Optimization Strategies for Managing Exhaust Back Pressure in Variable Compression Ratio Diesel Engines

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Abstract : The implementation of variable compression ratio (VCR) engines in diesel technology has improved performance, fuel efficiency, and pollution control. However, controlling exhaust back pressure (EBP) is a challenge for these engines. Efficient EBP management is crucial for optimal engine operation and desired performance outcomes. This review paper addresses the lack of studies on exhaust system configurations in VCR engines and provides insights into optimization strategies for tackling EBP challenges. The paper explores techniques such as after treatment systems (ATS), regeneration cycles, exhaust thermal management control, variable valve train strategies, and airflow management strategies. The goal is to provide practical guidance for managing this complex issue through innovative strategies. The study also highlights future directions and challenges, including the implementation of variable geometry turbochargers, active exhaust valve control systems, integrated thermal management solutions, innovative materials and manufacturing processes, and the use of sensors for real-time monitoring.

Key words: Variable compression ratio, Exhaust Back Pressure, After treatment systems, regeneration cycles, variable valve train strategies.

1 Introduction

The most recent development in the discipline of diesel engine technology is the introduction of variable compression ratio (VCR) engines. This innovation aims to improve performance, fuel efficiency, and pollution management [1]. Despite this, the effective management of the EBP remains a significant challenge for these advanced engines. The exhaust system's resistance can significantly influence the engine's performance, the generated pollutants' concentration, and the overall system's efficiency [2, 3]. In order to fully utilize the potential of diesel engines with VCRs, it is absolutely necessary to develop and implement optimization solutions that specifically target the reduction of issues brought on by EBP.

Efficient management of EBP is vital for ensuring optimal engine operation and achieving desired performance outcomes in VCR diesel engines. Engineers may optimise the engine and exhaust system by precisely adjusting different components to manage backpressure. This allows them to achieve a delicate equilibrium that maximises performance and reduces hazardous emissions [4, 5]. Few studies have attempted to develop a conceptual framework for monitoring backpressure and mitigating its impact, thereby enhancing the efficiency of the VCR diesel engine [6, 7, 8]. This is noticed by the lack of studies that involve a detailed investigation into the exhaust system configurations of the VCR diesel engines. Consequently, this review thoroughly examines optimisation solutions specifically aimed at addressing the difficulties caused by EBP in VCR diesel engines. Through a critical review of innovative approaches and best practices, this study aims to provide valuable insights and practical guidance for engineers and researchers seeking to optimize engine performance in a dynamic operating environment.

2 Fundamentals of EBP (EBP)

EBP is a crucial parameter in the operation of internal combustion engines, impacting performance, emissions, and overall efficiency. When exhaust gases exit the engine cylinders, they flow through the exhaust system to be expelled into the atmosphere [9]. Backpressure refers to the resistance encountered by these gases as they navigate through the exhaust system before exiting the tailpipe. This resistance is primarily caused by components such as catalytic converters, mufflers, exhaust pipes, and bends. An excessive amount of backpressure can disrupt the flow dynamics, leading to reduced engine performance, increased fuel consumption, and compromised emissions control [10, 11].

Efficiently managing the exhaust's backpressure is critical for optimizing engine efficiency and achieving desired outputs. Excessive levels of backpressure can cause a restriction in the exhaust system, limiting the movement of exhaust gases and reducing the engine's efficiency in discharging combustion waste [12]. As a result, this can lead to a decrease in power generation, a reduction in torque, and ineffective fuel burning. In addition, an excessive amount of backpressure can cause an increase in exhaust gas temperatures, which can potentially result in overheating problems, reduced engine dependability, and rapid deterioration of engine components.

On the other hand, to effectively control EBP, researchers need well-designed exhaust system components, good maintenance practices, and effective engine tuning. Researchers can help reduce backpressure and improve the engine's performance by selecting elements such as high-flow catalytic converters and mufflers that do not restrict flow excessively. For optimal exhaust flow and to avoid blockages, it is important to do regular maintenance, which includes cleaning and checking the exhaust system's parts [13]. Also, making changes to the engine's tuning, like adjusting the fuel flow and air-fuel ratios, can help lower backpressure and make the engine run more efficiently [14]. These are all strategies that can be potentially applied to manage the EBP and maximize the performance and longevity of internal combustion engines while promoting better overall efficiency and emissions compliance.

3 After treatment systems (ATS)

After treatment systems (ATS) in internal combustion (IC) engines have a crucial function in decreasing harmful emissions and complying with strict environmental laws. These systems have been designed to filter exhaust gases as they exit the engine, eliminating harmful substances including nitrogen oxides (NOx), particulate matter (PM), carbon monoxide (CO), and hydrocarbons prior to their discharge into the atmosphere [15]. Typical elements found in after treatment systems include die sel particulate filters (DPFs), selective catalytic reduction (SCR) catalysts, diesel oxidation catalysts (DOCs), and exhaust gas recirculation (EGR) systems.

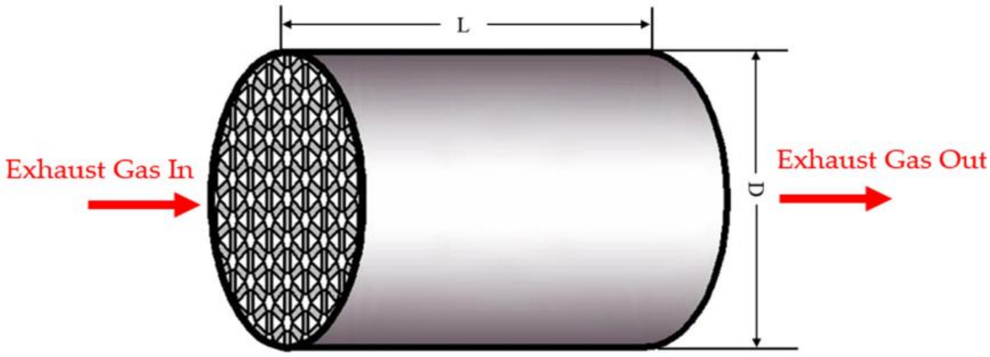
Previous studies have shown that high levels of backpressure can disrupt the flow of exhaust gases through the system, affecting the performance of components such as DPFs, SCR catalysts, and DOCs [16, 17]. It is crucial to maintain an ideal equilibrium between EBP and ATS performance in order to maximise the efficacy of emissions management and minimise any detrimental effects on engine running. Few studies have suggested that designers must take into account elements such as the design of the exhaust system, the location of components, and the tuning in order to ensure that the levels of backpressure are within acceptable limits for the efficient operation of after treatment [18, 19]. However, some scholars have reported that managing EBP requires more than monitoring the ATS, and it is an ongoing challenge within the scientific field.

3.1 Diesel particulate filter (DPF)

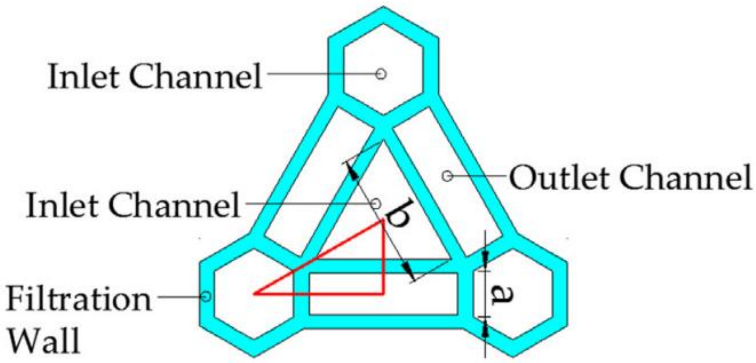
Diesel particulate filters (DPFs) are designed to collect and eliminate particulate matter present in the exhaust of diesel engines, thereby minimising the emission of black smoke and hazardous substances [20]. Regeneration procedures, whether passive (occurring at high exhaust temperatures during normal driving) or active (including purposefully increasing exhaust temperatures), are necessary for the combustion of accumulated soot and the preservation of DPF efficiency. In diesel engines equipped with DPFs, high levels of EBP can obstruct the regeneration process, which is essential for burning off accumulated soot and maintaining the filter's effectiveness. Increased backpressure may impede the flow of exhaust gases through the DPF, preventing the temperature from reaching the required levels for effective regeneration [21, 22]. The DPF has proven to be successful in reducing PM emissions from diesel engines. However, a drawback of the DPF is its adverse impact on the engine's fuel efficiency, as it also increases the EBP. Consequently, previous studies have shown that periodic or continuous regeneration events are essential for reducing the negative impact on fuel efficiency caused by high EBPs [23, 24, 25].

The filter's porous section captures PM. Nevertheless, the accumulation of PM on the filter wall causes the filter to gradually become blocked. DPF's carbon filtration efficiency can exceed 90%. During filtration, particulate deposition in the filter will lead to an increase in the exhaust back pressure of the diesel engine. Reduced EBP will definitely increase the costs associated with developing the exhaust system and diminish the sound quality. Therefore, it is crucial to maintain optimal back pressure levels for both performance engines and DPFs. Yang et al. [26] subsequently proposed that the design of the DPF should take into account factors such as filtration efficiency, pressure drop, and high temperature resistance. Similarly, Chiavola, Chiatti, and Sirhan [26] and Xiaobo Li [27] reported that in order to mitigate the blockage, the collected particles should undergo a reaction and combustion process. Alternatively, the operation of changing the filter should be carried out at specific intervals. Numerous studies have reported on this approach, which ensures an improvement in engine performance and efficient engine EBP management. Other studies have investigated the impact of injection parameters on particulate emissions and concluded that a micro-hole nozzle with high injection pressure will reduce particulate matter to a greater value [28, 29].

These current studies are evidence that, when designing the DPF, EBP should be a vital consideration. In fact, Bardon et al. [30] introduced a channel design with a wavy pattern. This design was based on a square symmetry channel filter and involved adding a sinusoidal undulation to the filtering system's walls. Through this approach, the volume of the inflow channel and the area available for filtering were enhanced, leading to a reduction in back pressure and an increase in ash storage capacity. Nevertheless, the filter wall proved to be insufficient in strength and prone to cracking, therefore rendering it impractical for use. Xiao et al. [31] proposed a new type of asymmetric channel particulate filter, named HRT filter, as the cross section of the channels is composed of hexagons, rectangles, and triangles (Figure 1). The HRT structure gains three potential advantages: (1) reducing the regeneration frequency and the regeneration cost of the DPF; (2) reducing the filter volume with equal soot load; and (3) reducing the EBP of the diesel engines, then improving the power performance and fuel economy.



a)



b)

Figure 1: a) Overall structure of the HRT filter body and

b) Cross-sectional diagram of the channel [31].

3.2 Selective catalytic reduction (SCR)

Selective Catalytic Reduction (SCR) is a widely employed technology for minimising nitrogen oxide (NOx) emissions from the exhaust systems of diesel engines. Although SCR systems are highly efficient in decreasing harmful emissions, they can also cause an increase in backpressure within the exhaust system [32]. SCR systems employ catalysts, such as AdBlue, which is based on urea, to transform NOx into nitrogen and water, resulting in a substantial decrease in NOx emissions [33, 34]. When employing SCR technology, it is crucial to design the exhaust system in a manner that reduces any potential rise in backpressure, thereby effectively managing it. Accurate dimensioning of components, such as the SCR catalyst and the related piping, is essential to prevent excessive restriction of exhaust flow, which may result in increased backpressure [35]. In addition, it is crucial to undertake routine maintenance and monitoring of the SCR system to ensure maximum efficiency and avoid accumulation or restriction that may lead to increased backpressure.

Several studies have been conducted aiming to manage backpressure while employing SCR. For instance, Karamitros and Koltsakis [36] reported that the backpressure across SCR catalyst coated on DPF (referred to as SCRF) can be minimized by the use of high porosity filters and by optimizing the wash coat loading of the filter without a large impact on the NOx reduction performance [37]. Similarly, Guan et al. [38] validated that integrating the SCR and DPF functions into one single unit by washing and coating the SCR catalyst onto the wall-flow DPF may be a viable solution to manage backpressure. The schematic diagram illustrated in Figure 2 presents the phenomena of PM filtration in a DPF, the passive soot oxidation in the soot cake layer, and the SCR reactions in the substrate wall [39, 40]. Many other researchers have reported that advanced coating technology and different concentrations of catalyst along the axis with different lengths will significantly assist in managing backpressure.

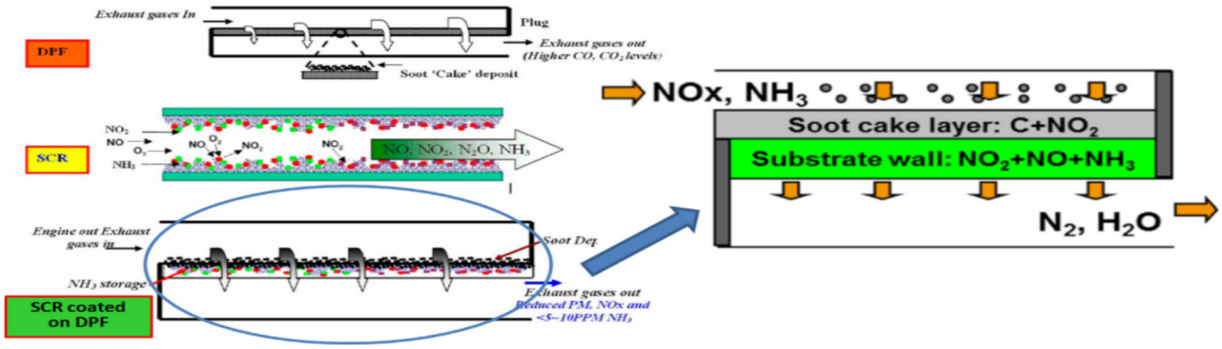


Figure 2: Schematic of physical and chemical processes in a single wall-flow substrate channel for the SCRF [40]

3.3 High-flow catalytic converters and mufflers

It is well known that catalytic converters and mufflers play crucial roles in automotive exhaust systems, but they can also influence EBP in different ways. Catalytic converters, which are critical for reducing harmful emissions, may cause backpressure due to their traditional honeycomb structure, which can obstruct the flow of exhaust gases [41]. The configuration and compactness of the catalyst, along with the overall dimensions of the converter, collectively influence the magnitude of the backpressure imposed on the system. Additionally, the backpressure is directly proportional to the pressure drop across the catalytic converter or design of complete exhaust system components causing the backpressure [42]. On the other hand, most muffler designs aim to reduce noise by utilizing baffles, chambers, and acoustic materials to absorb sound waves and produce acoustic reflections [43]. Nevertheless, while mufflers can effectively reduce noise, they may inadvertently result in an increase in backpressure. Consequently, researchers have been exploring potential strategies to effectively employ catalytic converters and mufflers while managing the backpressure [44, 45].

With reference to Pangavhane et al. [46], the backpressure varies nonlinearly, and it cannot be predicted by any equation. However, research has suggested that manufacturers must carefully balance the need for efficient emissions control with minimizing backpressure to maintain optimal engine performance. However, this has been a challenge for many engine manufacturers. Nevertheless, some scholars have reported that strategic design considerations, such as the placement of baffles and the design of perforated tubes inside the muffler, are crucial in managing backpressure levels while still effectively reducing noise. According to Baharudin and Watson [47], catalyst models include: (1) hexagonal-shaped, (2) trigonal-shaped, (3) square-shaped, (4) circular-shaped, triangular arrangement, (5) circular-shaped, square arrangement, and (6) circular shape, circular arrangement, as illustrated in Figure 3. Each model has distinct properties, such as wall thickness and the number of catalyst cells, which can influence its performance.

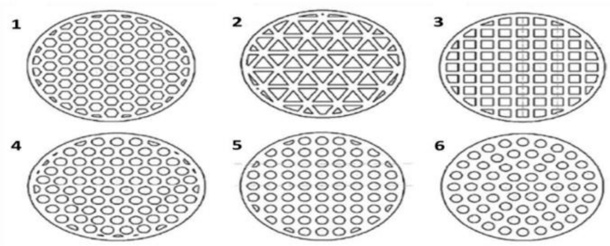


Figure 3: Various models of catalyst [47].

Reports have suggested that varying the porosity of the muffler has a pronounced effect on the backpressure. Also, if the diameter of the hole is increased, the backpressure decreases sharply. In an effort to manage backpressure, Lu et al. [48] designed and analysed the catalytic converter for conventional diesel engines, in which they modified the hole diameter in a honeycomb structure as seen in Figure 4. Modifications in the design were observed to enable the uniform spread of flow within the casing, effectively using the entire area of the honeycomb structure. This led to a decrease in pressure across the catalytic converter, hence reducing backpressure. In contrast, a study conducted by Xu et al. [49], showed that the greater the number of catalyst cells, the higher the conversion efficiency and durability. However, the thicker the surface wall of the catalyst, the higher the back pressure, which can reduce engine combustion efficiency.

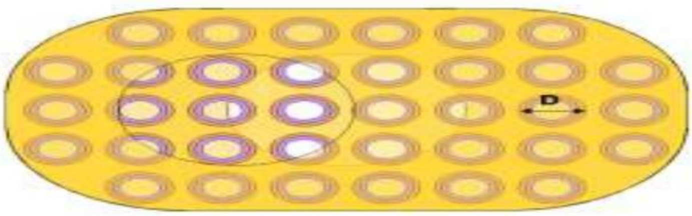


Figure 4: Modified honeycomb structure hole diameter [48].

3.4 Regeneration cycles

Regeneration cycles are frequently employed in exhaust after treatment systems, such as DPF, to effectively regulate and mitigate backpressure. The regeneration procedure entails the combustion of accumulated soot within the filter to prevent blockage and uphold optimal performance [50]. Optimal engine performance and emission control can be ensured by efficiently managing backpressure by adjusting the time and frequency of regeneration cycles. Several studies have been conducted to analyse the impact of regeneration cycles on EBP and system performance [51, 52].

Research has shown that optimizing the frequency of regeneration cycles can help reduce backpressure while ensuring effective soot combustion. Moreover, recent reports have suggested that adjusting the regeneration intervals based on engine operating conditions may reduce the backpressure and yield improved overall system efficiency. Zhang et al. [53] compared different regeneration strategies, such as passive, active, and forced regenerations, to evaluate their effectiveness in managing backpressure. Findings suggest that active regeneration methods can offer better control over backpressure levels and reduce the risk of filter clogging. Bagheri, Ershadi, and Assareh [54] developed computational models and simulations to assess the influence of regeneration cycles on backpressure dynamics. This study provided insights into the optimization of regeneration parameters and their impact on the exhaust system performance of a diesel engine. Luo et al. [55] conducted research that focused on evaluating the effects of various regeneration strategies on the overall performance of ATS. The study demonstrated that measuring backpressure under different regeneration conditions provides an insight into optimizing regeneration cycles for improved system efficiency and management of backpressure.

On the other hand, researchers have been focusing on developing and testing active regeneration control strategies to minimize backpressure in diesel engines. For instance, Miranda et al. [56] implemented the real-time control algorithms. The study aimed to optimize regeneration cycles for reduced exhaust restriction and enhanced engine efficiency. Dimaratos et al. [57] conducted a simulation-based study, where they modelled the impact of regeneration cycles on backpressure in light-duty vehicles. This study assisted in exploring the relationship between regeneration parameters and backpressure dynamics to inform optimal regeneration strategies. These studies collectively highlight the significance of regeneration cycles in managing and controlling EBP, showcasing the importance of strategic regeneration approaches in ensuring optimal engine performance and emission control.

3.5 Exhaust thermal management control

Exhaust thermal management control refers to the implementation of various strategies to regulate and optimize the temperature of exhaust gases in a vehicle's exhaust system [58, 59]. This control is crucial for improving overall engine performance, emission control, and fuel efficiency. Implementing exhaust thermal management control systems in diesel engines also facilitates compliance with emissions standards and plays a crucial role in reducing EBP [60]. By optimising the distribution of heat throughout the exhaust system, engineers can improve the performance of the engine and ensure that the aftertreatment components remain functional and work more efficiently. Several reports have suggested that by regulating the temperature of exhaust gases, several strategies can be employed to help mitigate and control backpressure effectively [61, 62]:

1. **Temperature modulation**: Adjusting exhaust gas temperatures through techniques like exhaust gas recirculation (EGR) or selective cooling can impact backpressure levels. Moreover, controlling the temperature of gases entering the ATS, the risk of excessive backpressure can be minimized.
2. **Catalyst efficiency**: Ensuring that the catalytic converter remains at the ideal operating temperature is essential for efficient emissions management. Researchers have demonstrated that by regulating exhaust temperatures to maintain catalyst operation, it is possible to minimise backpressure caused by ineffective pollutant conversion.
3. **Heat recovery systems**: Implementing heat exchangers or waste heat recovery systems can help utilize exhaust heat energy efficiently. Extracting heat from the exhaust gas and redirecting it for other purposes,

such as cabin heating or engine operation can immensely assist in reducing backpressure-causing thermal losses.

Additionally, some other scholars have emphasized that strategies for exhaust thermal management control may further involve the use of heat exchangers, insulation, EGR, selective cooling, variable geometry turbochargers (VGT), and temperature sensors to monitor and adjust exhaust temperatures in real time [63, 64]. This is evidence that researchers are making efforts to explore various ways of managing backpressure in diesel engines. However, there are few reports that specifically address this issue in the VCR diesel engines. This could be due to the complexity of this innovation or to negligence, as most scholars are familiar with the conversional diesel engine. Consequently, these reports have served as a foundation and assisted immensely in the research field of VCR diesel engines.

4 Variable valve train strategies

In diesel engines, the variable valve train method allows for precise adjustment of the timing, lift, and duration of intake and exhaust valves. This optimisation enhances engine performance, reduces emissions, and improves efficiency under various operating situations [65]. Additionally, this technology provides the ability to actively regulate valve events, allowing the engine to efficiently adjust to various conditions. Utilizing variable valve train strategies can be an innovative approach to managing backpressure in diesel engines. Reports have suggested that by dynamically adjusting valve timing, lift, and duration, these strategies can optimize engine performance, emissions control, and exhaust gas flow, ultimately influencing backpressure levels [66, 67].

Nora, Lanzanova, and Zhao [68] assessed the effects of valve timing, valve lift, and EBP on the performance of gasoline direct injection (GDI) engines. The study showed that adjusting valve timing and lift from 3mm to 8mm (Figure 5) can have a significant impact on EBP. Moreover, this study was validated by Abdelrahman et al. [69] when they demonstrated that strategically varying these parameters yields improvements in scavenging efficiency, EGR control, and overall engine performance. Other researchers have been interested in the impact of turbocharging systems. For instance, Jiaqiang et al. [70] investigated the performance and economic characteristics of a diesel engine with a variable nozzle turbocharger. The study concluded that coordinating valve timing with turbocharger functions has effects on exhaust gas flow, energy recovery, and backpressure management.

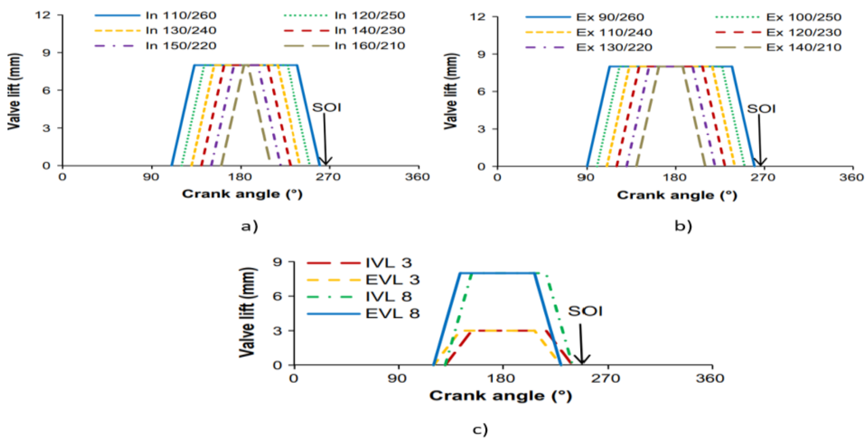


Figure 5: Positions and heights of a) intake valve, b) exhaust value, and c) the combination for these two [68].

Other scholars, on the other hand, have been investigating the role of variable valve timing in meeting emission regulations and improving ATS efficiency. Consequently, they have proven that optimizing exhaust gas temperatures through valve control may have an impact on exhaust emissions and backpressure levels [71, 72]. However, recent studies have shifted the focus to the development of advanced control algorithms for variable valve train systems. For example, Ding et al. [73] evaluated the effectiveness of real-time valve control in managing backpressure. The study concluded that dynamically adjusting valve timing based on engine load, speed, and other parameters could assist in managing backpressure in diesel engines. Other studies have explored the synergies between variable valve train strategies and other engine technologies and reported that a combination of these optimization techniques may be essential in managing backpressure, thus maximizing the engine performance [74, 75].

5 Airflow management

Airflow management in diesel engines involves regulating and maximising the flow of intake and exhaust air to improve combustion efficiency, engine performance, emissions control, and overall system operation [76]. Airflow management is crucial for optimising engine performance, managing backpressure and reducing environmental impact by carefully controlling the intake of air for combustion and the discharge of air through the exhaust system. The restriction of exhaust gases which results in backpressure can be cautiously managed by controlling the intake and exhaust flow of air [77]. In general, a reduction in airflow would result in a decrease in the overall air-fuel ratio, causing a rise in the combustion temperature and thus resulting in a higher exhaust gas temperature. This higher exhaust gas temperature may result in higher backpressure.

Excessive back pressure can have an impact on the turbocharger's functionality, resulting in changes in the air-to-fuel ratio that are typically enriched. This can potentially contribute to emissions and engine performance issues. The extent of the impact is contingent upon the nature of the charged air systems. High exhaust pressure may restrict the discharge of certain exhaust gases from the cylinder, particularly in naturally aspirated engines [78]. This can lead to the formation of an internal exhaust gas recirculation (EGR) system, which contributes to the reduction of nitrogen oxides (NOx). The observed decreases in NOx emissions with certain DPF systems, typically ranging from 2–3%, can perhaps be attributed to this phenomenon [79].

Researchers have discussed several ways in which airflow management can help to positively manage backpressure in diesel engines. For instance, Magar and Sundar [80] experimentally proved that 12°C reduction in intake manifold temperature through intercooler design optimization and adding insulating sleeves over the intake air system can significantly reduce the backpressure by 10%. Jiang et al. [81] reported that optimizing intake airflow through techniques like variable intake geometry, air filters, and intake manifold design can help reduce backpressure by ensuring the engine receives the correct air-fuel mixture for efficient combustion. Ukrop, Shanks, and Carter [82] on the other hand, predicted the running vehicle EBP using the airflow management technique. The analysis incorporated the function diagram for theoretical hot flow calculation (Figure 6), including all the necessary parameters that are vital for predicting EBP. The study further assessed the impact of the exhaust flowrate on the cold and hot EBP, as seen in Figure 7. The results in Figure 7 demonstrated a linear relationship, depending if it's a cold or hot EBP.

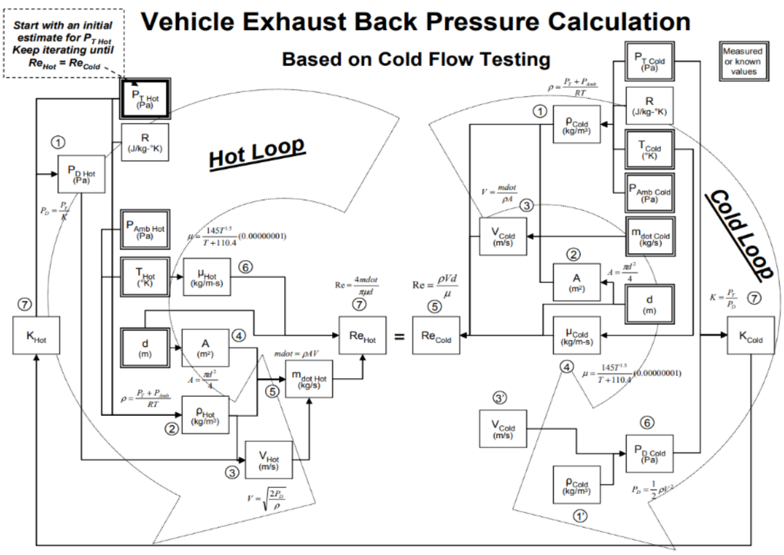


Figure 6: Function diagram for theoretical hot flow EBP Calculation [82].

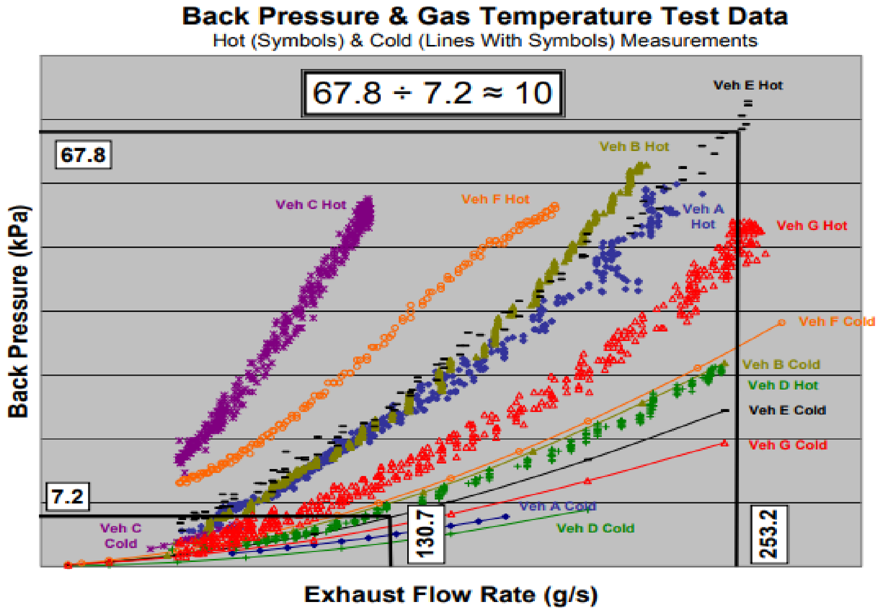


Figure 7: Measured cold and hot back pressure data [82].

Other studies have focused on turbocharger control to reduce backpressure. These reports have demonstrated that effective turbocharger control strategies, such as adjusting boost pressure and waste gate operation, can help manage backpressure in diesel engines [83, 84]. On the other hand, the correlation between airflow management and thermal management in diesel engines has been a topic of interest. In this area, many scholars have reported that optimizing exhaust gas temperatures and airflow distribution may offer improvements in reducing backpressure, enhancing combustion efficiency, and achieving better emissions control [85, 86].

6 Future directions and challenges

All these studies have provided an insight for future directions in managing EBP in VCR diesel engines, which could involve developing advanced technologies to optimize exhaust system designs. There are some notable gaps within the current studies. For example, some potential strategies and challenges that comprise a few studies include the implementation of the following technologies:

1. Implementation of variable geometry turbochargers for effective backpressure regulation based on engine operating conditions.
2. Utilization of active exhaust valve control systems to modulate backpressure by managing exhaust valve opening and closing.
3. Development of integrated thermal management systems to maintain optimal exhaust gas temperatures and reduce backpressure.
4. Innovation in materials and manufacturing processes to create lightweight and durable exhaust components conducive to minimizing backpressure.
5. Integration of sensors in the exhaust system for real-time monitoring and data analytics for insights on backpressure levels and predictive maintenance

Ultimately, the effective management of EBP in VCR diesel engines depends on the advancement of integrated and adaptive technologies that can seamlessly integrate the engine's variable compression capabilities with advanced turbocharging, EGR, and thermal management systems. To fully maximise the efficiency, performance, and emissions control of variable compression ratio diesel engines, it is crucial to address these difficulties by implementing innovative strategies and customised solutions.

7 Concluding remarks

This review paper highlights the critical importance of effectively managing EBP in the context of innovative VCR engines. It thoroughly explores the impact of EBP on engine performance, emissions control, and overall system efficiency. Several studies have made efforts to manage backpressure. However, this current literature discusses some key areas in detail, which include the fundamentals of EBP and ATS, including DPFs and SCR, as well as strategies involving high-flow catalytic converters and mufflers, regeneration cycles, variable valve train strategies, airflow management, and exhaust thermal management control. According to the reviewed literature integrating innovative technologies like variable geometry turbochargers, active exhaust valve control systems, and integrated thermal management systems, researchers and engineers can develop advanced solutions for managing EBP in diesel engines with VCRs effectively.

Despite the significant contributions these studies have made to the understanding of backpressure control, there are still some research gaps. This is due to the fact that backpressure is an ongoing concern within the IC engine area. With this being said, the present study discussed the importance of maintaining a delicate balance between achieving optimal engine performance and minimizing harmful emissions by effectively managing backpressure. It outlines various strategies and technologies that can be employed, such as optimizing airflow, utilizing advanced catalytic converters, designing effective regeneration cycles, and implementing variable valve train strategies. Based on all the literature explored in this context, future research and development in the field of managing EBP in VCR diesel engines is necessary. This includes the need for innovation in technologies that can seamlessly integrate variable compression capabilities with advanced turbocharging, EGR, and thermal management systems to maximize efficiency, performance, and emissions control.

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