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Research Article

The Effect of Hot and Cold EGR Applications on Exhaust Emissions in Diesel Engines

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Abstract **–** In this study, the effects of hot and cold Exhaust Gas Recirculation (EGR) applications on exhaust emissions in diesel engines were experimentally investigated. Tests were conducted by applying both hot and cold EGR at 10% and 20% rates, and the resulting emission values were compared with standard operating conditions. The results revealed that both types of EGR significantly reduced NOx emissions. However, as the EGR rate increased, notable increases were observed in HC, CO, and smoke emissions. These increases are attributed to the reduction in oxygen concentration and combustion temperature in the combustion chamber caused by EGR, which negatively affects combustion efficiency. In particular, the further decrease in combustion temperature with cold EGR applications exacerbated these negative effects. In conclusion, although EGR applications are effective in controlling NOx emissions, they must be carefully optimized due to their adverse impact on other harmful emissions. The findings suggest that to balance engine emissions effectively, EGR rate, application type (hot/cold), and engine operating parameters must be evaluated together.

Keywords – EGR, NOx, Smoke, HC, CO Emissions.

I. INTRODUCTION

Diesel engines are widely used, particularly in commercial transport vehicles and industrial applications. However, although these engines are known for their high efficiency and durability, they can have a significant impact on atmospheric air pollution. Diesel engine emissions contain harmful components such as carbon dioxide (CO_2), nitrogen oxides (NO_x), and particulate matter (PM). These emissions degrade air quality, pose risks to human health, and lead to environmental consequences. Therefore, reducing emissions from diesel engines is of great importance for both environmental sustainability and public health [1].

Various technological approaches have been developed to reduce emissions in diesel engines. These include systems designed to directly control exhaust emissions, fuel technologies, and in-cylinder improvements [2]. Today, the main methods used to limit emissions include exhaust gas recirculation (EGR), selective catalytic reduction (SCR), diesel particulate filters (DPF), and fuel additives. Each of these methods has its own advantages and challenges that can affect engine performance [3].

One of these technologies is the exhaust gas recirculation (EGR) system. EGR is one of the most commonly used methods for reducing engine emission levels [4]. The EGR system aims to reduce NOx emissions by redirecting a portion of the exhaust gases back into the engine's combustion chamber. By lowering the oxygen concentration in the combustion chamber, EGR helps to prevent the formation of NOx, which occurs at high temperatures [5,6]. The effectiveness of EGR can vary depending on the engine type, operating conditions, and the design of the EGR system. Overall, EGR applications are considered an important tool for improving the efficiency of diesel engines and reducing their environmental impact [7].

EGR application is a commonly used method for reducing emissions in diesel engines. Various studies have examined the effectiveness of EGR systems in reducing NO_x (nitrogen oxide) emissions and their impact on engine performance. Below are the results of some significant studies related to EGR applications:

Hira et al. demonstrated that a cooled EGR system reduced NO_x emissions by 24% in a single-cylinder, air-cooled, direct injection diesel engine. Additionally, the effect of EGR rate on engine performance was examined, and an optimal emission control was achieved with an EGR rate between 5% and 15%. The results showed that while EGR significantly reduced NO_x emissions, it had minimal adverse effects on engine efficiency [8]. Guan et al. reported that the combination of the Miller cycle and EGR technology reduced NO_x emissions by 57% and fuel consumption by 1.6% in heavy-duty diesel engines. This strategy ensured compliance with Euro VI emission standards without causing significant performance loss in the engine. The Miller cycle used alongside EGR stood out as an effective solution for improving both emissions and fuel efficiency [9].Schwoerer et al. noted that EGR systems used in diesel engines successfully controlled NO_x emissions and could reduce emissions by up to 40% in engines operating under heavy loads. They also emphasized that adjustments were required to optimize engine performance depending on the EGR rate, and excessive use of EGR could increase particulate matter (PM) emissions [10]. Shivashimpi et al. showed that EGR application in diesel engines running on Palm Oil Methyl Ester reduced NO_x emissions by 20%. As the EGR rate increased, particularly under low-load conditions, the engine operated more efficiently, and NO_x emissions were effectively reduced [11]. In a study conducted by Park et al., where EGR was used in combination with a selective catalytic reduction (SCR) system, NO_x emissions were found to be reduced by up to 70%. Although EGR was effective in reducing NO_x emissions, it was concluded that excessive EGR rates had negative effects on engine efficiency, thus requiring optimization of the EGR rate [12]. Lopez et al. investigated the effectiveness of EGR in reducing NO_x and PM emissions in diesel engines, with a particular focus on the performance of cooled EGR systems. The cooled EGR system reduced NO_x emissions by up to 30%, while increasing PM emissions by 10–15%. However, no significant negative impact on overall engine efficiency was observed. Even at high EGR rates, the increase in PM emissions was found to be limited [13]. Shao et al. examined the effects of EGR on NO_x and CO_2 emissions in diesel engines and analyzed the performance of the cooled EGR system. The study found that increasing the EGR rate reduced NO_x emissions by up to 25%, while CO_2 emissions increased by 5%. The cooled EGR system was more effective in reducing NO_x emissions while also helping control the rise in CO_2 emissions. Negative impacts of EGR on engine performance remained minimal [14]. Yang et al. studied the effects of EGR rates on high-performance diesel engines, particularly under high-load conditions. Under such conditions, increasing the EGR rate reduced NO_x emissions by up to 40%. However, fuel consumption increased by 2.3%, and a slight decrease in engine efficiency was observed. The effect of EGR on PM emissions was found to be limited [15]. Lapuerta et al. evaluated the effects of EGR application under different operating conditions in diesel engines and examined the interaction between engine internal variables and EGR. The study found that low EGR rates could reduce NO_x emissions by 15–20%, while higher EGR rates could achieve reductions of up to 30%. However, higher EGR rates increased PM production by about 5% [16]. Dundar et al. investigated the impact of different EGR rates in diesel engines and focused on the effectiveness of EGR under low temperature and load conditions. Tests on the performance of cooled EGR systems primarily focused on NO_x emissions. Under low temperature and load conditions, EGR could reduce NO_x emissions by 40%, although a 2% decrease in engine efficiency was observed. It was also found that higher EGR rates led to improved engine operation and lower CO_2 emissions [17]. Kim et al. examined the effects of EGR on emissions in diesel engines and the impact of various EGR rates on overall engine performance. The study also considered the effect of cooled EGR application. Increasing the EGR rate up to 20% reduced NO_x emissions by 32%. The cooled EGR system was found to reduce NO_x emissions more effectively without negatively affecting fuel consumption. Additionally, positive effects on power output and engine efficiency were observed [18]. Singh et al. investigated the effectiveness of EGR in diesel engines in relation to engine operating conditions and load levels. The study analyzed the effects of different EGR systems and their outcomes on emission control. EGR application reduced NO_x emissions by 18%, while PM emissions increased by 10%. It was also observed that EGR was more effective under low-load conditions, whereas the reduction rate of NO_x emissions was lower under high-load conditions [19].

This study aims to examine how the application of EGR (Exhaust Gas Recirculation) reduces emissions in diesel engines. The effects of different rates of hot and cooled EGR applications on exhaust emissions released from the engine are experimentally investigated. The operating principles, effectiveness, and limitations of the EGR system will be discussed in detail, and an analysis supported by data obtained from the literature will be presented.

II. MATERIALS AND METHOD

In this study, a single-cylinder, four-stroke, naturally aspirated, direct injection, and water-cooled diesel engine was used to investigate the effects of different EGR rates on engine performance and exhaust emissions. The experimental work was conducted under full load conditions and at various engine speeds.

The test setup was equipped with high-precision sensors and advanced data acquisition systems to ensure accurate and repeatable measurement of both engine performance parameters and emission values. This setup, along with all its components, is schematically illustrated in Figure 1.

For loading and braking the engine, a KEMSAN brand, 20 kW capacity, direct current type electric dynamometer was used. The test engine was connected directly to the dynamometer system via the crankshaft using a rigid coupling. The applied torque values were measured with high precision using an “S” type load cell mounted on the dynamometer arm. This system ensured the accuracy and repeatability of the measurements of the mechanical power produced by the engine.

Fuel consumption measurements were carried out based on the principle of precisely determining the amount of fuel consumed over a specific period. For this purpose, the diesel fuel supplied from the fuel tank was weighed using a high-precision electronic scale (with a resolution of ±0.1 grams) in conjunction with a stopwatch. Fuel consumption at each test point was measured at least three times, and the average of the obtained values was taken to minimize experimental error.

Exhaust gas temperatures were recorded using a “K” type thermocouple placed at the engine’s exhaust outlet. The thermocouple data were transferred to the data acquisition system in real-time and monitored digitally. For emission measurements, an MRU brand exhaust gas analyzer was used.

The EGR system was activated using an adjustable valve mounted between the engine’s intake manifold and exhaust outlet, enabling both hot and cold EGR at different rates (%0, %10, and %20). For each applied EGR rate, the engine was operated for a sufficient period to reach steady-state conditions, after which the measurements were taken. For the analysis of exhaust emissions, NOx, CO, HC, and smoke emissions were measured separately, and a comparative evaluation was performed for each test point.

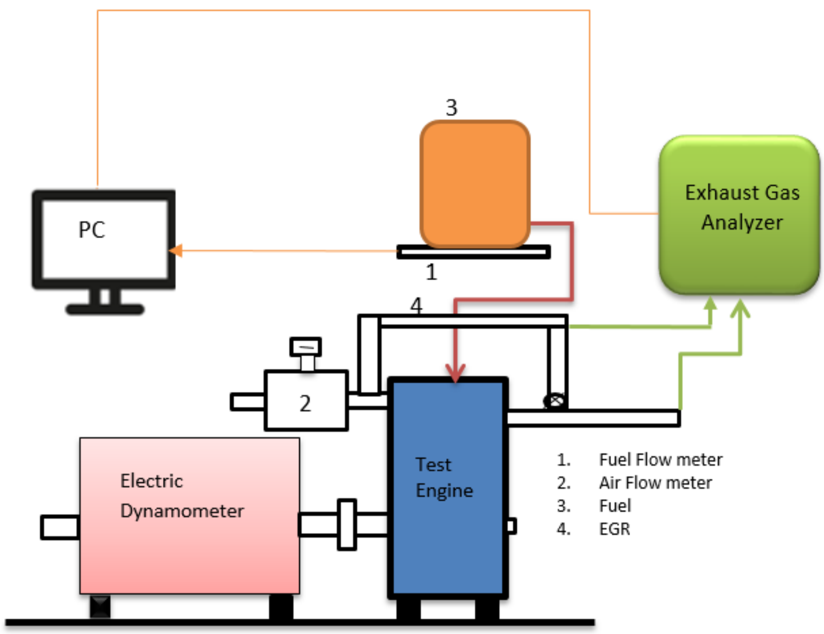

Fig.1 Test stand

III. RESULTS

This study experimentally investigates the effects of hot and cold EGR application on the exhaust emissions released from the engine. The experimental study was conducted under full load conditions and at different engine speeds.

Figure 2 shows the variation of NOx emissions depending on engine speed and the effects of different EGR rates on these emissions. The three conditions examined are: standard (no EGR applied), 10% EGR, and 20% EGR. It is observed that NOx emissions decrease in all three cases as the engine speed increases (from 1300 rpm to 2300 rpm). The highest emission values occur at low speeds, especially at 1300 rpm, while the lowest values are recorded at 2300 rpm. The application of EGR reduced NOx emissions across all speed ranges; the 20% EGR rate provided a greater reduction compared to 10% EGR. This indicates that the EGR system lowers the combustion temperature, thereby preventing NOx formation. These data demonstrate that EGR application significantly reduces NOx emissions at every engine speed. In particular, the 20% EGR rate achieved a larger decrease compared to 10% EGR. For example, at 1700 rpm, the standard NOx value is approximately 850 ppm, while with 20% EGR, this value drops to about 600 ppm, representing roughly a 29% reduction. In conclusion, the EGR system limits NOx formation by reducing combustion temperature and oxygen concentration, thus making a significant contribution to reducing environmental impacts. The reducing effect of higher EGR rates on NOx emissions is clearly illustrated in the graph.

The effect of the EGR system in reducing NOx emissions is based on the physical and chemical changes it induces in the combustion chamber. The EGR system redirects a portion of the engine's exhaust gases back into the intake manifold and subsequently into the cylinders. Since these recirculated exhaust gases are inert (non-combustible), they lower the peak temperature inside the combustion chamber. Because NOx formation accelerates at high temperatures, reducing the temperature directly inhibits NOx formation. Additionally, the exhaust gases have low oxygen content, which dilutes the oxygen concentration of the intake air, resulting in slower combustion at lower temperatures. This significantly reduces NOx production. Moreover, due to the high heat capacity of the exhaust gases, the temperature rise during combustion is more limited. As a result, the combustion process occurs both at a lower temperature and more slowly with EGR application, leading to a significant reduction in NOx emissions. Through these mechanisms, NOx formation is notably suppressed especially in high EGR rate applications, contributing to the reduction of environmental impacts.

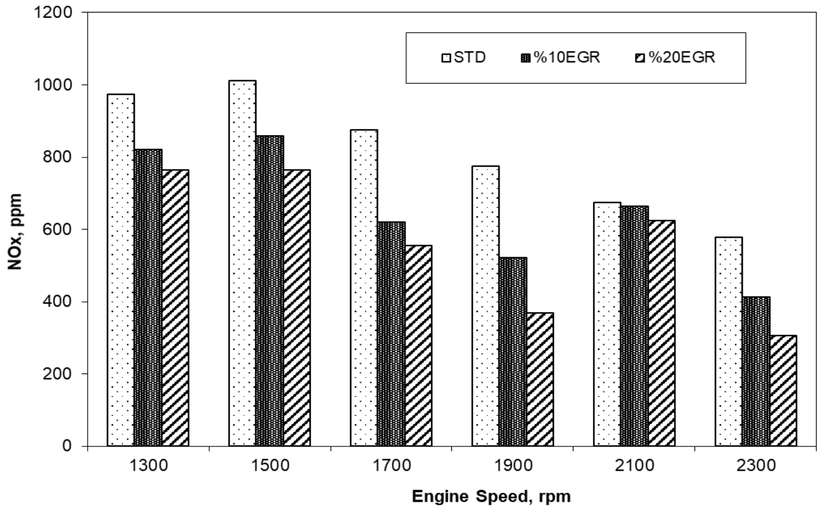

Fig. 2 Effect of Hot EGR Application on NOx Emissions

Figure 3 shows the variation of HC (hydrocarbon) emissions with engine speed and the effects of different EGR rates on these emissions. Three different conditions are compared: standard (without EGR), 10% EGR, and 20% EGR. In general, a significant increase in HC emissions is observed as the EGR rate increases. For example, at 1700 rpm, HC emissions are approximately 15 ppm under the standard condition, rising to 35 ppm with 10% EGR and about 55 ppm with 20% EGR. Similarly, the same trend is maintained across all engine speeds, with 20% EGR consistently producing the highest HC emissions.

The primary reason for this increase is the negative impact of EGR application on combustion efficiency. Since exhaust gases contain non-combustible components, they reduce the amount of fresh air and oxygen concentration entering the cylinder. This leads to incomplete combustion and causes partially burned fuel to remain in the exhaust gases. Additionally, effects such as reduced combustion temperature and slower flame propagation make complete combustion more difficult, especially at low and medium engine speeds. As a result, insufficient oxygen and low temperature conditions cause an increase in unburned or partially burned hydrocarbon compounds. Therefore, while the EGR system is beneficial for reducing NOx emissions, it has an adverse side effect of increasing HC emissions. This highlights the need for careful optimization of the EGR rate in engine tuning.

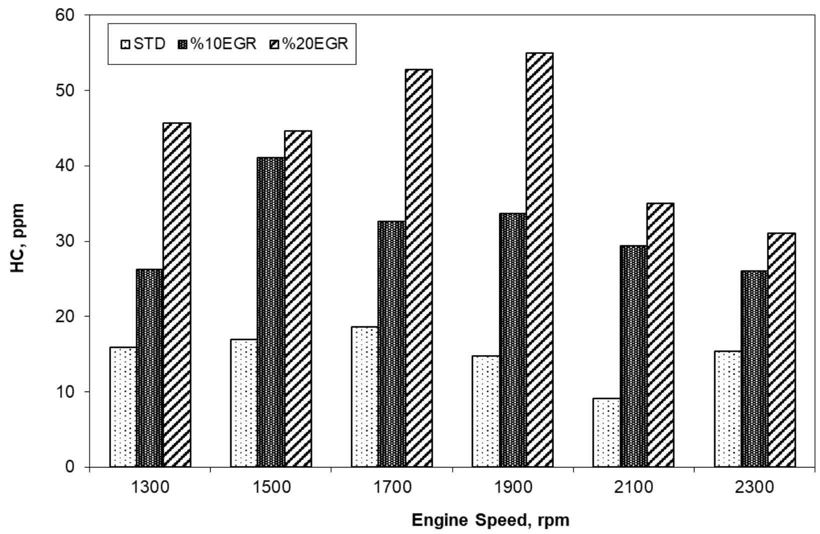

Fig. 4 Effect of Hot EGR Application on HC Emissions

Figure 4 shows the percentage change in CO (carbon monoxide) emissions depending on engine speed and the effects of different EGR rates on these emissions. Three conditions are compared: standard (no EGR), 10% EGR, and 20% EGR. The general trend indicates that as the EGR rate increases, CO emissions also noticeably increase. For example, at 1100 rpm, the standard CO emission is approximately 0.10%, while with 10% EGR it rises to 0.25%, and with 20% EGR it reaches around 0.50%. This increase is observed across all engine speed ranges, with the highest CO emission occurring at 20% EGR and 2100 rpm.

The main reason for the increase in CO emissions is that the EGR system reduces the amount of oxygen in the combustion chamber and lowers combustion efficiency. With the recirculation of exhaust gases, less fresh air (and therefore less oxygen) enters the cylinders. This leads to the formation of rich (oxygen-deficient) mixtures and incomplete combustion. When complete combustion does not occur, the carbon content cannot fully convert to CO_2 and instead forms CO. Additionally, the EGR's reduction of combustion temperature slows down the combustion kinetics, further increasing CO formation. As a result, as the EGR rate increases, combustion quality decreases and CO emissions rise. This shows that while the EGR system is effective in reducing NOx, it can negatively affect combustion efficiency and cause an increase in other harmful gases such as CO. Balancing this trade-off is crucial in engine design and emission control strategies.

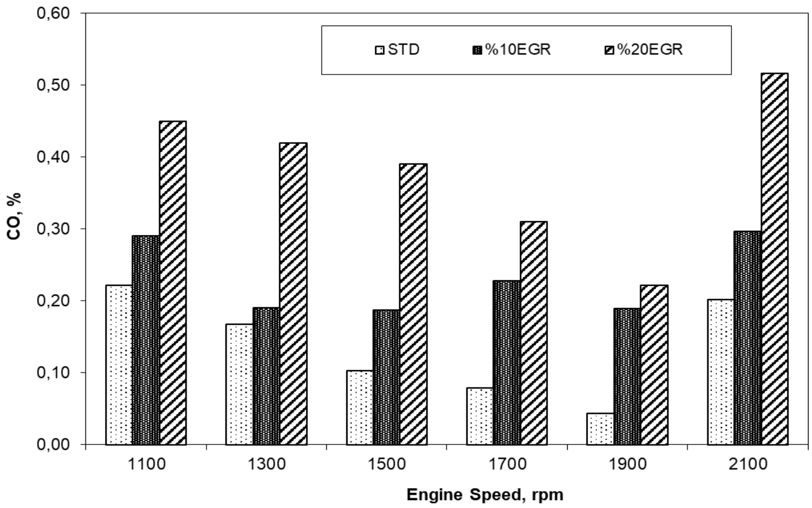

Fig. 4 Effect of Hot EGR Application on CO Emissions

Figure 5 shows the percentage change in smoke emissions depending on engine speed and the effect of different EGR rates on this change. Three conditions are compared: standard (without EGR), 10% EGR, and 20% EGR. According to the data obtained, smoke emissions generally increase as engine speed rises. Especially at speeds of 1700 rpm and above, smoke emissions significantly increase, and this increase becomes more pronounced with higher EGR rates. For example, at 1700 rpm, the smoke level is around 60% under standard conditions, rising to 70% with 10% EGR and approximately 75% with 20% EGR. The same trend is observed at higher speeds such as 2100 and 2300 rpm.

The main reason for this increase is that the EGR system reduces the oxygen concentration in the combustion environment and lowers the combustion temperature. Exhaust gases recirculated back into the engine partially replace fresh air, leading to a decrease in oxygen concentration in the cylinder. This causes incomplete combustion due to insufficient oxygen, especially under high load and speed conditions. The unburned fuel particles increase smoke (soot) formation. Additionally, lower temperatures slow down evaporation and combustion processes, resulting in more soot particles in the exhaust gas. Therefore, although the EGR system is effective in reducing NOx emissions, it tends to increase smoke emissions when used at high rates. This highlights the importance of optimizing the EGR rate by considering all emissions (NOx, HC, smoke) to achieve the best balance.

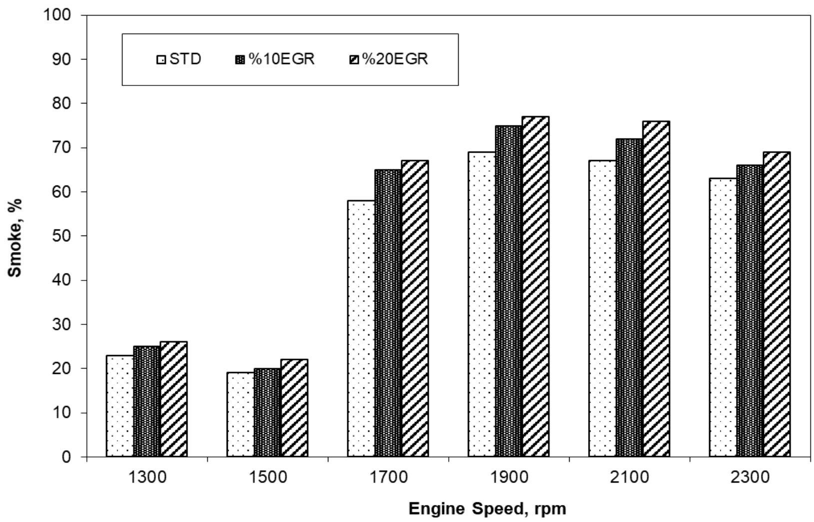

Fig. 5 Effect of Hot EGR Application on Smoke Emissions

Figure 6 shows the variation of NOx emissions with engine speed and the effect of different rates of cold EGR on these emissions. The three conditions examined are: without EGR (STD), 10% cold EGR, and 20% cold EGR. The general trend indicates that NOx emissions significantly decrease as the EGR rate increases. For example, at 1300 rpm, NOx emissions are approximately 1000 ppm under standard conditions, while they decrease to 650 ppm with 10% cold EGR and to about 400 ppm with 20% cold EGR. Similarly, a gradual and consistent reduction in NOx emissions is observed across all engine speeds as the EGR rate increases.

The main reason for this decrease is that the cold EGR system reduces the combustion chamber temperature more effectively. In cold EGR application, the exhaust gases leaving the engine pass through a cooler before being returned to the cylinders at a lower temperature. This lowers both the combustion temperature and the oxygen concentration in the cylinder, limiting NOx formation. NOx is a pollutant formed under high temperature and abundant oxygen conditions. Since the additional cooling effect provided by cold EGR results in a stronger temperature drop compared to conventional EGR, it is more effective in reducing NOx. Moreover, lower temperatures slow down combustion reaction rates, which restricts the time available for NOx formation. Therefore, cold EGR technology offers a significant advantage in reducing NOx emissions in diesel engines and is widely preferred to meet emission standards.

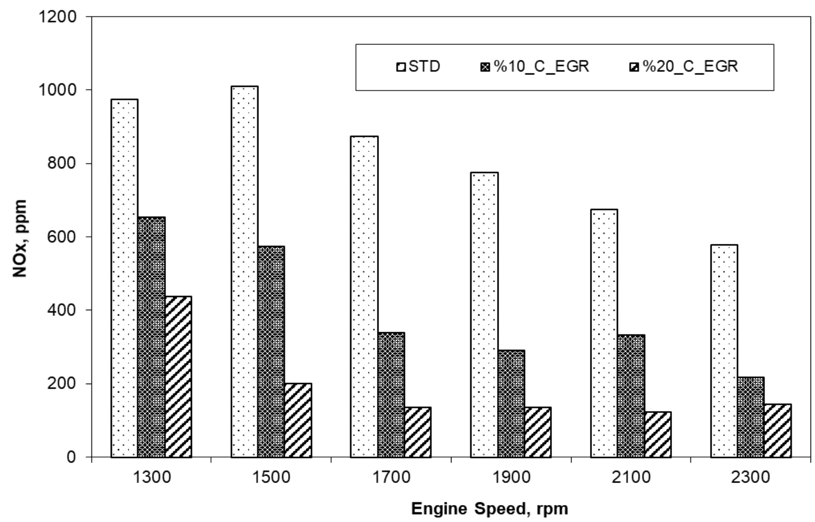

Fig. 6 Effect of Cold EGR Application on NOx Emissions

Figure 7 shows the effect of the cold EGR system applied to the diesel engine on HC emissions depending on engine speed. Three different conditions were examined: standard without EGR (STD), 10% cold EGR (%10_c_EGR), and 20% cold EGR (%20_c_EGR). According to the obtained data, a significant increase in HC emissions is observed as the EGR rate increases. For example, at 1500 rpm, HC emissions are approximately 15 ppm under standard conditions, while they rise to 45 ppm with 10% cold EGR and reach about 75 ppm with 20% cold EGR. A similar increasing trend is present across all engine speeds; the highest HC emission of 80 ppm was recorded at 2300 rpm with the 20% cold EGR application.

The main reason for this increase is the negative effect of cold EGR on combustion quality. The low-temperature exhaust gases supplied to the cylinder by cold EGR reduce the combustion temperature, increasing ignition delay and making it harder for combustion reactions to complete. Additionally, since the exhaust gases reduce the amount of oxygen entering the cylinder, rich mixture conditions occur, preventing complete fuel combustion. Unburned or partially burned hydrocarbons are then released as exhaust gases. For these reasons, while the cold EGR system is effective in reducing NOx emissions, it causes an increase in incompletely burned pollutants such as HC. This situation indicates that when determining the EGR rate, HC and other emissions must also be considered, and a comprehensive balance should be established for optimal emission control.

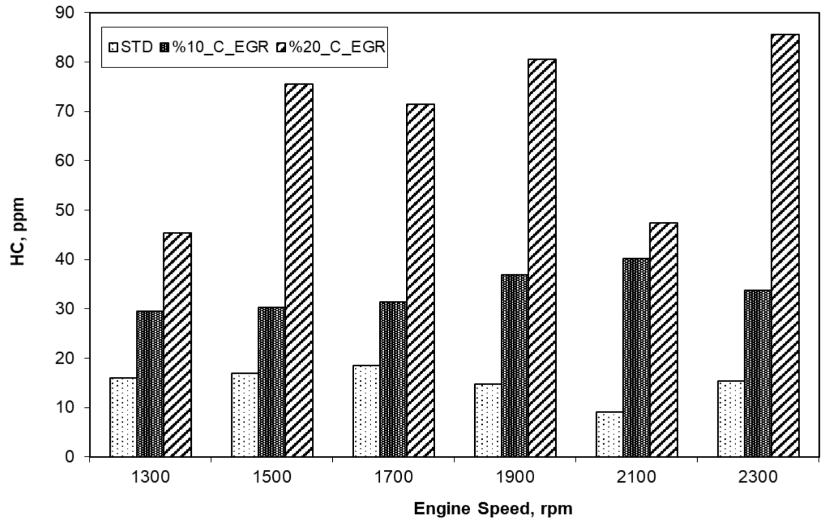

Fig. 7 Effect of Cold EGR Application on HC Emissions

Figure 8 shows the effect of the cold EGR system applied to the diesel engine on CO emissions depending on engine speed. Three different operating conditions were examined: standard system without EGR (STD), 10% cold EGR (%10_c_EGR), and 20% cold EGR (%20_c_EGR). The data indicate a significant increase in CO emissions as the cold EGR rate rises. For example, at 1500 rpm, CO emissions are approximately 0.2% under the standard condition, while this value increases to 0.75% with 10% cold EGR and reaches 1.6% with 20% cold EGR. A similar trend is observed across all engine speed ranges, with CO emissions increasing as the EGR rate increases.

The main reason for this increase is the low temperature and reduced oxygen concentration caused by cold EGR in the combustion chamber. The recirculation of cooled exhaust gases to the cylinder lowers the combustion temperature and reduces the amount of oxygen entering the cylinder. Under these conditions, complete combustion of the fuel becomes difficult, leading to the formation of partially burned products such as carbon monoxide. These effects are particularly pronounced at low and medium engine speeds because the combustion duration is shorter and low temperatures may not be sufficient to complete the combustion reactions. Additionally, since CO formation is more common in rich mixture regions, the oxygen-deficient environment created by EGR further increases CO emissions. Therefore, while cold EGR reduces NOx emissions, it decreases combustion efficiency and causes an increase in harmful combustion products like CO. This highlights the need for careful evaluation of multiple emission parameters in the design of EGR systems.

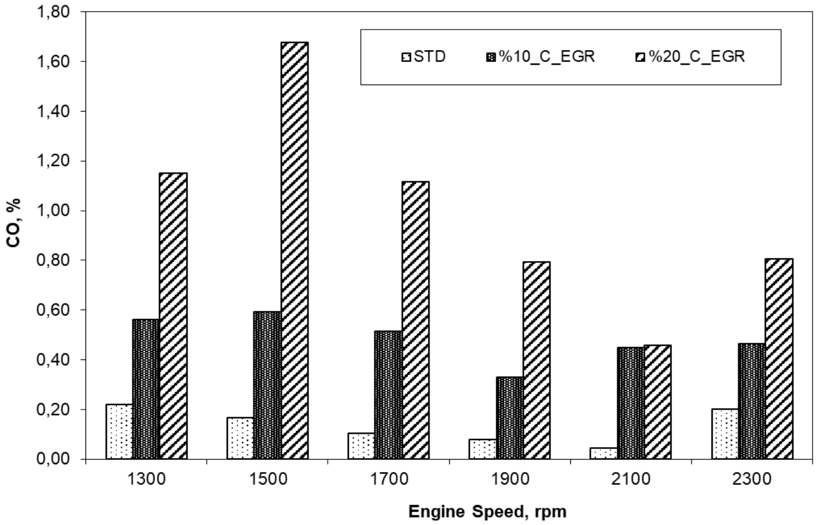

Fig. 8 Effect of Cold EGR Application on CO Emissions

Figure 9 shows the effect of the cold EGR system applied to the diesel engine on smoke emissions depending on engine speed. Three different conditions were examined: standard system without EGR (STD), 10% cold EGR (%10_c_EGR), and 20% cold EGR (%20_c_EGR). According to the data obtained, a significant increase in smoke emissions is observed as the EGR rate increases. For example, at 1900 rpm, the smoke level is approximately 75% in the standard system, while it rises to 80% with 10% cold EGR and about 85% with 20% cold EGR. This trend continues across all engine speed ranges, with the highest smoke emissions occurring under the 20% EGR condition.

The main reason for this increase is that the cold EGR system reduces the oxygen concentration and lowers the combustion temperature in the combustion chamber. The cooled exhaust gases recirculated back into the system with cold EGR reduce the amount of fresh air entering the cylinder. This leads to a decrease in oxygen concentration and a richer mixture. Under insufficient oxygen conditions, combustion cannot be completed fully, which increases soot (smoke) formation. Additionally, the cooling effect of the recirculated gases lowers the combustion temperature, reducing evaporation and flame propagation speeds, resulting in more unburned fuel particles. For these reasons, although cold EGR is effective in reducing NOx emissions, it tends to increase smoke emissions. This situation necessitates careful determination of the EGR rate during engine optimization and the development of strategies that balance different types of emissions.

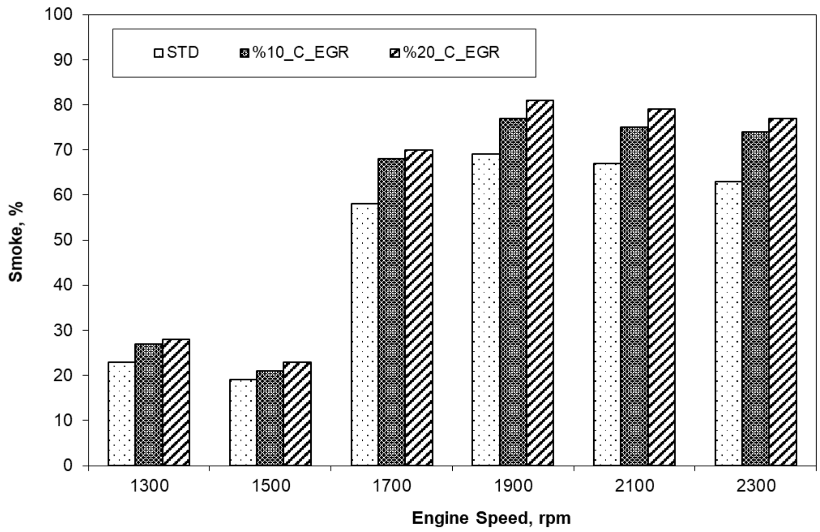

Fig. 9 Effect of Cold EGR Application on Smoke Emissions

IV. DISCUSSION AND CONCLUSION

This should explore the significance of the results of the work, not repeat them. The results should be drawn together, compared with prior work and/or theory and interpreted to present a clear step forward in scientific understanding. Combined Results and Discussion sections comprising a list of results and individual interpretations in isolation are particularly discouraged.

Experimental studies have comprehensively evaluated the effects of both conventional (hot) and cooled EGR applications on engine emissions in diesel engines. The results indicate that EGR systems are highly effective in reducing NOx emissions. In both hot and cooled EGR applications, a significant decrease in NOx emissions was observed with increasing EGR rates; this can be explained by the recirculated exhaust gases lowering the combustion temperature and reducing oxygen concentration in the cylinder. For example, NOx emissions, which were above 1000 ppm under standard conditions, dropped to below 400 ppm with a 20% EGR application.

However, the positive effects of EGR applications have been accompanied by some adverse impacts on other emission parameters. Notably, significant increases in HC, CO, and smoke emissions were detected. These increases can be attributed to the reduction in the amount of fresh air entering the cylinder, which lowers combustion quality. The decrease in combustion temperature and oxygen deficiency hinder complete combustion, thereby increasing HC and CO emissions; furthermore, incomplete combustion leads to a notable rise in smoke formation. These effects are especially pronounced in cooled EGR applications, where HC and CO emissions increased by more than double. Consequently, while EGR systems are effective in reducing NOx emissions, they negatively impact combustion efficiency and cause increases in HC, CO, and smoke emissions. This situation necessitates careful optimization of EGR implementation in engines and balancing among various emission types. The ideal solution involves integrating advanced combustion control technologies with EGR systems to reduce NOx without causing increases in other emissions.

This research provides an important contribution by examining the feasibility of emission control technologies in diesel engines in line with environmental sustainability goals. The experimental findings serve as guidance not only for academic literature but also for engine manufacturers and policymakers. Especially in a context where stricter emission standards are expected in the future, it is crucial to adapt EGR systems to different engine types, fuel characteristics, and operating conditions.

In conclusion, this study highlights the emission reduction potential of EGR technology in diesel engines while also drawing attention to performance losses and emission interactions encountered during its application. Future research should explore the integration of EGR with other aftertreatment systems (such as DPF and SCR), optimization of electronic control systems, and interactions with alternative fuels to enhance the effectiveness and efficiency of emission control strategies.

In this context, the study results contribute both to academic knowledge and provide practical guidance for engine manufacturers regarding the applicability of EGR systems. Future investigations addressing cooled EGR systems, EGR combined with variable geometry turbochargers, and interactions of EGR with alternative fuels will contribute to developing more sustainable and low-emission solutions in diesel engines.

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