Simulation Analysis of the Impact of Exhaust Backpressure on a Variable Compression Ratio Diesel Engine Performance

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Abstract

This study investigates the impact of exhaust backpressure (EBP) on the performance of a single-cylinder, four-stroke, variable compression ratio (VCR) diesel engine using Gamma Technologies (GT)-POWER software. The simulation of this engine varied EBP by adjusting an orifice diameter at the exhaust pipe's end and compression ratio (CR) incrementally from 12 to 18. The study found that, contrary to expectations, increasing CR significantly increased brake specific fuel consumption (BSFC), primarily due to increased EBP. While higher CRs generally improve thermal efficiency and increase brake power, the presence of high EBP reduced brake power, especially at lower CRs. Increased EBP also significantly reduced brake torque at higher CRs. Additionally, the impact of CR on hydrocarbon (HC) emissions was non-linear, with EBP significantly influencing HC and carbon monoxide (CO) emissions. The results highlight a trade-off between CR and EBP levels in optimizing engine performance and emissions. The study emphasizes the necessity of considering EBP and CR to optimize the performance and reduce emissions of VCR diesel engines.

Keywords: GT-Power, Simulation, Exhaust Back Pressure, Variable Compression Ratio, Brake Specific Fuel Consumption, Brake Power, Brake Torque, Carbon Monoxide, Hydrocarbons

1 Introduction

In the area of automotive engineering, understanding the complexities of diesel engine performance is crucial for optimizing efficiency and power output.The performance of diesel engines is heavily influenced by several factors, one of the most critical being exhaust backpressure (EBP). EBP refers to the resistance encountered by exhaust gases as they exit the engine, and it can significantly affect engine efficiency, power output, and overall performance [1,2]. An optimal level of backpressure ensures that exhaust gases are discharged efficiently, promoting better air-fuel mixing and enhanced combustion. In recent years, the development of variable compression ratio (VCR) technologies has gained attention in diesel engine design. A single-cylinder VCR diesel engine allows for dynamic adjustment of the compression ratio (CR) during operation, thus optimizing performance under various load conditions [3]. This adaptability can lead to improved fuel efficiency and reduced emissions, making VCR engines a promising solution for meeting stringent environmental regulations.

Many studies have evaluated the effect of CR on the performance of direct ignition (DI) diesel engines. Balasubramanian and Subramanian [4] experimentally investigated the impact of varying CRs (CR21, CR19, CR17) at different speeds (2200 and 3000 rpm) under high load conditions for B100 biodiesel. The results revealed that the higher CRs marginally enhanced hydrocarbon (HC) emissions due to the increased surface area-to-volume ratio of the combustion chamber. Conversely, carbon monoxide (CO) emissions showed the opposite trend; the higher CR minimized CO emissions. Raheman and Ghadge [5] conducted performance tests on a Ricardo E6 engine using the Taguchi technique, varying the CR (18:1–20:1) and injection timing (IT) (35–45 BTDC). They discovered that with increased CRs and advanced IT, brake-specific fuel consumption (BSFC) was reduced.

Pesic et al. [6] analysed the advantages and challenges of VCR diesel engines. They used Gamma Technologies (GT)-POWER software to investigate four CRs between 12:1 and 17.5:1 and found that specific HC and CO emissions were lowest at a high CR of 17.5:1. Muralidharan and Vasudevan [7] compared the performance, emissions, and combustion characteristics of a variable CR engine, conducting experiments with different CRs ranging from 18:1 to 22:1 at 1500 rpm. The test results demonstrated that brake power is dependent on CR. Satyanarayana et al. [8] conducted a performance analysis of a VCR diesel engine and demonstrated that the optimum CR for their operation is 19, achieving better fuel economy at this CR, while fuel consumption was higher at lower CRs, such as 16.5.

Khanyi and Inambao [9] reviewed the literature on the impact of EBP in VCR diesel engines. They reported that EBP can be harmful only at certain high magnitudes; however, the challenge lies in ensuring that it does not exceed the recommended levels for a particular engine and its parameters. These findings were validated by Huang et al. [10], who experimentally demonstrated that an increase in EBP from 10 kPa to 25 kPa has little effect on heat release, engine power, and torque. Additionally, Joardder et al. [11] concluded through GT-POWER software that an increase in EBP is harmless to compression ignition (CI) engines, particularly regarding CO emissions, when the EBP is less than 40 mm of Hg. Several studies have reported that the effect of increasing EBP on fuel consumption primarily depends on whether the influence of EBP temperature or fresh air intake dominates [12,13].

Sapra et al. [14] found that back pressure fluctuations have almost no effect on engine performance at high engine RPMs, while the effects are significant at low RPMs. Mittal et al. [15] primarily studied the effects of high EBP and low EBP on the emissions of CO and HC under different loads. The emission results showed that, under high EBP, the concentration of CO increased, but no significant difference was observed in HC emissions. Sivaram et al. [16] experimentally investigated the effects of EBP on the performance characteristics of a single-cylinder 4-stroke diesel engine. They discovered that fuel consumption and volumetric efficiency were maximized at a pipe length of 0.250m and minimized at a pipe length of 2 m. Consequently, as the length of the exhaust pipes increases, the back pressure of the exhaust gases also increases, negatively affecting engine performance. Several other studies have shown that the magnitude of EBP depends on the area of the exhaust pipe and exhibits a negative linear correlation [17,18].

From the reviewed literature, it is evident that most researchers have focused on the importance of varying the CR to enhance engine performance. Some of these studies have evaluated the benefits of using various biodiesel blends while varying the CR. Nevertheless, the literature has fallen short of integrating the advantages of VCR technology in the context of increasing EBP. On the other hand, very few studies have used GT-POWER to specifically model the effect of EBP on the benefits of CR technology. Instead, most researchers have employed techniques such as Taguchi, wave (using Ricardo software), computational fluid dynamics, and Diesel-RK, among others. Even in these cases, these studies frequently neglect the impact of increasing EBP with variations in CR.

The present study utilized GT-POWER software, a leading engine simulation tool widely employed by engine manufacturers and suppliers [6]. It aims to evaluate the impact of EBP on a single-cylinder 4-stroke VCR diesel engine. By simulating various EBP conditions alongside different CRs, the research was able to gain insights into how increases in back pressure can negate the benefits of VCR technology. Specifically, these variations can lead to adverse effects in key engine performance parameters such as brake torque, BSFC, power output, brake efficiency, volumetric efficiency, and emissions, including CO and HC.

Based on the researcher's best knowledge and the literature reviewed, this study represents a novel contribution that emphasizes the importance of achieving a balance between CR and EBP to enhance engine performance and reduce emissions.To achieve these optimum outcomes, it is essential to evaluate both factors in conjunction. The outcome of this work further contributes to a better understanding of the interplay between exhaust dynamics, VCR technology, and engine performance, paving the way for advancements in diesel engine technology and efficiency.

1.1 Validation of the proposed model

Before presenting the results from the simulations, a validation of the proposed model is conducted by comparing the output with similar recent studies on the same diesel engine. The results of the investigation are then elaborated upon, emphasizing the correlation between CR, back pressure, and engine performance parameters. First, a comparison is made in the absence of back pressure, using a similar diesel engine. Table 1 summarizes the previous findings, which serve as a benchmark for this work. A second comparison is then made that includes the impact of back pressure, as shown in Table 2.

Table 1: Summary of recent previous findings on the impact of varying compression ratios on the performance of diesel engines in the absence of back pressure.

Author	Study	Findings	Current findings
Senthil, Silambarasan, and Ravichandiran [19]	Influence of CR on Performance, Emission and Combustion Characteristics.	• 19.5 of CR gives the lowest BSFC. • 19.5 of CR gives the lowest CO emission. • 19.5 of CR gives the lowest HC emission.	Similar findings were obtained for BSFC and CO.
Kassaby and Nemit_allah [20]	Studying the Effect of CR on an engine-fuelled with Waste Oil Produced Diesel Fuel	• The BSFC for all blends decreases as the CR increases. • CO_2 emission increased by 14.28%. • HC and CO emissions were reduced by 52%, and 37.5%, respectively when CR was increased from 14 to 18.	Similar findings were obtained for CO and CO_2.
Bawane et al. [21]	Performance and Emission Characteristics of Diesel Engine Under Variation in CR, Engine Load, and Blend Proportion.	• An increase in CR results in to increase in brake power thus the BSFC goes on the decrease.	Similar findings were obtained when increasing CR.
Al-Dawody et al. [22]	Performance of a Diesel Engine with a Changing CR: Experimental Investigation.	• When the CR increases, all carbon emissions noticeably decrease, as well as the cylinder pressure and temperature rise, which increases NOx. • As the CR rises, the BTE rises, whereas the BSFC decreases.	Similar findings were obtained for CO and BSFC, as BTE was not investigated.
Balasubramanian and Subramanian [23]	Experimental Investigation on the Effects of CR on Performance, Emissions and Combustion Characteristics of a Biodiesel-Fuelled Automotive Diesel Engine.	• The HC emission increased from 0.0059 to 0.0087 g/kWh, when CR was increased from 19:1 to 21:1. • CO emission decreases with increased CR because of high in-cylinder temperature.	Similar trend was observed.

Table 2: Summary of findings from the recent previous studies of the impact of varying the compression ratio in the performance of diesel engines in the presence of exhaust backpressure.

Author	Study	Findings	Current findings
Zetai Ma et al. [24]	Experimental Study on Influence of High Exhaust Backpressure on Diesel Engine Performance.	• With the increase of EBP, the output power of the diesel decreases.	Similar findings were obtained.
Gülmez and Özmen [25]	Effect of EBP on Performance of a Diesel Engine: Neural Network-Based Sensitivity Analysis.	• Any increase in EBP would increase the BSFC of a diesel engine.	Similar findings were obtained.
Murali et al. [26]	A Review on the Correlation between EBP and the Performance of IC Engine.	• Higher EBP reduces the brake torque of the engine. • Higher EBP reduces the power output of the engine. • Higher EBP increases the BSFC of the IC engine. • CO, HC and PM increase due to higher EBP.	Similar findings were obtained, but for HC both increasing and decreasing trend was observed. PM was not investigated.
Gülmez and Güner Özmen [27]	Effects of EBP Increment on the Performance and Exhaust Emissions of a Single Cylinder Diesel Engine.	• The EBP increment caused an increase in CO emissions. • Engine torque decreased to 46.4 Nm from 48 Nm under high EBP.	Similar findings were obtained.
Huang et al. [28]	Experimental Investigation on Combustion and Performance of Diesel Engine under High Exhaust Back Pressure.	• The EBP affects the fuel consumption rate by affecting both the in-cylinder temperature and the fresh air intake volume.	Similar trend was observed for BSFC.

2 Materials and Methods

This section details the experimental setup and procedure followed for this research work. The experimental setup involved defining the engine specifications, including bore, stroke, compression ratio, fuel properties, etc, within the GT-POWER environment. The simulation procedure commenced with the creation of a detailed engine model that incorporated thermodynamic and fluid dynamic principles to accurately represent performance and emissions within the engine. Subsequently, operating conditions such as EBP, CR, and engine speed, were systematically varied to assess their impact on engine efficiency and emissions characteristics.

2.1 Experimental setup

The single-cylinder, 4-stroke, VCR diesel engine that uses conventional diesel fuel has been modelled and simulated using GT-POWER software. This diesel engine is designed for efficient and reliable operation in various applications. It features a single cylinder, which contributes to its compact design while delivering adequate power output. The 4-stroke cycle ensures smoother operation and improved fuel efficiency compared to 2-stroke engines. VCR technology allows for adjustable CRs, optimizing performance across different load conditions and enhancing versatility. The software can simulate the intake, compression, power, exhaust, heat transfer, and gas flow in the internal combustion engine's pipeline, as well as analyse and optimize key parameters. This model primarily consists of the intake pipe, throttle (restriction), intake valve, direct injector, cylinder, crankcase, exhaust valve, exhaust restriction (orifice), and exhaust tailpipe. The engine specifications are detailed in Table 3.

Table 3: Specifications of the proposed single-cylinder 4-stroke diesel engine.

Engine parameters	Units	Values
Make		Kirloskar
Type		1-cylinder, 4-stroke, VCR diesel
Cooling system		Water cooled
Rated power	kW	3.5
Speed	rpm	1500

Bore Diameter	mm	87.5
Stroke	mm	110
Connecting rod	mm	234
Compression ratio		Variable (12-18)
Displacement	Cc	661
Intake pipe diameter	mm	32
Exhaust pipe diameter	mm	32
Loading		Eddy current dynamometer
Inlet valve open		4.5° before TDC
Inlet valve close		35.5° after BDC
Fuel injection start		23° before TDC
Exhaust valve open		35.5° before BDC
Exhaust valve close		4.5° after TDC

The GT-POWER simulation incorporates a variety of key inputs to accurately model the performance of the engine, as outlined in Table 3. Among these inputs, precise valve timing is critically important for optimizing the engine's performance, efficiency, and emissions. Each component of the engine, including the cylinder, crankshaft, intake and exhaust valves, piping (intake and exhaust), and fuel injection system, was modelled using exact dimensions and specifications derived from the actual engine design. This modelling approach allows for a detailed analysis of the key performance parameters. Additionally, parameters such as fuel characteristics, exhaust restriction position, and CR conditions were integrated into the simulation to provide a comprehensive understanding of engine behaviour under various increasing EBP and CRs. The layout of the diesel engine bench test is presented in Figure 1. Following this, Figure 2 illustrates the flowchart for the modelling and simulation of the engine. Lastly, Figure 3 provides a depiction of the GT-POWER model, highlighting the interconnected components and overall structure of the simulation. This model serves as a valuable tool for predicting performance and optimizing the engine.

Figure 1: Test rig of the modelled diesel engine.

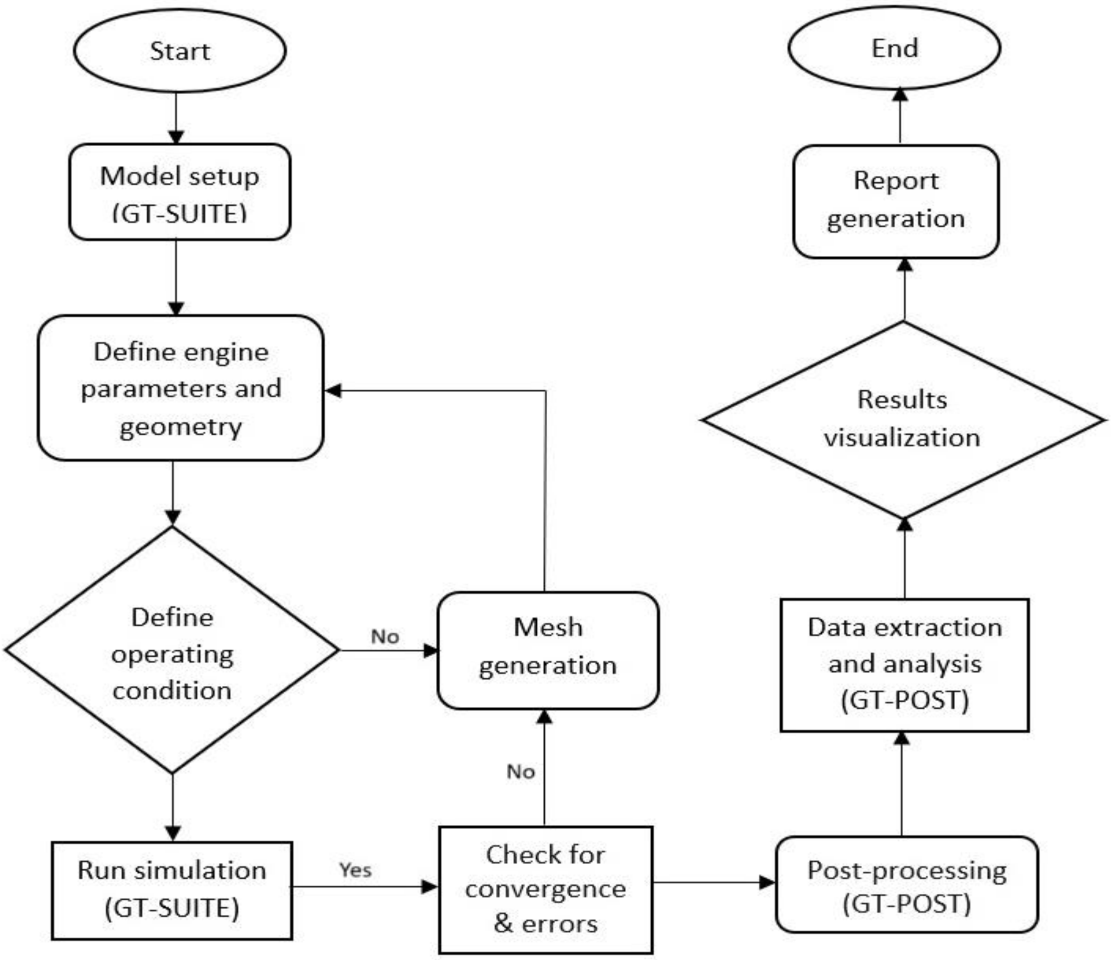

Figure 2: Flowchart for modelling and simulation of the engine.

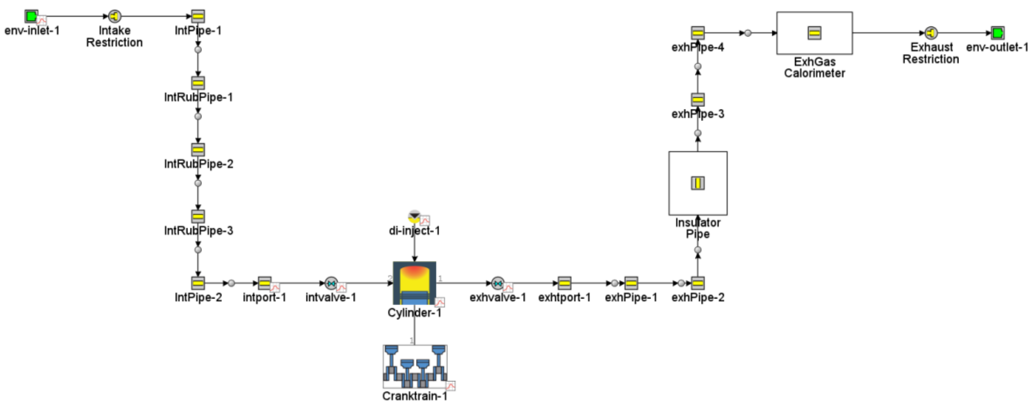

Figure 3: Simulation of the engine model.

2.1.1 Definition of the simulated components and arrangements

- **Intake Process**: The simulation begins at env-inlet-1 representing the ambient environment. Air enters through an intake restriction, modelling the physical limitations of the intake system. This air then flows through a series of pipes (IntPipe-1, IntRubPipe-1, IntRubPipe-2, IntRubPipe-3, and IntPipe-2), modelling different sections of the intake manifold based on the proposed engine.

- **Fuel Injection and Cylinder Operation:** The air reaches the intvalve-1 and intport-1 where it mixes with fuel injected by di-inject-1. The mixture enters Cylinder-1, the heart of the engine simulation. The Cranktrain-1 component models the engine's crankshaft and connecting rods. This section calculates the pressure, temperature, and volume changes within the cylinder during the four strokes of the engine cycle.
- **Exhaust Process:** The exhaust gases leave the cylinder through exhtport-1 and exhvalve-1. They travel through pipes (exhPipe-1, exhPipe-2, exhPipe-3, and exhPipe-4), of which these pipes are different sections and bends within the modelled engine. An Insulator pipe models the heat transfer within the exhaust system.
- **Exhaust Calorimeter:** The exhaust gases pass through an ExhGas Calorimeter for measurement and analysis of the exhaust gas properties, such as temperature and flow rate.
- **Exhaust Restriction and Exit:** Finally, the exhaust gases exit through an Exhaust Restriction (which is varied in diameter to increase the EBP for each case), modelling the pressure drop at the exhaust outlet, exiting to env-outlet-1, representing the ambient environment.

2.2 Experimental procedure

The impact of EBP on the performance parameters of a single-cylinder, 4-stroke, VCR engine under various CRs was investigated. This study was conducted by designing a mechanism in the form of an orifice to restrict the flow of exhaust gases within GT-POWER software. Positioned at the far end of the exhaust pipe, the orifice generated increased back pressure. The magnitude of the back pressure was controlled by varying the diameter of the orifice, starting from an initial value of 32 mm, which was based on the exhaust pipe diameter, and consistently reduced by 5 mm in each subsequent case, as shown in Table 4.

To ensure accurate and reliable results, essential components that account for exhaust flow dynamics were carefully incorporated into the model. These components included pipe diameter, length, bend radius, angle of bend, and the roughness of the material. Additionally, GT-POWER features thermal and pressure drop characteristics that depend significantly on factors such as pipe geometry, exhaust gas temperature, flow velocity, friction coefficient, and heat loss to the surroundings. All these attributes were integrated based on the specifications of the proposed engine design, facilitating a comprehensive analysis of performance under varying exhaust conditions.

Moreover, the CR was another significant parameter adjusted in the GT-POWER case setup mode. The CR was incrementally increased by two, from 12 to 18 (see Table 4), to determine if the advantages of adjustable CRs persisted under high magnitudes of EBP. Generally, the timing of the intake and exhaust valves is a critical factor influencing EBP, as it affects combustion cycle efficiency and gas flow dynamics. For this work, an optimal valve overlap of 4.5° + 4.5° = 9° was established to ensure efficient removal of exhaust gases while facilitating the intake of fresh air. The direct injector (DI), which automatically calculated the injection quantity based on the air intake volume, was included in the injector model, with parameters specified according to engine specifications. Conventional diesel fuel was used for the simulation to align with the engine's operational characteristics, as shown in Table 5.Conversely, uncertainty arises from various unknown sources of error, and the overall percentage variation is presented in Table 6. In this study, the uncertainty is calculated for all analysed parameters, including brake specific fuel consumption (BSFC), brake power, torque, volumetric efficiency, as well as CO and HC emissions. The error limits for these computed parameters were estimated using the root-mean-square method, as outlined by Holman [29].

Table 4: Parameter details of the four cases.

Parameters	Case 1	Case 2	Case 3	Case 4
Orifice diameter (mm)	32	27	22	17
Compression ratio	12	14	16	18

Engine speed (rpm)	1500	1500	1500	1500

Table 5: Properties of a conventional diesel fuel.

Property	Unit	Diesel Fuel
Density	kg/m^3	820
Cetane number		48.5
Lower heating value	MJ/kg	42.31
Viscosity	cSt	2.87
Final boiling point	°C	369.8
Element analysis		
C%	w/w	86
H%	w/w	12.935
S%	w/w	1

Table 6: Details of uncertainties.

Parameter	Uncertainty (%)
Brake Specific Fuel Consumption (BSFC)	$\pm$ 1.3
Brake power	$\pm$ 0.6
Brake torque	$\pm$ 0.5
Volumetric efficiency	$\pm$ 0.06
Hydrocarbon (HC)	$\pm$ 0.2
Carbon monoxide (CO)	$\pm$ 0.25
Cylinder pressure	$\pm$ 0.1
Exhaust gas temperature	$\pm$ 0.3

3 Results and Discussion

The performance parameters and exhaust gas emissions of a single-cylinder, 4-stroke VCR diesel engine were methodically analysed using GT-POWER simulation, adhering to a structured experimental procedure, and capturing substantial data throughout the process. Key performance parameters such as BSFC, brake power, brake torque, and volumetric efficiency were evaluated,while the emission characteristics, specifically HC and CO, were recorded across various CRs under differing levels of EBP. Initially, one-dimensional plots were created to provide a foundational overview of the data. The graphs (a) and (b) were subsequently compared to findings from previous literature, which are detailed in Tables 1 and 2 within the validation section. This was done to further validate the accuracy of the proposed model. A two-dimensional plot was then introduced, effectively illustrating the variations and impact of back pressure on engine performance and emissions under various CRs. This graphical representation clarifies the complex interdependencies within the system, promoting a thorough insight into how altering EBP influences both performance parameters and emission outputs, despite the presence of VCR technology.

3.1 Performance parameters

This section offers an in-depth discussion of the parameters critical to engine performance, as outlined in Section 3. These parameters were analysed to assess the engine's efficiency and effectiveness under increasing EBP and CR.

3.1.1 Brake Specific Fuel Consumption

In this subsection, the effect of CR on BSFC in the presence of varying back pressure is presented and analysed. Numerous previous studies, including those conducted by [30, 31, 32], have consistently demonstrated that an increase in CR typically results in a decrease in BSFC. This phenomenon can be attributed to enhanced combustion efficiency, which enables the engine to extract a greater amount of energy from a given volume of fuel, thus leading to improved performance under normal operating conditions. This is indeed validated in Figure 4(a), where increasing the CR from 12 to 18 reduces the BSFC from 610 g/kW-h to around 503 g/kW-h.

On the other hand, the results shown in Figure 4(b) display an interesting and surprising divergence from the usual trend. The data illustrate a directly proportional relationship between CR and BSFC, indicating that as CR is raised from 12 to 18, BSFC correspondingly increases. For instance, at a CR of 12, BSFC is 550 g/kW-h. As the CR gradually increases to its highest value of 18, the BSFC dramatically rises to approximately 4800 g/kW-h. The unusual relationship observed in this study can largely be attributed to the dynamics of back pressure within the engine system. As depicted in Figure 4(c), which illustrates the variation of EBP within the exhaust system, there is a marked increase in EBP from 138.8 kPa to 272 kPa as CR increases. This rise in EBP coincides with the observed increase in BSFC, further supporting the hypothesis that the variation (increase) of EBP plays a significant role in this unusual correlation.

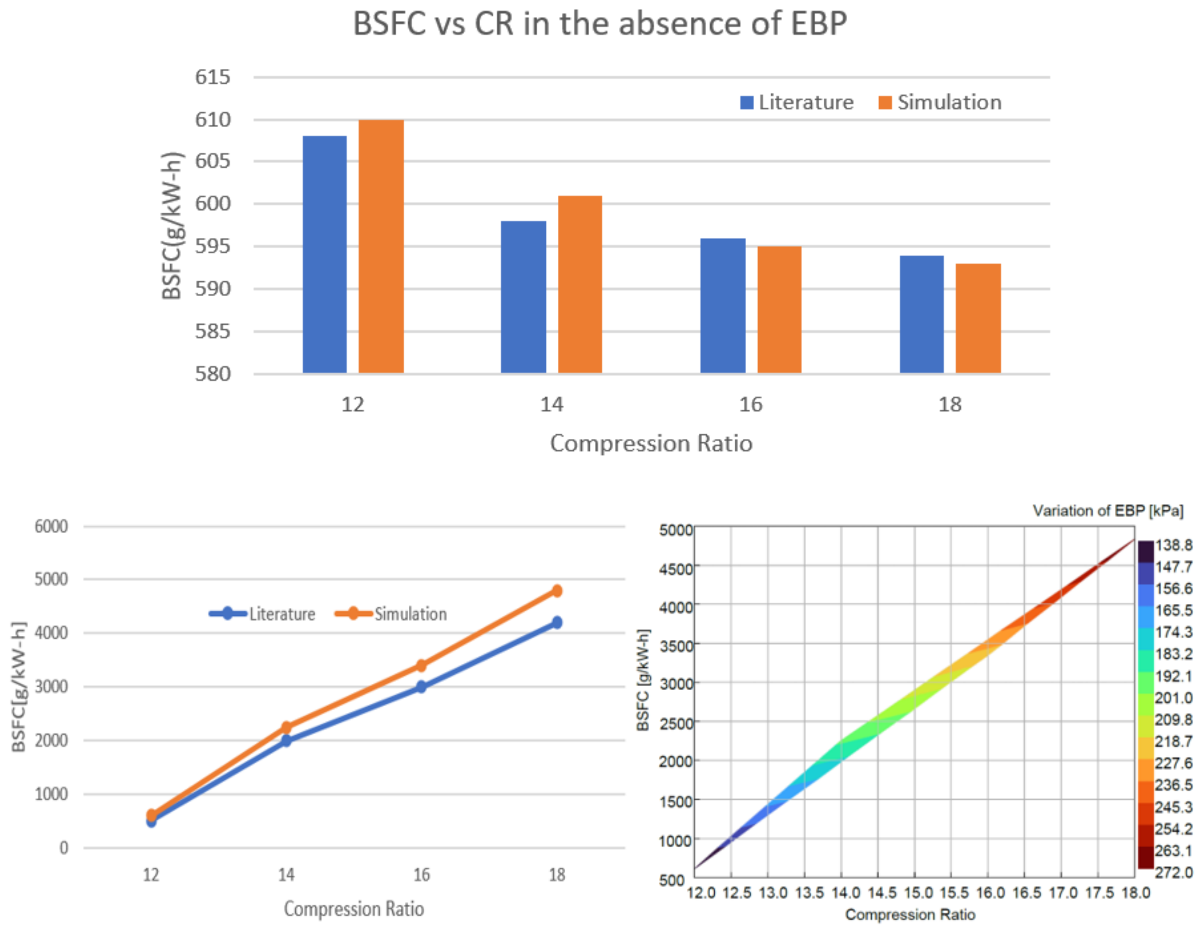

Figure 4: Variation of BSFC with CR, (a) 1D without EBP, (b) 1D with EBP, and (c) 2D with EBP.

3.1.2 Brake Power

CR generally leads to improved thermal efficiency, which can result in increased power output from the engine [33]. This is due to more efficient combustion and higher pressure and temperature at the end of the compression stroke [32,33]. Figure 5 (a) shows the variation of brake power with the increase in CR in the presence and absence of back pressure. It serves as a benchmark for Figures 5 (b) and (c). The brake power values for various CRs in the presence of EBP are shown in Figures 5 (b) and (c). Based on these figures, the graphs clearly demonstrate a strong inverse relationship between brake power and CR. As the CR increases, the brake power decreases. The most dramatic decrease in brake power occurs at lower CRs (between 12 and 14). After 14, the decline becomes more gradual.

Figure 5 (c) illustrates how brake power is affected by the introduction of back pressure into the system. The colour scale clearly shows that increasing EBP significantly reduces brake power across all CRs. The darkest (purple) regions represent the lowest EBP and highest brake power, which are 138.8 kPa and 5.8 kW, respectively. The darkest red regions indicate the highest EBP and lowest brake power (272 kPa and 0.77 kW). The relationship remains nonlinear. The reduction in brake power due to increased EBP is more pronounced at lower CRs. At higher EBP levels (darker reds), the effect of changing the CR on brake power is less pronounced compared to lower EBP levels. This means that at a back pressure of 272 kPa, the engine is already significantly constrained, and altering the CR to even the highest value of 18 has a smaller impact. Additionally, areas of higher brake power are concentrated in the upper left (lower EBP, lower CRs), showing a balance between CR and back pressure. There is no single optimal point; the ideal operating condition depends on the acceptable level of EBP.

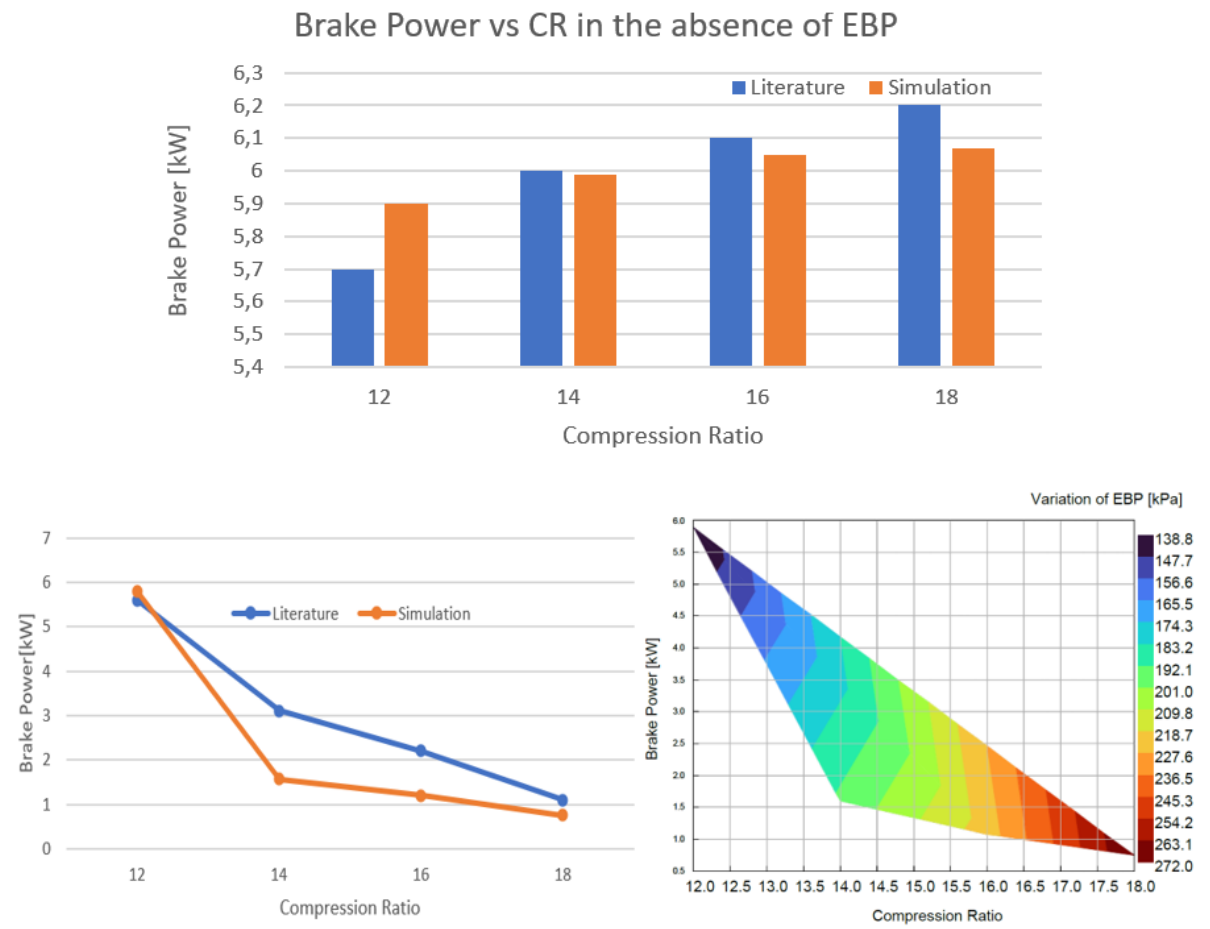

Figure 5: Variation of brake power with CR, (a) 1D without EBP, (b) 1D with EBP, and (c) 2D with EBP.

3.1.3 Brake Torque

Figure 6 (a) illustrates the basic relationship between brake torque and CR. A clear positive correlation is evident: as the CR increases from 12 to 18, brake torque also increases from the initial value of 37.55 N.m to a maximum of 38.65 N.m. This is expected, as higher CRs lead to more efficient combustion and greater power output [31]. The shape of the curve suggests that the rate of torque increase may be diminishing slightly at higher CRs, indicating potential limitation returns at the upper end of the tested range. However, upon closer observation, it is noted that these analyses are similar to those observed in Figure 4 regarding the variation of brake power with CR. This similarity may be due to the inherent relationship between brake power and torque as they relate to CR. Figures 6 (b) and (c) demonstrate how the introduction of back pressure significantly alters this relationship. Both figures show a clear negative correlation between CR and brake torque when back pressure is present. This is illustrated by the rapid decline of brake torque from 37.5 Nm. at a CR of 12 to approximately 10 Nm. at a CR of 14. Moreover, the relationship becomes more gradual until it reaches a CR of 18, which corresponds to a brake torque of 5 Nm. at a maximum back pressure of 272 kPa.

Figure 6 (c) presents a more detailed contour plot that depicts the nonlinear nature of this relationship and reveals the dependency on the level of EBP. Higher back pressure consistently reduces brake torque across all CRs tested (12-18). The extent of this reduction is more significant from a CR of 14 upwards, suggesting that increased CR worsens the negative effects of back pressure on engine performance. The contour plot allows for a precise analysis of how different levels of back pressure affect torque at various CRs. The data suggest that careful consideration of both CR and EBP is crucial for optimizing engine performance.

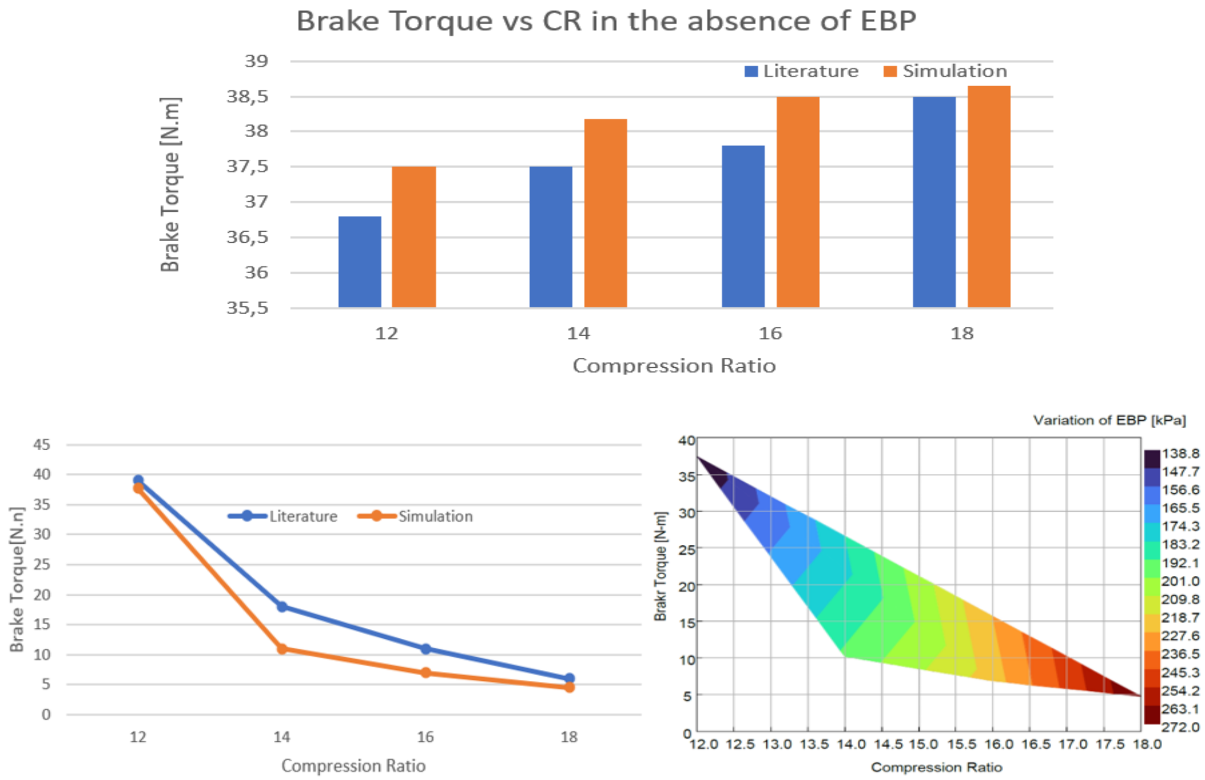

Figure 6: Variation of brake torque with CR, (a) 1D without EBP, (b) 1D with EBP, and (c) 2D with EBP.

3.1.4 Volumetric efficiency

Figure 7 (a) displays a positive correlation between CR and volumetric efficiency. As the CR increases from approximately 12 to 18, volumetric efficiency shows a steady increase. The trend indicates a substantial rise in volumetric efficiency over the observed range of CRs. Figure 7 (c) shows a different relationship between CR and volumetric efficiency in the presence of increasing EBP compared to Figure 7 (a). Instead of a simple linear increase, this plot shows a negative correlation: as the CR increases, volumetric efficiency decreases. The range of volumetric efficiency in this figure is considerably lower (approximately 0.14 to 0.36) than in Figure 7 (a) (approximately 0.3605 to 0.3616), representing a substantial decrease in engine efficiency. The decrease in volumetric efficiency is nonlinear, revealing a more intense decline at higher CRs. The reduction in brake power and torque can be linked to the decline in volumetric efficiency, as both parameters are significantly influenced by the variation of volumetric efficiency.

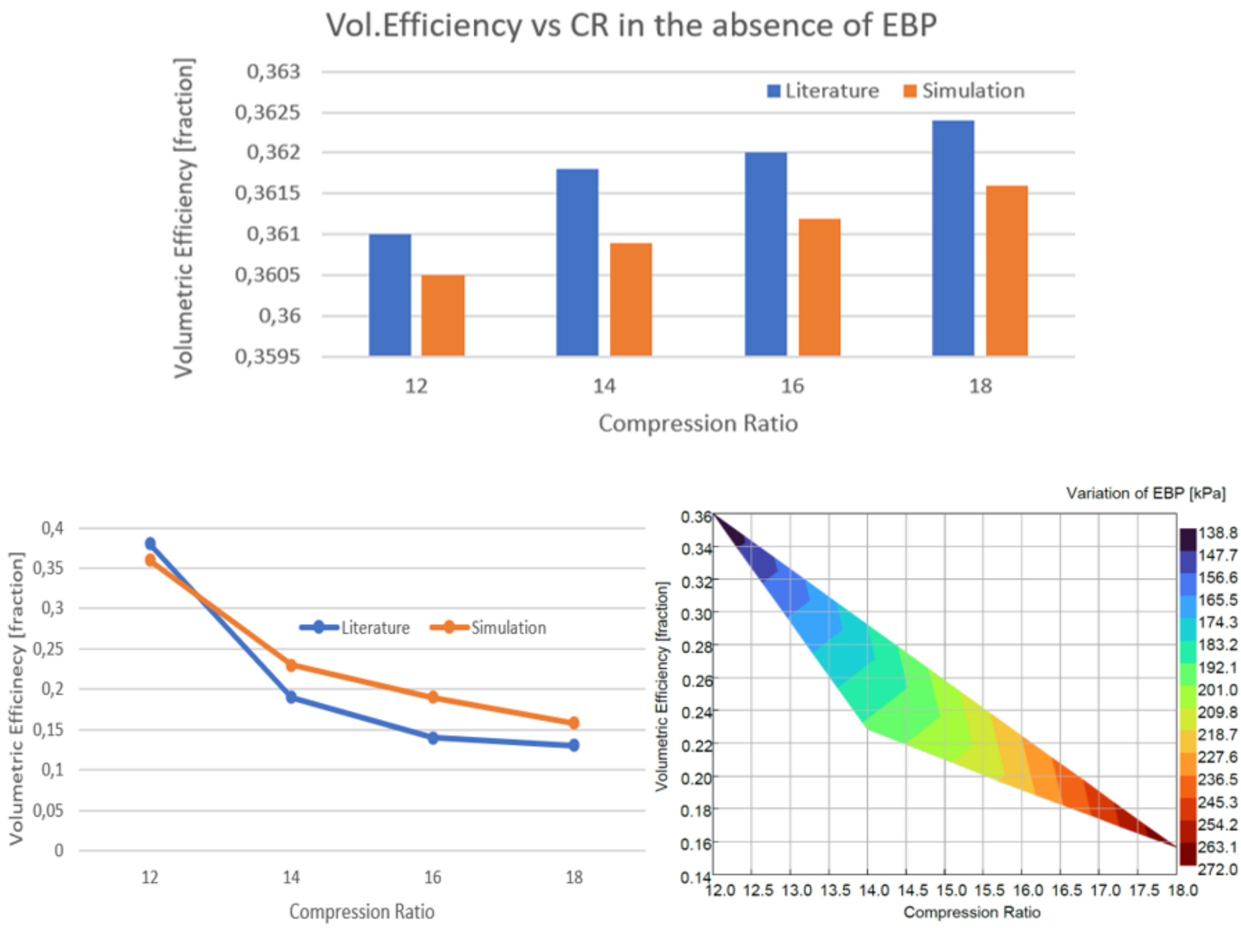

Figure 7: Variation of volumetric efficiency with CR, (a) 1D without EBP, (b) 1D with EBP, and (c) 2D with EBP.

3.2 Emission characteristics

In this section, the emissions characteristics are assessed within the framework of increasing EBP and variable CR. This approach enables a comprehensive evaluation of the engine's environmental impact.

3.2.1 Hydrocarbon

Several studies have reported that as the CR increases, HC concentration shows a corresponding increase. However, some researchers, such as [34,35], have challenged this phenomenon. Based on the current study, it is observed that at a CR of 12, HC concentration is approximately 0.149 parts per million (ppm), as shown in Figure 8 (b). At a CR of 14, HC concentration drops to approximately 0.142 ppm, a decrease of 0.007 ppm or roughly 4.7%. Surprisingly, it then increases to approximately 0.144 ppm at a CR of 18, which is a 2% increase from the minimum at a CR of 14 and a decrease of roughly 3.4% from the starting point at CR 12.This suggests that, specifically for a single cylinder 4-stroke VCR diesel engine, increasing the CR beyond 14 significantly improves engine emission, particularly HC.

The contour plot in Figure 8 (c) reveals that at lower CRs (around 12), HC emissions are higher and EBP varies less. As the CR increases to about 14, the lowest HC emissions are observed, coinciding with moderate EBP levels. However, a further increase in CR above 14 leads to an increase in HC emissions again, and EBP rises significantly. The contour plot provides a better understanding of how both CR and EBP interact in influencing HC emissions. In this case, varying the CR alone is insufficient; its effect relies heavily on the EBP level at the same time. Moreover, this demonstrates that to effectively reduce HC emissions, both factors need to be optimized together.

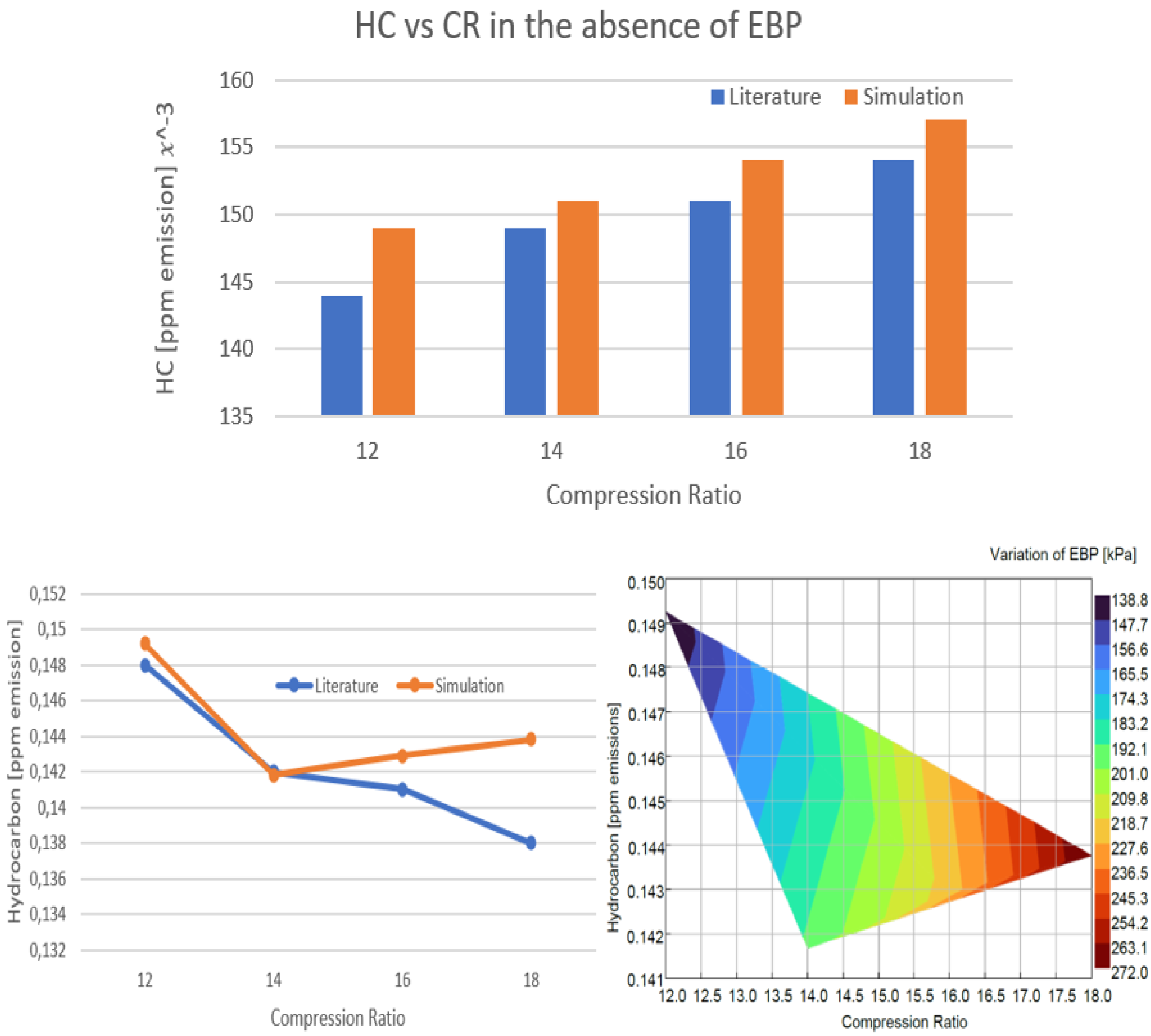

Figure 8: Variation of HC with CR, (a) 1D without EBP, (b) 1D with EBP, and (c) 2D with EBP.

3.2.2 Carbon Monoxide

Figure 9 (a) demonstrates that as the CR increases from approximately 12 to 18, the CO concentration displays a consistent decrease. The decrease appears to be approximately 6% to 8% of the initial CO concentration for each 1-unit increase in CR. This indicates that higher CRs are associated with significantly lower CO emissions, as also discussed by [19, 20]. On the other hand, the visualizations in Figures 9 (b) and (c) show that the effect of CR on CO emissions is greatly influenced by back pressure. The plot reveals a clear trend: higher CRs and higher EBP values are associated with higher CO emissions. Based on Figure 9 (c), the darkest red region, representing the highest CO emissions, is located at the highest values for both CR and EBP. Conversely, the lowest CO emissions are found in the darkest blue region, indicating the lowest values for both CR and EBP. This is evidence that the presence of EBP seems to overrule the potential benefits of a higher CR observed in Figure 9 (a).

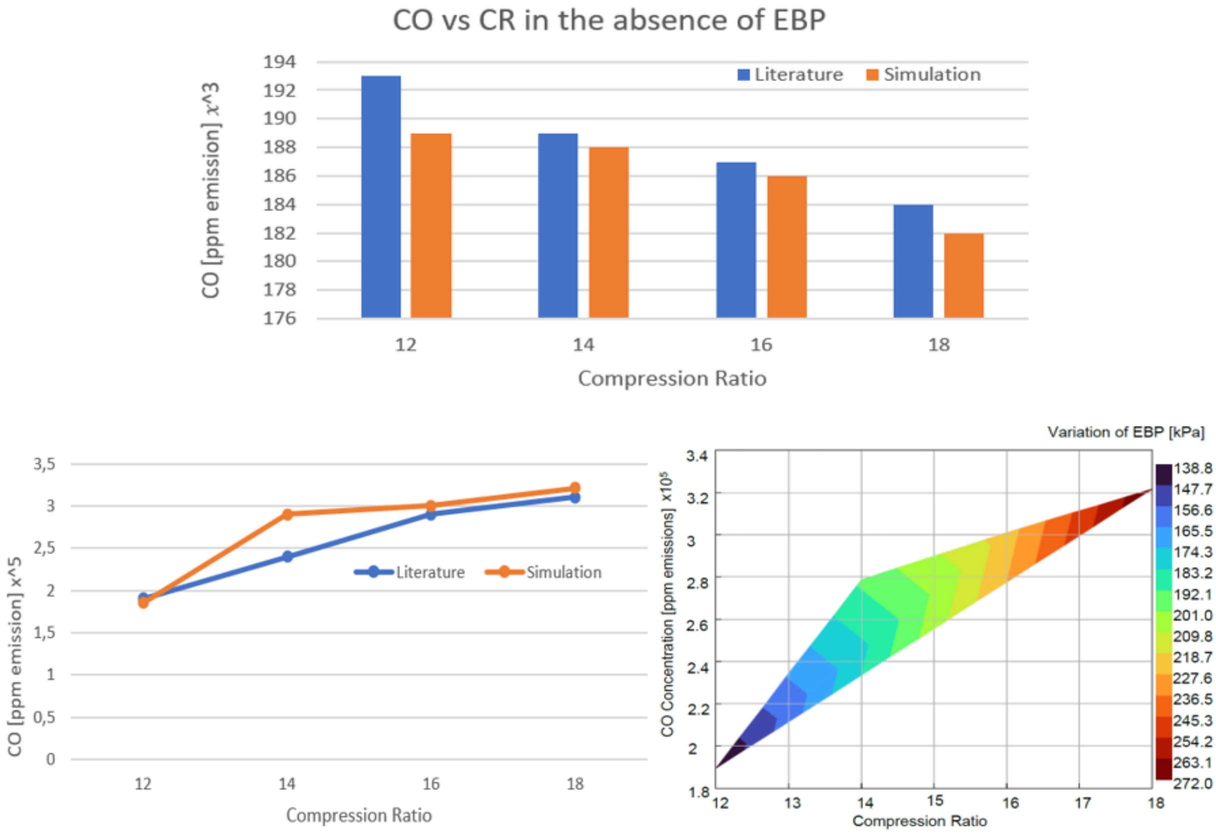

Figure 9: Variation of CO with CR, (a) 1D without EBP, (b) 1D with EBP, and (c) 2D with EBP.

3.3 Findings Implications

To get the idea of how the performance parameters and emission characteristics were affected by the presence of EBP under various CRs, the Tables 7 and 8 are presented. These percentage values are derived from all the plots above using the basic Equation 1 below for calculating the percentage change (increase/decrease).

$$\% \text{ change}= \frac{Final - Initial}{Initial} \times 100 \quad (1)$$

Based on Tables 7 and 8, among the performance parameters, BSFC is the most significantly impactedparameter followed by brake power and brake Torque. On the emissions in Table 8, CO is the most affected characteristic. However, an in-depth overall analysis is performed in Section 4.5 for greater understanding and clear insight.

Table 7: Performance parameters in percentage change at a CR of 12-18.

Performance parameters	In the absence of EBP (%)	In the presence of EBP (%)
BSFC	2,80 ↓	709,171 ↑
Brake power	2,88 ↑	87,18 ↓
Brake torque	2,88 ↑	86,93 ↓
Volumetric efficiency	0,28 ↑	56,39 ↓

Table 8: Emission characteristics in percentage change at CR of 12-18.

Emission characteristics	In the absence of EBP (%)	In the presence of EBP (%)
Carbon monoxide (CO)	0,36 ↓	69,84 ↑

Hydrocarbon (HC)	0,98 ↑	3,77 ↓

3.4 Overall Percentage Contribution

This section presents an illustration of how EBP compromises the advantages or benefits of CR technology in diesel engines. It effectively highlights which performance parameters and emission characteristics are most affected by the presence of EBP in a VCR diesel engine, as depicted in Figures 10 and 11. Through the analysis of these figures, it becomes uncomplicated to identify which parameters experience the most significant changes, whether in terms of increase/decrease in performance parameters or in emissions such as CO, CO_2, and HC. It further assists in interpreting the complex relationship between EBP, VCR, engine performance, and emission characteristics.

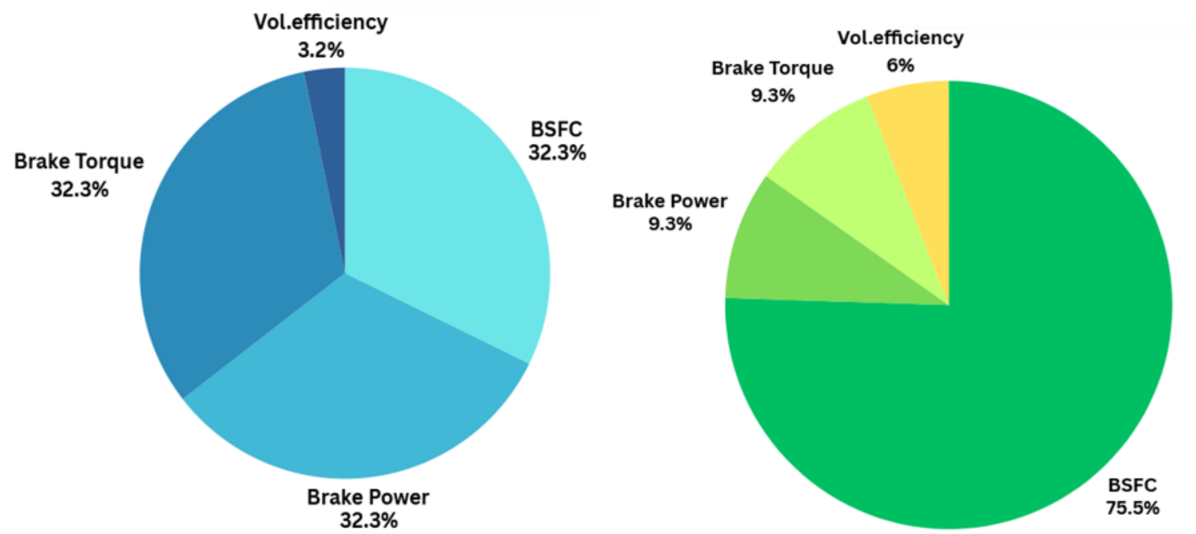

Figure 10: (a) Percentage improvement in performance parameters resulting from increasing compression ratio vs (b) effect of increasing exhaust backpressure in all analysed parameters in percentages.

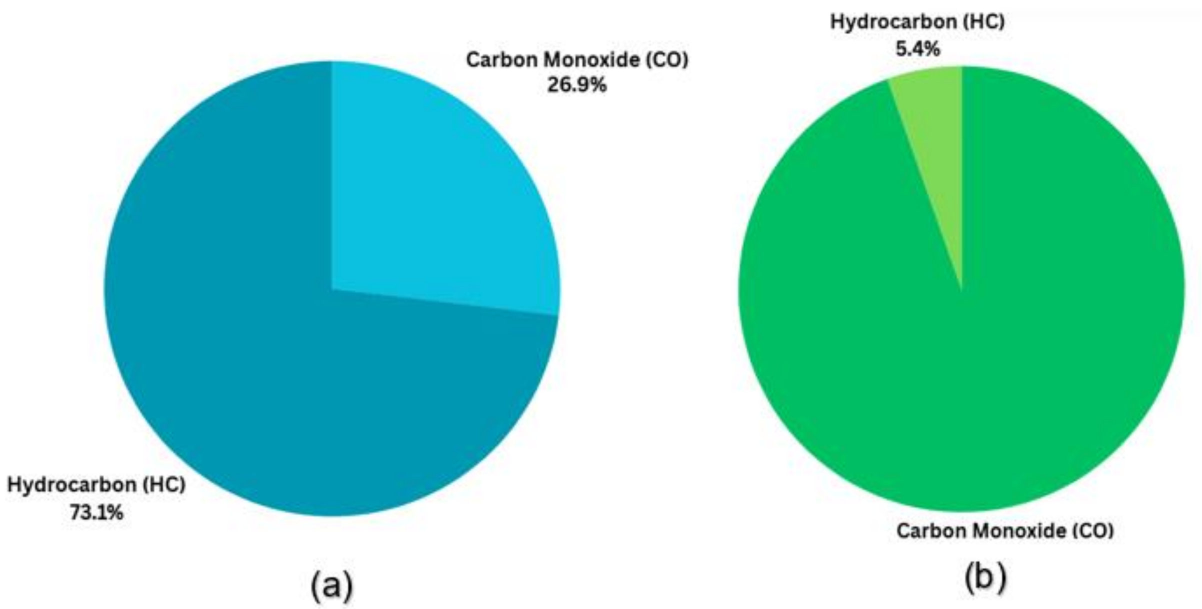

Figure 11: (a) Percentage change in emission characteristics resulting from increasing compression ratio vs (b) effect of increasing exhaust backpressure in all analysed emissions characteristics in percentages.

Based on Figure 10 (a), it is evident that varying the CR has a consistent impact on BSFC, brake power, and brake torque, as reflected in similar percentage changes across these parameters. When the CR is varied from 12 to 18, both brake power and brake torque experience a significant percentage increase of 32.5%, while BSFC decreases by 31.6%. However, the impact of CR variation on volumetric efficiency is minimal, showing only a slight increase of 3.3%. The presence of back pressure in the exhaust system eliminates the benefits associated with varying the CR. As noted in Figure 10 (b), both brake torque and brake power decrease by 9.3%, while volumetric efficiency is the least affected, experiencing only a 6% decrease. Interestingly, BSFC emerges as the most impacted performance parameter, demonstrating a substantial increase of 75.5% under increasing EBP. This escalation in BSFC may be attributed to incomplete combustion of the fuel, resulting in higher fuel consumption for the same power output.

On the other hand, Figure 11 (a) shows that increasing the CR from 12 to 18 results in a reduction of CO emissions by at least 26.9%. However, this same adjustment leads to a significant increase in HC emissions, rising by 73.1%. With the presence of back pressure, illustrated in Figure 11 (b), CO emissions drastically increase by 94.6%, while HC emissions decrease by 5.4%. The findings regarding HC are particularly surprising, as most studies indicate that increasing the CR generally has a negative linear relationship with HC content [36, 37, 38]. However, a few studies, including those by Nguyen et al. [39], Zardoya et al. [40], and Renish et al. [41], suggest that as the CR increases, the temperature and pressure in the combustion chamber also rise, theoretically leading to more complete combustion. Nevertheless, the presence of EBP may obstruct the effective removal of exhaust gases, resulting in the retention of unburned fuel and combustion by-products (HCs). This obstruction can ultimately lead to higher HC emissions, particularly at high CR levels, as the combustion process becomes less efficient.

4 Conclusions

In the current study, the influence of exhaust backpressure (EBP) and varying compression ratio (VCR) on the performance parameters and emission characteristics of the single-cylinder, 4-stroke VCR diesel engine was assessed under a constant engine speed of 1500 rpm. GT-POWER software was used to simulate these parameters and validation of this model was achieved through previous similar findings. The results obtained from this work are summarised as follows:

- Contrary to common findings, increasing the CR led to a significant increase in BSFC, primarily due to the substantial rise in EBP. Removing the exhaust orifice eliminated this unusual relationship, confirming EBP's dominant role. Moreover, BSFC was the most affected parameter up to 75% increase due to the presence of EBP.
- Higher CRs generally improve thermal efficiency and increase brake power; however, increased EBP significantly reduced brake power across all CRs. The reduction was more pronounced at lower CRs. There's a trade-off; higher CRs improve power at lower EBP levels.
- Like brake power, higher CRs initially increased brake torque. However, increased EBP led to a significant decrease in torque at higher CRs. The effect is more pronounced at higher CR levels.
- While higher CRs typically improve volumetric efficiency, the presence of EBP caused a significant decrease in efficiency.
- Increasing the CR showed unexpected HC emission patterns. Initially lowering, then increasing at higher CRs. EBP significantly influences HC emissions and interacts with CR in a non-linear way.
- Higher CRs reduced CO emissions, particularly without EBP. However, increased EBP offsets the positive impact of increased CR, leading to higher CO emissions.

While higher CR generally promotes better combustion and energy removal, the increase in EBP seems to eliminate these benefits, thereby greatly influencing engine performance. The present study emphasizes the necessity of finding a balance between CR and EBP to improve engine performance while minimizing emissions. To attain these optimal results, it is crucial to assess both factors together. The findings of this research contribute to a better understanding of the relationship between exhaust dynamics, VCR technology, and overall engine performance. This understanding paves the way for advancements in diesel engine technology and efficiency. Future work should incorporate the influence of varying the engine speed and load on the same diesel engine and observe the outcomes under varying CRs and in the presence of increasing EBP. Additionally, other researchers should look at how biodiesel blends may assist in improving these performance parameters and emission characteristics under the same conditions of VCR and variation of EBP.

Acknowledgements

Supporting information

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