBP mostly concentrate on single-cylinder and petrol engines rather than diesel engines [6, 7]. Very few studies have made efforts to develop the conceptualization that can be potentially used to monitor the magnitude of backpressure and mitigate its effect, thus improving the efficiency of the VCR diesel engine. Instead, researchers have been interested in petrol and diesel engines that are not equipped with VCRs. Moreover, the impact of EBP on the ignition delay and heat release rate in the combustion process of a VCR diesel engine has been entirely neglected by the researchers. This is evidence that there is a lack of studies that involve a detailed investigation into the exhaust system configurations of the VCR diesel engines.

2 Influence of exhaust backpressure on diesel engines

The exhaust system plays a vital role in the performance of any Internal Combustion (IC) engine. An inadequately designed exhaust system typically leads to an increase in exhaust backpressure, which serves as a resistance to the flow of exhaust gas. High backpressure impedes the efficient discharge of exhaust gas, consequently reducing the engine's performance [7]. Several previous research efforts have examined the impact of EBP on IC engine performance using Computational Fluid Dynamics (CFD) simulation, engine simulation, and experimental analysis. In some instances, Taguchi's method was employed to optimize the design of the exhaust manifold concerning reducing back pressure. However, most of these studies primarily concentrate on traditional IC engines, leading to certain deficiencies in the study of VCR.

In previous years, research has demonstrated that a reduction of 1 kPa in exhaust backpressure leads to a power increase in the engine, ranging from 0.22 kW to 0.45 kW [8]. Furthermore, a decrease in backpressure of 10 kPa results in a fuel consumption reduction of 1.5% to 3% [8, 9]. Conversely, high backpressure lowers Nitrous Oxides (NOx) emissions in the exhaust gas due to the higher temperature. Consequently, minimizing EBP is essential for enhancing the performance of any IC engine, especially if NOx emissions are not a primary concern. Another significant contribution was made by Hield [10] when he used the Ricardo Wave engine modelling software to examine the effect of increased back pressure on a turbocharged diesel engine. The novelty of his study was finding that the response of the engine to dynamic back pressure variations is strongly non-linear and depends on the engine speed, the load torque, the mean back pressure, and the amplitude and period of the fluctuations.

The engine EBP has a significant influence on the combustion properties and performance metrics of an engine, therefore leading to much research in recent years. Sapra et al. [11] discovered through simulation that small valve overlaps and pulse turbocharged engines are more effective in managing high exhaust pressure compared to big valve overlap and constant pressure turbocharged engines. The findings of Tauzia et al. [12] demonstrated that both dynamic back pressure and static back pressure have consistent effects on engine performance. These effects are characterised by a reduction in the air-fuel ratio, an elevation in exhaust temperature, and a decrease in the pressure differential between the cylinder's inlet and outlet. Recent reports have revealed that variations in back pressure have a minimal impact on engine performance when the engine is running at high RPMs [13, 14]. However, these variations have a notable influence when the engine is operating at low rpm. Zhang et al. [15] conducted a study comparing braking thermal efficiency (BTE), NOx emissions, CO emissions, and exhaust gas temperature. They concluded that a rise in EBP is not detrimental to the CI engine if the EBP remains below 40 mm of Hg. Table 1 summarises the findings of previous studies that were conducted by various researchers. These contributed immensely to the research community, as they were fundamental to most of the recent and modern studies.

Table 1: Summary of findings from previous studies [8].

Author and year	Findings
(Lahousse et al., 2006)	• 5.5 Nm torque increased when 40% catalyst backpressure (BP) decreased.
(Pesansky et al., 2009)	• CO_2 emission increase by 0.05% per 14 kPa BP • BSFC increases when BP increases at 950 and 1200 rpm but shows no impact at 650 rpm.
(Roy et al., 2010)	• CO increases when BP increases at 650 rpm but decreases at 950 and 1200 rpm
(Leman et al., 2016)	• The catalytic converter in an exhaust system will increase BP but decrease CO, unburned HC and NOx
(Pannone & Mueller, 2001)	• IC engine loses 0.3Kw power for one 1kPa BP
(Mayer, 2008)	• 100kPa BP will increase RGF by 4% which will decrease oxygen content and affect the combustion efficiency
(Millo et al., 2007)	• Higher BP increases BSFC and consumption efficiency
(Peixoto et al., 2009)	• EGR fitting increases BP which increases PM but decreases fuel consumption
(Bugarski et al., 2006)	• Increasing EGR rate decreases BSFC and NOx but increases HC
(Sutton et al., 2004)	• Soot increases by 89% for 10kPa BP
(Srinivas et al., 2016)	• 1.5% in BSFC when BP was 5.5-10kPa at 1800 and 1950 rpm, respectively

2.1 Fuel consumption rate, engine power and heat release rate

Diesel engine performance can be evaluated in terms of start-up time, engine power, fuel consumption rate, peak pressure, pressure rise rate, exhaust gas temperature, etc. In a more recent study, Li Huang et al. [16] experimentally investigated the performance of the medium-speed ship diesel engine under two high EBP conditions (10 kPa and 25 kPa) at different loads (50%, 75%, and 100%). They varied the intake/exhaust valve timing in three ways (Figure 1).

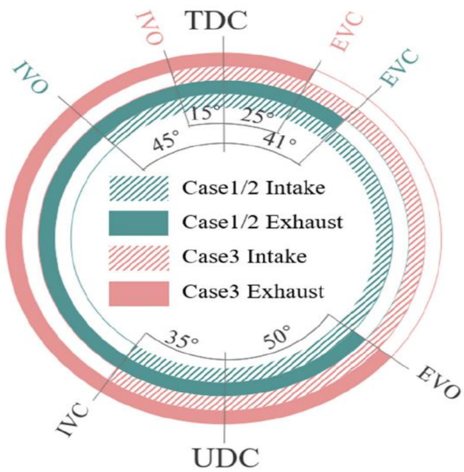


Figure 1: Intake/Exhaust valve timing of three cases [16].

The study proved to be significant as it made a comprehensive comparison of the three cases and provided suggestions for case selection according to different application conditions. Some of the critical comparisons involved parameters such as consumption rate and engine power. These results can be seen in Figures 2 and 3.

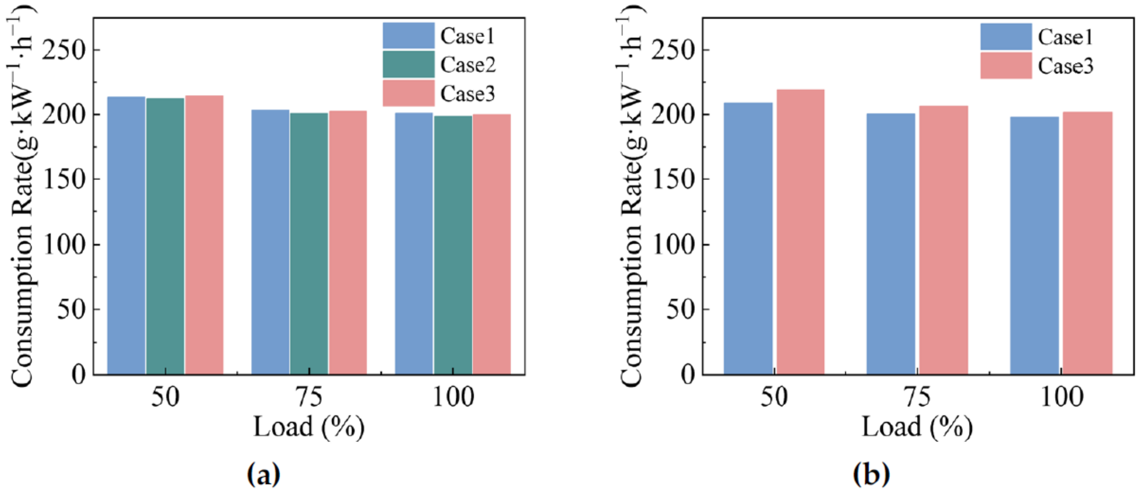


Figure 2: The trend of consumption rate for variable EBP rate at different loads.
(a) EBP = 10kPa; (b) EBP = 25kPa [16].

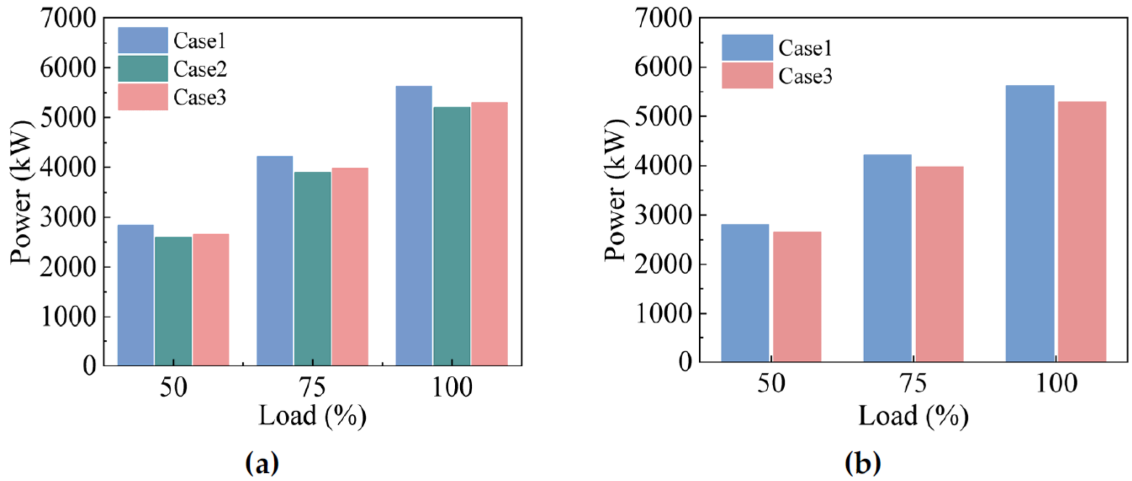


Figure 2: The trend of power for variable EBP rate at different loads. (a) EBP = 10kPa; (b) EBP = 25kPa [16].

Based on these findings and demonstrations, it can be said that the engine power is optimized by fine-tuning the intake pressure and fuel injection timing, ensuring that it remains at the ideal level while the EBP is between 10 kPa and 25 kPa [16]. The load increase leads to an increase in engine power, fuel consumption, and heat release rate (HRR) [16, 17, 18]. The variation in EBP has minimal impact on the optimal engine power, and due to the similarity in power, the HRR remains rather stable across different EBPs. By influencing both the temperature inside the cylinder and the volume of fresh air being taken in, the EBP impacts the rate at which fuel is consumed. The dominant influence mechanism determines whether the impact on fuel consumption rate leads to an increase or decrease [16, 17].

Other studies have previously validated the relationship between backpressure and engine power. Consequently, it is now well known that backpressure results in the engine expending additional energy to discharge the exhaust gas from the cylinder, leading to a reduction in power. The EBP poses resistance against the piston's movement, resulting in a power reduction. Pesansky et al. [19] researched to examine and validate the influence of three-way catalyst selection on backpressure and engine performance. The study revealed that in the 5.4L SI engine, a 7.3

kPa increase in backpressure led to a 4 kW decrease in engine power. Furthermore, the study indicated that for every 1 kPa rise in backpressure, the 5.4L SI engine would experience a power loss of 0.44 kW [19].

2.2 Thermal efficiency and brake specific fuel consumption

Numerous studies have been conducted on the effect of backpressure on the performance of diesel engines. The pursuit of enhanced engine performance indicators, such as greater power output, reduced fuel consumption, and lower emissions, necessitates a broader understanding of engine operations, additional empirical investigations, and the adoption of control systems grounded in numerical models. However, there has been a significant gap in the research community regarding the VCR system and its potential impact on EBP. For instance, Roy, Joardder, and Uddin [20] investigated the effect of engine backpressure on the performance and emissions of a CI engine. The study's interest was in this particular engine and it investigated the two performance parameters, which are BTE and fuel consumption. Using the following basic formulas:

$$\text{Thermal efficiency} = \frac{P\ (kW)}{CV\left({}^{kJ}/_{kg}\right) \times m\left({}^{kg}/_{s}\right)} \tag{1}$$

$$\text{BSFC} = \frac{M\left({}^{kg}/_{hr}\right)}{BP\ (kW)} \tag{2}$$

The study concluded that the BTE and brake specific fuel consumption (BSFC) are almost unchanged with increasing backpressure up to 40 mm of Hg pressure for all engine speeds and load conditions. When the EBP was increased, the emissions experienced a slight change (increase or decrease). A recent contribution was made by Fernoaga, Sandu, and Balan [21], when they predicted the effect of EBP on the performance of diesel engines using artificial intelligence (AI). They implemented and evaluated a selection of artificial neural networks (ANNs) and regressors to predict the EBP influence.

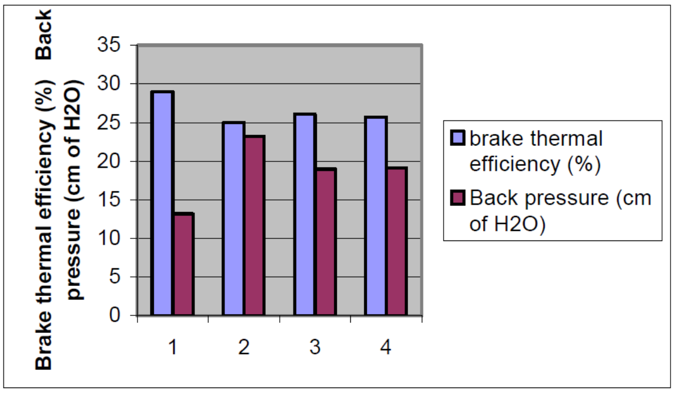
2.3 Impact on the toque

EBP can have a significant impact on an engine's torque. As a result, researchers have undertaken numerous studies to establish the correlation between backpressure and torque in both SI and CI engines. Ellyanie and Devan [22] experimented to optimize the design of an exhaust muffler and enhance the engine's performance. According to their findings, implementing the newly optimized exhaust muffler resulted in a 90% recovery of the engine's lost torque when backpressure was reduced [22, 23]. Similarly, in previous years, Lahousse et al. [24] investigated the impact of exhaust catalyst backpressure in the SI engine, revealing that a 40% reduction in catalyst backpressure resulted in a 5.5 Nm increase in torque.

2.4 Emission characteristics

In four-stroke engines, the rapid and complete release of exhaust gas from cylinders into the environment is necessary for the process of gas exchange. This action is measured by EBP, an indicator of flow resistance in the exhaust duct. Unsteady friction and inertial forces occur because of the gas velocity, shape, and dimensions of the channels [25 - 28]. The contributions made by Wittek, Geiger, and Vaz [29] showed that the NOx emission became constant or decreased a little with increasing backpressure. The formation of CO was slightly higher with an increase in load and back pressure at low engine speeds. However, under high-speed conditions, CO decreased significantly with increasing backpressure for all load conditions. The odour level was similar, or a little higher, with increasing backpressure for all engine speeds and load conditions. Hence, they concluded that backpressure up to a certain level is not detrimental for a CI engine [30]. Mittal et al., [31] performed a similar study to validate the work of [29], primarily investigating the impact of high EBP on the release of NOx, soot, PM, CO, and HC at varying loads. The emissions analysis demonstrated that, when subjected to high EBP, the level of NOx decreased. However, HC emissions did not show any substantial disparity.

It is well known that diesel engines produce emissions that contribute to air pollution, including PM, NOx, CO, and HC. However, advancements in diesel engine technology, such as particulate filters and selective catalytic reduction (SCR) systems, have immensely assisted in reducing these emissions [32, 33]. Additionally, biofuels and hybridization can further mitigate the environmental impact of diesel engines. Walke et al., [34] conducted a study assessing the emission characteristics of a CI engine using different catalytic converter catalysts. The study utilised three catalysts: copper oxide (CuO), cerium oxide (CrO_2), and zirconium dioxide (ZrO_2). The analyses revealed that the ZrO_2 catalyst reduced HC emissions, while all three catalysts decreased CO emissions. Additionally, ZrO_2 and CrO_2 were found to impact NOx emissions. Subsequently, the study compared BTE and back pressure when these catalysts were present (Figure 4). According to Figure 4, the presence of CrO_2 and ZrO_2 catalysts did not affect BTE, while CuO decreased it, leading to increased back pressure. However, this reduction was minor and deemed acceptable considering the potential environmental and human health benefits.



1) Without converter
2) Converter with copper oxide catalyst
3) Converter with cerium oxide catalyst
4) Converter with zirconium dioxide catalyst

Figure 4: Comparison of BTE and back pressure (constant torque and rpm 1500 for various catalysts [34].

3 Exhaust system design

The exhaust system, especially the exhaust manifold, is an important factor that affects the performance of any diesel engine. The most influential boundary condition in the exhaust manifold is backpressure. Therefore, it is important to effectively design an exhaust system that balances the need for exhaust gas scavenging with low backpressure to ensure optimal engine performance and emissions control. Additionally, understanding the effects of VCRs on exhaust gas properties and their subsequent influence on after-treatment performance and durability is crucial for exhaust system design. Effectively balancing these considerations while upholding optimal engine performance and efficiency presents a notable challenge in the development of exhaust systems for VCR diesel engines.

3.1 Exhaust emission considerations

Wang [35] conducted an optimum design for the intake and exhaust systems of a heavy-duty diesel engine by using the well-known design for six sigma (DFSS) methodology that adopts the IDDOV framework. In his work, he used the P-diagram, which can be seen in Figure 5.

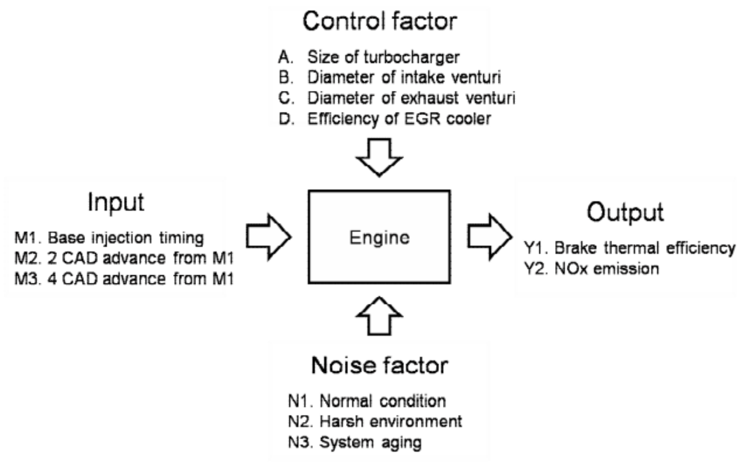


Figure 5: P-diagram of the optimum design work for the intake and exhaust system of a heavy-duty diesel engine [35].

As a result of his work, the NOx emission regulation limit was successfully satisfied while minimizing fuel consumption. The engine cycle simulation technique was employed to assess the effect of the various design parameters on NOx emissions and BTE performance. The final design proposal was verified through a real engine test. Ideally, the exhaust system for a VCR diesel engine should accommodate the varying CRs and corresponding combustion characteristics. The exhaust system should efficiently handle the range of exhaust gas temperatures, pressures, and flow rates resulting from the VCRs. In addition, to ensure compliance with emissions regulations [35 - 37], the exhaust system may need to integrate emissions control devices such as diesel particulate filters and selective catalytic reduction systems.

To address the above-mentioned factors, Kapparos et al. [38] created an overall diesel engine and after-treatment system model that integrates the diesel engine, exhaust system, engine emissions, and diesel particulate filter (DPF) models using MATLAB Simulink. Figure 6 shows the schematic for the overall exhaust system model.

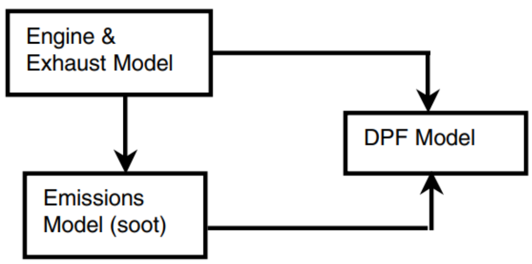


Figure 6: Schematic of the overall exhaust system mode [38].

WAVE was used to develop the 1-D engine and exhaust system models. The engine emissions model combines a phenomenological soot model with artificial neural networks to predict engine exhaust soot emissions. The schematic of the neutral network used can be seen in Figure 7. While this study is in the initial stages of development, groundwork has been laid for future work that will assist in the design and optimisation of diesel automotive systems for a reduction of emissions and a possible increase in engine performance. Moreover, future work could also escalate and focus on the enhancement of VCR diesel engines through exhaust system design.

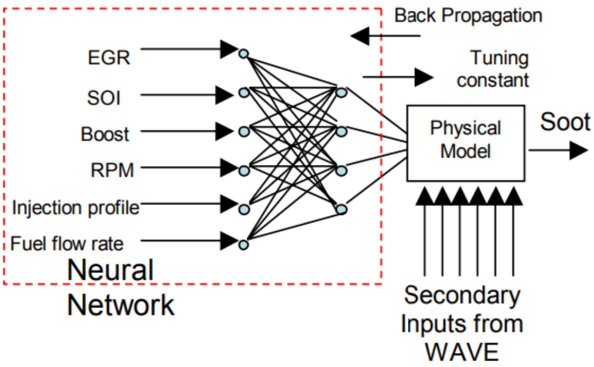


Figure 7: Schematic of neural network-based soot model [38].

A significant recent study conducted by Kang and Yang [39] in 2022 involved the design of three exhaust pipe systems, each modelled using UG NX12 software. Each exhaust system was configured with a Y pipe, X pipe, or H pipe as the confluence geometry, as depicted in Figure 8. The primary objective of the study was to explore the impact of changes in back pressure on exhaust emissions based on the confluence geometry of a dual exhaust system at idle. The analyses revealed that the H-type exhaust pipe system exhibited the highest pressure within the exhaust pipe, influenced by the confluence geometry, leading to the highest recorded Total Hydrocarbon Content (THC) in the exhaust emission results. On the other hand, the X-type exhaust pipe system, influenced by the confluence geometry, exhibited the lowest pressure, resulting in the lowest recorded THC in the exhaust emission results [39].

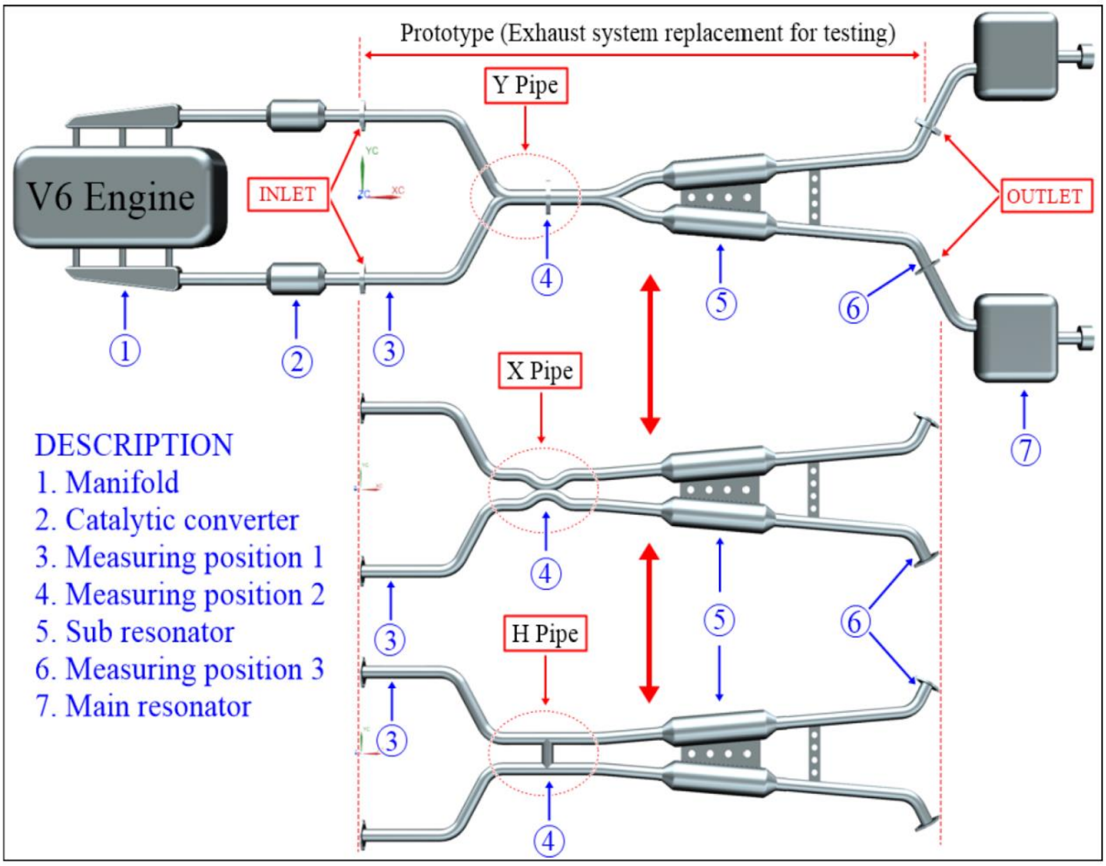


Figure 8: Details of the designed exhaust system and components [39].

As a result, the X Pipe, which demonstrated the lowest back pressure in the experimental findings, reduced the emission of THC in the exhaust gas by minimizing the recirculation of the burned exhaust gas [39]. This outcome can be regarded as the optimized confluence geometry of the dual exhaust pipe system. This research work represented a significant advancement for numerous researchers, as it proposed an ideal exhaust system for reducing THC and confirmed the significance of back pressure in exhaust system design.

3.2 Exhaust energy recovery

Exhaust energy recovery refers to the technique of capturing and harnessing the residual heat from engine exhaust emissions to enhance efficiency and reduce the consumption of fuel [39, 40, 41]. This approach is frequently employed in the automotive and industrial sectors to capture and utilise thermal energy that would otherwise be squandered. A prevalent approach to recovering exhaust energy involves employing a heat exchanger to transfer the heat from the exhaust gases to a working fluid, such as water or oil [42]. This transferred heat can then be used to provide supplementary power to the engine. Through the recuperation and utilization of this thermal energy, vehicles and industrial machinery can achieve enhanced operational efficiency and mitigate their environmental impact.

Liu et al. [43] conducted a study of the performance analysis and optimization design of the exhaust system for turbocharged diesel engines. The study investigated the effect of engine exhaust system structure on gas exchange performance and exhaust energy recovery. The authors quantitatively calculated and evaluated the exhaust energy in the exhaust system using the map diagram shown in Figure 9 and Equation 3, by utilizing the concept of air power. Consequently, they discovered that with a decrease in the outlet diameter of the exhaust manifold and the diameter of the exhaust pipe, the exhaust energy increases, the exhaust resistance increases, and the scavenging performance decreases [43].

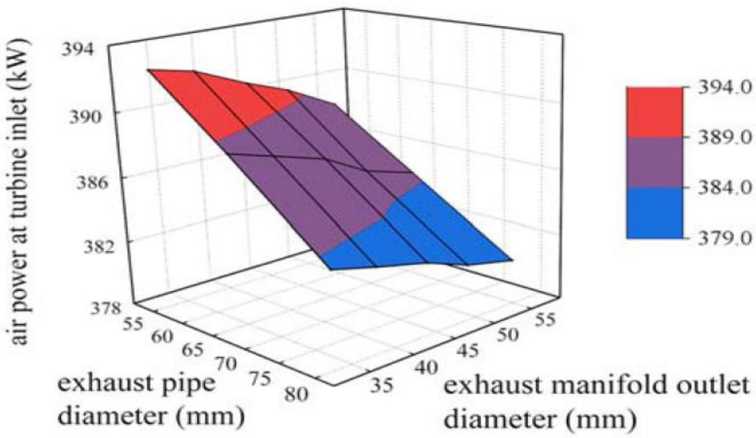


Figure 9: Effect of geometrical parameters on air power on turbine inlet [43].

$$P = pq_v\left[\ln\frac{p}{p_a} + \frac{c_p}{c_{p-1}}\left(\frac{T}{T_a} - 1 - \ln\frac{T}{T_a}\right)\right] \quad (3)$$

Based on Equation (3), the amount of air power is determined by both gas pressure and volume flow. Consequently, it serves as a thorough assessment factor that considers the potential energy and kinetic energy of the flow, the area of the gas pipe flow, and the dynamic performance under standard atmospheric conditions.

Advancements in IC engine technology indicate that the Organic Rankine Cycle (ORC) system can capture exhaust heat for additional utilisation, enhance system efficiency, and reduce negative environmental effects such as greenhouse gas emissions and PM [44 - 47]. Thaddaeus et al. [44] recently conducted an overview of recent developments in ORC technologies used for exhaust energy recovery in long-haul truck engines. The primary goal was to improve the thermal performance of these engines, ensuring lower greenhouse gas emissions and, consequently, low system operational costs. The results demonstrate that using ORC technology in trucks to recycle exhaust gas is a promising development with the potential for widespread adoption and utilization. Cipollone et al. [45] conducted a more precise and beneficial study, developing an ORC system for exhaust energy recovery in diesel engines. Their research work introduced a new approach by employing sliding vane technology for the pump and expander (Figure 10) of the recovery system to address the absence of established, effective, and dependable devices for waste heat recovery in automotive use.

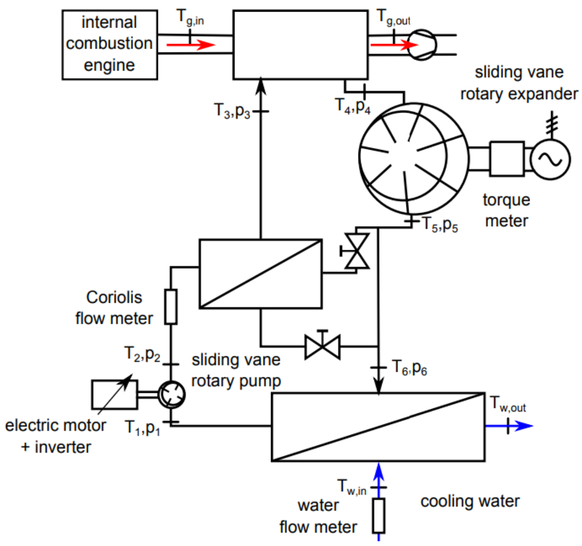


Figure 10: Plant layout and instrumentation [45]

According to the data presented in Figure 11, the recovered mechanical power reached a maximum of 1.9 kW, equivalent to 3% of the engine's mechanical power under those specific operating conditions [45]. This proportion rose during low engine loads and high revolution speeds. The overall cycle efficiency varied from 3.8% to 4.8%, with expander efficiency values ranging from 47.5% to 53.3%.

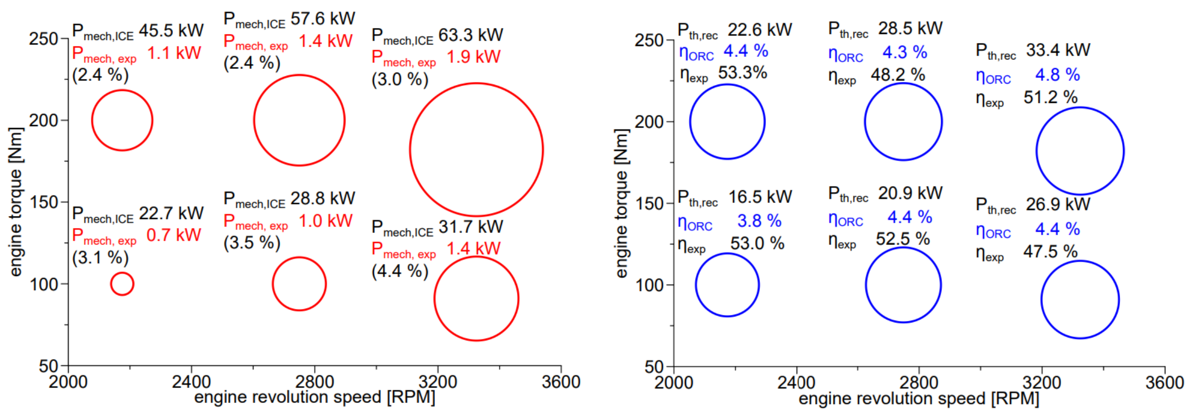


Figure 11: Summary of the energy recovery (left) performances and (right) efficiencies [45].

3.3 Effect of exhaust manifold and pipes

The primary function of the exhaust manifold is to gather the exhaust gases from the engine's cylinders and channel them towards the catalytic converter and the rest of the exhaust system [46, 47, 48]. Therefore, it has the potential to change (decrease or increase) the magnitude of the backpressure, thus improving the engine's performance. Murali et al. [49] conducted a study that aimed to reduce the backpressure in the exhaust manifold of the 115cc SI engine by optimising its lengths (by taking into consideration the impact of bending angles) through Computational Fluid Dynamic (CFD) analysis and Taguchi's method. In their results, it was observed that all optimal lengths were shorter than the existing ones, which resulted in reducing the backpressure by at least 13.56%. These findings contradicted the previous studies where it was mentioned that a longer exhaust manifold will reduce the backpressure produced at low end rpm [50 - 54]. However, the novelty of their study was the interference of the bending angle, which could not be neglected as the position of the inlet and outlet of the exhaust manifold was fixed. Thus, it can be concluded that the bending angle is more dominant in reducing the backpressure in the exhaust manifold, even when the lengths are optimised [49]. In fact, a lower bending angle does reduce the backpressure at low-end rpm.

In contrast, Sivaram et al. [50] experimentally investigated the impact of altering exhaust gas back pressure on the performance of a single-cylinder, four-stroke diesel engine. The study involved an experimental variation of the length of exhaust pipes, ranging from 0.250m to 2m. The results demonstrated that an increase in exhaust pipe length led to elevated exhaust back pressure, thereby reducing combustion efficiency. Additionally, the study found that optimal fuel economy and volumetric efficiency were associated with minimal exhaust pipe length. Therefore, it is reasonable to conclude that a thorough assessment of EBP, aiming for reduction, can potentially improve all these parameters. Carefully designing the exhaust system, including the manifold and pipes, can effectively address the correlation with EBP and achieve this goal.

The previously discussed studies have certainly made significant contributions to the advancement and conceptualization of exhaust system design, with the aim of mitigating the effects of EBP. However, they do not take the effect of the VCR system into consideration and observe the alterations in backpressure. This omission may be attributed to the intricacy of the VCR system in diesel engines, which presents numerous challenges during the design phase. One of the primary challenges involves accommodating a broad spectrum of exhaust gas temperatures, pressures, and flow rates resulting from the VCRs [51, 52]. This necessitates meticulous engineering to ensure that the exhaust components, such as turbochargers, exhaust manifolds, and after-treatment systems, can effectively manage these variable conditions without compromising performance or emissions control. Understanding the impact of VCRs on exhaust gas properties and their subsequent effects on after-treatment performance and durability is crucial in exhaust system design. Therefore, balancing these considerations while upholding optimal engine performance and efficiency presents a significant hurdle in the development of VCR diesel engine exhaust systems.

4 Exhaust Gas Recirculation (EGR) system

The Exhaust Gas Recirculation (EGR) system is employed in IC engines to reduce NOx emissions. The process involves redirecting a controlled amount of the engine's exhaust gas back into the combustion chamber, thereby decreasing the maximum combustion temperature and minimizing the production of NOx [53, 54]. The engine's electronic control unit (ECU) governs this procedure, which generally encompasses an EGR valve, an EGR cooler, and related pipework [55]. EBP and EGR are interconnected, as EGR has the potential to influence the EBP within an engine. Introducing EGR into the combustion chamber may impact the exhaust gas flow, hence influencing the overall backpressure in the exhaust system. Optimally controlled EGR can effectively mitigate NOx emissions and concurrently affect the backpressure, hence influencing the engine's operational efficiency. Proper design and calibration of the EGR system are crucial to ensuring its harmonious functioning with the entire exhaust system.

4.1 Principle of EGR

Previous work has utilized numerous mathematical formulations to measure the volume of the recirculated exhaust gas [56]. Despite the absence of a universally accepted and standardized definition for quantifying EGR recirculation, researchers have extensively employed two primary formulas to delineate the quantity or rate of EGR.

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4.1.1 Mass-based EGR

The depiction of EGR based on mass is illustrated in Figure 12. However, the mathematical representation of this concept is outlined as follows:

$$r_{EGR} = \frac{\dot{m}_{EGR}}{\dot{m}_{air}+\dot{m}_f+\dot{m}_{EGR}} \qquad (4)$$

where $\dot{m}_{EGR}$ is the mass flow rate of the recirculated exhaust gas, $\dot{m}_{air}$ is the mass flow rate of the fresh air, $\dot{m}_f$ is the mass flow rate of the injected fuel, and EGR is the mass fraction of the recirculated exhaust gas. As the measurement of fuel flow is generally significantly lower than the mass air flow, a simplified definition of EGR is commonly employed [57].

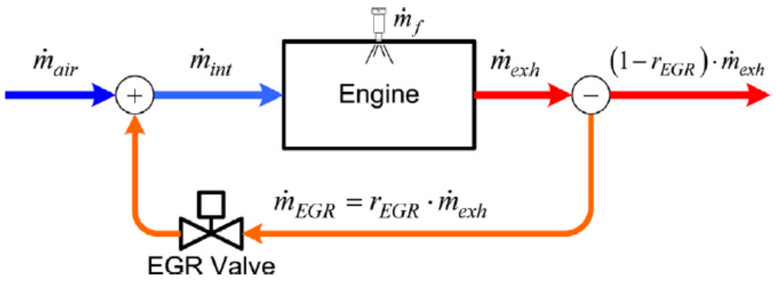

Figure 12: Defining EGR on mass basis [57]

$$r_{EGR} = \dot{m}_{EGR}/\dot{m}_{int} = 1 - \frac{\dot{m}_{air}}{\dot{m}_{int}} \qquad (5)$$

where the intake mass flow, $\dot{m}_{int} = \dot{m}_{air} + \dot{m}_{EGR}$. The practical application of the EGR definitions in Equations (4) and (5) is challenging due to the difficulties associated with directly measuring the EGR mass flow rate in the harsh diesel exhaust environment. However, under steady operating conditions, a reasonable estimate of the intake mass flow can be made based on the engine speed, in-take pressure and volumetric efficiency so that the EGR rate can be evaluated using the mass air flow (MAF) sensor (Equation (6)) where $MAF_{current}$ and $MAF_{initial(w/0\ EGR)}$ are the fresh air mass flow rates with and without EGR application, respectively.

$$r_{EGR} = 1 - \left(MAF_{current}/MAF_{initial(w/0\ EGR)}\right) \qquad (6)$$

4.1.2 Gas concentration based EGR

In typical engine test facilities, a widely employed definition utilizes the measurement of carbon dioxide (CO2) gas concentration (in terms of volume) to calculate the EGR fraction [57, 58, 59].

$$r_{EGR} \approx \frac{[CO_2]_{int}-[CO_2]_{amb}}{[CO_2]_{exh}-[CO_2]_{amb}} \approx \frac{[CO_2]_{int}}{[CO_2]_{exh}} \qquad (7)$$

Alternately, the EGR fraction can also be determined by measuring the oxygen concentrations in the intake and exhaust streams:

$$r_{EGR} \approx \frac{[O_2]_{air}-[O_2]_{int}}{[O_2]_{air}-[O_2]_{exh}} \qquad (8)$$

These definitions may yield slightly different outcomes compared to the mass-based EGR definition (with variances of up to ±0.5%) for a specific engine operating condition. However, consistent trends have been observed across a broad spectrum of engine operating conditions [60, 61]. In the context of EGR estimation, prioritizing the repeatability of the results generally takes precedence over the absolute accuracy of the results, if the same EGR definition is consistently utilized.

4.2 Enhancement methods

Given that the current EGR system in diesel engines effectively reduces the NO_X content in the exhaust gases [62, 63, 64], it is important to develop a system that can simultaneously reduce all harmful components and fuel consumption. This is necessary because the entry of soot micro particles into the working cavity of the engine leads to a decrease in its lifespan. Several studies have proved that improving the efficiency of EGR can have a positive impact on EBP by potentially reducing it. Some of the methods that are currently employed to enhance the EGR system are listed and discussed below [65, 66]:

- Enhanced control algorithms: Developing advanced control algorithms can help optimize the EGR flow rates, ensuring efficient emissions reduction without compromising engine performance.
- Cooler efficiency: Improving the design and efficiency of EGR coolers can enhance their ability to lower the temperature of recirculated exhaust gas, leading to better combustion control and reduced NOx emissions.
- Cleaner valves: Implementing cleaner and more reliable EGR valve designs can help prevent potential issues such as clogging and improve overall system performance.
- Integrated systems: Integrating the EGR system with other engine controls and emissions systems can lead to more coordinated and effective operation, maximizing the benefits of EGR usage.
- Innovative materials and components: Researching and adopting advanced materials for EGR system components can enhance durability, corrosion resistance, and overall system reliability.

d'Ambrosio, Ferrari, and Spessa [67] undertook an initiative to improve the EGR system. Their research involved a thorough examination of the primary elements of a cooled short-route EGR system utilizing a numerical-experimental approach. Two distinct EGR shell and tube coolers were subjected to testing at the dynamometer cell to evaluate how variations in the cooler's thermal effectiveness might impact the engine. Figure 13 illustrates the thermal effectiveness graphs.

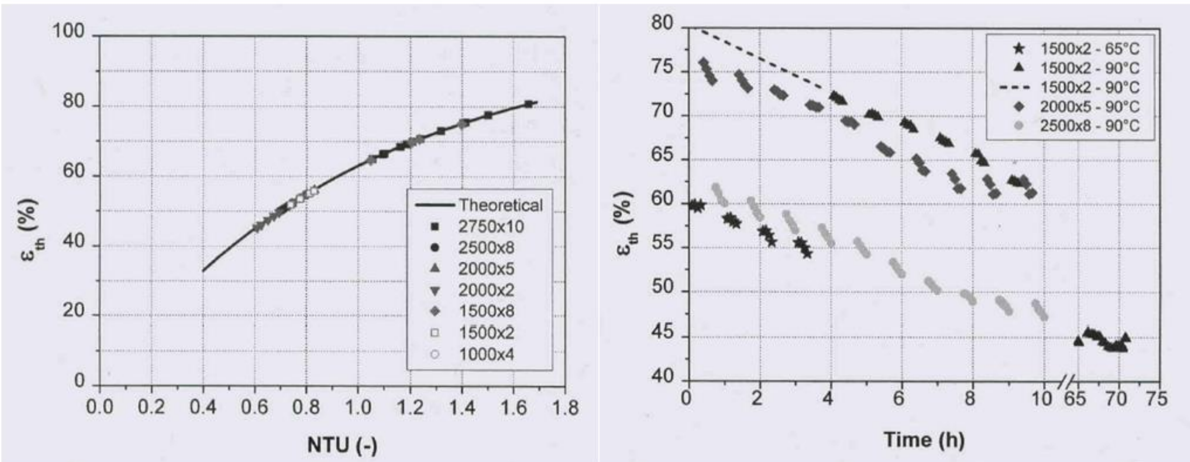

Figure 13: Thermal effectiveness vs NTU (left) and Thermal effectiveness vs time (right) [67].

The thermal effectiveness of the EGR cooler can be accurately determined using the e ε_{th}- NTU method, as illustrated in Figure 13 (left). Theoretical and experimental results show that the thermal effectiveness is mostly affected by the EGR mass flow rate, the thickness of the fouling layer, the temperature of the hot gas, and the mass flow rate of the coolant. When the thermal efficiency of the EGR cooler was improved, the temperature of the recirculated gas at the cooler exit decreased. This caused the EGR mass fraction in the in-cylinder charge to rise, which is advantageous because it lowers NOx emissions at the engine outlet. However, the enhanced thermal effectiveness of the cooler may lead to a decline in BFSC [68, 69]. Furthermore, the study also assessed the effect of aging on EGR performance, as illustrated in Figure 13 (right). According to Figure 13 (right), the thermal effectiveness of the EGR cooler notably decreased after the initial 10 hours of operation. Consequently, the exhaust gas velocity at the EGR cooler inlet decreased significantly, making it challenging for previously adhered particles to dislodge from the cooler walls.

Other research efforts have also focused on enhancing the EGR system using existing methodologies. For example, Ivanov [70] dedicated efforts to improving the EGR system by introducing an original solution to enhance the efficiency of the exhaust gas recirculation system for diesel engines. This approach, based on the TRIZ-FSA system, led to the acquisition of a patent for the method and device. The study involved the development of a self-regulated EGR system for diesel engines to mitigate harmful emissions and enhance efficiency. Furthermore, the research leveraged electrostatic action in recirculation systems to synergistically reduce harmful emissions and fuel consumption [70]. Despite all of this, there remains a notable disparity, as there is potential for substantial enhancements to the EGR system in a manner that prevents an increase in backpressure, resulting in reduced PM and HC emissions.

4.3 Effect of backpressure

To effectively predict the effect of backpressure on the EGR system, Bhure [71] contributed, where he studied the effect of backpressure on the performance and emission of diesel engines equipped with EGR and Diesel Oxidation Catalyst (DOC). This was achieved by varying the back pressure of the exhaust system using a back pressure control valve (BPCV) operated manually at three positions, which are 100%, 87.5%, and 75% BPCV lifts. The findings indicate that as the back pressure rises with brake torque, BTE and BMEP decrease. This is due to increased pumping losses and a reduction in the specific heat value of the fuel, resulting in the need for additional fuel to compensate for these losses and ultimately decreasing brake power.

On the other hand, researchers have been making efforts to understand the correlation between EBP and EGR. Consequently, Baert, Beckman, and Veen [72] discussed that introducing EGR leads to an increase in backpressure, resulting in a rise in PM emissions for a 12L turbocharged CI engine, while fuel consumption exhibited a declining trend. Additionally, Peixoto et al. [73] noted that a higher EGR rate reduces the formation of NOx and fuel consumption, but it also contributes to an increase in EBP, leading to extended combustion delay and increased HC emissions. In contrast to that, Millo et al. [74] observed a reduction in NOx of approximately 13% with EGR implementation but noted an increase in fuel consumption due to higher EBP. Therefore, the introduction of EGR may decrease NOx formation in IC engines, but it has the potential to increase PM and HC emissions and combustion delay. Fuel consumption will decrease if the EGR rate predominates over the EBP, and vice versa. Despite all of this, there remains a notable disparity, as there is potential for substantial enhancements to the EGR system in a manner that prevents an increase in backpressure, resulting in reduced PM and HC emissions.

5 Variable Compression Ratio system

The VCR is an innovation that has captivated the interest of researchers since the 1890s. In 1900, the concept of VCR was granted its initial patent [75, 76]. The VCR system is a modern marvel that allows an engine to dynamically modify its CR. The CR is the ratio between the largest and smallest volumes in the combustion chamber of an internal combustion engine [77]. By modifying this proportion, the VCR system enables the engine to enhance performance and efficiency according to varying driving conditions. A VCR system offers advantages such as enhanced fuel efficiency and decreased pollution [78, 79]. This is accomplished by allowing the engine to function at a greater CR during times when maximum power is needed and at a lesser CR when cruising or under minimal load, hence improving overall efficiency. This technology has the potential to enhance torque and power output.

The automobile industry has faced a longstanding issue in designing and effectively creating a production-ready VCR engine. Several inventive inventions have been submitted, and various designs have been developed to alter the CR. Typical methods used to date include adjusting the position of the crankshaft axis, modifying the geometry of the connecting rod, relocating the cylinder head, altering the combustion chamber capacity using a secondary piston or valve, adjusting the piston deck height, and shifting the crankpins [80 - 83]. More studies should be conducted to investigate other possible methods that can be potentially used to effectively design the VCR system.

5.1 Optimum Compression Ratio

In 2016, Satyanarayana et al. [84] conducted experimental research to determine the optimal CR for achieving the best performance in a single-cylinder, four-stroke VCR diesel engine using an engine test rig. Testing was conducted at CRs of 16.5, 17.0, 17.5, 18.0, and 19.0 under varying loads. Their findings indicated a noteworthy enhancement in performance at a CR of 19.0. CRs lower than 19.0 showed a decline in BTE and an increase in fuel consumption. Consequently, the following conclusion was drawn [84]:

- Improved fuel efficiency is achieved with a CR of 19
- Lower smoke density is observed at CR 19.0
- Exhaust gas temperatures are moderate at CR 16.5
- To obtain more power at higher loads, the engine should operate at CR 19 to minimize specific fuel consumption.
- For lower power output at lighter loads, the engine should operate at CR 16.5 to reduce fuel consumption.

The above research was significant in establishing optimal compression ratios, particularly for diesel engines. It is recommended that future studies also examine the influence of CR on EBP. This relationship has been explored in limited studies due to its complexity. Generally, an increase in CR may contribute to higher backpressure. This is attributable to the potential rise in cylinder pressures during the combustion process, which can consequently exert increased force when expelling exhaust gases. However, the specific connection can vary based on factors such as engine design, operational conditions, and exhaust system efficiency.

5.2 Effects on specific fuel consumption

The relationship between BSFC and thermal efficiency (Equation 9) is influenced by alterations in the CR. This association can be described in the following manner:

$$\eta_f = \frac{1}{BSFC \times Q_{HV}} \tag{9}$$

An increment in the CR leads to a rise in efficiency, resulting in decreased fuel consumption [85]. However, spark advance in spark-ignition (SI) engines constrains the CR value. Based on the work done by Vagesh Shangar and Hariram [86], a reduction of about 30% in BSFC was noticed when the CR was raised from 16 to 18, and BTE improved by 13% at full load as the CR was increased for their VCR CI engine.

5.3 Influence of BSFC maps

Several studies have been conducted to further prove that VCR systems are the future of IC engines. For example, Wittek et al. [87] conducted an experimental investigation on a VCR system applied to a gasoline passenger car engine. Their aim was to prove the potential of this technology when applied to a state-of-the-art 3-cylinder, direct injection, turbocharged engine fuelled with regular RON 95 gasoline. To assess the influence of changing CR values from 9.56 to 12.11 on BSFC, a BSFC map for each CR is plotted in Figure 14. Based on Figure 14, the observed disparity in BSFC between high and low CR operations closely aligns with the anticipated discrepancy predicted by basic constant volume cycle calculations, which can be seen in Equation 10. An apparent discrepancy of 5% was observed in a large area of the map. Additionally, the VCR engine has greater friction compared to the conventional engine. The impact on BSFC intensified as the loads decreased. Through the analysis of motored testing and theoretical considerations, they determined that the negative impact of the heavier VCR connecting rods on BSFC is projected to be less than 1% within the relevant operating range.

$$\nabla BSFC_{rel} = \frac{BSFC_{CRhigh} - BSFC_{CRlow}}{BSFC_{CRlow}} \times 100 \tag{10}$$

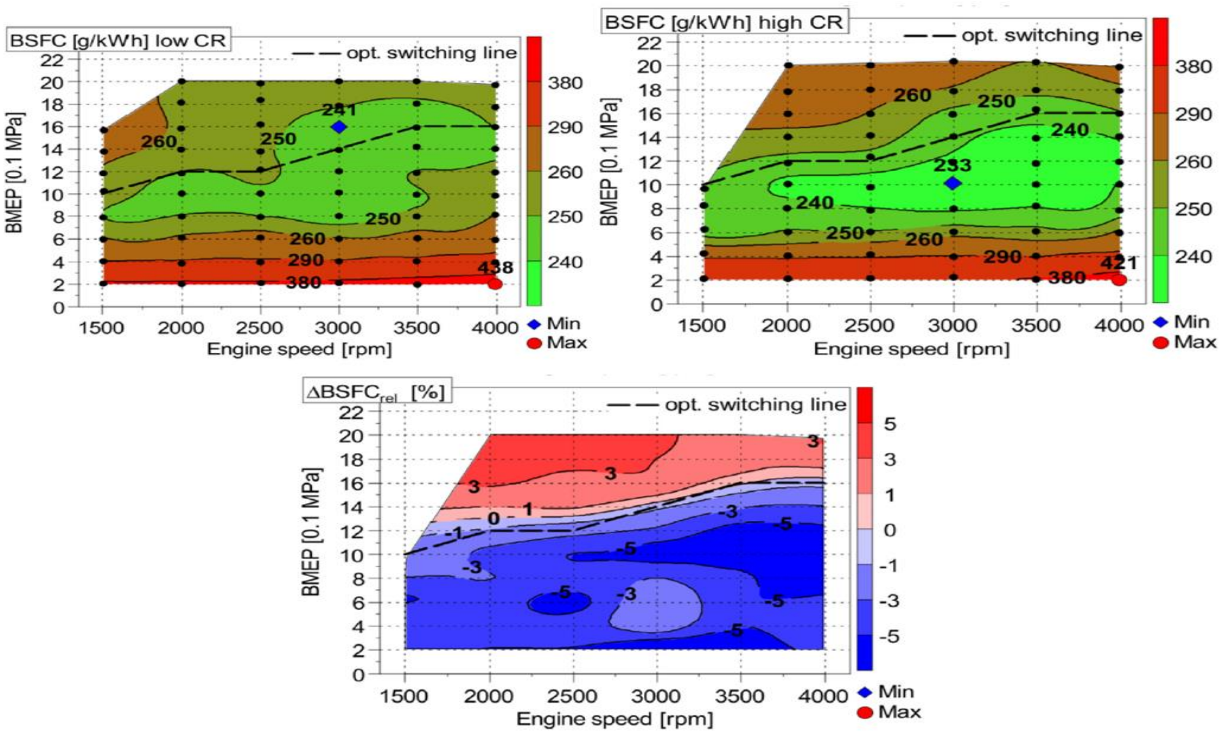

Figure 14: BSFC maps measured with the VCR engine at both CR stages, with either optimum or knock-limited combustion phasing and with series ECU settings [87].

5.4 Effects on BMEP

Brake mean effective pressure (BMEP) is the average pressure necessary to be exerted on the piston from the top dead centre (TBD) to the bottom dead centre (BDC) in order to generate the rated brake power [88]. Figure 15 illustrates the influence of CR changes on the BMEP in SI engines. Typically, higher CR values allow for greater BMEP; however, it becomes evident that the effect becomes counterproductive for CR values above approximately ≈ 11. This is attributed to the advanced spark timing, causing the CR at spark to be lower than intended. Higher CRs result in more readily occurring self-ignition (knock), leading to more advanced spark timing. Nonetheless, increasing the CR from the common value of 9 for SI engines to 11 results in a notable rise in BMEP [89].

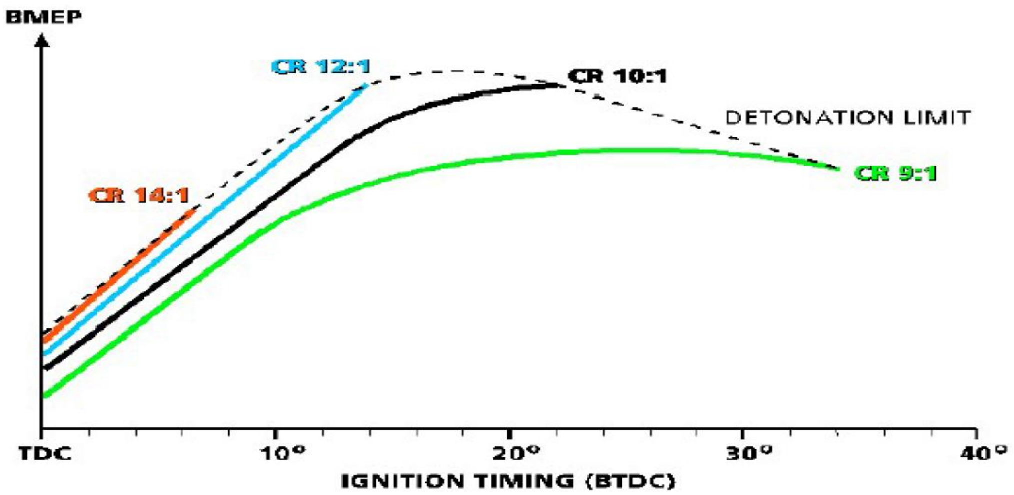

Figure 15: BMEP vs Ignition with different CR [89].

5.5 Effects on emissions

Singh and Shukla [90] conducted a simulation of a single-cylinder diesel engine using Diesel-RK software to evaluate the engine's performance, emissions, and combustion characteristics when utilising palm biodiesel and petro-diesel. The simulation was conducted for three different CRs (16, 17, and 18) at a consistent speed of 1500 rpm. Analysis of the simulation results revealed that there is a decrease in BTE and an increase in BSFC when employing palm biodiesel rather than normal diesel. Conversely, thermal efficiency and BSFC improve with a rise in CR. Higher CRs prompt increased in-cylinder pressure and heat release rate, along with reduced ignition delay. High CRs lead to higher NOx and CO_2 emissions due to the heightened pressure and temperature. However, specific PM emissions and smoke opacity decrease at higher CRs.

When biodiesel is used as fuel for diesel engines, there is an increase in the levels of NOx and CO_2 due to higher in-cylinder temperatures [91]. The rise in temperature is linked to a higher heat release rate for higher CRs, as shown in figure 16. In contrast, raising the CR from 16 to 18 leads to a decrease in the quantity of PM and smoke opacity [86].

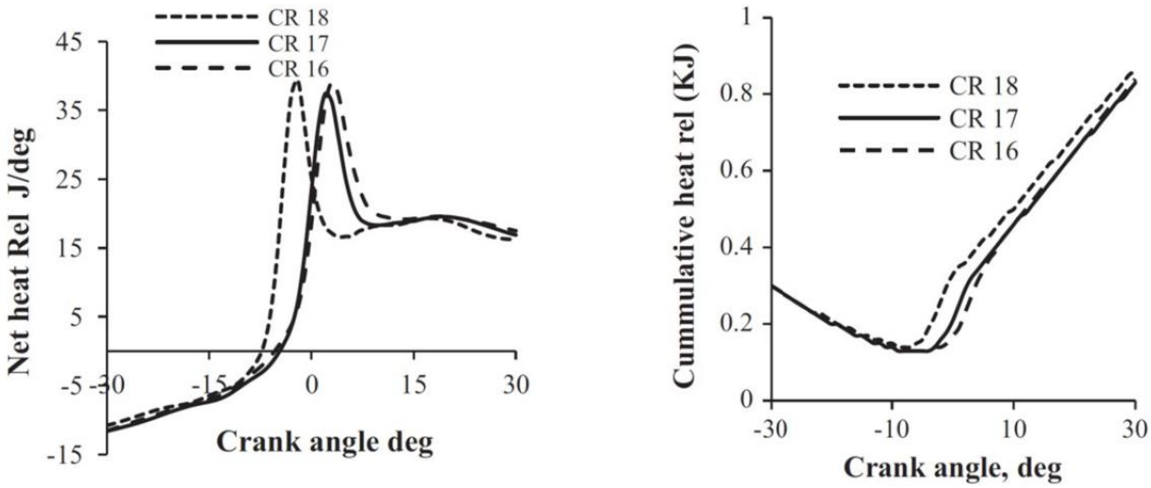

Figure 16: Net HRR (left) and Cumulative HR (right) vs CAD for different CRs [86].

5.6 Design technological advancements

For high fuel economy, an improvement in thermal efficiency is essential, which is in turn strongly related to the CR. The quality of fuel and the tendency to knock during full-load operations are the governing factors for CR. Therefore, for everyday automobiles, a balance between partial throttle and full throttle is typically observed. Thus far, one of the main challenges is designing a low-friction VCR engine. These engines are complex machines that require expertise and knowledge to be designed efficiently. Mostly, the VCR engine is run at low loads, at which friction losses are especially penalising [92]. Therefore, an increase in friction losses due to the VCR design would impair or even wipe out the advantages and benefits of the VCR system. Few studies have focused on the advancement of the existing VRC system to mitigate the effect it has on IC engines.

In 2016, Asthana et al. [93] contributed to describe various techniques by which VCR is being implemented and provided a comparative study of original and modified VCR technology (Table 2) based on efficiency, engine friction, specific fuel consumption, engine rigidity, and piston kinematics. The study examined the fundamental principles that can be used to design a VCR engine, including the alteration of the cylinder head, connecting rod geometry, crankshaft axis, piston deck height, and the implementation of dual piston and gear mechanisms. The principles were analysed in relation to eight parameters: combustion chamber integrity, kinematics of the crankshaft-piston assembly, mechanical losses, overall rigidity of the engine, the impact of varying CR on engine displacement, accuracy of CR control, ability to control CR on a cylinder-by-cylinder basis, and suitability for converting a stock engine to a VCR engine.

Based on the above study, it is evident that each parameter has its own constraints. Therefore, it is crucial to select principles that are highly compatible with the existing engines. To accomplish this, it is crucial that the form of the combustion chamber and the movement of the piston closely resemble those of a traditional engine. On the contrary, VCR promises to reduce the consumption of fuels by decreasing fuel consumption at low loads. It claims to minimise the damage to the environment by reducing CO_2 emissions while providing increased power and torque at high loads.

Table 1. A comparison between original engine and VCR engine [93]

CR Varying Principle	**Shifted Mono Head**	**Multilink Rod Crank Mechanism**	**Eccentrics On Rod End Bearing**	**Eccentrics On Main Bearings**	**Piston Deck Height Bearing**	**Additional Pistons**	**Gear Based Crank Mechanism**
Factors							
Schematic Diagrams							
Combustion Chamber Integrity	Preserved	Preserved	Preserved	Preserved	Preserved	Significantly Deteriorated	Preserved
Crankshaft -Piston Assemble Kinematics	Not Changed	Significantly Deteriorated	Slightly Changed	Slightly Changed	Not Changed	Not Changed	Slightly Improved
Mechanical Losses	Not Changed	Significantly Deteriorated	Not Changed	Not Changed	Not Changed	Not Changed	Slightly Improved
Engine Overall Rigidity	Deteriorated	Preserved	Preserved	Preserved	Preserved	Preserved	Preserved
CR Varying Effect On Engine Displacement	Null	Significant	Null	Null	Null	Null	Null
CR Control Accuracy	Good	Very Good	Poor	Good	Poor	Good	Very Good
Capability To Control CR Cylinder By Cylinder	Low	High	Medium	Null	Medium	High	High
Suitability For Converting A Stock Engine To VCR Engine	Very High	Low	Medium	High	Medium	High	Null

Shaik et al. [94] reviewed the geometric approaches and solutions used to achieve VCR, where they considered the results of prior research. In their concluding remarks, they emphasised that the primary obstacle to the adoption of the VCR lies in its lack of compatibility with key components in modern production and the difficulties of combining VCR and non-VCR manufacturing within existing plants. Researchers should conduct further studies on manipulating the VCR system to ensure compatibility with all key components in modern production.

A VCR design solution featuring eccentric movement of the crankshaft was described by Woś et al. [95]. Emphasis was placed on the integration of this solution into the underlying engine. The resulting design proved to be an optimal balance between weight, packaging, and cost, serving as a foundation for fuel efficiency enhancement strategies based on downsizing. Khan [96] conducted a study of VCR and different innovations to achieve VCR. The results showed that under full load conditions, the performance and efficiency of an engine with a CR that is adapted to load demands can reduce knock susceptibility. The potential for pre-ignition, significant knocking, and engine jerking due to delayed combustion stages can be minimised. Finally, the VCR also provides further potential to control the exhaust gas temperature, contributing to protecting component temperatures and thus reducing the possible EBP.

6 Conclusions

VCR diesel engines offer several benefits, including improved fuel efficiency, reduced emissions, and enhanced overall performance. By allowing for adjustment of the CR based on operating conditions, VCR engines can achieve optimised combustion, leading to increased efficiency and reduced fuel consumption. Several studies aiming to understand the correlation between EBP and engine performance have been conducted. Most of these studies are focused on the conventional IC engine with a constant VCR. This literature review addressed the critical importance of comprehending the influence of EBP particularity in VCR engines. A thorough understanding of the influencing factors, such as the VCR system on EBP, is vital for optimising engine efficiency and emissions control. This work also discussed the significant factors contributing to increased EBP, including exhaust system design, EGR system enhancement, and VCR system technological advancements, and highlighted the potential enhancing methods.

According to the reviewed literature, both dynamic back pressure and static back pressure have consistent effects on engine performance but can only be detrimental at certain high magnitudes. It is an on-going challenge to predict the precise magnitude and vital contributing factors. Few studies have demonstrated that EBP is not harmful to the engine if it remains below 40 mm of Hg. However, the obstacle is ensuring that EBP does not surge in such a manner that it exceeds the recommended numeral. Having said that, researchers are tasked with developing concepts that will potentially manage the effect of EBP on the VCR diesel engine's performance.

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