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PERFORMANCE ANALYSIS OF AN EXHAUST GAS RECIRCULATION SYSTEM UNDER INJECTION TIMING AND ENGINE SPEED VARIATIONS FOR EMISSION REDUCTION IN AN R180 DIESEL ENGINE

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Abstract

In In efforts to comply with increasingly stringent environmental regulations, particularly those related to nitrogen oxide (NOx) emissions, exhaust emissions from conventional diesel engines remain a major concern. The Exhaust Gas Recirculation (EGR) system is one of the most widely developed emission control techniques, functioning to reduce combustion temperature by recirculating a portion of exhaust gases back into the combustion chamber. This study employs a simulation-based approach to investigate the impact of EGR implementation on the performance and emissions of an R180 diesel engine. The objective of this research is to analyze the effects of EGR application under variations in injection timing and engine speed. Simulation software is used to model a one-dimensional (1D) single cylinder four stroke R180 diesel engine. Injection timing is varied at several crank angles before top dead center (BTDC), along with changes in engine speed. The evaluated parameters include nitrogen oxide (NOx), carbon dioxide (CO_2), carbon monoxide (CO), hydrocarbon (HC) emissions. The simulation results indicate that increasing the EGR rate significantly reduces NOx emissions due to a decrease in combustion temperature. However, under certain operating conditions, variations in injection timing and engine speed significantly influence the effectiveness of the EGR system. An appropriate combination of these parameters can achieve an optimal balance between emission reduction and engine performance. This study is expected to serve as a reference for developing simulation-based emission control strategies for conventional diesel engines, particularly for small-scale applications.

Keywords: *R180 Diesel Engine; Exhaust Gas Recirculation (EGR); Injection Timing; Engine Speed; Exhaust Gas Emissions*

Abstrak

Dalam upaya untuk memenuhi regulasi lingkungan yang semakin ketat, terutama yang berkaitan dengan emisi nitrogen oksida (NOx), emisi gas buang dari mesin diesel konvensional masih merupakan masalah besar. Sistem Exhaust Gas Recirculation (EGR) adalah salah satu teknik pengendalian emisi yang paling banyak dikembangkan. Fungsinya adalah menurunkan suhu pembakaran dengan mensirkulasikan kembali sebagian gas buang ke dalam ruang bakar. Metode simulasi digunakan dalam penelitian ini untuk mempelajari dampak penerapan sistem EGR terhadap kinerja dan emisi mesin diesel R180. Pengaruh penerapan sistem EGR terhadap variasi waktu injeksi dan kecepatan mesin adalah tujuan penelitian ini. Untuk simulasi, perangkat lunak digunakan untuk memodelkan mesin diesel R180 satu silinder empat langkah satu dimensi (1D).Ketika variasi waktu injeksi diterapkan pada beberapa sudut sebelum titik mati atas (BTDC), kecepatan mesin berubah. Parameter yang dievaluasi termasuk emisi nitrogen oksida NOx, karbon dioksida (CO_2), karbon monoksida (CO), hidrokarbon (HC). Hasil simulasi menunjukkan bahwa, karena penurunan temperatur pembakaran, peningkatan laju EGR dapat menurunkan emisi NOx secara signifikan. Namun, pada kondisi tertentu, variasi waktu injeksi dan kecepatan mesin memberikan pengaruh yang signifikan terhadap efektivitas EGR. Diharapkan bahwa penelitian ini akan menjadi referensi untuk membangun metode pengendalian emisi berbasis simulasi untuk mesin diesel konvensional, terutama untuk aplikasi skala kecil.

Kata kunci: Mesin Diesel R180; Exhaust Gas Recirculation (EGR); Waktu Injeksi; Kecepatan Mesin; Emisi Gas Buang

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1. Introduction

Diesel engines are the primary source of propulsion for global maritime transportation and play a crucial role in supporting international trade. Despite their high thermal efficiency and operational reliability, marine diesel engines are also significant contributors to air pollution due to the exhaust gases produced during combustion. The main emissions from marine diesel engines include particulate matter (PM), carbon dioxide (CO_2), sulfur oxides (SO_x), and nitrogen oxides (NO_x), which are primarily generated during the combustion of heavy fuel oil under high-temperature and high-pressure conditions (Čampara et al., 2018).

Engine speed is a key operational parameter that directly affects combustion efficiency, fuel consumption, and pollutant formation mechanisms. Variations in engine speed across different operational modes, such as cruising, acceleration, and idling, result in distinct emission characteristics. At low engine speeds or during idling conditions, incomplete combustion caused by lower in-cylinder temperatures and insufficient air–fuel mixing often leads to increased emissions of carbon monoxide and unburned hydrocarbons. In contrast, high engine speeds and high-load conditions are associated with elevated combustion temperatures and excess oxygen availability, which promote the formation of nitrogen oxides (Zhang et al., 2016).

Since the invention of the diesel engine in the late nineteenth century, significant advancements have been made to improve efficiency and reduce emissions. Early developments focused on higher compression ratios and mechanical fuel injection systems, which enabled superior thermal efficiency compared to spark-ignition engines. In response to increasingly stringent environmental regulations, modern diesel engines have incorporated advanced emission control technologies. One of the most widely applied methods is Exhaust Gas Recirculation (EGR), which reduces NO_x formation by recirculating a portion of exhaust gas back into the intake system. This process lowers the oxygen concentration and peak combustion temperature inside the cylinder, thereby suppressing thermal NO_x formation (Flynn, 2000).

The primary factors responsible for NO_x formation are high combustion temperature, oxygen availability, and the residence time of gases inside the cylinder. A significant reduction in NO_x emissions has been observed with the retardation of injection timing (IT). When the injection timing is retarded, the combustion process becomes slower, leading to a reduction in peak in-cylinder temperature. As a consequence, NO_x formation decreases (Banapurmath et al., 2018).A subsequent study by Jayabal et al. (2019) investigated NO_x emissions as a function of engine load. The NO_x emissions from no-load to full-load conditions ranged from 51 to 2849 ppm, 124 to 2729 ppm, 89 to 3029 ppm, and 126 to 2973 ppm for diesel, B40, B40 + 10% DMC, and B40 + n-butanol (10%), respectively.Kumar et al. (2022) investigated the combined application of emission control systems in a diesel engine, namely exhaust gas recirculation (EGR), diesel particulate filter (DPF), and selective catalytic reduction (SCR), to identify the most effective configuration for reducing harmful exhaust emissions.

Although previous studies have demonstrated the effectiveness of fuel blending strategies, injection timing retardation, and after-treatment technologies such as EGR in reducing exhaust emissions, these approaches are often investigated in isolation. Studies on injection timing primarily focus on a single operating condition, while investigations on EGR systems commonly emphasize fixed engine speeds or loads without considering their interaction with injection timing. Moreover, research on emission control technologies largely relies on exhaust after-treatment systems, with limited emphasis on in-cylinder control strategies that can directly influence combustion behavior. Furthermore, comprehensive investigations examining the combined effects of exhaust gas recirculation (EGR), injection timing variation, and engine speed on both engine performance and emission characteristics remain scarce, particularly for small single-cylinder diesel engines such as the R180. Addressing this gap is essential for developing optimized, cost-effective emission reduction strategies that minimize reliance on complex after-treatment systems. Therefore, the present study aims to perform a performance and emission analysis of an EGR-equipped R180 diesel engine under varying injection timing and engine speed conditions to identify optimal operating parameters for emission reduction with minimal performance penalties using simulation.

2. Literature review

Exhaust Gas Recirculation (EGR) is a widely adopted technique in modern automotive engines to mitigate nitrogen oxide (NOx) emissions. NOx formation primarily occurs during engine operation as a consequence of elevated combustion temperatures. Significant NOx concentrations are generated when in-cylinder temperatures exceed approximately 2400–2500 °C. The operating principle of the EGR system involves redirecting a controlled fraction of exhaust gases into the intake manifold, where it mixes with the incoming air–fuel charge before entering the combustion chamber. The introduction of inert exhaust gases dilutes the oxygen concentration of the intake mixture and increases its specific heat capacity, thereby reducing peak combustion temperatures. As a result, the thermal conditions responsible for NOx formation are effectively suppressed. During the intake process, fresh air mixed with recirculated exhaust gas is drawn into the cylinder, initiating the subsequent combustion cycle under moderated temperature conditions.

The numerical investigation was carried out using a one-dimensional gas dynamics simulation program. The developed model was employed to evaluate the influence of varying Exhaust Gas Recirculation (EGR) rates on engine performance parameters, combustion characteristics, and nitrogen oxide (NOx) emissions of a single-cylinder diesel engine fueled with D100. The EGR rate was defined as the ratio of the mass flow rate of recirculated exhaust gas to the total intake charge, which consists of fresh air and recirculated exhaust gas. By adjusting the EGR percentage, the effect of exhaust gas dilution on in-cylinder thermodynamic conditions and emission formation could be systematically analyzed. The equation given by equation :

$$EGR(\%) = \frac{\dot{m}EGR}{\dot{m}air + \dot{m}EGR} \times 100 \qquad (1)$$

3. Methodology

In this study, a four-stroke Shark R180 diesel engine was used. The engine is a single-cylinder inline configuration. The Shark R180 engine is capable of producing an average power output of 5.15 kW at 2600 rpm, with a brake specific fuel consumption (BSFC) of less than 278 g/kW·h. The engine has a bore and stroke of 80 mm, and a compression ratio of 21:1. Figure 3 shows the setup to investigate the effect of exhaust gas recirculation (EGR) on engine performance characteristics and exhaust emissions, this study evaluates the implementation of an EGR system on the R180 diesel engine using simulation software. In addition to the incorporation of the EGR system, the study analyzes the performance of different EGR rates of 0%, 10%, 15%, and 20% under varying injection timing conditions of 18°, 20°, and 22° crank angle (CA) before top dead center, across different engine speeds of 2200, 2400, and 2600 rpm.

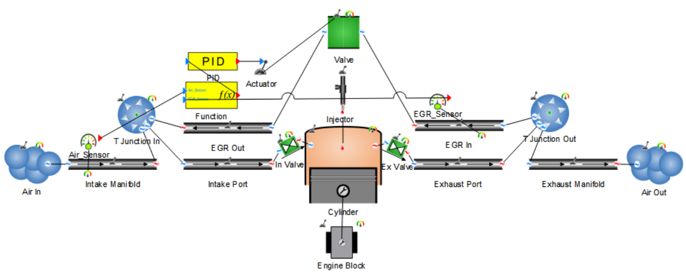

Figure 3. EGR Setup

Simulation data obtained from simulation are analyzed to evaluate the performance of the EGR system under combined variations of injection timing and engine speed with respect to exhaust emissions produced by the R180 diesel engine. The analysis aims to determine the most effective EGR rate for mitigating emissions generated under the simulated operating conditions.

4. Result and Discussion

4.1. NO_x Emissions

Figure 4.1(a) illustrates the relationship between engine speed (2200–2600 RPM) and NO_x emissions (ppm) at EGR rates of 0%, 10%, 15%, and 20% using D100 fuel at an injection timing of 22° CA. The numerical data were obtained from validated simulation results. As shown in the figure, variations in the exhaust gas recirculation (EGR) rate have a significant influence on NO_x formation across the entire range of engine speeds investigated.

Under the no-EGR condition (0% EGR), NO_x emissions at 2200 RPM were recorded at 605.97 ppm. As the engine speed increased to 2400 RPM, NO_x emissions slightly increased to 606.38 ppm, representing the highest value under this condition. This increase indicates that, at medium engine speed, higher combustion temperatures and accelerated chemical reaction rates promote NO_x formation. However, when the engine speed was further increased to 2600 RPM, NO_x emissions slightly decreased to 606.99 ppm, suggesting a reduction in the residence time of combustion gases at high temperatures, which begins to inhibit NO_x formation.

With the application of 10% EGR, NO_x emissions were consistently lower than those observed without EGR at all engine speeds. At 2200 RPM, NO_x emissions were 535.51 ppm, decreasing to 513.33 ppm at 2400 RPM and further declining to 487.54 ppm at 2600 RPM. This decreasing trend demonstrates that the introduction of recirculated exhaust gases into the combustion chamber effectively reduces combustion temperature through mixture dilution and increased specific heat capacity of the in-cylinder gases, thereby suppressing NO_x formation even as engine speed increases.

When the EGR rate was increased to 15%, a more pronounced reduction in NO_x emissions was observed. NO_x emissions decreased from 479.74 ppm at 2200 RPM to 450.54 ppm at 2400 RPM and further to 416.57 ppm at 2600 RPM. This consistent reduction indicates that a higher fraction of inert gases in the air–fuel mixture more effectively lowers peak combustion temperature and reduces oxygen concentration in the reaction zone, leading to enhanced suppression of NO_x formation mechanisms.

At the highest EGR rate of 20%, NO_x emissions reached the lowest values across all tested conditions. NO_x emissions were 396.83 ppm at 2200 RPM, decreased to 358.06 ppm at 2400 RPM, and reached a minimum value of 319.14 ppm at 2600 RPM. These results indicate that, at 20% EGR, the combined effects of combustion cooling and oxygen dilution dominate, significantly reducing NO_x formation despite increasing engine speed. Overall, it can be concluded that increasing the EGR rate consistently reduces NO_x emissions across the entire engine speed range, while the influence of engine speed on NO_x becomes less pronounced as the EGR fraction increases.

Figure 4.1(b) presents the relationship between engine speed (2200–2600 RPM) and NO_x emissions (ppm) at EGR rates of 0%, 10%, 15%, and 20% using D100 fuel at an injection timing of 20° CA. These results are further compared with those obtained at an injection timing of 22° CA, as discussed previously. The figure indicates that retarding the injection timing from 22° CA to 20° CA generally leads to a reduction in NO_x emissions across all EGR rates and engine speeds.

Under the no-EGR condition (0% EGR), NO_x emissions were 589.04 ppm at 2200 RPM, decreased slightly to 588.64 ppm at 2400 RPM, and then marginally increased to 589.31 ppm at 2600 RPM. These values are lower than those observed at an injection timing of 22° CA, confirming that injection timing retardation reduces peak combustion temperature due to the shift of the combustion phase closer to or after top dead center (TDC). As a result, the rate of thermal NO_x formation is reduced.

With the application of 10% EGR, NO_x emissions exhibited a clearer decreasing trend with increasing engine speed, with values of 513.93 ppm at 2200 RPM, 493.86 ppm at 2400 RPM, and 466.01 ppm at 2600 RPM. Compared to the 22° CA injection timing, this condition demonstrates that the combined effects of injection timing retardation and EGR application are more effective in reducing in-cylinder temperature and oxygen concentration, thereby suppressing NO_x formation more efficiently.

When the EGR rate was increased to 15%, NO_x emissions continued to decrease with engine speed, recording 454.89 ppm at 2200 RPM, 428.53 ppm at 2400 RPM, and 392.88 ppm at 2600 RPM. This reduction indicates that, at a more retarded injection timing, the cooling effect of EGR becomes more dominant, as combustion occurs at relatively lower pressures and temperatures compared to more advanced injection timing.

At the highest EGR rate of 20%, NO_x emissions reached the lowest levels among all tested conditions. NO_x emissions were 369.18 ppm at 2200 RPM, decreased to 330.48 ppm at 2400 RPM, and reached a minimum value of 295.63 ppm at 2600 RPM. These results confirm that retarding the injection timing from 22° CA to 20° CA consistently reduces NO_x emissions, particularly when combined with high EGR rates. Overall, injection timing retardation proves to be an effective strategy for controlling NO_x formation by lowering peak combustion temperature and shifting the combustion phase toward the expansion stroke. However, its implications for other exhaust emissions and overall engine performance require further investigation.

Figure 4.1(c) illustrates the relationship between engine speed (2200–2600 RPM) and NO_x emissions (ppm) at EGR rates of 0%, 10%, 15%, and 20% using D100 fuel at an injection timing of 18° CA. Based on the graphical trends and numerical data, further retardation of the injection timing from 20° CA to 18° CA results in a consistent reduction in NO_x emissions across all EGR rates and engine speeds.

Under the no-EGR condition (0% EGR), NO_x emissions were recorded at 571.24 ppm at 2200 RPM, decreased to 569.59 ppm at 2400 RPM, and slightly increased to 569.60 ppm at 2600 RPM. Compared with the injection timings of 20° CA and 22° CA, these values confirm that further injection timing retardation progressively reduces peak combustion temperature due to the shift of the combustion onset away from top dead center (TDC), thereby lowering the intensity of thermal NO_x formation.

With the application of 10% EGR, NO_x emissions decreased more noticeably with increasing engine speed, reaching 485.36 ppm at 2200 RPM, 466.44 ppm at 2400 RPM, and 440.42 ppm at 2600 RPM. This trend indicates that the combined effects of injection timing retardation and EGR-induced cooling more effectively reduce in-cylinder temperature and oxygen concentration, resulting in improved suppression of NO_x formation compared to more advanced injection timings.

When the EGR rate was increased to 15%, NO_x emissions continued to decline consistently, with values of 425.98 ppm at 2200 RPM, 397.73 ppm at 2400 RPM, and 365.11 ppm at 2600 RPM. This reduction suggests that, at an injection timing of 18° CA, combustion occurs at relatively lower pressures and temperatures, further inhibiting the mechanisms responsible for NO_x formation.

At the highest EGR rate of 20%, NO_x emissions reached the lowest levels among all tested conditions. NO_x emissions were 337.55 ppm at 2200 RPM, decreased to 303.39 ppm at 2400 RPM, and reached a minimum value of 269.13 ppm at 2600 RPM. These results confirm that injection timing retardation to 18° CA has the most pronounced effect on reducing NO_x emissions, particularly when combined with high EGR rates. Overall, the findings indicate that increasingly retarded injection timing leads to lower NO_x emissions due to reduced peak combustion temperature and a shift of the combustion phase toward the expansion stroke. However, the potential impacts on engine efficiency and other exhaust emissions should be addressed in subsequent discussions.

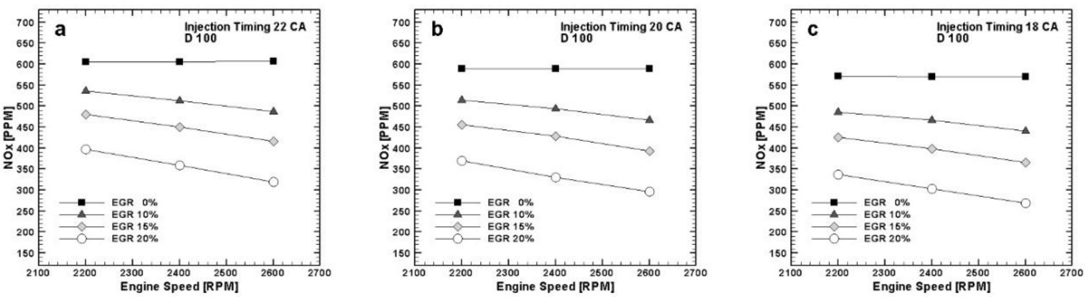

Figure 4.1. (a) NO_x Emission at 22 CA; (b) NO_x Emission at 20 CA; (c) NO_x Emission at 18 CA

4.2. CO_2 Emission

Figure 4.2(a) illustrates the relationship between engine speed (2200–2600 RPM) and carbon dioxide (CO_2) emissions (ppm) at EGR rates of 0%, 10%, 15%, and 20% using D100 fuel at an injection timing of 22° CA. The numerical data were obtained from validated simulation results. As shown in the figure, CO_2 emissions generally increase with increasing engine speed for all EGR rates, while a significant reduction in CO_2 emissions is observed as the EGR rate increases.

Under the no-EGR condition (0% EGR), CO_2 emissions were recorded at 6.81 ppm at 2200 RPM. As engine speed increased to 2400 RPM, CO_2 emissions rose to 8.54 ppm and further increased to 10.67 ppm at 2600 RPM. This increasing trend indicates that higher engine speeds lead to increased fuel consumption and combustion intensity, resulting in a greater formation of CO_2 as a primary product of carbon oxidation.

With the application of 10% EGR, CO_2 emissions were significantly lower than those observed without EGR. CO_2 emissions were 1.30 ppm at 2200 RPM, increased to 1.72 ppm at 2400 RPM, and reached 2.17 ppm at 2600 RPM. The reduction in CO_2 emissions under this condition suggests that the recirculation of exhaust gases reduces the amount of fresh air available for combustion, thereby lowering the effective combustion rate and the total amount of CO_2 produced.

When the EGR rate was increased to 15%, a further reduction in CO_2 emissions was observed. CO_2 emissions were recorded at 0.73 ppm at 2200 RPM, increased to 0.93 ppm at 2400 RPM, and reached 1.15 ppm at 2600 RPM. This trend indicates that a higher fraction of inert gases in the combustion chamber increasingly limits complete combustion, thereby reducing CO_2 formation as the final oxidation product of carbon.

At the highest EGR rate of 20%, CO_2 emissions reached the lowest values among all tested conditions. CO_2 emissions were 0.36 ppm at 2200 RPM, increased to 0.47 ppm at 2400 RPM, and reached 0.59 ppm at 2600 RPM. The low CO_2 emissions at high EGR rates demonstrate that the dominance of recirculated exhaust gases in the combustion mixture significantly suppresses carbon oxidation reactions. Overall, these results confirm that increasing the EGR rate effectively reduces CO_2 emissions when using D100 fuel, although increasing engine speed still leads to a gradual rise in CO_2 emissions under each EGR condition.

Figure 4.2(b) illustrates the relationship between engine speed (2200–2600 RPM) and carbon dioxide (CO_2) emissions (ppm) at EGR rates of 0%, 10%, 15%, and 20% using D100 fuel at an injection timing of 20° CA. Based on the graphical trends and numerical data, CO_2 emissions increase with increasing engine speed for all EGR rates, while a significant reduction in CO_2 emissions is observed as the EGR rate increases.

Under the no-EGR condition (0% EGR), CO_2 emissions were recorded at 7.55 ppm at 2200 RPM. As engine speed increased to 2400 RPM, CO_2 emissions rose to 9.40 ppm and further increased to 10.89 ppm at 2600 RPM. This increase indicates that higher engine speeds lead to increased fuel consumption and combustion intensity, resulting in greater CO_2 formation as the final product of carbon oxidation.

With the application of 10% EGR, CO_2 emissions were notably lower than those observed without EGR. CO_2 emissions were 1.37 ppm at 2200 RPM, increased to 1.83 ppm at 2400 RPM, and reached 2.31 ppm at 2600 RPM. This reduction suggests that the recirculation of exhaust gases reduces fresh air availability and combustion intensity, thereby decreasing the amount of carbon fully oxidized to CO_2.

When the EGR rate was increased to 15%, a further reduction in CO_2 emissions was observed. CO_2 emissions were 0.77 ppm at 2200 RPM, increased to 0.99 ppm at 2400 RPM, and reached 1.23 ppm at 2600 RPM. This trend indicates that a higher fraction of inert gases in the cylinder increasingly limits complete carbon oxidation, resulting in lower CO_2 formation.

At the highest EGR rate of 20%, CO_2 emissions reached the lowest values at an injection timing of 20° CA. CO_2 emissions were 0.38 ppm at 2200 RPM, increased to 0.51 ppm at 2400 RPM, and reached 0.63 ppm at 2600 RPM. The low CO_2 emissions under this condition demonstrate that the dominance of recirculated exhaust gases in the combustion mixture significantly suppresses combustion intensity and the extent of complete fuel oxidation. Overall, at an injection timing of 20° CA, increasing the EGR rate effectively reduces CO_2 emissions, although increasing engine speed still results in a gradual rise in CO_2 emissions under each EGR condition.

Figure 4.2(c) illustrates the relationship between engine speed (2200–2600 RPM) and carbon dioxide (CO_2) emissions (ppm) at EGR rates of 0%, 10%, 15%, and 20% using D100 fuel at an injection timing of 18° CA. Based on the graphical trends and numerical data, CO_2 emissions increase with increasing engine speed for all EGR rates, while increasing the EGR rate consistently reduces CO_2 emissions.

Under the no-EGR condition (0% EGR), CO_2 emissions were recorded at 7.90 ppm at 2200 RPM, increased to 9.77 ppm at 2400 RPM, and further rose to 11.31 ppm at 2600 RPM. This increase indicates that higher engine speeds lead to enhanced combustion intensity and fuel consumption, resulting in a greater formation of CO_2 as the final product of carbon oxidation.

With the application of 10% EGR, CO_2 emissions were significantly lower than those observed without EGR. CO_2 emissions were 1.49 ppm at 2200 RPM, increased to 1.97 ppm at 2400 RPM, and reached 2.44 ppm at 2600 RPM. This reduction suggests that the recirculation of exhaust gases reduces fresh air supply and combustion intensity, thereby lowering the amount of carbon fully oxidized to CO_2.

When the EGR rate was increased to 15%, a more pronounced reduction in CO_2 emissions was observed. CO_2 emissions were 0.82 ppm at 2200 RPM, increased to 1.06 ppm at 2400 RPM, and reached 1.29 ppm at 2600 RPM.

This trend indicates that a higher fraction of inert gases in the cylinder increasingly limits complete carbon oxidation, resulting in reduced CO_2 formation.

At the highest EGR rate of 20%, CO_2 emissions reached the lowest values at an injection timing of 18° CA. CO_2 emissions were 0.41 ppm at 2200 RPM, increased to 0.53 ppm at 2400 RPM, and reached 0.66 ppm at 2600 RPM. The low CO_2 emissions under this condition demonstrate that the dominance of recirculated exhaust gases in the combustion mixture significantly suppresses combustion intensity and the extent of complete fuel oxidation. Overall, at an injection timing of 18° CA, increasing the EGR rate is effective in reducing CO_2 emissions, although increasing engine speed still results in a gradual rise in CO_2 emissions under each EGR condition.

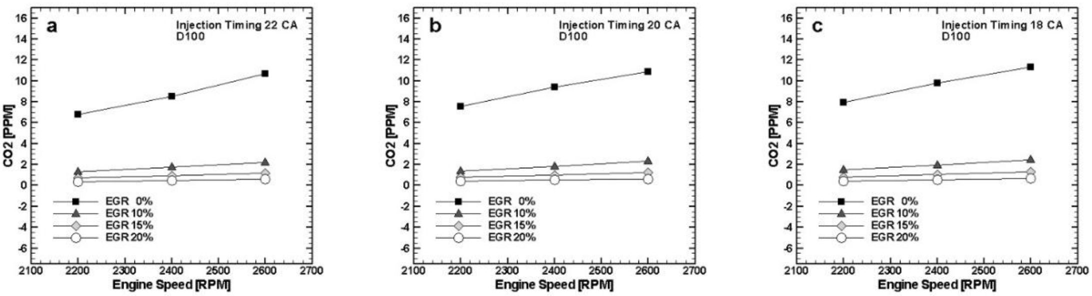

Figure 4.2. (a) CO_2 Emission at 22 CA; (b) CO_2 Emission at 20 CA; (c) CO_2 Emission at 18 CA

4.3. CO Emission

Figure 4.3(a) illustrates the relationship between engine speed (2200–2600 RPM) and carbon monoxide (CO) emissions (ppm) at EGR rates of 0%, 10%, 15%, and 20% using D100 fuel at an injection timing of 22° CA. The numerical data were obtained from validated simulation results. As shown in the figure, CO emissions generally increase with increasing engine speed for all EGR rates, while a substantial reduction in CO emissions is observed as the EGR rate increases.

Under the no-EGR condition (0% EGR), CO emissions were recorded at 10.70 ppm at 2200 RPM. As engine speed increased to 2400 RPM, CO emissions rose to 13.41 ppm and further increased to 16.77 ppm at 2600 RPM. This increase indicates that at higher engine speeds, the oxidation of CO to CO_2 becomes less complete due to reduced residence time for combustion reactions.

With the application of 10% EGR, CO emissions were significantly lower than those observed without EGR. CO emissions were 2.04 ppm at 2200 RPM, increased to 2.71 ppm at 2400 RPM, and reached 3.41 ppm at 2600 RPM. The reduction in CO emissions under this condition suggests that EGR contributes to stabilizing the combustion process by moderating combustion temperature and reaction rates, thereby suppressing CO formation compared to the no-EGR condition.

When the EGR rate was increased to 15%, a further reduction in CO emissions was observed. CO emissions decreased to 1.15 ppm at 2200 RPM, increased to 1.47 ppm at 2400 RPM, and reached 1.82 ppm at 2600 RPM. These lower CO levels indicate that at moderate EGR rates, combustion remains sufficiently stable, allowing more effective oxidation of CO despite the reduced oxygen concentration.

At the highest EGR rate of 20%, CO emissions reached the lowest values across all tested conditions. CO emissions were 0.57 ppm at 2200 RPM, increased to 0.74 ppm at 2400 RPM, and reached 0.93 ppm at 2600 RPM. The low CO emissions at 20% EGR suggest that the combined effects of controlled combustion temperature and improved mixture homogeneity promote more complete combustion. Overall, these results indicate that increasing the EGR rate when using D100 fuel is effective not only in reducing NO_x emissions but also in significantly suppressing CO emissions. Nevertheless, increasing engine speed still leads to a gradual rise in CO emissions under all EGR conditions.

Figure 4.3(b) illustrates the relationship between engine speed (2200–2600 RPM) and carbon monoxide (CO) emissions (ppm) at EGR rates of 0%, 10%, 15%, and 20% using D100 fuel at an injection timing of 20° CA. Based on the graphical trends and numerical data, CO emissions increase with increasing engine speed for all EGR rates, while a significant reduction in CO emissions is observed as the EGR rate increases.

Under the no-EGR condition (0% EGR), CO emissions were recorded at 11.87 ppm at 2200 RPM. As engine speed increased to 2400 RPM, CO emissions rose to 14.77 ppm and further increased to 17.11 ppm at 2600 RPM. This increase indicates that at higher engine speeds, the available residence time for CO oxidation to CO_2 becomes increasingly limited, resulting in incomplete oxidation of CO.

With the application of 10% EGR, CO emissions were considerably lower than those observed without EGR. CO emissions were 2.15 ppm at 2200 RPM, increased to 2.89 ppm at 2400 RPM, and reached 3.64 ppm at 2600 RPM. This reduction suggests that the application of EGR at an injection timing of 20° CA stabilizes the combustion process and suppresses CO formation compared to the no-EGR condition, although the increasing trend with engine speed remains evident.

When the EGR rate was increased to 15%, a further reduction in CO emissions was observed. CO emissions were 1.21 ppm at 2200 RPM, increased to 1.56 ppm at 2400 RPM, and reached 1.93 ppm at 2600 RPM. These lower CO levels indicate that at moderate EGR rates, combustion remains sufficiently stable to promote more effective CO oxidation despite the reduced oxygen concentration in the cylinder.

At the highest EGR rate of 20%, CO emissions reached the lowest values at an injection timing of 20° CA. CO emissions were 0.60 ppm at 2200 RPM, increased to 0.80 ppm at 2400 RPM, and reached 0.99 ppm at 2600 RPM. The low CO emissions under this condition demonstrate that the combined effects of injection timing retardation and high EGR rates effectively suppress CO formation by controlling combustion temperature and improving mixture homogeneity. Overall, at an injection timing of 20° CA, increasing the EGR rate is effective in reducing CO emissions, although increasing engine speed still leads to a gradual increase in CO emissions under all EGR conditions.

Figure 4.3(c) illustrates the relationship between engine speed (2200–2600 RPM) and carbon monoxide (CO) emissions (ppm) at EGR rates of 0%, 10%, 15%, and 20% using D100 fuel at an injection timing of 18° CA. Based on the graphical trends and numerical data, CO emissions increase with increasing engine speed for all EGR rates, while increasing the EGR rate generally leads to a reduction in CO emissions.

Under the no-EGR condition (0% EGR), CO emissions were recorded at 12.42 ppm at 2200 RPM. As engine speed increased to 2400 RPM, CO emissions rose to 15.36 ppm and further increased to 17.77 ppm at 2600 RPM. This increase indicates that at a more retarded injection timing, the oxidation of CO to CO_2 becomes increasingly limited at higher engine speeds due to reduced residence time for combustion reactions.

With the application of 10% EGR, CO emissions were considerably lower than those observed without EGR. CO emissions were 2.35 ppm at 2200 RPM, increased to 3.09 ppm at 2400 RPM, and reached 3.83 ppm at 2600 RPM. This reduction demonstrates that the application of EGR at an injection timing of 18° CA effectively suppresses CO formation compared to the no-EGR condition, although the increasing trend with engine speed remains evident.

When the EGR rate was increased to 15%, a further reduction in CO emissions was observed. CO emissions decreased to 1.30 ppm at 2200 RPM, increased to 1.67 ppm at 2400 RPM, and reached 2.03 ppm at 2600 RPM. These lower CO levels indicate that at moderate EGR rates, combustion remains relatively stable, allowing more effective oxidation of CO despite the reduced oxygen concentration in the cylinder.

At the highest EGR rate of 20%, CO emissions reached the lowest values at an injection timing of 18° CA. CO emissions were 0.64 ppm at 2200 RPM, increased to 0.84 ppm at 2400 RPM, and reached 1.04 ppm at 2600 RPM. The low CO emissions under this condition confirm that the combined effects of injection timing retardation and high EGR rates significantly suppress CO formation by controlling combustion temperature and improving gas mixture homogeneity. Overall, at an injection timing of 18° CA, increasing the EGR rate effectively reduces CO emissions, although increasing engine speed still results in a gradual increase in CO emissions under all EGR conditions.

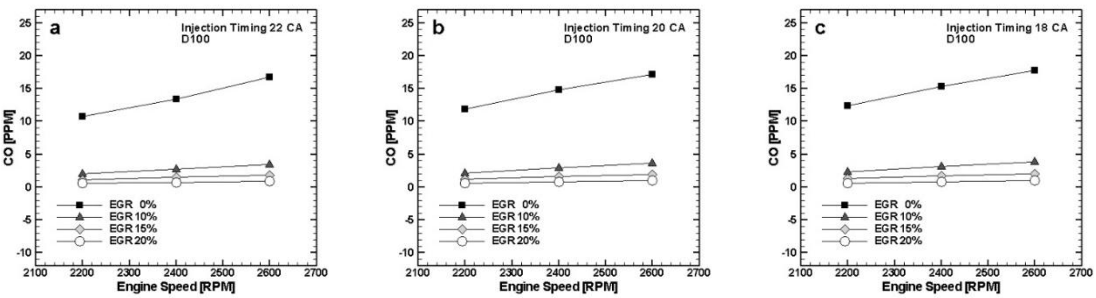

Figure 4.3. (a) CO Emission at 22 CA; (b) CO Emission at 20 CA; (c) CO Emission at 18 CA

4.4. HC Emission

Figure 4.4(a) illustrates the relationship between engine speed (2200–2600 RPM) and hydrocarbon (HC) emissions (ppm) at EGR rates of 0%, 10%, 15%, and 20% using D100 fuel at an injection timing of 22° CA. The numerical data were obtained from validated simulation results. As shown in the figure, HC emissions generally increase with increasing engine speed across all EGR rates.

Under the no-EGR condition (0% EGR), HC emissions were recorded at 13.56 ppm at 2200 RPM. As engine speed increased to 2400 RPM, HC emissions rose to 14.44 ppm and further increased to 15.23 ppm at 2600 RPM. This increase indicates that at higher engine speeds, the residence time available for hydrocarbon oxidation becomes shorter, resulting in incomplete combustion and higher HC emissions.

With the application of 10% EGR, HC emissions were higher than those observed under the no-EGR condition across all engine speeds. HC emissions increased from 15.32 ppm at 2200 RPM to 16.26 ppm at 2400 RPM and reached 17.01 ppm at 2600 RPM. This increase suggests that the introduction of exhaust gases into the combustion chamber reduces oxygen concentration and combustion temperature, thereby limiting the effectiveness of hydrocarbon oxidation, particularly at higher engine speeds.

When the EGR rate was increased to 15%, HC emissions continued to rise across the entire engine speed range. HC emissions were 15.50 ppm at 2200 RPM, increased to 16.37 ppm at 2400 RPM, and reached 17.18 ppm at 2600 RPM. This trend indicates that a higher fraction of inert gases further promotes incomplete combustion due to the reduced availability of reactive oxygen species in the combustion chamber.

At the highest EGR rate of 20%, HC emissions reached the highest values among all tested conditions. HC emissions were recorded at 15.72 ppm at 2200 RPM, increased to 16.53 ppm at 2400 RPM, and reached a maximum value of 17.19 ppm at 2600 RPM. These results demonstrate that although EGR is highly effective in reducing NO_x emissions, excessive EGR rates can significantly increase HC emissions due to deteriorated combustion quality. Overall, the findings confirm the existence of a trade-off between NO_x reduction and HC formation, particularly at high EGR rates and elevated engine speeds.

Figure 4.4(b) illustrates the relationship between engine speed (2200–2600 RPM) and hydrocarbon (HC) emissions (ppm) at EGR rates of 0%, 10%, 15%, and 20% using D100 fuel at an injection timing of 20° CA. Based on the graphical trends and numerical data, HC emissions generally increase with increasing engine speed across all EGR rates.

Under the no-EGR condition (0% EGR), HC emissions were recorded at 13.56 ppm at 2200 RPM, increased to 14.46 ppm at 2400 RPM, and further rose to 15.24 ppm at 2600 RPM. This trend indicates that at higher engine speeds, the residence time available for hydrocarbon oxidation becomes shorter, resulting in incomplete combustion and higher HC emissions.

With the application of 10% EGR, HC emissions were higher than those observed under the no-EGR condition across the entire engine speed range. HC emissions increased from 15.34 ppm at 2200 RPM to 16.27 ppm at 2400 RPM and reached 17.01 ppm at 2600 RPM. This increase suggests that the introduction of exhaust gases into the combustion chamber reduces oxygen concentration and combustion temperature, thereby limiting the effectiveness of hydrocarbon oxidation, particularly at elevated engine speeds.

When the EGR rate was increased to 15%, HC emissions continued to increase across all tested engine speeds. HC emissions were 15.51 ppm at 2200 RPM, increased to 16.39 ppm at 2400 RPM, and reached 17.09 ppm at 2600 RPM. This trend indicates that a higher fraction of inert gases further promotes incomplete combustion due to reduced availability of reactive oxygen in the cylinder.

At the highest EGR rate of 20%, HC emissions reached the highest values among all EGR conditions. HC emissions were recorded at 15.73 ppm at 2200 RPM, increased to 16.55 ppm at 2400 RPM, and reached 17.20 ppm at 2600 RPM. These results demonstrate that at an injection timing of 20° CA, increasing the EGR rate significantly increases HC emissions as a consequence of deteriorated combustion quality.

Figure 4.4(c) illustrates the relationship between engine speed (2200–2600 RPM) and hydrocarbon (HC) emissions (ppm) at EGR rates of 0%, 10%, 15%, and 20% using D100 fuel at an injection timing of 18° CA. Based on the graphical trends and numerical data, HC emissions at this injection timing continue to exhibit an increasing trend with increasing engine speed for all EGR rates.

Under the no-EGR condition (0% EGR), HC emissions were recorded at 13.59 ppm at 2200 RPM, increased to 14.48 ppm at 2400 RPM, and reached 15.27 ppm at 2600 RPM. This increase indicates that at higher engine speeds, the effective combustion duration becomes shorter, resulting in incomplete oxidation of part of the fuel and higher HC emissions.

With the application of 10% EGR, HC emissions increased significantly compared to the no-EGR condition. HC emissions rose from 15.35 ppm at 2200 RPM to 16.28 ppm at 2400 RPM and reached 17.03 ppm at 2600 RPM. This behavior suggests that the combination of injection timing retardation to 18° CA and exhaust gas recirculation reduces combustion temperature and the availability of reactive oxygen, thereby limiting hydrocarbon oxidation.

When the EGR rate was increased to 15%, HC emissions continued to increase across the entire engine speed range. HC emissions were 15.53 ppm at 2200 RPM, increased to 16.40 ppm at 2400 RPM, and reached 17.10 ppm at 2600 RPM. This trend indicates that a higher fraction of inert gases further promotes incomplete combustion, particularly under more retarded injection timing conditions.

At the highest EGR rate of 20%, HC emissions reached the highest values at an injection timing of 18° CA. HC emissions were recorded at 15.74 ppm at 2200 RPM, increased to 16.56 ppm at 2400 RPM, and reached 17.21 ppm at 2600 RPM. These results demonstrate that although injection timing retardation is effective in suppressing NO_x emissions, its combination with high EGR rates significantly increases HC emissions due to deteriorated combustion quality. Overall, at an injection timing of 18° CA, increasing the EGR rate tends to increase HC emissions as a consequence of incomplete combustion.

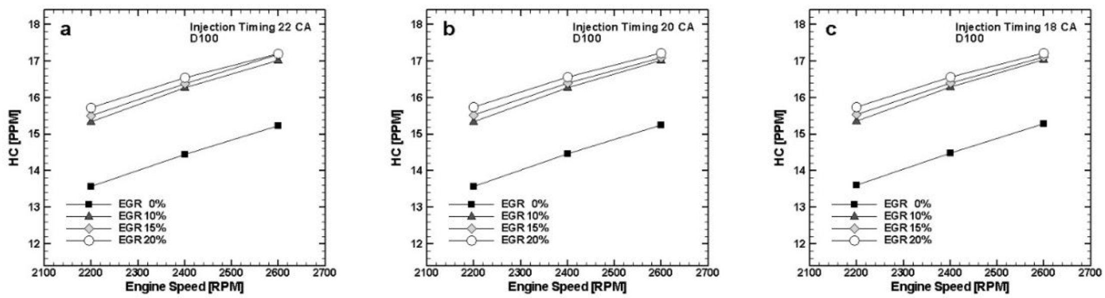

Figure 4.4. (a) HC Emission at 22 CA; (b) HC Emission at 20 CA; (c) HC Emission at 18 CA

4.5. Conclusion

This study investigated the effects of exhaust gas recirculation (EGR), injection timing, and engine speed on exhaust emissions of an R180 diesel engine fueled with D100 using validated simulation results. NO_x emissions decreased significantly with increasing EGR rate and retarded injection timing, with the highest NO_x emission observed at 22° CA, 0% EGR, and 2400 RPM (≈606 ppm) and the lowest NO_x emission obtained at 18° CA, 20% EGR, and 2600 RPM (≈269 ppm) due to reduced peak combustion temperature and oxygen availability. CO_2 emissions increased with engine speed but decreased markedly with higher EGR rates; the maximum CO_2 emission occurred at 18° CA, 0% EGR, and 2600 RPM (≈11.31 ppm), while the minimum CO_2 emission was recorded at 22° CA, 20% EGR, and 2200 RPM (≈0.36 ppm). Carbon monoxide (CO) emissions rose with engine speed as a result of limited oxidation time, reaching the highest value at 18° CA, 0% EGR, and 2600 RPM (≈17.77 ppm), whereas the lowest CO emission was achieved at 22° CA, 20% EGR, and 2200 RPM (≈0.57 ppm). In contrast, hydrocarbon (HC) emissions increased with both EGR rate and injection timing retardation, with the highest HC emission observed at 18° CA, 20% EGR, and 2600 RPM (≈17.21 ppm) and the lowest HC emission recorded at 22° CA, 0% EGR, and 2200 RPM (≈13.56 ppm). Overall, the results confirm that combining EGR with injection timing retardation is highly effective in reducing NO_x, CO_2, and CO emissions, but it introduces a clear trade-off in the form of increased HC emissions, emphasizing the importance of optimizing EGR rate and injection timing to achieve balanced emission performance.

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