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EGR Cooler Technology for Euro 7 Compliance and Fuel Economy: A Review from SI Engines to Hybrid and Hydrogen Powertrains

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Abstract
Sustainable transportation has led to a surge in zero-carbon engine technologies. The environmental impact of internal combustion (IC) engines has become a crucial concern. To meet Euro 7 emission norms and fuel economy, the Exhaust Gas Recirculation (EGR) system technology has emerged as a promising technology for enhancing engine efficiency and reducing nitrogen oxide (NO_x) emissions. This paper covers the following essential aspects. The Euro 7 emission norms are more stringent than Euro 6, by 35-56 percent for NO_x and 13-27 percent for particulate matter (PM). EGR rate can vary between 10 percent and 60 percent, depending on the emission-reduction strategy adopted by the engine manufacturer. Almost 70 percent of diesel vehicles adopted EGR technology over other technologies. The market trend is shifting toward hybrid EGR-plus-SCR and EGR-plus-LNT technologies. Cooled EGR technology appears to be a standard adaptation for gasoline engines rather than an optional technology for fuel economy, with 2-10 percent fuel economy gains depending on the engine manufacturer's adaptation. Based on comprehensive technological advances over the past two decades in diesel engines, the study proposed that cooled EGR is a promising technology for NOx reduction up to 80 percent, hinting at the future of automotive technology to meet Euro7 emission norms.

Keywords- Exhaust gas recirculation cooler, Euro 7, Emission, Nitrogen oxide emission, Green hydrogen, Hybrid, Bharat stage 7, Gasoline direct injection, Particulate matter.

1. Introduction

The technological evolution of IC engines over the past two decades has been significantly influenced by the need for emission reduction. This has led to a focus on three key aspects: improving efficiency, downsizing for improved fuel economy, and reducing emissions. Emission reduction is the primary driver of technology for modern transportation systems. As the world moves towards carbon neutrality, there is a significant drive across the auto community to replace fossil fuels, considering the emission limitations of fossil fuels. However, it's essential to note that Internal Combustion Engines (ICEs) cannot be entirely replaced by battery-powered electric vehicles (BEV) technology due to their limitations in battery power density and challenges in availability. This balanced view is crucial in understanding the need for alternative solutions. In response to these challenges, auto manufacturers are adapting future engine technologies like Hybrid engines (a combination of ICE and battery-powered), Green Hydrogen ICE engines (Carbon-free fuel) (Rao et al., 2023; Szwaja et al., 2024); and alternative fuel (Sethin et al., 2024; Yang et al., 2022) (Biodiesel fuel). Both technologies show promise, but emission treatment is still required in these technologies to meet the global emission standard Euro 7 (Dornoff & Rodríguez, 2024; Euro 7 Standards: New Rules for Vehicle Emissions, 2022).

1.1 Emission Legislation Evolution Over the Last 20 Years

The automotive industry is growing rapidly at the same time; it's producing more pollution across the globe with damage to the environment; therefore, stringent emissions norms are essential to reduce greenhouse gas emissions and protect human health from the harmful effects of carbon monoxide (CO), Hydrocarbon (HC), Particulate matter (PM) NO_x & Carbon dioxide (CO_2). Over the last 20 years, emissions standards have evolved in line with the driving cycle and specific applications. Europe adopted Euro norms, which progressed from Euro 1 to Euro 7 over the last two decades (Singh et al., 2023), and the US adopted Environmental Protection Agency (EPA) norms, which evolved from Tier I to Tier V. Similarly, other countries like Japan, China (Ma et al., 2025), and Australia adopted emission standards in line with the global standard. Although these norms vary, depending on the vehicle's weight and its driving cycle, to bring commonality across the driving cycle, the Worldwide Harmonised Test Cycle (WHTC) was introduced by the United Nations Economic Committee for Europe (UNECE), which would represent real-world driving and verify that statutory limits are not exceeded during actual driving.

The Euro 7 norms are being implemented in 2 phases across Europe (Euro 7 Standards: New Rules for Vehicle Emissions, 2022). The first phase is expected to be implemented by November 2026 for passenger cars and vans, and the second phase will be implemented in the next 2 years for trucks and buses. The implementation of these norms is to simplify and harmonise emission norms across Europe. These comprehensive norms will not only control tailpipe emissions but also cover non-exhaust emissions, such as particulate matter from tyres and brakes, leaving no stone unturned in the fight against emissions. With the implementation of these strict emissions norms, not only ICE but also non-ICE vehicles like BEVs and fuel cell electric vehicles (FCEV) will also come under the Euro 7 norm. Under this strict regulation, harmful gases like CO, total hydrocarbon (THC), non-methane hydrocarbon (NMHC), NO_x, PM, and particulate number (PN) will be regulated, which ultimately reduces greenhouse gas emissions. The impact of these norms will be felt across all vehicle types, from passenger cars to trucks and buses, as shown in **Table 1**.

The main highlight of Euro 7 norms compared to Euro 6 norms.
(i) NO_x reduction by 35% from cars, vans, 56% from buses and trucks.
(ii) PM reductions 13% from cars, vans, 39% from buses and trucks.
(iii) PM reductions from brakes by 27% from cars and vans.

Table 1. Emission regulation evolution over the last 20 years from Bharat stage I to Bharat stage VI and Euro VII, showing limitations for CO, HC, NO_x, PM in g/KWh.

Norms	CO (g/KWh)	HC (g/KWh)	NO_x (g/KWh)	PM (g/KWh)
Bharat Stage I	4.50	1.10	8.00	0.36
Bharat Stage II	4.00	1.10	7.00	0.15
Bharat Stage III	2.10	1.60	5.00	0.10
Bharat Stage IV	1.50	0.96	3.50	0.02
Bharat Stage VI	1.50	0.16	0.46	0.01
EURO VII	1.50	0.08	0.20	0.008

As an emerging hub for the automotive industry, India has taken a significant step by adopting BS norms from BS 1 to BS 7 in line with European norms from Euro 1 to Euro 7. These norm limits are carefully selected based on the fuel and its application. A typical graph, as shown in **Figure 1**, this represents the significant evolution of emission norms over the last 20 years for Compression Ignition (CI) and spark ignition (SI) engines. The BS 7 norms have yet to be released; however, they will align with the Euro 7 norms standard, as explained in this paper.

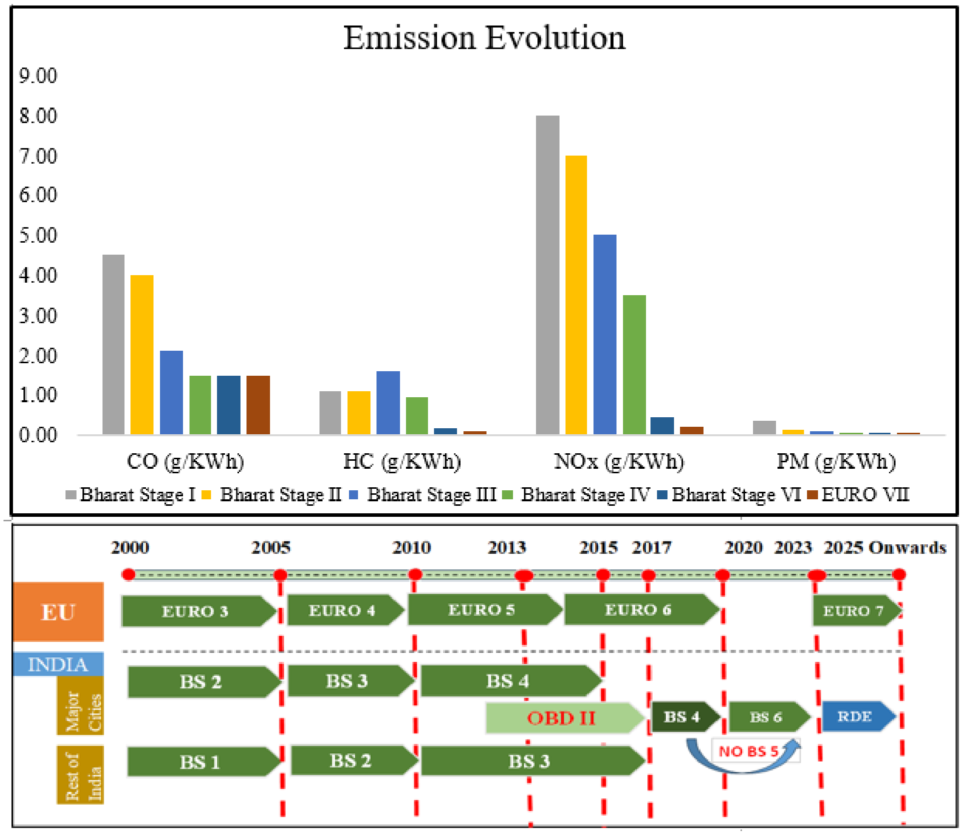


Figure 1. Emission legislation over the last 20 years, showing Bharat stage I to Bharat stage VI, also Euro 7, in which CO, HC, NO_X and PM emission reduction in g/kWh from the year 2000 to 2025 for Europe and India for major cities and the rest of the country.

One of the predominant emission contributors in IC engines is NO_x. Its chemical composition classification is mainly in the form of

- Nitric Oxide (NO) is the primary form of NO_x produced during combustion processes.
- Nitrogen dioxide (NO_2) is formed from the oxidation of NO.
- Other oxides of nitrogen, such as nitrous oxide (N_2O), produced in small amounts, have an impact on greenhouse gas emissions.

When exhaust temperature exceeds 1500 degrees Celsius, part of the excess oxygen is combined with free nitrogen to form NO_x. To minimise NO_x, several researchers have explored both pre-combustion and post-combustion methods. A typical engine pre- and post-treatment, most promising technologies schematic is explained in **Figure 2.** The advantages and disadvantages of the future application of this pre- and post-technological approach are outlined in **Table 2.** EGR is the most prominent NO_x reduction technology in exhaust pretreatment (Khair & Jääskeläinen, 2006; Persiko-Karakash & Sher, 2006).

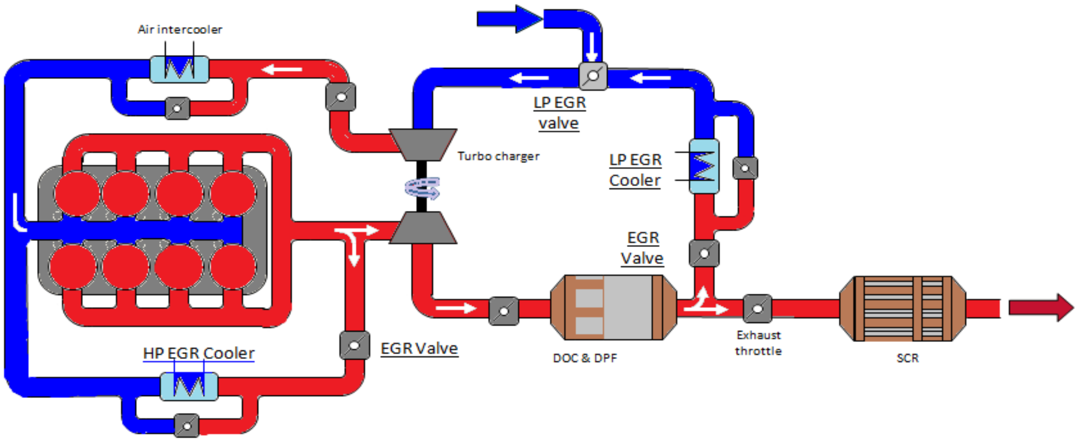


Figure 2. Combined HP EGR, LP EGR and SCR system engine layout for NO_x reduction through pre- and post-treatment.

Table 2. NO_x control technology, for both pre- and post-treatment engine technologies, with % of reduction and engine applications.

Treatment type	Technology	Application	Limitation	% Reduction	Future adaptation	Pre-treatment	Post-treatment	Engine application
Pre-Combustion	Fuel Modification (Sethin et al., 2024)	Use of alternative fuels like biodiesel (Fernandes et al., 2024), natural gas. Green Hydrogen	Fuel availability, cost	Up to 50%	Increasing use of renewable fuels	Fuel blending	-	Light, Medium & Heavy-duty vehicle (LCV, MCV, HCV), Off-road & Stationary
	Exhaust Gas Recirculation (EGR)	Reduces oxygen concentration in the combustion chamber	Increased particulate emissions, engine wear	Up to 90%	Advanced EGR systems with better control, SI engine for fuel economy	-	Particulate filter	Passenger vehicle (PV), LCV, MCV, HCV, Offroad & Stationary
	Pilot Injection	Early injection of a small amount of fuel	Complex control, potential for increased HC emissions	Varies	Integration with other technologies	-	Main injection control	HCV, Stationary
Post-Combustion	Selective Catalytic Reduction (SCR)	Industrial and automotive exhaust treatment	High cost, requires precise control of ammonia injection	Up to 90%	Increasing use in various industries due to stringent regulations	Particulate removal	Ammonia slip control	LCV, MCV, HCV & Stationary

Table 2 continued…

Post-Combustion	Selective Non-Catalytic Reduction (SNCR)	Industrial boilers and furnaces	Less efficient than SCR, temperature-sensitive	Up to 75%	Limited due to lower efficiency compared to SCR	Temperature control	Ammonia slip control	Boilers and furnaces
	Diesel Particulate Filter (DPF)	Captures particulate matter from exhaust	Requires periodic regeneration, backpressure	Up to 90%	Integration with other after-treatment systems	-	Regeneration system	LCV, MCV, HCV, Offroad & Stationary
	Lean NOx Trap (LNT)	Traps NO_x during lean operation, releases and reduces during rich operation	Requires periodic regeneration, sulphur sensitivity	Up to 80%	Improved materials for better efficiency	-	Regeneration system	PV & LCV

The EGR System is considered a pre-treatment technology, whereas the SCR system and LNT system are considered post-treatment technologies for NO_x reduction. Each technology has its advantages and disadvantages. Many automakers prefer both technologies in combination, as shown in **Figure 2** to balance fuel and AdBlue consumption (Lou et al., 2022). The engine can operate without losing its power at the same time, and overall expense trade-off on aftertreatment can be minimised. NO_x emissions can be reduced by up to 90% when combined (Zhang et al., 2024). Technology selection also depends on the value proposition and its application. For a small engine with a displacement of up to 3 litres, EGR technology or a combination with LNT is preferred, given its system cost. Similarly, for a low-cost NA engine with a mechanical pump, EGR technology is chosen to meet low NO_x and low system cost requirements. For a heavy-duty engine application, an EGR with SCR system is commonly used to balance system cost and engine fuel consumption per kilometre.

The EGR System, a complex network, is primarily composed of EGR Valves (Dumitrache & Deleanu, 2021), which play a crucial role in regulating the exhaust flow. These valves, the key to controlling the system's operation, are connected to EGR tubes (Munde et al., 2024a), which, in turn, are linked between the exhaust and intake manifolds via the EGR Cooler and valve. The bypass valve, another key component, regulates the amount of hot and cold EGR for cold start and during catalytic converter regeneration. The EGR Cooler is instrumental in enhancing volumetric efficiency by reducing the exhaust gas temperature through heat exchange. After heat transfer, the cooled gases recirculate back to the combustion chamber through the intake manifold, effectively reducing excess oxygen, combustion temperature, and NO_x (Wu & Wu, 2012).

In exhaust pre-treatment, NO_x formation can be reduced by reducing excess oxygen inside the combustion chamber during combustion, while maintaining the compression ratio needed to ensure the amount of air in the combustion chamber. The EGR system can address this problem by recirculating exhaust gas (oxygen-free) back into the cylinder. While recirculating this exhaust gas back to the combustion chamber, the EGR system must ensure volume accuracy by maintaining its flow and temperature to achieve volumetric efficiency (Cha et al., 2001).

The EGR rate in diesel engines has a significant impact on NO_x reduction. For a turbocharged diesel engine, researcher indicates that when the EGR rate reaches approximately 8%, NO_x is reduced by 25% across different engine operating conditions. EGR rate can go up to 60% in the Euro 7 engine (Huang et al., 2022a), reducing NO_x to almost negligible levels. The EGR rate is controlled by a DC-motor EGR valve that operates based on the ECU signal and engine duty cycle. Therefore, the EGR rate varies across the engine map. More EGR also adversely affects engine power, especially in a TC engine, where more EGR causes turbo lag; to avoid it, a low-pressure (LP) EGR system is introduced in addition to high-pressure (HP) EGR.

The EGR system, initially introduced in the ICE engine for NO_x reduction in diesel engines, has evolved beyond its original purpose. Scientists have found that this technology can be utilised not only for emission reduction but also for improving pumping losses and fuel economy for gasoline engines by eliminating fuel enrichment. EGR rate can vary based on its application and engine configuration. For a natural aspirated (NA) engine, internal EGR is mainly used for low-speed and no-load engine operating conditions to minimise the pumping losses. EGR mixing rate varies between 2 and 5%; similarly, cooled EGR is introduced at 10 to 15% to reduce peak combustion temperature, as an alternative to fuel enrichment, thus achieving fuel economy up to 5%. Similarly, for the gasoline direct injection (GDI) engine, cooled EGR is used up to 25% across the engine operating map to improve fuel economy up to 10% (Wei et al., 2012). As the automotive industry transitions towards greener technology through hybrid and H_2 ICE powertrains, the wider application of the EGR system for emission reduction and fuel economy is a promising development.

The EGR Cooler, being the most crucial part of the EGR system, is a testament to the system's effectiveness. The need for highly efficient advanced EGR cooler technologies that seamlessly integrate with these new engine technology systems is evident. Recent studies have demonstrated the substantial benefits of using cooled EGR in gasoline and diesel engines. By lowering the temperature of the recirculated exhaust gas, EGR coolers can significantly improve engine parameters such as indicated thermal efficiency, combustion characteristics, and pollutant emissions, providing reassurance about the system's effectiveness.

The primary objective of the present study is to review the use of EGR, a technology with significant potential in CI (Climent et al., 2022), SI (Wei et al., 2012) engines. Apart from that, we also review its use in future engine technologies like hybrid powertrains (Wang et al., 2022), Port fuel Injection PFI engines (Liu et al., 2017), gasoline direct injection GDI engines (Huang et al., 2022b), Homogeneous charged compression ignition HCCI (Kim & Lee, 2006), Reactive charged compression ignition RCCI (Duraisamy et al., 2019; Dwarshala et al., 2023), and Hydrogen ICE (Duan et al., 2019; Yu et al., 2019). A close examination of the above review articles reveals that EGR cooler application is not limited to NO_x reduction, but it also improves fuel economy and inhibits engine knock tendency (Božić et al., 2018; Grandin et al., 1998), it is crucial to carefully select the most suitable design to optimise performance with maximum durability, underscoring the importance of our role as engineers and researchers in the field.

The Euro 7 emission norms significantly reduce emissions from its previous norms for both ICE and non-ICE vehicles. In this context, EGR technology emerges as one of the most prominent NO_x reduction technologies and is widely acceptable for all types of fuel and modern engines. EGR is not only an efficient way to reduce engine knock and improve fuel economy (Knocking in Gasoline Engines 2018), but also a crucial tool in meeting the stringent Euro 7 emission standards. Most previous reviews and research articles focus on the effect of EGR on the performance and emission characteristics of CI or SI engines. No review discusses the EGR system, which is a significant research gap. In this review paper, the design and durability of the EGR system are highlighted, and various EGR techniques used to reduce NO_x emissions and their roles in achieving Euro 7 norms and improving fuel economy are discussed in detail.

2. Classification of EGR

The classification of the EGR System is a crucial aspect that can be studied through various designs based on its functionalities, as described in the literature survey. This classification serves to categorise EGR systems based on their configuration and integration with engine subcomponents, as shown in **Figure 3**. For instance, a design feature like the hydroformed EGR tube (Munde et al., 2024b) connects the exhaust and intake manifold, optimising its curvature to improve pressure drop, enhance EGR mixing, and improve efficiency. Another example is positioning the EGR system before the Turbocharger, High-pressure EGR (HP) after the turbocharger LP EGR (Zhou, 2013) (Low-pressure EGR) to optimise the maximum EGR flow through the dual loop (Dimitriou et al., 2018) without turbo lag. In addition to NO_x reduction, EGR can be used in SI engines for knocking reduction and improving fuel economy (Wei et al., 2012).

Figure 3. Mind map of the EGR system classification by design, application, and location.

2.1 Based on Combustion Location

The classification can be done by focusing on combustion within the cylinder and external EGR systems (Khoa & Lim, 2022). Internal EGR systems (Tian et al., 2023), as described in the research, utilise passages within the cylinder head to recirculate exhaust gases directly back into the combustion chamber, significantly enhancing combustion efficiency and reducing emissions. This method enables better mixing of exhaust gases with incoming air, as indicated by the uniform distribution in the intake manifold (Cho et al., 2018). Unlike external EGR, Internal EGR does not use any EGR tubes, valves, or coolers to recirculate the exhaust gas; internal EGR is achieved by overlapping the operating time of intake and exhaust valve opening and closing timing. This overlap allows the exhaust gas's draw back to return to the intake manifold. This system is suitable for low EGR mixing up to 10%. Internal EGR also helps to reduce pumping losses and is therefore commonly used for SI engines at low load conditions. However, this system is unsuitable for high EGR loads, as precise valve opening and closing at different engine operating loads and revolutions per minute (rpm) can be very difficult to manage. Also, this system calls for high maintenance due to more carbon deposition on the cylinder head.

Conversely, external EGR systems involve a more complex setup where exhaust gases are routed through an EGR valve, EGR tubes, and a cooler before being reintroduced into the intake manifold (Khoa & Lim, 2022; Munde et al., 2024b). This system can be finely controlled through the EGR valve and intake or exhaust throttle to adjust the recirculation rate, optimising engine performance under varying conditions. This system's adaptability and control make it most widely used in CI and SI (Dimitriou et al., 2018). Engines are due to their low maintenance and high durability.

Both systems (Khoa & Lim, 2022) share a common goal of lowering NO_x emissions and improving fuel efficiency, but their effectiveness can vary based on engine design and operational parameters. Overall, the choice between internal and external EGR systems depends on % of EGR mixing, specific engine requirements, and desired performance outcomes (Tian et al., 2024). This paper will cover an in-depth review of external EGR systems.

2.2 Based on Temperature

EGR systems can be classified into hot and cold EGR systems based on operating conditions. In modern engine environments, both systems are required, especially for light-duty CI engines, to maintain EGR flow across the engine map. Depending on the emission strategy, the manufacturer adapts the technology for heavy-duty and off-road applications.

Hot EGR systems (Solaimuthu et al., 2023) were introduced in the 1940s to recirculate exhaust gases directly from the engine without cooling. This is beneficial for reducing NO_x emissions during low-load conditions, as they help maintain lower peak combustion temperatures. Typically, this system is suitable for low-flow EGR rates up to 10-15% EGR, as rates beyond this can lead to overheating of the intake air, resulting in a reduction in volumetric efficiency in the combustion chamber. Hot EGR, as shown in Figure 4, is also suitable for cold start conditions, as it helps increase the light-off temperature of the catalytic converter. Also, some engine manufacturers use hot EGR for catalyst regeneration (Senthilkumar et al., 2013). In summary, the main application of Hot EGR in modern engines is to operate under a dual loop in bypass mode and operate under faster transient response.

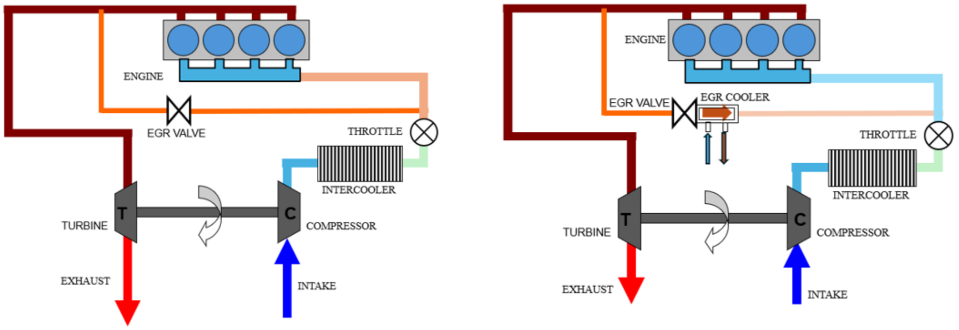


Figure 4. Hot & cold EGR System layout, hot system with only EGR tube between intake and exhaust manifold and EGR cooler is placed between EGR valve and intake manifold.

Cold EGR (Beatrice et al., 2018), as explained in **Figure 4**, involves the cooling of exhaust gases before recirculation, which enhances the reliability and longevity of the EGR components by mitigating high-temperature impacts. Recent advancements have led to the development of controllable EGR systems that integrate hot and cold EGR functionalities (Khair & Jääskeläinen, 2006). These systems, with their precise regulation of EGR flow and temperature based on engine operating conditions, optimise performance and emissions control (Galindo et al., 2020; Khoa & Lim, 2022). Cold EGR (Shon et al., 2015) systems uniformly distribute EGR across the combustion cylinders, thereby aiding in controlling volumetric efficiency (Liu et al., 2020) and maintaining the amount of oxygen & equal combustion pressure across the cylinder. The dual EGR system (Nyerges & Zöldy, 2023) approach, with a bypass system utilising hot EGR for both HP and LP EGR (Dimitriou et al., 2018), enhances the adaptability of EGR systems to varying engine demands, thereby improving overall efficiency and reducing emissions. These systems have played a significant role in improving engine efficiency, instilling confidence in their performance.

2.3 Based on Pressure

The EGR system can be classified based on its mounting location in the engine layout. If the EGR system is placed before the turbocharger or upstream of the exhaust line, it is called a high-pressure system or HP EGR. Similarly, if the EGR system is placed after the turbocharger, it is called low-pressure or LP EGR. **Figure 5** illustrates the dual-loop EGR system. Both HP and LP EGR systems are used in CI and SI engines, depending upon the emission reduction strategy adopted by the engine manufacturer. Modern engines, especially for passenger cars, PCs, and small utility vehicles such as SUVs, use both HP and LP EGR (Dimitrakopoulos et al., 2019) and are being adapted by engine manufacturers. Both systems have played a significant role in improving engine efficiency and achieving emission reduction, thereby contributing to a cleaner and more sustainable environment; however, both these systems operate under different working conditions.

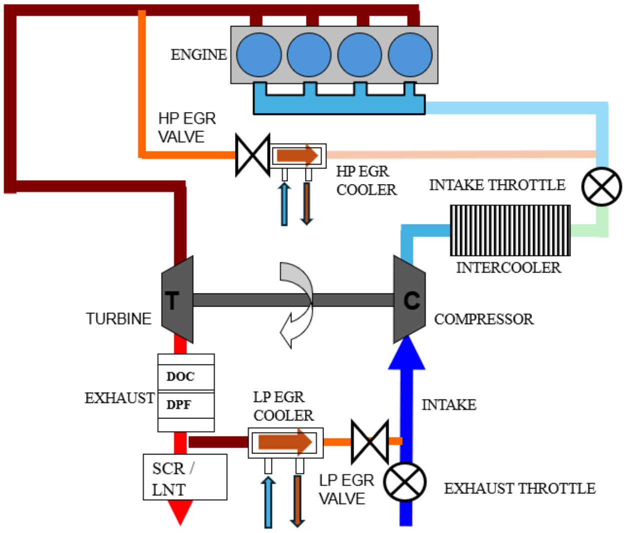


Figure 5. Dual loop EGR system with EGR cooler placed between high-pressure and low-pressure exhaust lines.

The HP EGR (Wang et al., 2023) system, as shown in **Figure 5**, is most suitable for low-flow EGR and working under transient operating conditions. Due to its quick response time and ability to operate under high pressure, it can function effectively in both low- and mid-load EGR conditions. Depending on the EGR mixing strategy, this system can work with or without an EGR Cooler. This system is generally less sensitive to differential pressure, which means EGR coolers' 'I' and 'U' types can work comfortably. The bypass system can be adapted for cold start applications using the HP layout. This system is most suitable for CI engines as it is less sensitive to fuel economy for SI engines as compared to LP EGR.

The LP EGR system is most suitable for a higher rate of EGR as it is positioned after the turbocharger or downstream of the exhaust system. This placement is beneficial as it helps to reduce 'turbo lag', a delay in engine response that occurs when the turbocharger is not yet spinning fast enough to provide significant boost. Operating under high EGR flow, this EGR system's response time is slow and less sensitive during transient response. Since this system operates under low pressure, it is more sensitive to EGR gas pressure drops. The typical design for an LP EGR system features an 'I' type EGR cooler layout, as illustrated in **Figure 6.** In the LP EGR System, the EGR System can be placed before or after the emission treatment system, depending on the layout. However, based on its placement location, fin construction changes are considered, taking into account a change in fouling behaviours due to soot deposition. This system is widely used in SI engines (Shen et al., 2018), and dual-loop EGR systems in CI engines are considered its defining advantages, as they improve indicated thermal efficiency and reduce specific gas and fuel consumption. At the same time, this system helps to reduce knock as it is less sensitive to spark timing.

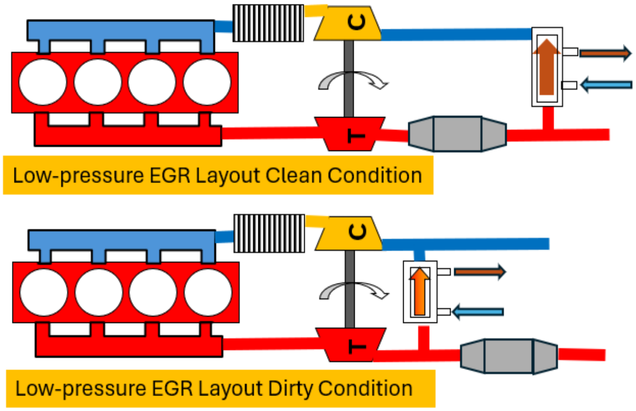


Figure 6. Low Pressure EGR Layout with 2 different configurations, configuration 1(clean condition) with EGR cooler placed after catalytic convertor and configuration 2 (dirty condition) with EGR cooler placed before catalytic convertor.

A dual-loop EGR system is adapted for modern CI & SI engines, considering its significant advantages over a single-loop conventional EGR system. This system was introduced to enhance overall engine performance by optimizing exhaust gas flow in the turbocharged (TC) engine and simultaneously controlling NO_x emissions through maximum EGR flow across all engine operating conditions. The single-loop EGR system effectively operates within specific operating regions, which present additional challenges for engine calibration, as it is less sensitive during engine transient responses. To meet modern emission norms (BS6 and above), the urgent need for NO_x reduction through the EGR system necessitates a higher rate of cooled EGR operation at higher engine speeds. At the same time, TC becomes ineffective if the EGR system is placed before TC. Engines operating at low speeds and low load conditions require less cooled EGR flow to maintain combustion temperature. Therefore, EGR's optimum sizing becomes a big challenge, which can be overcome by adopting a small EGR cooler in the HP loop and a large EGR cooler in the LP loop. Depending on the EGR requirements, HP, LP, or a dual loop can be considered as an emission reduction strategy.

2.4 Based on Engine Combustion

The EGR system, initially adapted in CI engines, was primarily focused on its NO_x reduction capability. However, researchers have found its applicability in SI engines, demonstrating its versatility. This adaptability reduces engine knock, minimises pumping loss, and enhances fuel economy by avoiding fuel enrichment at high engine speeds, as well as promoting NO_x reduction. This technology found its place in the naturally aspirated (NA) and TC engines. The CI Engine EGR technology was developed in the 19th century to reduce NO_x emissions. However, this NO_x reduction technology was not widely known until the implementation of emission standards worldwide. NO_x regulation was initially introduced in 1992 for Euro 1 emission standards for heavy-duty diesel engines, which were subsequently implemented across all diesel engines, including passenger cars from Euro 2 onwards (Bhatt & Roychoudhury, 2019; Auto fuel policy, 2025), as shown in **Figure 7**.

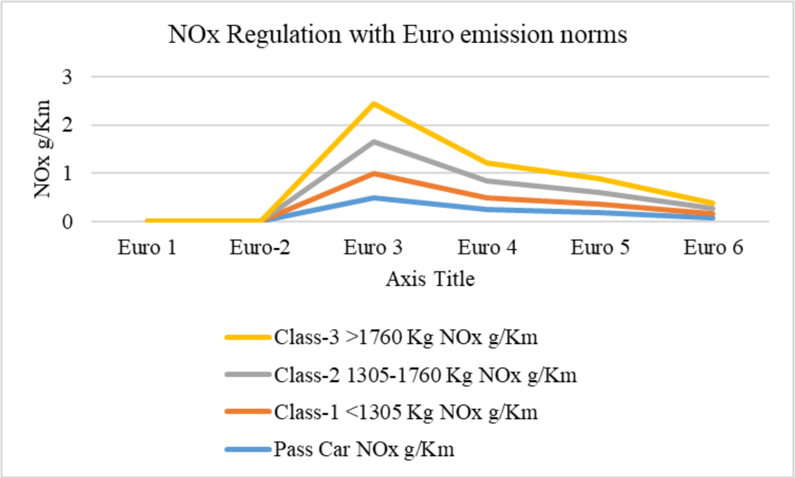


Figure 7. NO_x Regulation for Euro emission norms from Euro 1 to Euro 6.

The combustion behaviour in IC engines (Abd-Alla, 2002; Ashok et al., 2022) is described through the flow chart shown in **Figure 8**. In incomplete combustion, the primary pollutants are CO, HC, PM and NO_x, out of which NO_x is mainly formed at high temperatures above 1800 degrees Kelvin (Iavarone & Parente, 2020; Wei et al., 2012).

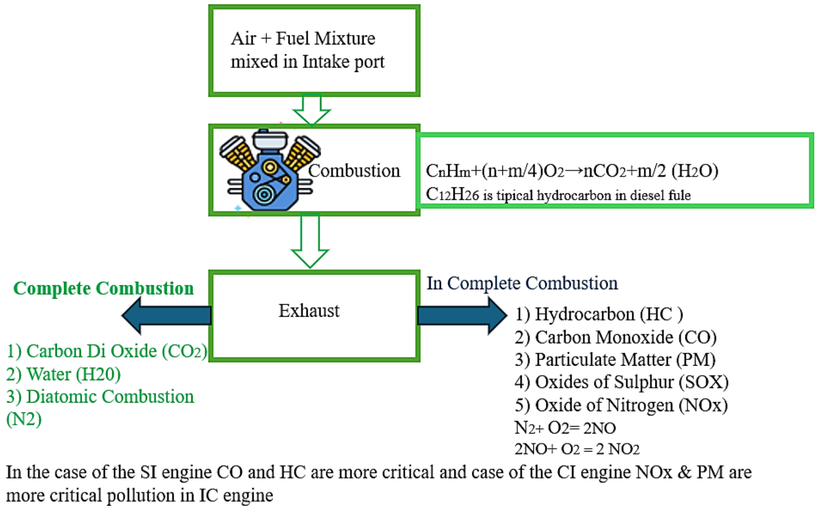


Figure 8. Emission in IC engine, exhaust classification based on combustion.

The SI engine EGR system is primarily used to reduce combustion temperature (Wei et al., 2012) by recirculating exhaust gas, which is inert and does not combust. This process, occurring in the absence of oxygen, reduces the overall combustion temperature when mixed with fresh air in the intake manifold. The reduction in temperature not only helps to reduce engine knock (Božić et al., 2018) but also improves fuel economy. The EGR system also helps reduce pumping losses when operating under low-load conditions. Therefore, it contributes to an overall improvement in fuel economy by 2-10%, enhances engine longevity with better combustion, and simultaneously reduces NO_x at higher temperatures (Hoseini et al., 2016).

2.5 Based on Flow

The EGR System can be classified based on its EGR Cooler flow propulsion pattern. Primary can be classified into four categories: 'I' flow, 'U' flow, parallel flow, and crossflow. Each category has distinct thermal and flow characteristics that influence EGR system performance and durability, as shown in **Figure 9**.

The 'I' flow EGR cooler (Agarwal & Batista, 2023; Hoseini et al., 2016) a single-directional gas coolant flow, introduced for NA engines due to its distinctive advantages of low-pressure drop across the system. Its simple design has made it a popular choice for light, medium, and off-road applications for both NA and TC engines. The SI engine has primarily adopted the 'I' flow design to work under low pressure, showcasing its adaptability. The coolant flow can be parallel or cross, depending on the engine layout architecture.

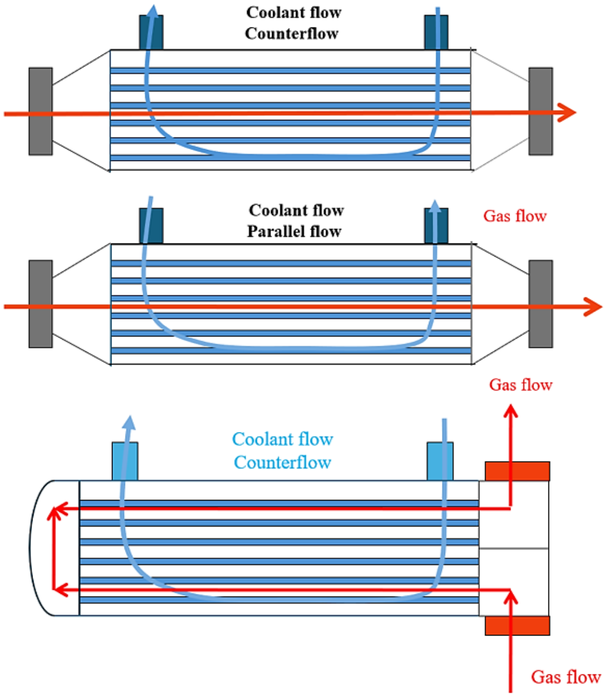


Figure 9. 'I' type Counter flow, 'I' type parallel, and 'U' type EGR cooler.

The 'U' flow EGR cooler, initially introduced in compact passenger car applications, has played a significant role in the evolution of engine design. Its compactness has made it a popular choice for a variety of vehicles, including small utility vehicles (SUVs) and light commercial vehicles (LCVs). As engine design architecture becomes more complex after the implementation of Euro 4/BS, the need for higher-precision control of DC and stepper motors, as well as EGR and bypass valves, becomes more pronounced. These valves are instrumental in controlling EGR flow under cooled /non-cooled conditions to meet real driving emission (RDE). Some engine manufacturers discovered the applicability of bypass valves during the active regeneration process for the catalytic converter. In the U-type of cooler, the gas inlet and outlet locations are on the same side; therefore, it facilitates the packing of the EGR valve and bypass valve using a manifold commonly referred to as a mixing unit. Depending on engine operating conditions, this mixing unit helps determine the direction of the EGR gas, either in cooler or bypass mode. ‘U’ type EGR cooler has 10% more cooling efficiency than ‘I’ (Shon et al., 2015). The U-type, more astonishing gas flow direction is one side cross flow and one side parallel flow, which helps to make this type of heat exchanger more efficient; however, for a significantly longer length, it also increases the gas pressure drop across the system. Due to this reason, this system is not suitable for low-pressure applications. Additionally, this system exhibits a higher fouling tendency due to the greater pressure drop across the EGR cooler.

2.6 Depending on the Flow Direction of the EGR

The cooler can be categorised as parallel or crossflow. Both parallel and crossflow coolers have distinct advantages. When gas and coolant travel in the same direction, it is referred to as parallel flow; if the direction is opposite, it is called reverse or cross flow, as shown in **Figure 10**. Parallel flow is mainly preferred for its ability to significantly reduce thermal fatigue, especially in SI engines, where the temperature gradient is comparatively high. This reassures engineers about the reliability of this design. Similarly, crossflow is used to improve the efficiency of heat exchangers.

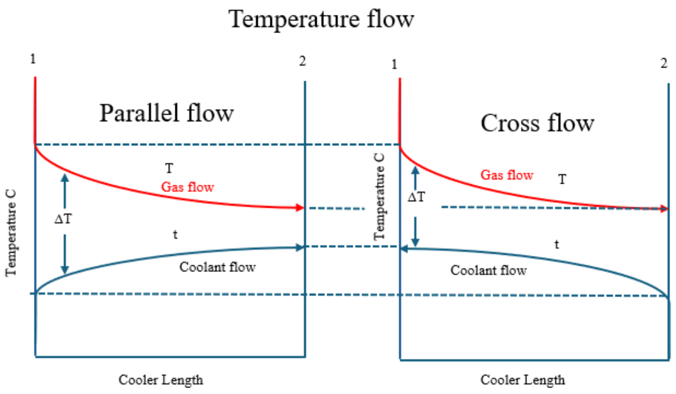


Figure 10. Parallel & cross flow temperature gradient.

2.7 Based on the EGR Cooler Design

EGR coolers can be categorised based on their design, mainly into four types: plain tube, corrugated tube, shaped tube, and the hybrid tube construction (Jabbar & Ahmed, 2023), as shown in **Figure 11**. Plain tubes are the simplest form of construction, and hybrid tube designs, known for their superior durability, are the most complex form of construction. Modern engines require higher heat rejection with compactness and higher durability, a feat that can be confidently achieved by the reliable hybrid design (Shon et al., 2015).

‘Q’ (Heat transfer rate) generally represents the amount of heat transferred, which is measured in watts (W), and ‘U’ (Overall heat transfer coefficient) accounts for all modes of heat transfer (convection, conduction and radiation between gas and coolant. It is measured in W/m^2K. Log mean temperature difference (LMTD) (Gumus & Otkur, 2023) is the average temperature difference between exhaust gas and engine coolant.

‘A’ is the surface area for heat transfer measured in square meters (m^2). Typically, a corrugated tube design improves the ‘U’ value by increasing gas velocity and enhancing turbulence through the Renault number; the shaped tube has a slight advantage over a corrugated tube due to its higher surface area. However, the hybrid tube, a fascinating innovation, increases both ‘U ‘and ‘A’, therefore improving the heat transfer by 20 to 30%. EGR Coolers design, construction, and its comparison with other design is shown in **Table 3**.

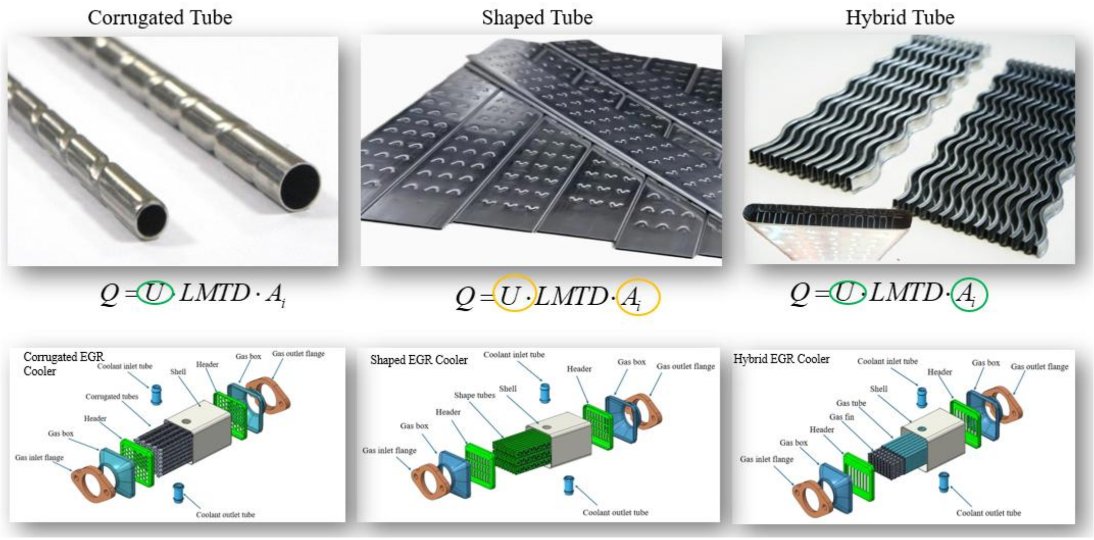


Figure 11. EGR cooler with different internal core construction, corrugated type, shaped tube and hybrid tube core construction.

Table 3. EGR cooler construction: corrugated tube, shaped tube and hybrid tube.

Feature	**Corrugated tube**	**Shaped tube**	**Hybrid tube**
Application	Diesel PC, LCV, HD	Diesel PC, LCV, HD	Diesel PC, LCV, HD, Gasoline, Natural gas, Hydrogen
Efficiency	<85-90%	<90%	>90%
Cost-effectiveness & Light weight	Cost-effectiveness & Light weight	Expensive compared to corrugated tube & lightweight	Expensive
Packaging Compactness	Not compact	easy to package in a rectangular cooler	compact design, 20-30% more compact compared to corrugated and shaped tube
Ease of manufacturing	Best	more difficult compared to corrugated	Difficult to manufacture
Pressure durability	Best	Low	High
Thermal fatigue resistance	Good	Average	Very High
Vibration	Average	Average	High
Pitting Corrosion resistance	Average	Average	Very High
Coolant distribution	Simple structure	Simple structure	Complex structure

2.8 Based on EGR Cooler Construction

EGR coolers can be classified by construction design: Monoblock, floating core, and manifold designs, as shown in **Figure 12**.

A Monoblock or fixed core design is most used for light and medium-duty SI and CI engines. The internal core structure of the design is rigidly fixed to the outer structure. This design is preferred to avoid thermal elongation when the overall cooler length is less than 300 mm. All cooler components could be brazed or welded together. This design is unsuitable for higher core length as it creates thermal stress at header joints during thermal expansion at high temperatures.

The floating core cooler (Grande et al., 2018), a design that demonstrates remarkable adaptability, is primarily suitable for light- and medium-duty engines, typically those with a displacement of 3L and above. This design, which was adapted to prevent thermal expansion damage at header joints during high temperatures, is a reliable choice for engines with an overall cooler core length exceeding 300 mm. The core is attached to the body with the aid of decoupling elements, allowing it to expand and contract to its original length in response to the temperature gradient. This flexibility, achieved with the help of a small 'O' ring or flexible bellow at the EGR cooler outlet, as illustrated in **Figure 12** is a testament to the floating core design's adaptability. The floating core design is housed in aluminium or steel, depending on the packaging and complexity of the design.

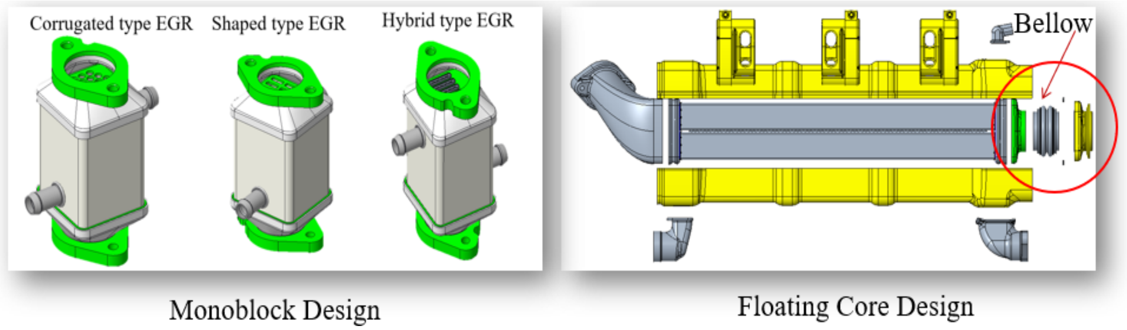
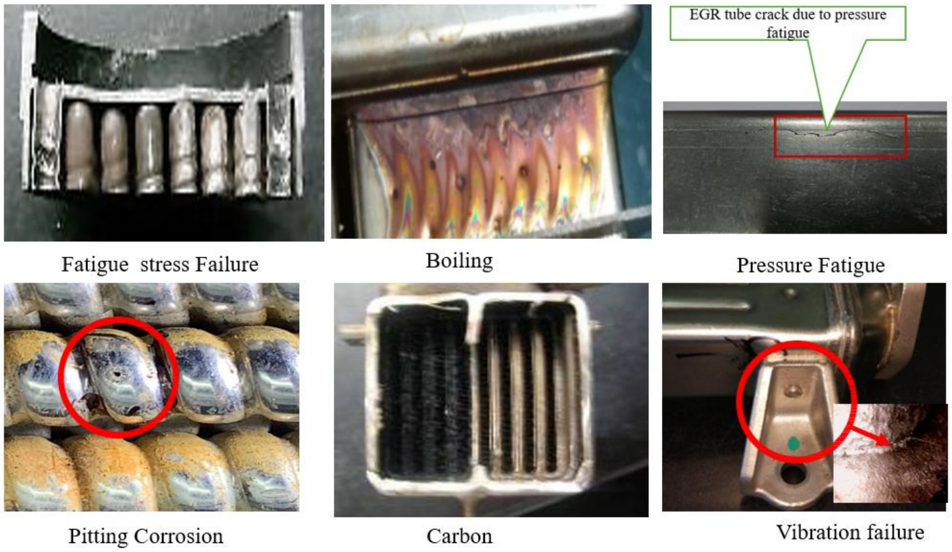


Figure 12. Monoblock, floating core & manifold design, EGR Cooler construction.

Manifold cooler design is primarily used for large engines exceeding 15L, making it most suitable for train or marine applications. Two or more EGR coolers are connected in parallel through a manifold. This type of design is adopted when the EGR heat rejection requirement is substantial, and for low-volume applications, manufacturers employ such a methodology, as illustrated in **Figure 12**.

3. Failure Mode in EGR Cooler

EGR coolers are designed to last the engine's lifetime; however, for some reason, they can fail during this period. This failure can be categorized into four subcategories: fouling, boiling, fatigue, and pitting corrosion, as shown in **Figure 13**.



Fatigue stress Failure Boiling Pressure Fatigue

Pitting Corrosion Carbon Vibration failure

Figure 13. EGR cooler has different failure modes, e.g., thermal fatigue, boiling, vibration, pressure fatigue, and pitting corrosion.

3.1 Fouling

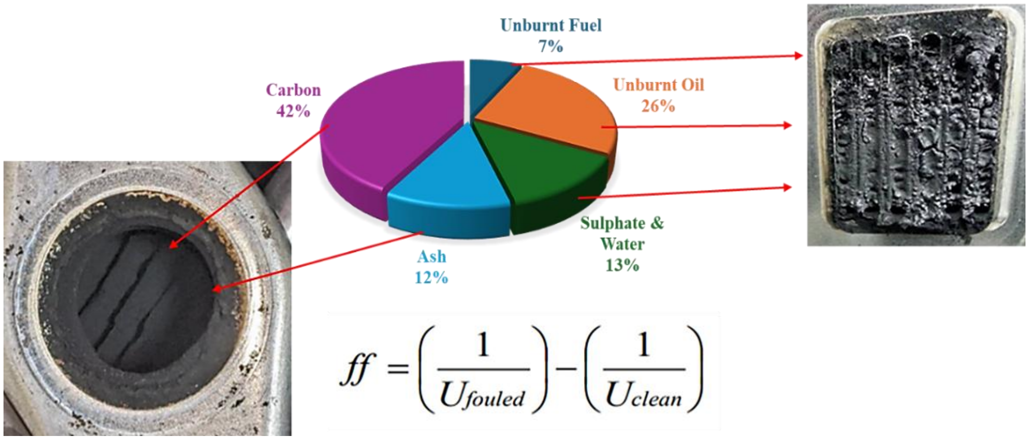
Fouling is the most common concern observed in EGR systems, which affects their thermal performance. Fouling is caused by the deposition of particulate matter, soot, and unburned hydrocarbon condensation in the heat exchanger gas circuit, which can lead to blockage of the gas circuit and reduced heat exchange efficiency.

Mechanism of fouling

Particulate deposition: Micron-sized particles significantly contribute to fouling, with gravity playing a key role in influencing their deposition patterns. Studies show that lower sections of EGR coolers accumulate more particles, with larger diameters observed in these areas (Yao et al., 2024) as illustrated in **Figure 14**.

Hydrocarbon condensation: Unburned hydrocarbons in exhaust gases undergo condensation, transforming fouling characteristics. This process can enhance fouling density, positively impacting heat exchange efficiency up to a specific temperature, beyond which efficiency declines. Generally, two types of fouling are observed in the EGR cooler, i.e., dry fouling and wet fouling (Hountalas et al., 2013). Dry fouling is the phenomenon that occurs at maximum EGR flow and maximum EGR temperature conditions. Wet Soot is a phenomenon that occurs when the engine operates primarily in a low EGR flow zone at part-load or no-load conditions. The cooler outlet temperature drops below 100°C, causing excessive condensation. This condensation water is mixed with (Han et al., 2023). Soot and causes clogging on the outlet side of the EGR cooler. For the 'U' type of EGR cooler, maximum fouling is observed at the gas outlet and the low flow zone. A factor defines efficiency reduction as a fouling factor, which is represented by 'ff'(Hountalas et al., 2013). To calculate the fouling factor, need to calculate the coefficients of heat transfer 'U' in clean and foul conditions for the heat exchanger.

Fouling factor (Abd-Elhady et al., 2011) change based on engine operation condition and driving cycle. For a given engine, fouling can vary according to its operating conditions; therefore, the engine manufacturer conducts a fouling test to determine the average fouling. This test was conducted at both the engine test bench and the efficiency test bench levels. The test engine operates in low EGR mode with low coolant inlet temperatures to generate more condensation and wet soot. Similarly, dry soot is generated when the engine is run in high-EGR mode at higher exhaust gas temperatures (Styles et al., 2010). For the experimental method, a smoke generator can also be used to create smoke with a filter smoke number (FSN). Some research was also done to calculate fouling through the simulation method (Abarham et al., 2010; Park et al., 2018).



$$ff = \left(\frac{1}{U_{fouled}}\right) - \left(\frac{1}{U_{clean}}\right)$$

Figure 14. Fouling on the EGR cooler internal core and a factor to calculate the amount of fouling.

3.2 Boiling

The development of a modern EGR system requires a higher EGR rate across the engine's operating map to increase overall heat rejection; therefore, it is necessary to have a high-performance EGR cooler operating under variable coolant flow, based on engine rpm. Although the EGR's more astonishing heat rejection requirement increases due to higher NO_x reduction, it does not improve the coolant flow across the cooler as the pump has limited operating under different rpm connections, therefore increasing the thermal load in the cooler and creating boiling (Carrera, 2016) due to insufficient coolant flow at the topmost position of the cooler. Boiling can also develop if the more extraordinary location is higher or parallel to the radiator venting cap. It can also develop in case of improper packaging, i.e., the coolant inlet is from the top, and the outlet is from the bottom, or the coolant outlet is not at the topmost position or in the absence of a vent connected to the vacuum tank, in the case of such a layout as shown in **Figure 15**.

Boiling cannot be eliminated from an EGR cooler, but can be optimised by operating under critical heat flux (CHF). When CHF exceeds, film boiling starts, increasing the cooler outlet temperature and reducing the heat transfer rate.

Stages of boiling can be classified as nucleate boiling, transition boiling and film boiling.

Nucleate boiling: also known as initial boiling, occurs at low surface temperatures. Tiny bubbles are created at a heated surface, at a discrete point, and move to the liquid's surface to carry heat away from the surface. The impact of this heat transfer is significant, as during this stage, the bubbles help to increase surface area and carry heat away from the surface (Dedov, 2019). This process helps to improve the uniformity of temperature distribution by reducing the risk of hot spots that could lead to material damage (Shoji, 2004).

Transition boiling: This unstable boiling occurs between nucleate and film boiling. This phase boiling process is unstable and fluctuates between nucleate and film boiling. Due to this fluctuation, the heat transfer rate varies, and the critical heat flux transition begins; after this point, the efficiency of heat transfer drops. Transition boiling is critical for EGR coolers to maintain efficient heat transfer to prevent overheating hotspots (Carrera, 2016).

Film boiling: Click or tap here to enter text.It is a boiling phase where a thin vapour layer between the liquid and the heating surface creates an insulation barrier. In this boiling process, heat transfer occurs through the vapor film, which has much lower thermal conductivity than the liquid, resulting in lower thermal conductivity. This phenomenon occurs when the coolant temperature reaches CHF. A cooler subjected to severe thermal stress under these conditions will have its lifespan reduced.

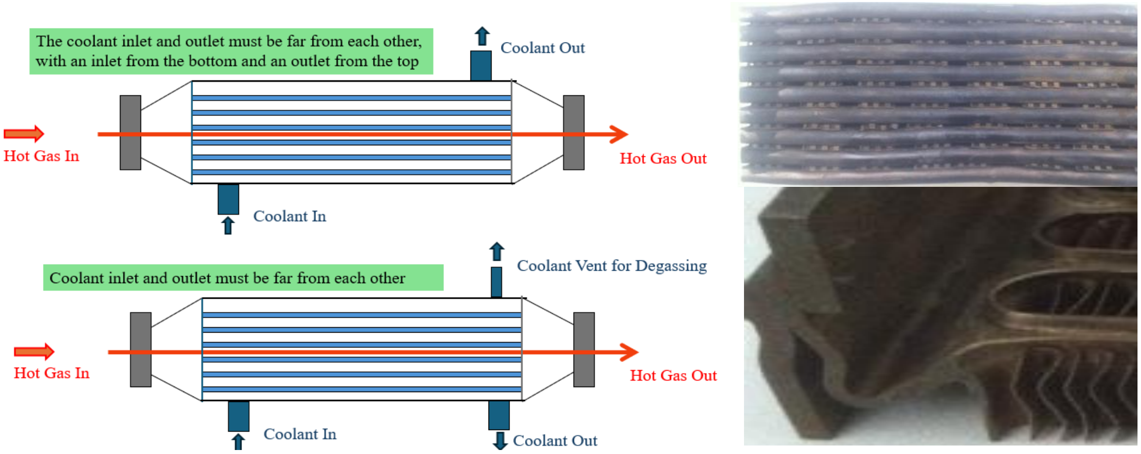


Figure 15. EGR cooler coolant location to avoid boiling & boiling failure.

In summary, boiling in an EGR cooler helps improve heat transfer before the CHF point. Beyond this point, the more astonishing efficiency drops drastically with coolant degradation, creating thermal stress, a hot spot zone, and superheated steam. Boiling can be avoided by carefully designing the cooler and optimising the more astounding packaging in the engine layout with coolant flow. CFD analysis also helps define the boiling stages and predict the boiling risk and hotspot zones where coolant distribution is low; it also helps define a longer design life by controlling the boiling phenomenon. The boiling level can be validated at the bench level with the help of a boiling test (Carrera, 2016). In this test, with the help of a high-speed and thermal camera, image capturing can be done to identify boiling and hot spot zone levels (Rathod et al., 2019).

3.3 Thermal Fatigue

Thermal fatigue in the EGR system is critical due to the significant temperature variation between exhaust gases and coolant. The impact of this phenomenon can lead to material degradation and cracking, which in turn affects the lifespan of the EGR system. This phenomenon causes early failures, such as gas leakage resulting from the mixing of gas and coolant in EGR tubes. The primary responsible factors are the material selection in the area is subject to higher thermal stress, such as the header, which separates gas and coolant, gas tubes, and bellows. Materials capable of sustaining higher yield stress at elevated temperatures have higher fatigue life, as shown in the EN curve in **Figure 16**.

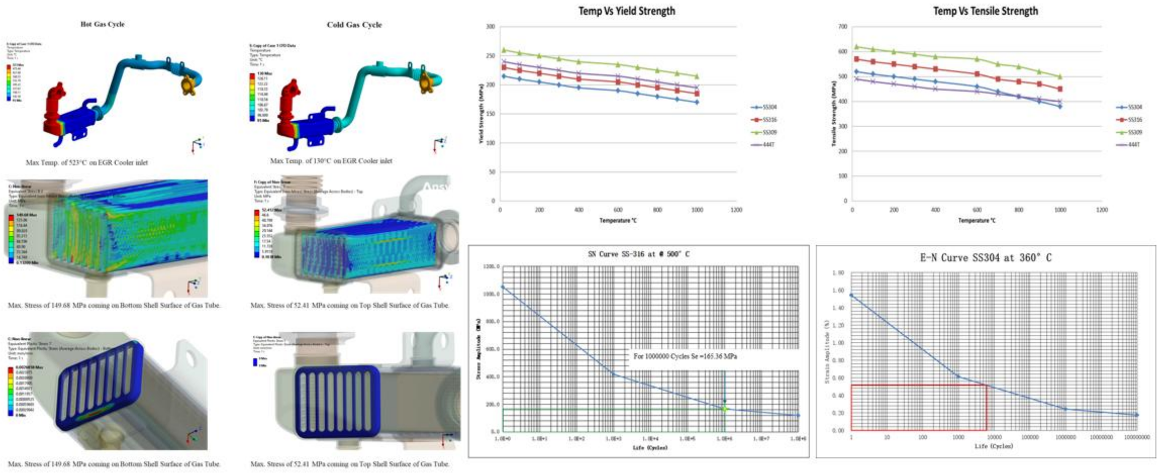


Figure 16. Yield strength & tensile strength for different materials, SS304, SS316, SS309, SS444T for varying temperatures. theoretical E – N curve for 304 & 316L and elevated temperature.

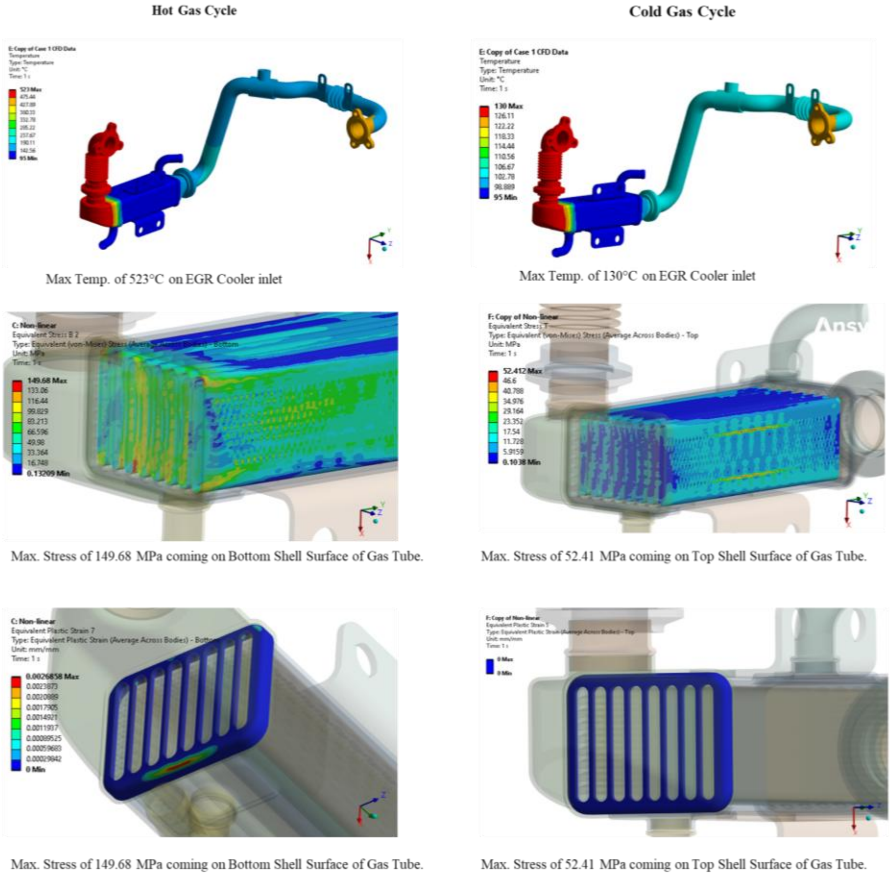


Figure 17. FEA Analysis of thermal fatigue behaviour of EGR system subjected to hot and cold cycles.

Design is vital in enhancing high-cycle thermal fatigue life in heat exchangers. Design parameters like tube bellow size (Munde et al., 2024a), thickness, number of convolutions, and location play a significant role in calculating thermal fatigue life. Similarly baffle design, location, internal tube construction, cooler length, coolant inlet and outlet, and types of coolant flow also play a significant role in enhancing thermal fatigue life. To avoid thermal elongation, a more conservative length of less than 300 mm is advisable for the Monoblock cooler structure (Holland et al., 2015). The boiling effect on the EGR cooler also plays a significant role in determining thermal fatigue. Coolant flow across the tube must be uniform and lower than CHF (Carrera et al., 2015) to improve its life, as shown in **Figure 17**. Joining processes like welding and brazing can also impact thermal fatigue, as processes like brazing reduce the residual stress for the joint through the annealing process, as compared to welding, in which a heat-affected zone (HAZ) is developed, which increases the risk of failure (Dutt et al., 2011).

3.4 Pressure Fatigue

EGR coolers are subjected to pressure pulsation based on the engine firing sequence during engine operation. Pressure pulsation can also develop during engine exhaust braking operation in heavy-duty engines. Due to pressure pulsation, the material is subjected to high-cycle fatigue, which causes failure of the tube base material. Due to this phenomenon, exhaust gas coolant gets mixed and supplied to the combustion chamber, which causes white smoke in the initial stage and leads to hydrostatic lock or engine seizure in the final stage of this failure, as shown in **Figure 18**.

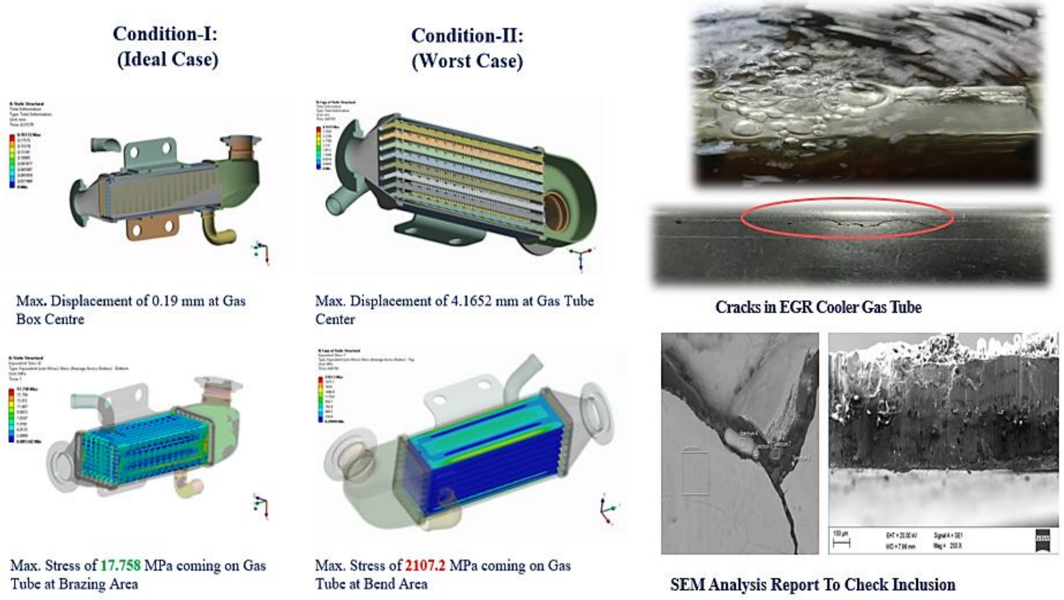


Figure 18. FEA analysis of the EGR cooler failed due to pressure fatigue. The same failure is correlated in the EGR cooler, tube crack, due to pressure fatigue in the pressure fatigue test bench.

The main causes of developing pressure fatigue are due to below reasons:

- Fouling and soot deposition, blocking the gas passage flow, causing pressure fatigue, excessive back pressure during exhaust brake operation.
- Placement of EGR cooler on hot side before EGR valve with very high pulsation effect, valve chocking.

- Very high flexible bellow profile in EGR tubes not as per design calculations EGR Cooler internal core structure is not rigid (Pires et al., 2022). Reduced flexibility in EGR tubes and Coolers can minimize pressure fatigue.

The typical method of strengthening is by increasing tube thickness and changing the cross-section, which improves the rigidity modulus. Pressure fatigue life can be estimated using FEA by using a modified Goodman diagram. Simulation results can be verified using a pressure pulsation test at accelerated cyclic pressure for a given number of cycles, considering factors of safety and design life.

3.5 Vibration

Failure of the EGR system on account of vibration is one of the most common phenomena; therefore, necessary measures are needed during the system design stage to ensure the robustness of the assembly. Since the EGR valve has moving parts, it creates additional challenges for the design of the EGR System. The following measures are needed to avoid this failure during the development phase.

Proper mounting brackets for EGR systems is designed by conducting FEA analysis to find the system's natural frequency (Dhummansure et al., 2021), if the natural frequency is below the engine critical frequency zone, strengthen the cooler by adding more brackets or conduct resonance durability for ten million cycles under the resonance point.

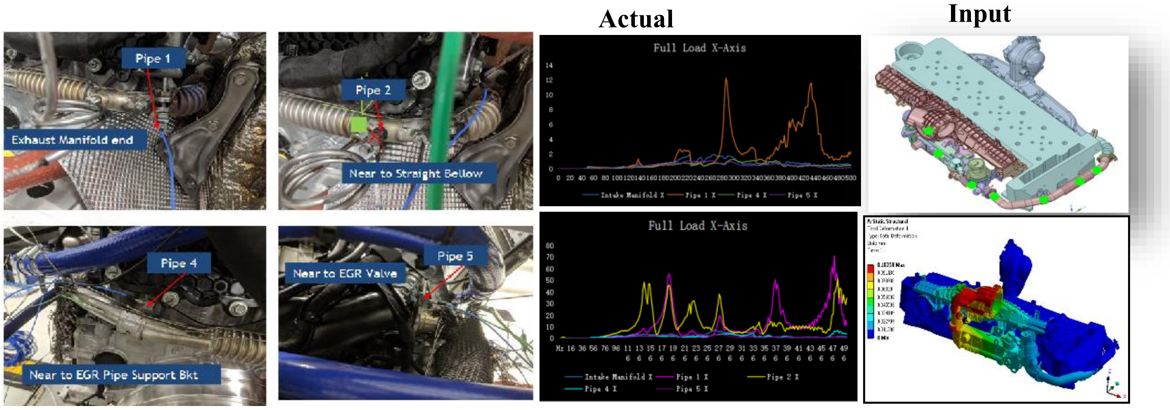


Figure 19. Example of data measurement as per the indicated locations for of the Acceleration vs frequency data with the help of a triaxle accelerometer.

Perform the vibration measurement at the engine dynamometer by using an accelerometer placed at different locations viz engine block, engine head, exhaust manifold, intake manifold, EGR cooler body (Dhummansure et al., 2021), EGR valve body and EGR tube as shown in **Figure 19**.

Time series data captured for all three directions of engine movements (X, Y, Z) from idle speed (engine rpm) to the maximum speed at different engine operating conditions and, based on the above data, find resonance point at the EGR system concerning the base level of engine excitation (Munde et al., 2024b). This data will be further filtered for CAE analysis and use in the shaker test.

Based on the data measurements, we perform a resonance durability test on an electrodynamic shaker for 10 million cycles at each resonance point within the engine's critical frequency zone, in the X, Y, and Z directions. The test's acceptance criteria is to maintain resonance within a 20Hz zone constantly for 10 million cycles. This test is crucial as it helps us predict the performance of the EGR system, ensuring it can withstand the rigours of engine operation.

3.6 Corrosion

Corrosion in the EGR system is due to the following reasons.
A high % of sulphur in fuel is converted to SO_2 and SO_3 during the combustion and oxidation process, with condensation converted to H_2SO_4 mixed with exhaust gas, creating internal corrosion at base metal and brazing/welding joints (Zrubecký, 2015). This phenomenon can be avoided by selecting low-sulphur fuel, unique materials for base metal and brazing material, and optimising the brazing process. In the presence of high chromium and molybdenum in steel, selecting a high corrosion resistance brazing material can eliminate this problem. The location of the catalytic converter (CATCON) also plays a significant role. Placing the CATCON after the EGR can help avoid oxidation in the case of a high-sulphur CI engine in LP EGR. For gasoline applications, considering negligible amounts of sulphur, an EGR cooler can be placed after the catalytic converter. This strategic placement helps prevent the harmful effects of high sulphur on the EGR system.

Sensitisation in stainless steel is a phenomenon in which the metal becomes susceptible to internal granular corrosion due to chromium chloride at the grain boundary. This can cause the failure of welding and brazing joints. Sensitisation typically occurs in Austenitic stainless steel; however, it can also be developed in Ferritic steel at temperatures ranging between 425°C and 900°C for long periods or a slow cooling process. The formation of chromium carbide ($M_{23}C_6$) at the grain boundary, due to the combination of chromium and carbon in the alloy, reduces chromium in the surrounding area, leading to sensitisation. Understanding this process is crucial for preventing sensitisation-related corrosion in the EGR cooler.

External corrosion is due to environmental and temperature impacts. This type of corrosion can be avoided in the EGR system by selecting the appropriate material. Further, we can conduct the salt spray test at elevated temperatures for specified hours per the design life to validate the material.

Pitting corrosion (Bhandari et al., 2015; Burstein et al., 2004; Nishimoto et al., 2023). It is a localised form of corrosion developed in EGR coolers and EGR tubes, mainly in the form of small pit holes. This type of corrosion is critical as it is almost impossible to detect unless it spreads widely and creates significant damage to the engine. Pitting corrosion can be initially identified with the help of white smoke and more coolant consumption at the initial stage. Over a period of time, it can create a hydrostatic lock or an engine seized by mixing large amounts of gas and coolant in the combustion chamber. Pitting is caused (Bhandari et al., 2015) due to fuel adulteration (Kerosene mixed with gasoline and diesel), working in salty environments or salty water entry through the intake manifold or due to usage of unbounded PP (polypropylene) in the intake or exhaust system gas passage at elevated temperature.

The following stages can be classified as pitting stages.

a. *Pitting nucleation*: Pitting (Obeyesekere, 2017) typically, it begins post-condensation of exhaust gases accumulated at a point where the chloride concentration is very high for some time and gets dry to exhaust heat if the surface has any defects like microcracks, inclusions or sites where protective films have been compromised, disrupting the protective oxide layer and exposing bare metal.

b. *Pitting propagation*: Once a pit has been initiated, several factors contribute to its propagation inside a pit with high chloride with low pH, acidic conditions, metal dissolves inside the pit and releases positively charged metal ions, which react with condensate water and accelerate the corrosion process, as shown in **Figure 20**.

c. *Autocatalytic process*: The chemical reactions within the pit create a cycle that sustains and accelerates pit growth. The pit environment becomes more acidic, while metal ions inside the pit attract chloride ions to balance the charge, worsening the corrosive environment. This autocatalytic reaction continues, causing the pit to deepen over time. To reach this stage of corrosion, parts need to be unused for some time to accelerate pitting.

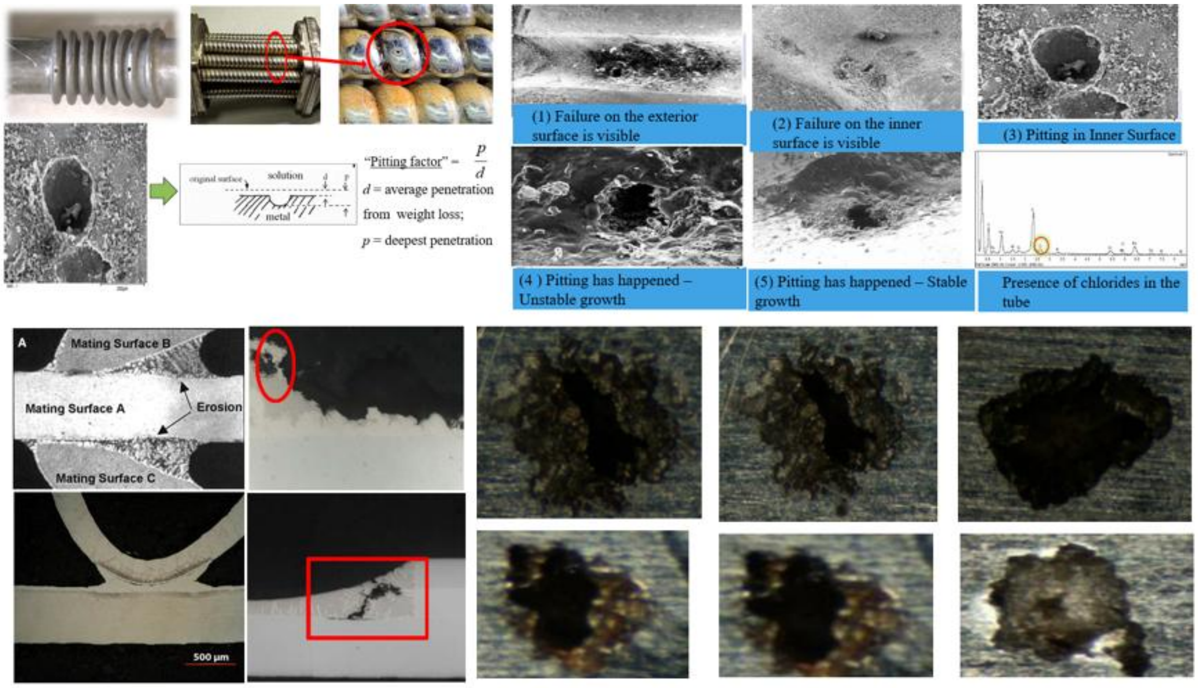


Figure 20. Pitting corrosion & sensitisation in EGR cooler and EGR tube, scanned electron beam microscope (SEM) analysis to find pitting corrosion.

4. Impact of Biofuel on EGR Durability and Life

The Government of India is promoting biofuel blending, particularly ethanol-based E10 to E100 for gasoline, and B5 to B100 (Biodiesel) as an alternative to fossil fuels to achieve energy security, reduce fuel imports, improve farmers' disposable income, and meet climate control goals. As the percentage of blending increases, balancing combustion and emissions becomes more challenging. The auto industry is developing a flex engine to mitigate this challenge. Also, engine durability becomes a challenge due to oxidised and unstable fuel. In biofuel production, water quality plays a significant role, as it is not controlled by the farmer, which creates a challenge in maintaining the total dissolved solids (TDS) percentage. Chloride and sulphate, which mix with the fuel, can cause pitting corrosion in the EGR cooler. To improve the life of the EGR cooler, automakers are working closely with system suppliers to develop EGR coolers with high-corrosion-resistant materials, such as super stainless steel, in addition to design modifications. Soot deposition in the EGR system due to improper combustion can be optimised by using a flex engine and suitable design modifications in the EGR cooler and valve.

5. EGR Cooler Technology Preferences

Based on the above study, the preference for EGR cooler technology can be diversified between diesel and gasoline engines, as summarized below.

- *Diesel*: EGR cooler technology preference for medium-duty TC diesel engines is a monoblack, hybrid 'U' type EGR with medium-density gas fins having overall cooling efficiency up to 95% in clean conditions and 85% in fouled conditions. For a heavy-duty engine, this technology preference changes to an 'I' type, floating core, HP, hybrid medium density gas fins having overall cooling capacity up to 90% in clean and 80% in fouled condition. Both the cooler designs are robust enough to meet the targeted engine durability and design life. For NA engine applications, cooler preference for both medium and high duty engines is 'I' type with low-density gas fins to reduce pressure drop under fouled conditions.
- *Gasoline*: EGR cooler technology preference for NA engine is 'I' type, high-density gas fins, with monoblock EGR Cooler construction. Special ferritic or super austenitic materials are used to withstand high thermal fatigue and provide pitting corrosion resistance.

6. Application of EGR for Modern Combustion Engine

EGR is a widely adopted technology in modern combustion engines, including Homogeneous Charge Compression Ignition (HCCI) (Kalaskar et al., 2014), Partially Premixed Combustion Ignition (Alemayehu et al., 2022) (PCCI), Reactivity Controlled Compression Ignition (Kakoee et al., 2024) (RCCI), hybrid engines, and even in engines utilizing green hydrogen and liquid ammonia (Chiong et al., 2021) as a combustion fuel, EGR helps improve fuel efficiency and reduce NOx emissions. Below is an overview of how EGR applies to each of these engine types.

6.1 HCCI Engine

It is an advanced engine technology developed to combine the features of CI and SI engines. HCCI engines (Duan et al., 2021) are mainly developed to achieve high thermal efficiency and low emissions by utilizing a homogeneous air-fuel mixture that auto-ignites under high-pressure and temperature conditions. Unlike traditional SI engines that rely on spark plugs for ignition, HCCI engines (Fathi et al., 2011), like CI engines, achieve combustion through compression alone. This results in a more uniform combustion process, leading to lower NOx and PM emissions than conventional engines. Both internal and external EGR is widely used to control NO_x emissions by lowering the combustion peak temperature (Zhou et al., 2018). Research has been conducted to investigate the benefits, and every researcher has concluded that reducing the oxygen concentration and operating at lean helps reduce NO_x. Optimizing internal and external EGR reduces fuel consumption and engine knock. Although external EGR significantly helps to reduce NO_x, CO & HC can increase slightly.

6.2 PCCI

PCCI engine has proven its capability to deliver superior fuel economy and ultra-low NO_x and particle matter emissions compared with the conventional combustion engine. Modern advanced engine technology focuses on taking advantage of SI and CI engines, i.e., low emissions and higher thermal efficiency. Modern combustion technologies like GDI and HCCI have significantly improved above the requirements; however, some issues, like relatively higher HC and CO emissions, are not improved under specific operating conditions. Developing the PCCI engine focused mainly on reducing NO_x and particulate matter emissions by achieving lean combustion with a well-mixed fuel-air charge before ignition. High efficiency and low emissions are achieved through a controlled auto-ignition process and EGR mixing. PCCI combustion strategy mainly focuses on fuel injection timing, in which fuel is injected early during the compression stroke by allowing it to be mixed homogeneously with air. After mixing, combustion is controlled by operating under a lean and low-temperature zone. Thus, it achieves a clean combustion with lower emissions (Hoang, 2024).

6.3 RCCI

RCCI engine technology (Duraisamy et al., 2019) is developed with an advanced combustion strategy that works under the principle of a dual fuel combustion strategy, out of which one fuel is high-reactivity and the other is low-reactivity fuel. This strategy is adapted to optimise engine efficiency and reduce emissions. The EGR system plays a pivotal role in achieving emission reduction in RCCI engine technology, especially during high engine load, to control pressure increase. Although the rate of EGR can go up to 50 percent in RCCI engines depending on the fuel used and applied load in regular operating conditions, the rate of EGR is relatively low since the rate of burning is regulated through altering the mixture reactivity by bi fuel strategy with selecting fuels with significantly varied reactivity. Both internal and external EGR techniques are applied in RCCI engines; however, externally cooled EGR is more effective at higher operating pressures.

6.4 GDI & Port Fuel Injection (PFI) Engine

EGR was introduced to downsize the gasoline engine without compromising its performance. Due to this new requirement, a turbocharged spark ignition engine was introduced since it helps to downsize the engine with high power density (Piqueras et al., 2020); however, it creates the problem of knock and high-temperature exhaust at high load conditions, which impacts engine durability. To address both points, a cooled EGR system (Piqueras et al., 2020) was introduced, which reduces precombustion and knock and lowers peak combustion temperatures, improving engine life and fuel economy. GDI engine (He et al., 2025) is designed to operate under lean and ultra-lean environments; therefore, conventional NO_x reduction technology like TWC does not work efficiently. Therefore, both hot and cool EGR were introduced, which reduces NO_x emission but also helps to reduce the pumping losses, reduces engine knock, and improves fuel economy. PFI engine is the design work under stoichiometric conditions; EGR is introduced in PFI engine mainly due to three reasons, i.e., reducing the pumping losses by reducing the amount of fresh air, reducing loss of heat transfer from cylinder wall due to less combustion temperature and degree of disassociation of exhaust burned gasses which allows more fuel chemical energy converted into sensible energy at top dead center (TDC). Combining all these factors eventually reduces the fuel consumption in PFI engines.

6.5 Green Hydrogen ICE

Carbon, especially CO_2, plays a significant role in the Earth's climate system. The primary source of $C0_2$ is fossil fuel combustion; CO_2 concentration in the atmosphere is increasing substantially every year, which has a significant impact on human health in three ways, i.e., by increasing global warming through greenhouse gas emissions, ocean acidification by consuming 30% of emitted CO_2 & carbon cycle imbalances. Therefore, every country in the world is moving towards carbon-free fuel technology. Hydrogen (Szwaja et al., 2024) is one of the most promising fuels, potentially replacing fossil fuels in ICE. When hydrogen is produced with the help of renewable energy like solar or wind energy, it is called green hydrogen (Purayil et al., 2024). Green hydrogen internal combustion engine vehicles (HICEV) operate similarly to conventional ICE engines. The main difference between green and fossil fuels is that hydrogen does not contain carbon, resulting in significantly lower emissions. When hydrogen combusts, the primary byproducts are water vapour and trace amounts of nitrogen oxides (NO_x, eliminating CO and CO_2 emissions. Hydrogen can be used both in CI and SI engines. The CI engine can blend diesel with HCCI or RCCI ignition. In SI engines, it can be mixed with gasoline, CNG or PNG or used independently as a primary fuel. EGR is the most effective technology for balancing power output and controlling NO_x emissions in H_2 ICE. EGR helps to reduce emissions both in hydrogen (H_2) ICE-PFI, H_2 ICE and Late direct injection (LDI) engines by slowing down the flame speed and reducing the in-cylinder temperature, leading to NO_x reduction. EGR application in H_2 ICE can reduce NO_x emissions by up to 85% at high load conditions.

7. Conclusion

Emission regulators are working towards implementing Euro 7 and BS 7 standards for all on-road automotive applications. EGR technology has proven its credibility for the last 2 decades. Based on a detailed review, this paper summarises the results of studies from 2002 to 2025, summarised as points:

- By implementing Euro 7 emissions in Europe and BS 7 emissions in India, tailpipe and particulate emissions can be brought down between 13-56 % for all types of vehicles, including non-ICE vehicles.
- EGR technology is one of the most prominent technologies across all types of ICE engines, including hybrid engines for NO_x reduction.
- EGR technology can reduce fuel consumption in gasoline and HEV, in addition to NOx reduction, to meet Euro 7 Emission legislation
- Different EGR techniques, like HP and LP and internal and external loops, help reduce NO_x by more than 50%.
- Different types of EGR coolers and more astonishing internal construction, including plain, corrugated, shaped tubes, and hybrid tubes, help achieve a thermal efficiency of up to 97% with a minimum pressure drop across the system.
- The robustness of an EGR cooler depends on many factors: its application, environmental conditions, quality of fuel, and design configuration. The life of the EGR cooler can be extended by carefully applying certain design principles.
- EGR technology is best suited to current ICE vehicles, future engine technologies like HCCI, PPCI, RCCI, GDI, and HEV engines, and future fuels like H_2, NH3, Biodiesel, and flex-fuel.

List of Abbreviations

Term	Abbreviation
Bharat Stage	BS
Battery Electric Vehicle	BEV
Internal Combustion Engine	ICE
Exhaust Gas Recirculation	EGR
Nitrogen Oxides	NOx
Internal Combustion	IC
Carbon Monoxide	CO
Hydrocarbon	HC
Total Hydrocarbon	THC
Carbon Dioxide	CO2
Particulate Matter	PM
Particulate Number	PN
Hybrid Electric Vehicle	HEV
Spark Ignition	SI
Compression Ignition	CI
Nitric Oxide	NO
Nitrogen Dioxide	NO2
Nitrous Oxide	N2O
Pure Electric Vehicle	PEV
Three-Way Catalytic Converter	TWC
Port Fuel Injection	PFI
Multi Point Fuel Injection	MPFI
Fuel Cell Electric Vehicle	FCEV
Common Rail Direct Injection	CRDI
Diesel Oxidation Catalyst	DOC
Selective Catalytic Reduction	SCR
Top Dead Centre	TDC
Bottom Dead Centre	BDC
Direct Injection	DI
Homogeneous Charge Compression Ignition	HCCI
Reactivity Controlled Compression Ignition	RCCI
Gasoline Direct Injection	GDI
Premixed Charge Compression Ignition	PCCI

Hydrogen	H2
Finite Element Analysis	FEA
Computational Fluid Dynamics	CFD
Fouling Factor	FF
Spark Assisted Compression Ignition	SACI
Real Driving Emission	RDE
Cetane Number	CN
Compression Ratio	CR
Engine Control Unit	ECU

Conflicts of Interest

The authors confirm that there is no conflict of interest to declare for this publication.

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