Effect of Exhaust Gas Recirculation Combined with Selective Catalytic Reduction on NO\textsubscript{x} Emission Characteristics and Their Matching Optimization of a Heavy-Duty Diesel Engine

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ABSTRACT: Exhaust gas recirculation (EGR) and selective catalytic reduction (SCR) have become important technologies to reduce the NO\textsubscript{x} emission of heavy-duty diesel engines and meet the increasingly stringent emission regulations. This paper studied the effect of EGR combined with SCR on the NO\textsubscript{x} emission characteristics of a heavy-duty diesel engine based on the engine bench test. The results showed that the NO reduction rate of EGR-coupled SCR increased with the increase of engine load, and the effect was no longer significant when the NO reduction rate exceeded a certain limit under the same working conditions. EGR combined with SCR has little effect on NO\textsubscript{2} emission reduction, and the increase of engine speed can significantly improve the NO\textsubscript{2} reduction rate at 75 and 100% load. 25% opening of the EGR valve (OEV) and 50% OEV have very similar effects on the NO\textsubscript{x} reduction rate when the engine speed is at a low level. Compared with low engine speeds, increased OEV or ammonia NO\textsubscript{x} molar ratio (ANR) had a more obvious effect on the NO\textsubscript{x} reduction rate at high engine speeds. SCR combined with low valve-opening EGR had a more significant effect on the NO\textsubscript{x} reduction rate. The increase of OEV led to the increase of fuel consumption rate, but the effect on the fuel consumption rate decreased gradually with the increase of diesel engine speed. Meanwhile, this study optimized the matching relationship between OEV and ANR based on the data of the genetic algorithm, which provides a theoretical research method and application basis for diesel engine-matching of EGR and SCR.

1. INTRODUCTION

Today, with the increasing attention to the energy problem, diesel engine has been widely used because of its low fuel consumption.\textsuperscript{1} NO\textsubscript{x} in diesel engine exhaust is an important component of photochemical smog. The particulate matter in exhaust is an important component of smog.\textsuperscript{2} Both of them cause great harm to the environment\textsuperscript{4} and the human body.\textsuperscript{4,5} With the increasingly stringent emission regulations, the latest emission regulations cannot be met only by electronically controlled fuel injection, intake pressurization, and other technologies.\textsuperscript{6} The exhaust gas recirculation (EGR) technology helps to promote the NO\textsubscript{x} reduction from the inside of the engine,\textsuperscript{7,8} while the selective catalytic reduction (SCR) technology controls NO\textsubscript{x} emission from the outside of the engine to meet the regulatory requirements.\textsuperscript{9,10}

Scholars have done a lot of research work on EGR and SCR technology. The effect of EGR on combustion and emission characteristics can be divided into thermal effect,\textsuperscript{11} dilution effect,\textsuperscript{12,13} and chemical effect.\textsuperscript{14,15} Research has shown that a lower level of NO\textsubscript{x} emissions can be achieved by using EGR and that the effect is very significant;\textsuperscript{16} moreover, EGR combined with cylinder bypass and exhaust gas bypass reduces NO\textsubscript{x} emissions.\textsuperscript{17} Meanwhile, the EGR rate also has a certain impact on soot emission, which decreases significantly with the EGR rate under different forms of EGR and excess air ratios.\textsuperscript{18} However, some research results have shown that higher EGR...

Received: February 25, 2022
Accepted: June 9, 2022
Published: June 22, 2022
decreases the ignition performance and rapidly increases the brake-specific fuel consumption (BSFC). Tang et al.\textsuperscript{19} studied high-pressure EGR (HP EGR) and donor-cylinder EGR (DC-EGR), and conducted BSFC comprehensive optimization by adaptive particle swarm optimization; two EGR patterns are more inclined to achieve comprehensive optimization of BSFC under different loads. Oommen et al.\textsuperscript{20} studied part-cooled EGR applied in varying rates (12, 18, and 24%) in order to analyze the BSFC; the fuel consumption of the test engine was reduced up to 12.28% with the application of 18% of part-cooled EGR. In actual application, it is difficult to achieve the best design and calibration of EGR. Li\textsuperscript{21} studied the effects of CR, EGR, and ignition timing strategies on the performance, combustion, and NO\textsubscript{x} emission characteristics. At lower engine speeds, the 50% combustion location, 10–90% combustion duration, and effective expansion ratio (EER) are only slightly affected by the EGR strategy; however, with the increase of engine speed, the influence of EGR on the performance characteristics becomes more important. Two EGR systems (HP EGR(1) and LP EGR(2)) were investigated in terms of influence of different rates on the brake-specific fuel consumption (BSFC) and the NO\textsubscript{x} emissions by Wang.\textsuperscript{22} The results showed that when the HP EGR system and the LP EGR system were all operating at a maximum EGR rate, the LP EGR system showed more advantages. In addition, high-pressure (HP) and low-pressure (LP) EGR were studied by Wang.\textsuperscript{23} HP EGR requires a wide high-efficiency area at a constant pressure ratio, while LP EGR needs a high-efficiency area as long as possible in its demand direction.

SCR is the most commonly used technique for decreasing the emission of nitrogen oxides (NO\textsubscript{x}) from a heavy-duty diesel engine.\textsuperscript{24,25} However, the same injection strategy in the SCR system shows significant variations in NO\textsubscript{x} emissions even at the same operating mode. This kind of heterogeneity poses challenges to the development of emission inventories and to the assessment of emission reductions.\textsuperscript{26} McCaffrey et al. found that NO\textsubscript{x} emissions were strongly dependent on the SCR temperature, with SCR temperatures below 200 °C resulting in elevated brake-specific NO\textsubscript{x}.\textsuperscript{27} Wang et al. studied the thermal management strategy to improve the SCR NO\textsubscript{x} conversion efficiency based on transient SCR simulations; it was found that a selective increase in exhaust temperature in a low-temperature period would be a useful measure to increase the SCR efficiency on WHTC mode.\textsuperscript{28} In addition to the influence of temperature, the ammonia nitrogen ratio is also an important factor affecting NO\textsubscript{x} emission. Tan et al. developed a mathematical model to predict the NO\textsubscript{x} conversion efficiency and analyzed the effects of NH\textsubscript{3}/NO\textsubscript{x} ratio on the NO\textsubscript{x} conversion efficiency in detail.\textsuperscript{29} Wang et al. found that the increasing ammonia/nitrogen oxides feed ratio contributes to reducing the NO\textsubscript{x} emission. The research results indicated that the increasing ammonia/nitrogen oxides feed ratio contributes to reducing the emission of nitrogen oxides; due to the NO\textsubscript{x} conversion rate reaching a higher level when the exhaust temperature is 450 °C, the performance of the system becomes worse as the exhaust flow rate increases.\textsuperscript{30} The upper limit of the NO\textsubscript{x} conversion performance of SCR is limited by the low ratio of NO\textsubscript{2}/NO\textsubscript{x} or the change of engine working conditions.\textsuperscript{31} It can be found that achieving efficient NO\textsubscript{x} emission reduction is a complex work.

The applicabilities of EGR and SCR are also different under the same working conditions. Bacenetti et al. observed that the emission reduction effects of EGR and SCR on two similar engines were very different.\textsuperscript{32} Studies have shown that though both technologies fully reduce NO\textsubscript{x}, EGR is more suitable for low-load engines, whereas SCR is suitable for high-load engines.\textsuperscript{33} Some scholars have studied the effect of EGR combined with SCR on engine performance and emissions,\textsuperscript{34,35} with the hope of finding a balance between the two technologies.\textsuperscript{36} In a recent article, the authors mentioned that it is necessary to analyze the correlation between the ECU signal and the DCU signal to derive a factor in the future, which also shows the importance of close cooperation between EGR and SCR to the engine.\textsuperscript{37} The main characteristic of the genetic algorithm is to operate the structure object directly,\textsuperscript{38} and it has certain advantages in solving combinatorial optimization problems.\textsuperscript{39}

Till date, many scholars have carried out extensive research on EGR and SCR, but few scholars give systematic matching strategies between OEV and ANR. In the meantime, there are few reports on using the genetic algorithm to solve the matching problem between EGR and SCR. In view of the fact that the genetic algorithm does not have the limitations of derivation and function continuity, and has the advantages of implicit parallelism and global optimization ability, this paper will deeply study the characteristics of EGR combined with SCR under the European Steady-State Cycle (ESC) 12 working conditions and optimize the engine NO\textsubscript{x} emission and operating cost using the genetic algorithm. The optimal combination data of OEV and ANR is conducive to the rapid matching of SCR and EGR in application.

2. EXPERIMENTAL MATERIALS AND METHODS

2.1. Test Engine and Fuel. The diesel engine used in this study and its specifications are listed in Table 1. The engine was fueled with locally available commercial diesel, and the specifications are listed in Table 2.

### Table 1. Specifications of the Test Engine

| parameter                  | value   |
|----------------------------|---------|
| weight (kg)                | 950     |
| bore (mm)                  | 126     |
| stroke (mm)                | 130     |
| cooling system             | water cooled |
| turbocharged engine displacement (L) | 9.7     |
| rated power (kW @ rpm)     | 274 @ 2100 |
| maximum torque (N·m @ rpm) | 1525 @ 1200–1500 |
| minimum stable engine speed (rpm) | 2300   |
| minimum stable engine speed (rpm) | 600 ± 50 |

### Table 2. Physical and Chemical Properties of the Fuels

| parameter                  | value   |
|----------------------------|---------|
| density (kg/m\textsuperscript{3} @ 20 °C) | 821.9   |
| viscosity (mm\textsuperscript{2}/s @ 20 °C) | 4.5     |
| flash point (°C)           | 92.0    |
| cold filter plugging point (°C) | −34.0   |
| solidifying point (°C)     | −45.0   |
| cetane number              | 52.3    |
| carbon content (%)         | 86.1    |
| hydrogen content (%)       | 13.4    |
| oxygen content (%)         | 0.4     |
2.2. EGR Device. The external high-pressure cooling exhaust gas recirculation (EGR) system was used in this study, as shown in Figure 1. The external EGR serves to introduce part of the exhaust gas into the intake system through the external pipeline. The exhaust gas leaves the engine first and then circulates into the engine. The EGR rate is controlled by adjusting the opening of the EGR valve to adjust the exhaust gas return flow.

2.3. Specifications of SCR. The parameters of selective catalytic reduction (SCR) are presented in Table 3, and the specifications of AdBlue are shown in Table 4.

Table 3. Specifications of SCR

| parameter               | feature/value |
|-------------------------|---------------|
| diameter (mm)           | 330.2         |
| length (mm)             | 152.4         |
| volume (ft³)            | 0.46          |
| cell density (cell/m²)  | 400           |
| wall thickness (mm)     | 0.17          |
| catalyst                | V₂O₅–TiO₂     |
| catalyst load (g/ft³)   | 8             |

Table 4. Specifications of AdBlue

| parameter                  | value range  |
|---------------------------|--------------|
| urea proportion (w/%)     | 32.1–33.1    |
| undissolved substance (mg/kg) | ≤20         |
| alkalinity (calculated by NH₃) (w/%) | ≤0.2 |
| biuret (w/%)              | ≤0.3         |
| density, 20 °C (g/mL)    | 1.087–1.092  |
| refractive index, 20 °C   | 1.3817–1.3840|

2.4. Definition. Opening of the EGR valve (OEV) is the control parameter of EGR, which is responsible for the working state adjustment of the EGR valve under various working conditions. Ammonia is hydrolyzed from AdBlue, and NOₓ is a component of exhaust gas. The ammonia NOₓ molar ratio (ANR) is the control parameter of the SCR system, which controls the working state of the SCR system by adjusting the proportion of AdBlue and NOₓ.

2.5. Test Method. The main instruments and equipment include the AVL-ATA404 electric dynamometer, AVL-439 smoke meter, AVL-735 fuel consumption meter, various sensors, ECU calibration tools, AVL-i60 emission meter, and AVL-PEUS multicomponent gas analyzer. The sampling frequency of AVL-i60 and the AVL-PEUS multicomponent gas analyzer is set to 10 Hz. The AVL-PUMA automatic measurement and control bench communicates with the electric dynamometer, fuel consumption meter, emission test system and sensors, operates the action of the whole test bench, and displays and outputs the feedback equipment information and test results (Figure 2).

Figure 1. Schematic of EGR.

Figure 2. Test system based on the AVL-PUMA automatic measurement and control platform.

In this study, the effect of EGR combined with SCR on the emission of a heavy-duty diesel engine is studied. The OEV is set as closed (OEV0), 25% (OEV25%), and 50% (OEV50), respectively. The AdBlue injection amounts in SCR to make the ANR are 0.5 (ANR0.5) and 1.0 (ANR1.0), respectively. The hydrolyzed NH₃ is calculated according to the AdBlue injection amount; for AdBlue proportions, refer to Table 4. Although ANR = 0.5 alone will result in an NO and NOₓ reduction rate of less than 50% (without EGR), ANR = 0.5 is necessary to test the effect of the combination of OEV and ANR. The engine speed and load characteristics, and the effects of different combinations of OEV and ANR on the emission of a heavy-duty diesel engine were studied. It is important to analyze the variation of NO, NO₂, and NOₓ emissions with diesel engine load and speed under different values of OEV and ANR. In the test, the minimum activation temperature of SCR was considered based on the load characteristic conditions, which are 50, 75, and 100% loads corresponding to 1295, 1590, and 1885 rpm, respectively.

2.6. Calculation Method. The reduction rate of oxynitride was calculated as follows

\[
R = \frac{C_{X_{1}=0, X_{2}=n}}{C_{X_{1}=m, X_{2}=n}}
\]

where \(C_{X_{1}=0, X_{2}=n}\) presents the volume concentration of oxynitride under OEV = 0 and ANR = 0, and \(C_{X_{1}=m, X_{2}=n}\) presents the volume concentration of oxynitride under OEV = \(m\) and ANR = \(n\).

3. RESULTS AND DISCUSSION

3.1. Relationship between Exhaust Temperature and Engine Load. EGR changes the exhaust temperature of the diesel engine by affecting the combustion in the cylinder; the relationship between the exhaust temperature and engine load is shown in Figure 3.

It can be seen from Figure 3 that the exhaust temperature of the diesel engine increases with the increase of load when the EGR valve is closed. At low engine speed, the exhaust temperature of the diesel engine increases with the increase of OEV, and the increase of the exhaust temperature at high load...
is greater than that at low load. At medium and high speeds with low engine load, the exhaust temperature increases with the increase of OEV. However, at 100% engine load, the exhaust temperature begins to decrease when the OEV exceeds 75%. At 1590 rpm and 100% engine load, the corresponding exhaust temperatures of OEV0%, OEV25%, OEV50%,
OEV75%, and OEV100% are 418, 420, 428, 441, and 384 °C, respectively. Further, the exhaust temperature of OEV100% is lower than the corresponding exhaust temperature of OEV0. This is mainly because too large OEV results in the increase of exhaust gas reflux, the deterioration of combustion in the cylinder, and the decrease of exhaust temperature under high-speed and high-load conditions.

### 3.2. Analysis of NO Emission

According to the test results, the variation of NO emission with engine load under different OEV and ANR values is shown in Figure 4. It can be seen from Figure 4 when EGR and SCR were used in the diesel engine at the same time, SCR further reduced the NO in the exhaust gas on the basis of reduction of NO emission by EGR. The effect of EGR combined with SCR on reducing the NO becomes more and more significant with the increase of diesel engine load at the same speed. EGR combined with SCR to reduce NO emission has a certain threshold under the same working conditions; once the threshold is exceeded, the increase of OEV and ANR will no longer have a significant effect on reducing the NO emission.

Quantitative analysis shows that when the diesel engine was operated at 1295 rpm and 50% load, the combinations of OEV and ANR were set as follows: OEV25% + ANR0.5, OEV25% + ANR1.0, OEV50% + ANR0.5, and OEV50% + ANR1.0; the corresponding reductions of NO volume concentration are 218.8, 327.6, 268.3, and 382.7 ppm, respectively. Therefore, it can be seen that the effect of SCR on reducing the NO emission is obvious no matter the size of the OEV under a high engine load. From the NO reduction rate side, when the diesel engine was operated at 75% load and 1295 rpm, the combinations of OEV and ANR were set as follows: OEV25% + ANR0.5, OEV25% + ANR1.0, OEV50% + ANR0.5, and OEV50% + ANR1.0; the corresponding NO reduction rates are 59.8, 66.9, 80.9, and 90.1%, respectively. With a similar setup, but the engine speed changed to 1590 rpm, the corresponding NO reduction rates are 65.6, 73.4, 83.7, and 91.5%, respectively. Again with a similar setup, but with the engine speed changed to 1885 rpm, the corresponding NO reduction rates are 68.6, 83.7, 87.3, and 94.5%, respectively. The NO reduction rate is more than 50% at ANR = 0.5, because it is due to the combined effect of EGR and SCR. It can be seen that the NO reduction rate increases steadily with the increase of engine speed under the same medium−high engine load. The average NO reduction rates of OEV25% + ANR1.0 corresponding to 1295, 1590, and 1885 rpm are 81.0, 88.2, and 88.5%, respectively, under 75 and 100% engine load. For OEV50% + ANR1.0, the average NO reduction rates are 92.6, 93.3, and 94.1%, respectively. The results show that the NO reduction rate increases significantly when the diesel engine used EGR and SCR together; especially the use of EGR further improves the NO reduction rate of SCR. The change trends of the NO reduction rate are very similar at the three different engine speeds.

![Figure 5. Variation of NO\textsubscript{2} emission with engine load under different OEV and ANR values: (a) 1295 rpm; (b) 1590 rpm; and (c) 1885 rpm.](image-url)
3.3. Analysis of NO2 Emission. According to the test results, the variation of NO2 emission with engine load under different OEV and ANR values is shown in Figure 5.

Figure 5 shows that the NO2 volume concentration in the engine was at a low level during low-load operation of the diesel engine. Therefore, EGR combined with SCR has little effect on NO2 reduction. The NO2 volume concentration in the engine was also at a low level when the diesel engine was operated at medium load (75%) and the engine speeds were 1295 and 1590 rpm, respectively. With the increase of engine load, the NO2 volume concentration in the engine was at a high level when the engine load was 100 or 75%. Meanwhile, the engine speed was 1885 rpm. It can be seen that EGR combined with SCR has a very obvious effect on NO2 reduction, so the NO2 reduction rate achieved is more than 50% at ANR = 0.5, the NO2 average volume concentration is reduced by more than 250 ppm, and the NO2 average reduction rate is more than 97%. This is mainly because the introduction of EGR reduces the production of NO2 in the engine.

3.4. Analysis of NOx Emission. According to the test results, the variations of NOx emission under OEV, ANR, and the combination of OEV and ANR are shown in Figures 6−8, respectively.

Figure 6 shows that the overall NOx reduction rate increases with the increase of OEV. Compared with the OEV of 0, the average NOx reduction rates corresponding to the OEV of 25, 50, 75, and 100% are 37.23, 48.68, 54.26, and 55.71%, respectively, when the engine speed is 1295 rpm. The average NOx reduction rates are 54.59, 63.78, 67.05, and 68.33%, respectively, when the engine speed is 1590 rpm. The average NOx reduction rates are 58.06, 70.72, 76.28, and 77.99%, respectively, when the engine speed is 1885 rpm. When OEV exceeds 50%, the increasing trend of NOx reduction rate is no longer significant.

Figure 7a shows that the NOx reduction rate increases with the increase of ANR under 50% engine load. In particular, the NOx emission reduction rate increases sharply when the ANR changes from 0.5 to 0.8. After that, although the NOx reduction rate continues to increase with the increase of ANR, the increasing trend is no longer significant. The NOx reduction rates under low, medium, and high engine speeds increase by 3.9, 4.1, and 6.3%, respectively, when the ANR changes from 1 to 1.2. However, excessive NH3 supply may lead to secondary pollution of the NH3 slip. Figure 7b shows that the NOx reduction rate gradually increases when the ANR increases from 0.2 to 1.2 under 75% engine load, and the increase is large at high engine speed. When the ANR is 1.0, the corresponding NOx reduction rates under 1295, 1590, and 1885 rpm are 81.7, 80.6, and 66.4%, respectively. Combined with Figures 2 and 7c, the increase of combustion temperature promotes the generation of NOx under 100% engine load. The NOx reduction rate increases obviously when the ANR increases from 0.2 to 0.5. The increasing trend of the NOx reduction rate begins to slow when the ANR is greater than 0.5. When the ANR increases from 1.0 to 1.2, the NOx reduction rates under 1295, 1590, and 1885 rpm increase from 72.8, 69.8, and 65.0% to 75.7, 73.8, and 68.9%, respectively. It can be seen that simply increasing the Adblue...
injection cannot effectively reduce the \( \text{NO}_x \) emission when the \( \text{NO}_x \) reduction rate reaches a larger value.

Figure 8 shows that the variation trend of \( \text{NO}_x \) volume concentration with engine load is basically consistent with that of NO. However, the variation trend of \( \text{NO}_x \) changes slightly due to the increase of \( \text{NO}_2 \) emission at high engine load.

The combinations of OEV and ANR were set as follows: OEV25% + ANR0.5, OEV50% + ANR0.5, OEV25% + ANR1.0, and OEV50% + ANR1.0. When the diesel engine is operated at 1295 rpm and 50% load, the corresponding \( \text{NO}_x \) reduction rates are 49.3, 56.7, 80.0, and 92.1%, respectively. When the engine load is changed to 75%, the corresponding \( \text{NO}_x \) reduction rates are 57.8, 65.3, 78.2, and 87.8%, respectively. On further changing the engine load to 100%, the corresponding \( \text{NO}_x \) reduction rates are 70.0, 78.2, 85.7, and 95.3%, respectively. It can be found that the effects of OEV25% and OEV50% on \( \text{NO}_x \) emission reduction are very similar when the diesel engine speed is at a low level.

Compared with the diesel engine running at low engine speeds, EGR combined with SCR has different effects on the \( \text{NO}_x \) reduction at high engine speeds. The combinations of OEV and ANR were set as follows: OEV25% + ANR0.5, OEV25% + ANR1.0, OEV50% + ANR0.5, and OEV50% + ANR1.0. When the diesel engine is operated at 1885 rpm and 50% load, the corresponding \( \text{NO}_x \) reduction rates are 49.3, 56.7, 80.0, and 92.1%, respectively. When the engine load is changed to 75%, the corresponding \( \text{NO}_x \) reduction rates are 57.8, 65.3, 78.2, and 87.8%, respectively. On further changing the engine load to 100%, the corresponding \( \text{NO}_x \) reduction rates are 70.0, 78.2, 85.7, and 95.3%, respectively. It can be found that the effects of OEV25% and OEV50% on \( \text{NO}_x \) emission reduction are very similar when the diesel engine speed is at a low level.

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3.5. Analysis of the Fuel Consumption Rate. According to the test results, the variation of fuel consumption rate with engine load under different OEV and ANR values is shown in Figure 9.

Figure 9 shows that the fuel consumption rate of the diesel engine decreases with the increase of engine load. The increased fuel consumption rates under 50, 75, and 100% engine load are 6.3, 8.5, and 5.1 g/(kW·h), respectively, when the diesel engine runs at 1295 rpm, OEV25% and ANR0.5. The corresponding increase percentages are 2.96, 3.97, and 2.43%, respectively. Keeping other parameters unchanged at 1885 rpm, the corresponding increase percentages are 0.60, 3.08, and 2.88%, respectively. The fuel consumption rate increases when OEV further increases to 50%, but the increase rate slows down. Overall, the increase of fuel consumption rate is more significant when the engine is running at low speed.

Figure 7b shows that the fuel consumption rate is higher than that of the original engine when the diesel engine runs at 1590 rpm, OEV25% and ANR0.5. It continues to increase with the increase of OEV, but the increasing trend slows down. The corresponding increased fuel consumption rates under 50, 75, and 100% engine load are 1.0, 4.1, and 1.1 g/(kW·h), respectively.
respectively, when OEV increases from 25 to 50% and ANR is 0.5. OEV obviously leads to the increase of fuel consumption rate. In short, increasing the OEV will increase the fuel consumption rate of the diesel engine at 1295, 1590, and 1885 rpm.

4. MATCHING OPTIMIZATION

4.1. Optimization Method. In order to meet the higher emission requirements of diesel engine and take into account the power and economy, the genetic algorithm is used to globally optimize the ESC 13 working conditions of the diesel engine. Because the idle working condition in ESC 13 is not suitable for EGR and SCR, the matching optimization of OEV and ANR is carried out under ESC 12 working conditions composed of three engine speeds and four engine loads (details of the combination are given in Table 5). Based on the ESC 12 working conditions, the variation functions of fuel consumption rate, operating cost, NOx emission, and diesel engine exhaust flow with OEV and ANR are fitted, which provides the preconditions for the optimization of OEV and ANR. Finally, the combination of OEV and ANR under ESC 12 working condition is optimized using the genetic algorithm.

Figures 10 and 11 show how to reasonably use EGR and SCR when the diesel engine operates from 25% load to 100% load.

In this study, the NOx emission limit is kept at less than or equal to 2.0 g/kW·h as per the China-V emission regulations and the ESC test cycle; the fluid consumption cost (fuel consumption cost and Adblue consumption cost) of the diesel engine is minimized by optimizing the OEV and ANR. The weighted sum model of the operating cost of diesel EGR combined with SCR under ESC 12 working conditions is as follows

\[ \text{min } F(x_1, x_2) = \sum_{k=2}^{13} w_k f_k(x_1, x_2) \]  

The weighted sum of the NOx emission under the ESC 12 cycle is subject to

\[ E(x_1, x_2) = \frac{\sum_{i=2}^{13} \text{NOx}_{\text{em}} w_i}{\sum_{i=2}^{13} P_i w_i} \]

\[ \leq \frac{\sum_{i=2}^{13} 0.001587 w_i m(x_1, x_2) e(x_1, x_2)}{\sum_{i=2}^{13} P_i w_i} \leq 2.0 \]  

where \( x_1 \) represents the value of OEV, \( x_2 \) represents the value of ANR, \( w_i \) represents the weight coefficient of the cost under the ESC 12 cycle, \( w_i \) represents the NOx emission weight coefficient under the ESC 12 cycle, \( m(x_1, x_2) \) represents the exhaust flow of the diesel engine, and \( e(x_1, x_2) \) represents the NOx volume emission concentration under each working condition.

The operation cost of a single working condition is as follows

\[ f_k(x_1, x_2) = w_1 y(x_1, x_2) + w_2 n(x_1, x_2) \]
where $w_1$ and $w_2$ represent the weight coefficient of the current market price of diesel and Adblue, respectively, $Y(x_1, x_2)$ represents the fuel consumption, and $N(x_1, x_2)$ represents the Adblue consumption.

The prices of diesel and Adblue are 5800 and 1500 yuan/t, respectively, and the price weight relationship between diesel and Adblue is shown in eqs 5 and 6

$$\frac{w_1}{w_2} = \frac{5800}{1500}$$  

$$w_1 + w_2 = 1$$  \hspace{1cm} (6)

Therefore, for $w_1 = 0.795$, $w_2 = 0.205$, eq 4 is as follows

$$f_k(x_1, x_2) = 0.795Y(x_1, x_2) + 0.205N(x_1, x_2)$$  \hspace{1cm} (7)

The fuel consumption and Adblue consumption are shown in eqs 8 and 9

$$Y(x_1, x_2) = \frac{T_{H2O}}{9550}r(x_1, x_2)$$  \hspace{1cm} (8)
where $T_tq$ represents the engine torque, $N$ represents the engine speed, and $r(x_1, x_2)$ the presents the effect function of OEV and ANR on the fuel consumption rate under each working condition.

To sum up, the weighted operation cost of the diesel engine is shown in equation 10:

$$
\min F(x_1, x_2) = \sum_{k=2}^{13} w_k \left[ 0.795 T_tq(x_1, x_2) + 0.205 N^2(x_1, x_2) \right] + 5.087 \times 5.087
$$

Table 6. Optimization Results of OEV and ANR

| working condition | OEV value (%) | ANR value |
|-------------------|--------------|-----------|
| A100              | 0            | 1.0       |
| B50               | 36.5         | 0.673     |
| B75               | 28.3         | 0.883     |
| A50               | 22.1         | 0.742     |
| A75               | 26.8         | 0.827     |
| A25               | 45.4         | 0         |
| B100              | 0            | 0.943     |
| B25               | 15.4         | 0         |
| C100              | 0            | 0.864     |
| C25               | 42.8         | 0         |
| C75               | 48.9         | 0.812     |
| C50               | 44.2         | 0.673     |

Figure 12 shows the flow chart of optimizing the OEV and ANR based on the genetic algorithm. The floating-point coding scheme is used to code the two parameters $\{x_1, x_2\}$ to be optimized. The initial population is 18 and the maximum genetic algebra is 50 generations. Based on the adaptive crossover rate and mutation rate, the weighted sum of the diesel engine operating cost and fuel consumption rate is selected as the fitness function of the genetic algorithm.

4.2. Optimization Results. In the process of genetic evolution, the optimization value of NOx emission gradually approaches the NOx emission constraint value. The combination with the lowest operating cost is selected among the individuals meeting the emission constraints. Through the optimization of OEV and ANR at 12 operating points of the diesel engine, the combined optimization results of OEV and ANR are shown in Table 6. At the same time, the maps of OEV and ANR are shown in Figures 13 and 14.
necessary to reasonably match the OEV and ANR. OEV shows an increasing trend with the increase of diesel engine speed. Increasing the OEV is conducive to increase the exhaust gas return flow and reduce the generation of NO\textsubscript{x}. OEV increases first and then decreases with the increase of diesel engine load. Due to the NO\textsubscript{x} emission being at a low level under a low engine load, the proportion of low-load condition in the fuel economy and emission constraint calculation is small. Therefore, OEV can be taken as a low value. At high engine loads, the increase of OEV will lead to the rapid increase of the fuel consumption rate. OEV can be appropriately reduced and compensated by increasing the AdBlue injection in SCR. ANR shows an increasing trend with the increase of diesel engine load. This is because the exhaust temperature and the conversion effect of NH\textsubscript{3} on NO\textsubscript{x} increase significantly when the load of the diesel engine increases, so the role of SCR in reducing NO\textsubscript{x} becomes more and more prominent. At this time, the operating cost of the diesel engine can be minimized on the premise of controlling the NO\textsubscript{x} emission by increasing the AdBlue injection and reducing the OEV.

5. CONCLUSIONS

In this study, the test bench was built and used to study the effects of EGR combined with SCR on the NO, NO\textsubscript{2}, NO\textsubscript{x} and fuel consumption rate of a diesel engine under different working conditions. The combination of OEV and ANR was optimized using the genetic algorithm under ESC 12 working conditions. The details are summarized as follows:

1. SCR further reduces the NO in exhaust gas on the basis of reduction of the NO emission by EGR when EGR and SCR are used in the diesel engine at the same time. The effect of EGR combined with SCR on reducing the NO becomes more and more significant with the increase of diesel engine load at the same engine speed. EGR combined with SCR to reduce NO emission has a certain threshold under the same working condition; once the threshold is exceeded, the increase of OEV and ANR will no longer have a significant effect on reducing the NO emission.

2. The NO\textsubscript{2} volume concentration in the engine was at a low level during low-load operation of the diesel engine. EGR combined with SCR has little effect on the NO\textsubscript{2} emission reduction. With the increase of engine load, the NO\textsubscript{2} volume concentration in the engine was at a high level when the engine load was 100 or 75%; meanwhile, the engine speed was 1885 rpm.

3. Compared with the diesel engine running at a low engine speed, EGR combined with SCR has a different effect on the NO\textsubscript{x} emission reduction at a high engine speed. The effect of increasing the OEV or ANR on reducing the NO\textsubscript{x} emission is more obvious at the high engine speed than at the low engine speed. Meanwhile, the effect of SCR on reducing the NO\textsubscript{x} emission is more significant with low OEV.

4. The fuel consumption rate of the diesel engine decreases with the increase of engine load. The maximum fuel consumption increased by 3.97% and the minimum fuel consumption increased by 0.60% after being equipped with EGR and SCR, which indicated that the effect of EGR on the fuel economy of the diesel engine is limited.

5. These optimized data and the maps of OEV and ANR provide a theoretical research method and application basis for diesel engine-matching of EGR and SCR at the same time.

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Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This work was supported by the Perspective Study Funding of Nanchang Automotive Institute of Intelligence and New Energy (TPD-TC202110-11).

■ REFERENCES

(1) Park, S.; Woo, S.; Kim, H.; Lee, K. Effect of diesel-water emulsified fuel on the NO\textsubscript{x} and PM emissions of a diesel engine. Energy Fuels 2016, 30, 6070–6079.
(2) Dhal, G. C.; Mohan, D.; Prasad, R. Preparation and application of effective different catalysts for simultaneous control of diesel soot and NO\textsubscript{x} emissions: An overview. Catal. Sci. Technol. 2017, 7, 1803–1825.
(3) Zhou, H.; Zhou, M.; Liu, Z.; Cheng, M.; Chen, J. Modeling NO\textsubscript{x} emission of coke combustion in iron ore sintering process and its experimental validation. Fuel 2016, 179, 322–331.
(4) O’Driscoll, R.; Stettler, M.; Molden, N.; et al. Real world CO\textsubscript{2} and NO\textsubscript{x} emissions from 149 Euro 5 and 6 diesel, gasoline and hybrid passenger cars. Sci. Total Environ. 2018, 621, 282–290.
(5) Daya, R. Emission control of nitrogen oxides-current status and future challenges. SAE Int. J. Sustainable Trans., Energy, Environ., Policy 2021, 2, 121.
(6) Li, C. G.; Dixit, P.; Welch, B.; et al. Yard tractors: Their path to zero emissions. Transp. Res. Part D: Transp. Environ. 2021, 98, No. 102972.
(7) Jain, A.; Singh, P.; Agarwal, A. Effect of split fuel injection and EGR on NO\textsubscript{x} and PM emission reduction in a low temperature combustion (LTC) mode diesel engine. Energy 2017, 122, 249–264.
(8) Sun, C. H.; Liu, Y.; Qiao, X. Q.; et al. Experimental study of effects of exhaust gas recirculation and combustion mode on combustion, emission, and performance of DME-methanol-fueled turbocharged common-rail engine. Int. J. Energy Res. 2021, 46, 2385.
(9) Martinovic, F.; Andana, T.; Piumetti, M.; et al. Simultaneous improvement of Ammonia mediated NO\textsubscript{x} SCR and soot oxidation for enhanced SCR-on-filter application. Appl. Catal., A 2020, 596, No. 117538.
(10) Liu, G.; Cui, Y.; Ji, J.; Shen, D.; et al. A technical method to improve NO\textsubscript{2}-NH\textsubscript{3} mixing ratio in SCR system and its engineering applications. J. Energy Inst. 2019, 92, 1757–1764.
(11) Zhang, W.; Feng, T.; Li, Z. H.; et al. EGR thermal and chemical effects on combustion and emission of diesel/natural gas dual-fuel engine. Fuel 2021, 302, No. 121161.

(12) Asad, U.; Zheng, M. Exhaust gas recirculation for advanced diesel combustion cycles. Appl. Energy 2014, 123, 242–252.

(13) You, J. W.; Liu, Z. C.; Wang, Z. S.; et al. Experimental analysis of inert gases in EGR on engine power and combustion characteristics in a stoichiometric dual fuel heavy-duty natural gas engine ignited with diesel. Appl. Therm. Eng 2020, 180, No. 115860.

(14) Jafarmadar, S.; Nemati, P. Multidimensional modeling of the effect of exhaust gas recirculation on exergy terms in a homogeneous charge compression ignition engine fueled by diesel/biodiesel. J. Cleaner Prod. 2017, 161, 720–734.

(15) Ramesh, N.; Mallikarjuna, J. Low temperature combustion strategy in an off-highway diesel engine-experimental and CFD study. Appl. Therm. Eng. 2017, 124, 844–854.

(16) Nitta, Y.; Yoo, D. H.; Nishio, S.; et al. Evaluation of emissions characteristics of marine diesel engine intake of exhaust gas of lean burn gas engine. J. Eng. Gas Turbines Power 2018, 140, No. 022802.

(17) Wang, Z. G.; Zhou, S.; Feng, Y. M.; et al. Research of NOx reduction on a low-speed two-stroke marine diesel engine by using EGR (exhaust gas recirculation)-CB (cylinder bypass) and EGB (exhaust gas bypass). Fuel 2017, 42, 1933–1945.

(18) Gong, C. M.; Qi, X. K.; Liu, F. H. Combined effects of excess air ratio and EGR rate on combustion and emissions behaviors of a GDI engine with CO2 as simulated EGR (CO2) at low load. Fuel 2021, 293, No. 120442.

(19) Tang, X. Y.; Wang, P.; Zhang, Z. Y.; et al. Effects of high-pressure and donor-cylinder exhaust gas recirculation on fuel economy and emissions of marine diesel engines. Int. J. Hydrogen Energy 2022, 309, No. 122226.

(20) Oommen, L. P.; Kumar, G. Experimental studies on the impact of part-cooled high-pressure loop EGR on the combustion and emission characteristics of liquefied petroleum gas. J. Therm. Anal. Calorim. 2020, 141, 2265–2275.

(21) Li, Y. Y.; Wang, P.; Wang, S. Q.; et al. Quantitative investigation of the effects of CR, EGR and spark timing strategies on performance, combustion and NOx emissions characteristics of a heavy-duty natural gas engine fueled with 99% methane content. Fuel 2019, 255, No. 115803.

(22) Wang, Z.; Zhou, S.; Feng, Y.; Zhu, Y. EGR modeling and fuzzy evaluation of low-speed two-stroke marine engines. Sci. Total Environ. 2020, 706, No. 135444.

(23) Wang, D. W.; Zhu, S. P.; Liu, Bo.; et al. Numerical and thermodynamic study on effects of high and low pressure exhaust gas recirculation on turbocharged marine low-speed engine. Appl. Energy 2020, 261, No. 114346.

(24) Praveena, V.; Martin, L. J. A review on various after treatment techniques to reduce NOx emissions in a CI engine. J. Energy Inst. 2018, 91, 704–720.

(25) Xu, H. T.; Luo, Z. Q.; Wang, N.; et al. Experimental study of the selective catalytic reduction after-treatment for the exhaust emission of a diesel engine. Appl. Therm. Eng. 2019, 147, 198–204.

(26) Wang, X.; Song, G. H.; Wu, Y. Z.; et al. A NOx emission model incorporating temperature for heavy-duty diesel vehicles with urea-SCR systems based on field operating modes. Atmosphere 2019, 10, 337.

(27) McCaffery, C.; Zhu, H. W.; Tang, T. B.; et al. Real-world NOx emissions from heavy-duty diesel, natural gas, and diesel hybrid electric vehicles of different vocations on California roadways. Sci. Total Environ. 2021, 784, No. 147224.

(28) Wang, T. J.; Jung, H. K. Simulation study on thermal management strategy to achieve 99% SCR efficiency of a heavy-duty diesel engine over a transient cycle. Int. J. Automot. Technol. 2018, 19, 597–603.

(29) Tan, L. G.; Guo, Y.; Liu, Z.; et al. An investigation on the catalytic characteristic of NOx reduction in SCR systems. J. Taiwan Inst. Chem. Eng. 2019, 99, 53–59.

(30) Wang, J.; Hu, Y.; Cai, Y.; et al. Influence of urea-SCR system parameters on NOx conversion rate and liquid film. Energy Sources, Part A 2021, 43, 2027–2040.

(31) Chundru, V.; Parker, G.; Johnson, J. The effect of NOx/NOy ratio on the performance of a SCR downstream of a SCR catalyst on a DPF. SAE Int. J. Fuels Lubr. 2019, 12, 121–141.

(32) Bacenetti, J.; Lovarelli, D.; Facchinetti, D.; Pessina, D. An environmental comparison of techniques to reduce pollutants emissions related to agricultural tractors. Biosyst. Eng. 2018, 171, 30–40.

(33) Suresh Kumar, P.; Joshi, S.; Kumari, N. P.; et al. Reduction of emissions in a biodiesel-fueled compression ignition engine using exhaust gas recirculation and selective catalytic reduction techniques. Heat Transfer 2020, 49, 3119–3133.

(34) Theisls, H.; Danninger, A.; Sacher, T.; et al. A study on operation fluid consumption for heavy duty diesel engine application using both, EGR and SCR. SAE Int. J. Engines 2013, 6, 1500.

(35) Radhakrishnan Lawrence, k.; Tharigonda, H.; Alluru, G. An experimental investigation on combined effect of EGR and SCR for diesel engine fueled with the addition of TiO2 nanoparticle to M.Elangi methyl ester blend. Aust. J. Mech. Eng. 2020, 18, 220–233.

(36) D’Aniello, F.; Arsie, I.; Pianese, C.; Stola, F. Development of an integrated control strategy for engine and SCR system based on effective EGR rate. IFAC PapersOnLine 2020, 53, 14034–14039.

(37) Kim, H. J.; Jo, S.; Kwon, S.; et al. NOx emission analysis according to after-treatment devices (SCR, LNT plus SCR, SDPF), and control strategies in Euro-6 light-duty diesel vehicles. Fuel 2022, 310, No. 122297.

(38) Katoh, S.; Chauhan, S. S.; Kumar, V. A review on genetic algorithms: past, present, and future. Multimedia Tools Appl. 2021, 80, 8091–8126.

(39) Figueroa, O. R.; Castellanos, M. Q.; Monteás, E. M.; Kharel, R. Variation Operators for Grouping Genetic Algorithms: A Review. Swarm Evol. Comput. 2021, 60, No. 100796.