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Effects of Intake Components and Stratification on the Particle and Gaseous Emissions of a Diesel Engine

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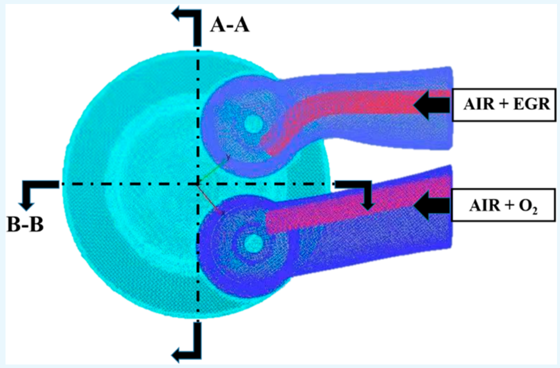
ABSTRACT: It is of great significance to improve the performance of diesel engines by adjusting the intake components and their distribution. In this work, various proportions of exhaust gas recirculation (EGR) gas and oxygen (O_2) have been introduced to the intake charge of a diesel engine and the effects of different intake components and stratification conditions on pollutant emissions, especially for particles, have been explored. The results show that the introduction of O_2 into the intake charge is beneficial to alleviate the deterioration of particles and hydrocarbon (HC) emissions caused by high EGR rates. Compared with the pure air intake condition, the introduction of moderate O_2 at high EGR rate conditions can simultaneously reduce nitrogen oxides (NO_x) and particles, when the intake oxygen content (IOC) is 0.2 and the EGR rate is 20%, the NO_x and particles are reduced by 45.66% and 66.49%, respectively. It is worth noting that different intake components have a significant impact on the particle size distribution (PSD) of diesel engines. In addition, the in-cylinder O_2 concentration distribution formed by the stratified intake is advantageous for further improving the combined effect of NO_x, particles and HC emissions relative to the homogeneous intake. At a condition of 0.2 IOC and 20% EGR rate, the NO_x, particles, and HC emissions are about 8.8%, 14.3%, and 26% lower than that of intake components nonstratification, respectively.



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1. INTRODUCTION

In recent years, with the increasing retention of internal combustion engines (ICE), pollutant emissions from ICE have already caused considerable damage to the atmospheric environment. Compared with other types of ICE, diesel engines are widely used in various fields such as agriculture, transportation, and industry because of their advantages in reliability and fuel economy.[1,2] However, gaseous emissions such as NO_x and HC, and particulate emissions mainly composed of soot and unburned carbonaceous compounds are inevitably generated due to inhomogeneous mixture concentration and temperature distribution.[3,4] Among them, NO_x has a significant impact on the atmospheric chemistry and climate. NO_x in the atmosphere can be oxidized to HNO_3 and then deposited as acid rain, which will adversely affect drinking water, soil, and biodiversity.[5,6] The particles produced by diesel engines can easily penetrate into the respiratory tract and affect human health. Especially the ultrafine particles (D_P < 100 nm) formed by the modern low mass emission engines are more harmful to the human body and environment.[7−9] Therefore, strict regulations have been enacted all over the world to limit the pollutant emissions from diesel engines,[10] and research work on low-emission technologies for diesel engines is in full swing.[11,12]

Exhaust gas recirculation (EGR) is an effective technology used to reduce NO_x emissions from diesel engines.[13−16] However, a too high EGR rate will cause some changes in the combustion process, including the lower IOC, longer ignition delay, lower heat release rate, and decreased combustion completeness, which lead to a series of problems, such as the deterioration of HC, CO, and particulate emissions and the decline of engine power and fuel economy.[17] In order to cope with these problems arising from high EGR, some researchers have adopted the method of intake supercharging to increase the IOC and optimize the engine emissions and fuel economy comprehensively through the coordinated control of EGR and supercharging technology.[18,19] However, limited by the mechanical strength, the compression ratio of intake supercharging cannot be too high, and this means will consume exhaust energy. Therefore, it has been difficult to introduce a large proportion of EGR at high intake pressure conditions.[20]

Introducing O_2 into the intake charge can also increase the IOC and facilitate the introduction of a high proportion EGR. In

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the early days, due to the limitation of cost and other issues, the technology of increasing the IOC by directly introducing O_2 to achieve oxygen-enriched combustion has mainly been used in the industrial fields such as thermal power generation.[21] With the rapid development of gas components separation technology, the oxygen enrichment technology has been gradually applied to the adjustment of the intake components in ICE.[22] Therefore, it is of certain research value to optimize the engine combustion process and control the pollutant emissions by adjusting the engine intake components with EGR and oxygen enrichment technology.

In addition, since the primary generation areas of NO_x and soot are different, the technique of the intake components stratification represented by the EGR stratification is an effective means to solve the trade-off relationship between NO_x and particulate emissions.[23,24] Kosaka et al.[25] have conducted a pilot study on the combustion characteristics of diesel in a rapid compressor and expander machine (RCEM) at various intake distribution conditions, and the effect of asymmetric oxygen distribution in the cylinder on emissions has been clarified. Shen et al.[26] have used the in-cylinder EGR stratification technique to form a nonuniform distribution of oxygen concentration and temperature in the combustion chamber for simultaneously control the generation of NO_x and particles. At present, many studies on EGR intake stratification technology have been done and encouraging results have been achieved,[27] but EGR stratification can only reduce the oxygen concentration and cannot make up for the lack of oxygen in the oil-rich area. In fact, soot is often generated in the oil-rich area in diesel engines. Therefore, adding oxygen on the basis of the stratification of intake components can not only increase the oxygen concentration in the cylinder but also reduce the soot generation more effectively.

On the basis of the combined application of EGR and oxygen enrichment technology, we have used the self-designed and developed intake system on a common rail four-valve diesel engine to investigate the effects of intake components on the particles and gaseous emissions in this study. Moreover, in terms of the particulate emissions, the formation processes and the harm to the human body of different size particles are different. The effect of diesel engine combustion on the particle size distribution (PSD) of different intake components has great research value, and that aspect is lacking in previous research, especially when the addition of oxygen is even more lacking.[28−31] The present study has also investigated the effects of different intake component conditions on the particle size distribution of diesel engines. In addition, we have used different gas flow characteristics of intake port structures to explore the potential effects of intake component stratification to reduce pollutant emissions.

2. RESULTS AND DISCUSSION

2.1. Effect of EGR on Emissions of Diesel Engines. The EGR technology can reduce the IOC and combustion temperature by introducing exhaust gas into the intake charge. However, the current EGR technology still has problems like causing deteriorations of particles and HC emissions of the diesel engine. Figure 1 shows the comparison of NO_x and particulate mass (PM) emissions at different EGR rates. And in this paper, the PM refers to the total particulate mass. Figure 2 shows the comparison of HC emissions at different EGR rates.

It can be seen from Figure 1 that the increasing EGR rate is beneficial to suppress NO_x emissions, but the high EGR rate leads to a sharp increase in PM emissions. For the NO_x formation mechanism, the thermal (Zeldovich), prompt (Fenimore), and fuel NO mechanism are the most common mechanisms for NO_x formation in diesel combustion. Among them, thermal NO is the dominant mechanism of NO_x formation in diesel engines due to the lower nitrogen content of vehicle diesel and the lean mixture in the cylinder.[32] And there are two main reasons for the increase because of thermal NO in NO_x emissions. On the one hand, the introduction of EGR brings a large amount of triatomic molecule CO_2 with high specific heat capacity (SHC), thereby lowering the combustion temperature. On the other hand, the introduction of exhaust gas reduces the O_2 concentration in the cylinder. Both of them have an inhibitory effect on the production of NO_x. However, the anoxic environment produced by application of a high EGR rate promotes the formation of particles. Because it is very detrimental to the late oxidation of particles, it results in severe deterioration of particulate emissions.[33] In addition, Figure 2 shows that a higher EGR rate will also cause a markedly increased HC emissions. It indicates that the higher EGR rate leads to more serious incomplete combustion and less oxidization time for the unburned HC.

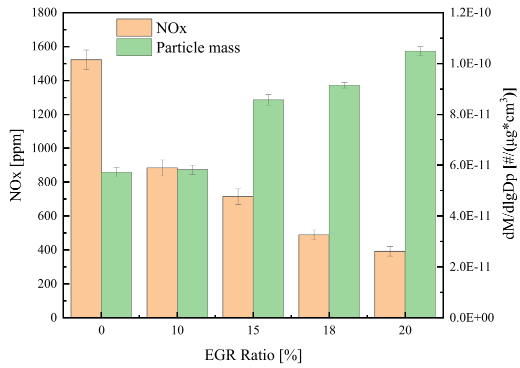

Figure 1. NO_x and PM emissions at various EGR rates.

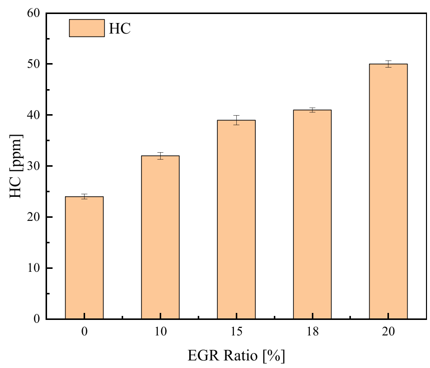

Figure 2. HC emissions at various EGR rates.

2.2. Effect of Intake Components on Emissions of Diesel Engines. For the purposes of this study mentioned in the previous section, in order to reduce the effects of the high EGR rate (>10%) on particles and HC emissions, the effect of adding oxygen at a high EGR rate conditions on diesel emissions has been experimentally investigated.

2.2.1. Analysis of NO_x and PM Emissions. Figure 3 and Figure 4 respectively show the comparison of NO_x emissions and PM emissions generated with different intake components. It can be seen that increasing the oxygen concentration of the intake charge at the same EGR rate is conducive to inhibition of

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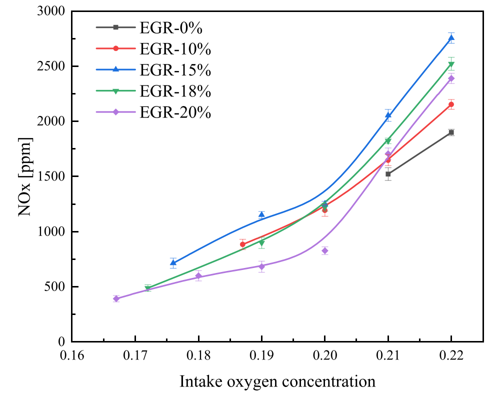

Figure 3. NO_x emissions with various intake components.

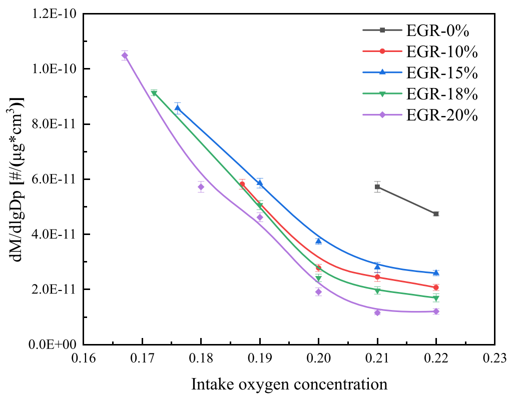

Figure 4. PM emissions with various intake components.

particulate emissions but leads to an increase of NO_x emissions. However, compared with the pure air intake condition, when O_2 is introduced at a high EGR rate and the IOC is still lower than that of the atmosphere, simultaneous reduction of NO_x and particulate emissions can be achieved. Compared with the pure air intake condition, when the IOC is 0.2 and the EGR rate is 10%, 15%, 18%, and 20%, the NO_x emissions are reduced by 21.62%, 17.74%, 26.35%, and 45.66% and the PM emissions are reduced by 51.48%, 34.72%, 57.77%, and 66.49%, respectively. The result indicates that the simultaneous reduction in NO_x and particulate emissions can be achieved through intake components optimization by properly regulating the EGR and oxygen supplementation at the intake. The reason is that the low combustion temperature brought by the high EGR rate is conducive to inhibiting both NO_x and particulate emissions. In addition, with the increase of the EGR rate at the same IOC condition, the N_2 component in the intake charge is getting smaller, which is also one of the factors causing the reduction of the NO_x emissions.[34]

It can also be found from the above data that at the same IOC condition, both NO_x and particulate emissions show an increasing trend at first, and then a decreasing tendency with the increased EGR rate. This is because the combustion temperature becomes an important factor affecting NO_x and particulate emissions when the oxygen concentration is fixed, and the lower combustion temperature is conducive to inhibiting NO_x and particles formation. And the combustion temperature is affected by the fraction of premixed combustion and the SHC of the mixture. A larger premixed combustion fraction leads to a higher combustion temperature, while a larger mixture SHC leads to a lower combustion temperature.[35] As supporting evidence, it can be seen from Figure 5 that at the same oxygen concentration condition, the ignition delay is

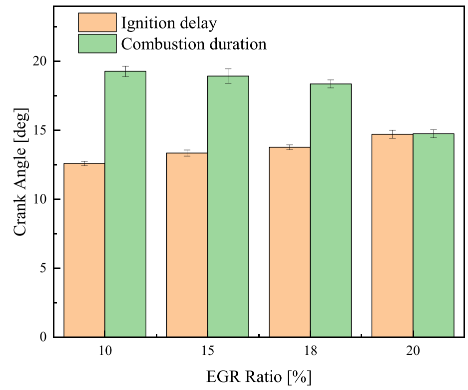

Figure 5. Ignition delay and combustion duration at various EGR rates for an IOC value of 0.2.

prolonged and the combustion duration is shortened with the increased EGR rate, indicating that the higher EGR rate leads to an increased proportion of premixed combustion. At the same time, with a fixed oxygen concentration, the SHC of the mixture also increases with the increased EGR rate. At a small EGR rate, e.g., less than 15%, the change of SHC is also small, and the effect of premixed combustion on the combustion temperature is dominant. But when the EGR rate turns higher than 15%, the effect of SHC on the combustion temperature becomes more remarkable due to the greater change in SHC value. Therefore, at the same IOC condition, when the EGR rate is less than 15%, the maximum temperature in the cylinder increases with the increase of the EGR rate; when the EGR rate is higher than 15%, the temperature in the cylinder decreases with the increase of the EGR rate.

2.2.2. Analysis of HC Emissions. Figure 6 shows the effect of different intake components on HC emissions. It can be seen

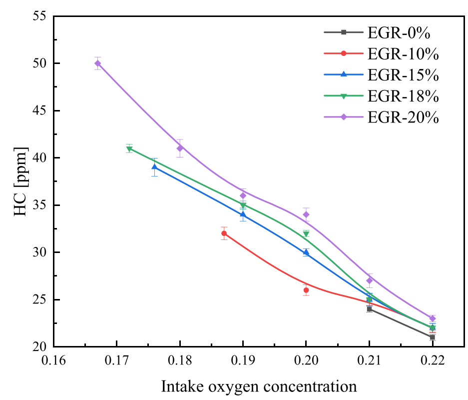

Figure 6. HC emissions with various intake components.

from the figure that increasing the IOC is beneficial to suppress HC emissions caused by a high EGR rate. At an EGR rate of 20%, the HC emissions with oxygen concentrations of 0.18, 0.19, 0.20, and 0.21 could be reduced by 18%, 28%, 32%, and 46%, respectively, comparing to that measured without oxygen addition into the intake. The reason is that increasing the IOC is conducive to form the gas/fuel mixture suitable for combustion, the combustion completeness is improved, and the oxidation of the unburned HC is promoted.

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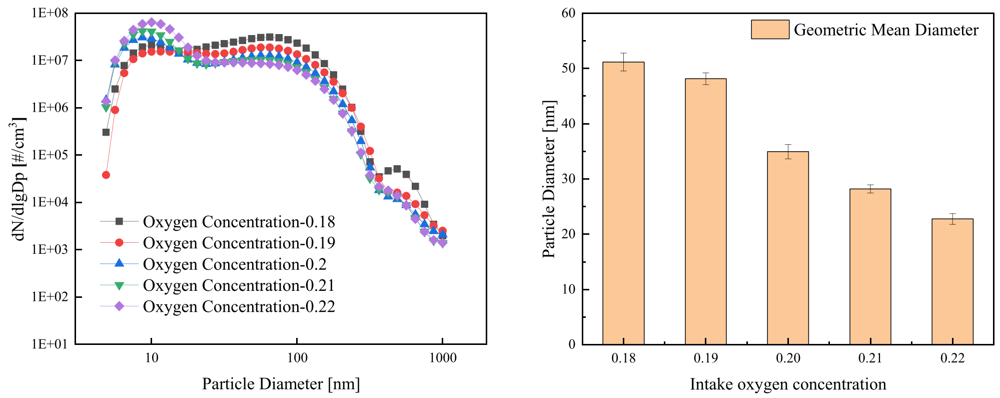
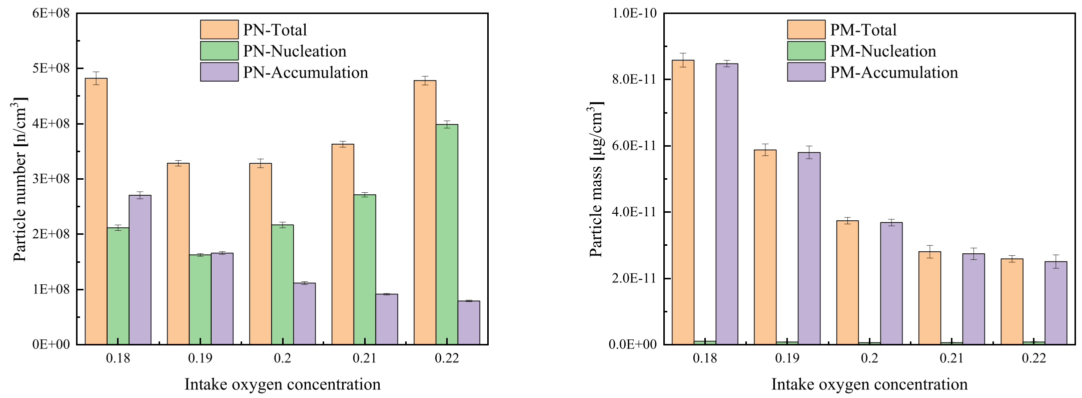


(a) Particle number distribution versus particle diameter

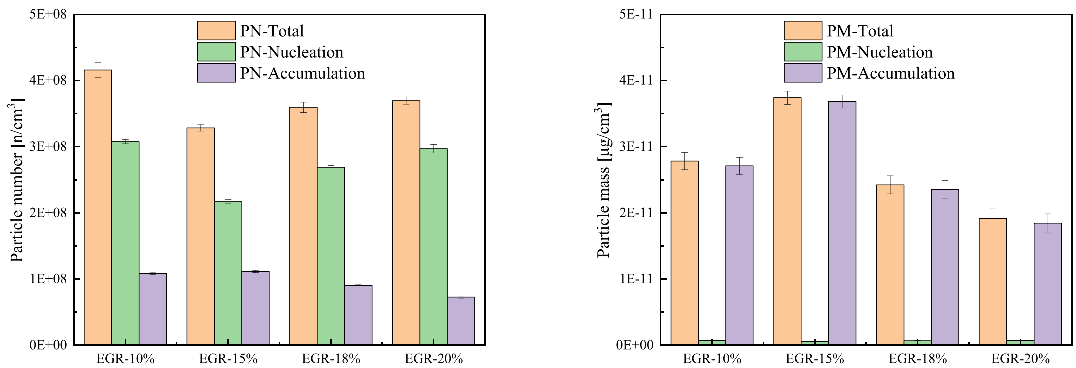
(b) Geometric mean diameter



(c) Particle number distribution of different modes

(d) Particle mass distribution of different modes

Figure 7. Characteristics of particle emission distribution at various IOCs for a 15% EGR rate.



(a) Particle number distribution of different modes

(b) Particle mass distribution of different modes

Figure 8. Characteristic of particle emission distribution at various EGR rates for 0.2 IOC.

2.2.3. Analysis of Emission Characteristics of Particles in Different Modes. In this section, the effect of the IOC on the PSD at different EGR rates was analyzed. The results show that the effects of oxygen concentration on the PSD are similar for different EGR rates, so that only the case with the 15% EGR rate is taken as an example and analyzed to illustrate the effect of the IOC on PSD, as shown in Figure 7. In order to classify the particles with different sizes, all the particles with the size below 35 nm are defined as nuclear mode (NM) particles and particles with the size above 35 nm are defined as accumulated mode (AM) particles in this study.

As can be seen from Figure 7, increasing the oxygen concentration is effective to reduce both the mass and number of the AM particles, but for the NM particles, both parameters are decreased at first and then increased with the oxygen concesntration increment. Because the number of NM particles and the mass of AM particles account for large proportions in diesel particulate emissions, the total number of particles

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decrease at first and then increases with the increased IOC, while the total mass of particles decreases continuously. It is generally believed that the NM particles are mainly formed due to condensation of some saturated HC components during the cooling and dilution process of the exhaust gas,[36] while the AM particles are formed by aggregated porous carbonaceous particles that have large specific surface areas that can absorb unburned hydrocarbons in the cylinder.[37] As the IOC increases, the lean oxygen area will be reduced, so that the formation of graphitized carbon particles at a high temperature can be avoided. As a result, the mass and number of AM particles will be greatly reduced. But for the NM particulate emissions, the HC emissions are significantly reduced, so that the less saturated HC to form the NM particulates. Moreover, as the amount of graphitized carbon particles decreases, the adsorption capacity of it for the unburned HC decreases, resulting in an increase in the number of NM particles. The combined effect of these two aspects results in an increase following by a decrease in the measured NM particle numbers with a rising IOC value. Therefore, with the increase of the IOC, the geometric mean diameter of the particles decreases greatly.

The effects of EGR rates on the particle characteristics at different IOCs were also analyzed in this study. The results show that the effects of the EGR rate on particle characteristics are similar for different oxygen concentrations. It can be concluded from the above analysis that the comprehensive effect of particles and NO_x emissions is relatively superior when the oxygen concentration is 0.2. In this section, the results of particle characteristics with different EGR rates are illustrated when the oxygen concentration is 0.2 as shown in Figure 8. It can be seen from Figure 8 that with the increase of the EGR rate, at the same oxygen concentration condition, the overall change in the number of the particles belonging to different modes is small, and the variation trend for NM particles and AM particles are opposite. With the increase of the EGR rate and the 15% EGR rate as the turning point, the number and mass of nucleate particles decreases at first and then increases and the number and mass of the AM particles increases at first and then decreases, which lead to the total particle number decreases at first and then increases, and the PM increases at first and then decreases. The reason for this phenomenon is similar to that described in the previous paragraph.

2.3. Effect of Intake Stratification on Emissions Characteristics of Diesel Engines.

The intake components adjustment can effectively improve the engine pollutant emissions; however, the stratification of the intake component can further optimize the engine intake process with less cost on the basis of the intake components adjustment. In this section, the effects of intake components stratification on engine pollutant emissions were studied, and the potential of reducing engine pollutant emissions through intake component stratification was explored.

2.3.1. Analysis of Intake Stratification Process and in-Cylinder Oxygen Concentration Distribution. The numerical simulation method was used to study the intake stratification process of the engine at the condition of introducing EGR into the helical intake port and O_2 into the tangential intake port. The numerical simulation software used in this study is CONVERGE v2.3. Among them, the initial gas mass concentrations of the tangential intake port were 30% O_2 and 70% N_2, the initial gas mass concentrations of the helical intake port were 20% CO_2, 18.4% O_2, and 61.6% N_2. The effects of differently shaped intake ports on three-dimensional gas flow and gas concentration distribution are revealed. The simulation model parameters are shown in the Table 1. Since the intake process is very important

Table 1. Simulation Model Parameters

category	properties
base grid size	0.001 mm × 0.001 mm × 0.001 mm (adaptive)
start time	360 °CA BTDC
end time	0 °CA BTDC
time-step	1×10^{-8} to 5×10^{-5} s (adaptive)
turbulence model	renormalized $k-\varepsilon$ model
wall heat transfer model	O'Rourke and Amsden
solver type	SOR

for this study, the in-cylinder pressure of the intake process after the intake valve open is verified. As shown in Figure 9, the

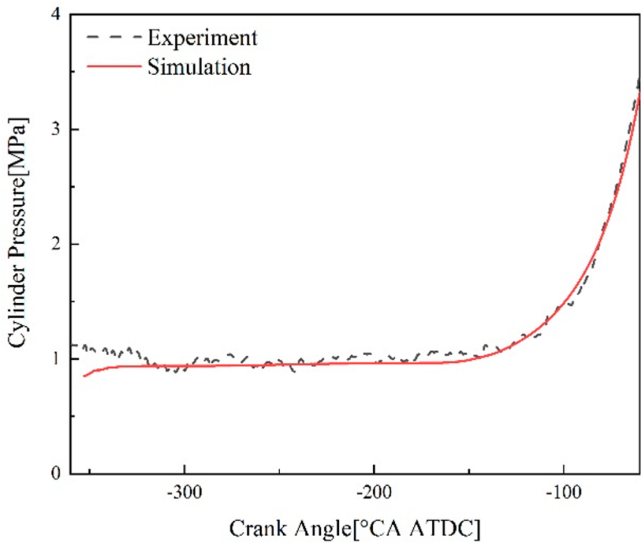

Figure 9. Comparison of in-cylinder pressure curves between simulation and experiment.

simulated pressure profiles are consistent with that of the experimental results. On the basis of these model validations, the established numerical models can be used for subsequent calculation.

Figure 10 shows the distribution of the velocity field in the cylinder at different times during the intake process, the H in the figure represents the height of valve lift. It can be seen from Figure 10 that the airflow guided by the helical intake port forms a strong rotation above the valve seat. And the tangential intake port has a relatively straight shape, so the airflow guided by it has a high speed in the axial direction. The gas introduced through the tangential intake port rotates close to the cylinder wall, while the gas introduced by the helical intake port rotates close to the center of the cylinder. Figure 11 shows the distribution of oxygen concentration in the cylinder at 8 °CA BTDC, and the directions of sections A−A and B−B are shown in Figure 11. As illustrated in Figure 11, the oxygen concentration is low in the center of the combustion chamber, and the oxygen concentration is high around the combustion chamber, especially in the pit area of the combustion chamber. Since the soot is mainly generated in the pits of the combustion chamber due to the diffusion combustion, and NO_x is mainly formed in the high temperature region of the center of the combustion chamber,[27] the gas distribution state formed by introducing oxygen through

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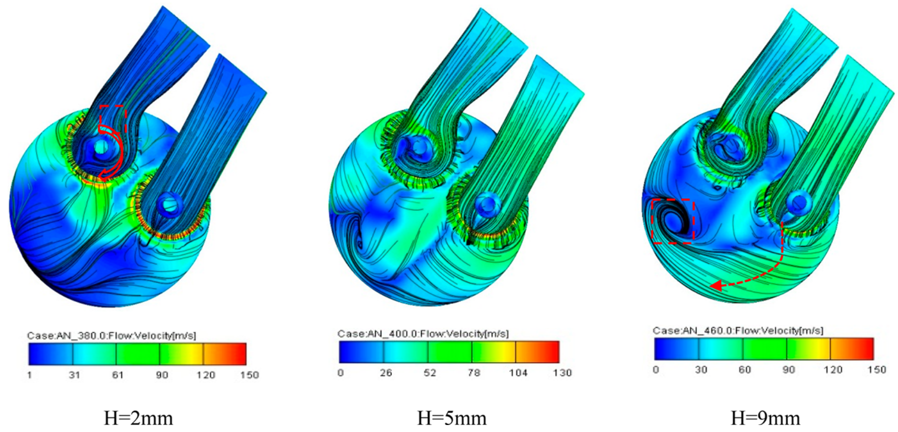

Figure 10. Distribution of the velocity field in the cylinder at different times during the intake process.

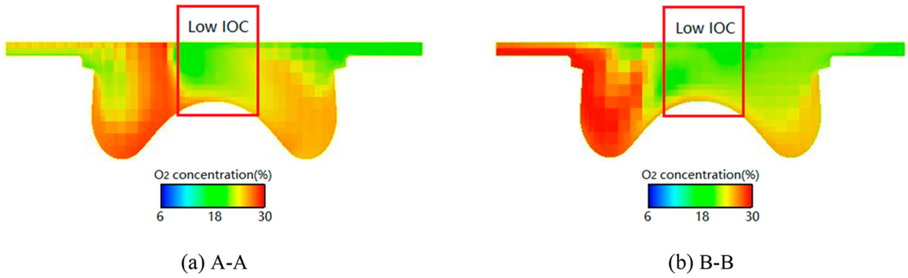

Figure 11. Distribution of oxygen concentration in the cylinder at 8 °CA BTDC: (a) A−A direction and (b) B−B direction.

the tangential intake port and EGR through the helical intake port is beneficial to simultaneously reduce soot and NO_x emissions.

2.3.2. Analysis of NO_x and PM emissions. Figure 12 shows the comparison of NO_x emissions and PM emissions obtained at the stratified intake condition and homogeneous intake condition, respectively. At both conditions, the NO_x increases monotonically and the PM decreases monotonically with the increase of oxygen content at the same EGR rate. Therefore, using the PM and NO_x emissions as the horizontal and vertical coordinates to draw the PM-NO_x curves with the different oxygen concentration at the same EGR rate and intake form, the comprehensive improvement effect of stratification on PM and NO_x emissions could be clearly demonstrated.

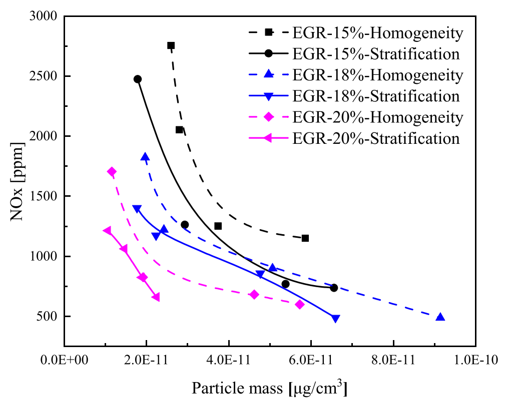

Figure 12. NO_x and PM emissions with different intake configurations and components.

It can be seen from Figure 12 that when the oxygen concentration is too high or too low, either the NO_x emission or the particulate emission will be seriously deteriorated. In contrast to the stratified intake and homogeneous intake conditions at different EGR rates, it can be found that the PM-NO_x comprehensive emissions are poor at the condition of the 15% EGR rate, while the PM-NO_x curve of the stratified intake form is at the lower left of the homogeneous intake form. It indicates that the effect of stratified intake is more obvious for the comprehensive reducing pollutant emissions on the 15% EGR rate. For the 18% and 20% EGR rates, the PM-NO_x comprehensive emissions are relatively superior, while the stratified intake has a better effect than the homogeneous air intake only in the cases where the NO_x or particulate emissions deteriorate severely. For example, when the IOC is 0.2 and the EGR rate is 20%, the NO_x and particulate emissions are about 8.8% and 14.3% lower than that of homogeneous intake components, respectively. This is caused by the NO_x formation region being closer to the center of the combustion chamber relative to the generation region of the soot according to preliminary researches,[38] the introduction of O_2 through the tangential intake port and the EGR through the helical intake port results in low oxygen concentration at the center of the combustion chamber and high oxygen concentration in the off center regions. The above oxygen concentration distribution form can simultaneously reduce the amount of NO_x and PM in the original high generation region.

2.3.3. Analysis of HC Emissions. Figure 13 shows the comparison of HC emissions between stratified and homogeneous intake conditions. It can be seen from the figure that stratified intake is beneficial to reduce HC emissions at all EGR rates and oxygen concentrations. Compared with the homogeneous intake condition, when the IOC is 0.2 and the EGR rate is 20%, the HC emission is reduced by 26% under stratification. The reason is that the HC emissions of a diesel engine are mainly caused by the inhomogeneous distribution of the mixture

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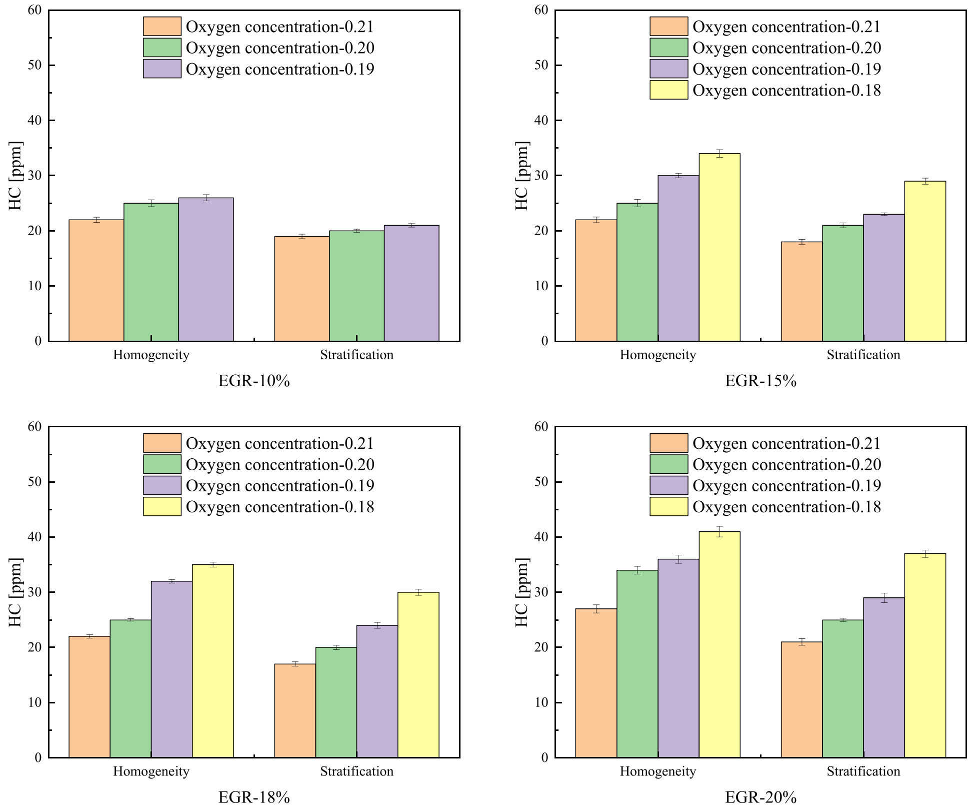

Figure 13. HC emissions with different intake forms and components.

concentration in the cylinder, which is generated at the end of the diesel fuel spray and the area around the cylinder wall where the mixture is thin. However, the low central oxygen concentration and high edge oxygen concentration of the combustion chamber can accelerate the oxidation of unburned HC around the cylinder wall, thus reducing HC emissions.

3. CONCLUSIONS

In this study, the self-developed single-cylinder diesel engine with flexible intake components control system was used to investigate the effects of intake components and stratification on pollutant emissions. The results can be summarized as follow:

1. The introduction of O_2 into the intake charge is beneficial to alleviate the deterioration of particulate and HC emissions at a condition with a high EGR rate. Compared with the pure air intake condition, the introduction of O_2 with an appropriate amount at high EGR rate conditions can reduce NO_x and particulate emissions simultaneously. At the same oxygen concentration, the NO_x and PM emissions of the engine increase at first and then decrease with the increased EGR rate, where the 15% EGR rate is the turning point. Compared with the pure air intake conditions, when the IOC is 0.2, at a 20% EGR condition, the NO_x and PM are reduced by 45.66% and 66.49%, respectively.
2. With a constant EGR rate, increasing the IOC is conducive to reducing both the number and mass of the AM particles. But for the NM particles, it leads to a first decreased and then increased trend in both the number and mass of the particles. However, with an increased IOC value and an unchanged EGR rate, the geometric mean diameter of the particles can be greatly reduced. At the same IOC, with the increase of the EGR rate and the 15% EGR rate as the turning point, the particle number decreases at first and then increases, and the PM increases at first and then decreases.
3. The in-cylinder oxygen concentration distribution formed by the stratified intake is advantageous for further improving the combined effect of NO_x and particulate emissions in comparison to homogeneous intake, especially in the conditions that severe deterioration of NO_x or particulate emissions occurred. Meanwhile, the stratified intake has a certain effect on improving HC emissions compared to the effects of homogeneous intake.

This work has clarified the effects of different EGR rates and oxygen proportions and the corresponding stratification on the diesel engine combustion process and emissions and provides a reference for the use of oxygen-enriched technology to solve the combustion deterioration and particulate emissions caused by large proportions of EGR. In future studies, it is necessary to further optimize the design of the intake port structure to form a better intake components stratification, and to maximize the utilization of the potential of oxygen-enriched and EGR technology.

4. EXPERIMENTAL SECTION

4.1. Experimental Engine and Test Equipment. The test engine is a single-cylinder diesel engine modified from a four-stroke, four-cylinder, direct-injected turbocharged diesel engine. The key specifications of the engine are shown in Table 2. The third cylinder of the test engine has an independent intake, exhaust, and fuel injection system, and the other three cylinders remaining do not have injectors installed. The fuel injection

Table 2. Engine Specifications

category	properties
geometric compression ratio	17.7
cylinder diameter (mm)	95.4
piston stroke (mm)	104.9
connecting rod length (mm)	162
intake valve closing moment (°CA ATDC)	−143
exhaust valve closing moment (°CA ATDC)	366
injector orifice number	6
injector orifice diameter (mm)	0.12
oil jet cone angle (deg)	12
eddy current ratio	0.97

system is dynamically adjusted online by an open electronic control unit (ECU). Moreover, the temperature of cooling water and intake charge are controlled at 358 ± 2 and 290 ± 2 K, respectively, with a temperature control system. The pressure and the components of the intake can be flexibly adjusted using a self-designed two-stage dummy supercharging system and intake components control system. The two-stage dummy supercharging system is adopted to adjust the intake pressure between 0.1 and 0.3 MPa flexibly. The intake components control system has two high pressure cylinders filled with 99% O_2 and CO_2, respectively. Due to the large fluctuations in exhaust back pressure of single-cylinder engine, it is difficult to accurately control the EGR rate. Therefore, the high purity CO_2 is used to simulate the actual exhaust gas of the engine. Among them, the EGR rate in this study is defined as the ratio of the purity CO_2 mass flow and total intake gas mass flow. And the O_2 and CO_2 flow are real time monitored with two flow sensors that range from 0 to 100 L/min.

An intake stratification device shown in Figure 14 is also developed on the basis of the helical/tangential dual intake port

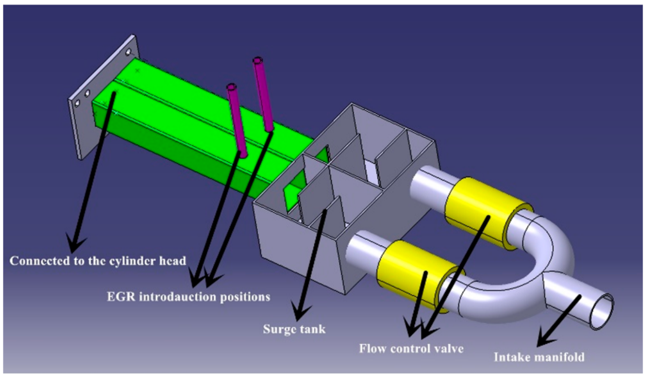

Figure 14. Intake stratification device.

system of the test engine, and the in-cylinder component stratification is realized by introducing O_2 and CO_2 of different flows into different intake port. The three-dimensional model of the intake port is shown in Figure 15. The intake port on the left and the intake port on the right in Figure 15 are defined as a helical intake port and a tangential intake port, respectively. Previous studies have shown that introducing EGR into the helical intake port and O_2 into the tangential intake port can form a preferred in-cylinder charge distribution.[39] So only such an intake stratification configuration is investigated in this study, and the intake gas introduction diagram is shown in Figure 16.

4.2. Measurement and Control System. The schematic diagram of the measurement and control system used in this

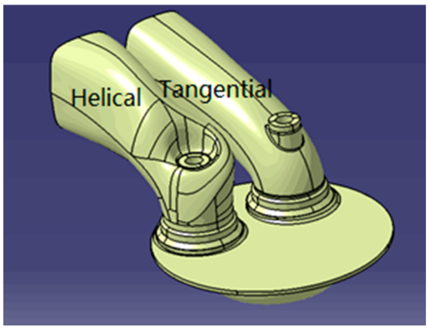

Figure 15. Three-dimensional model of the intake port.

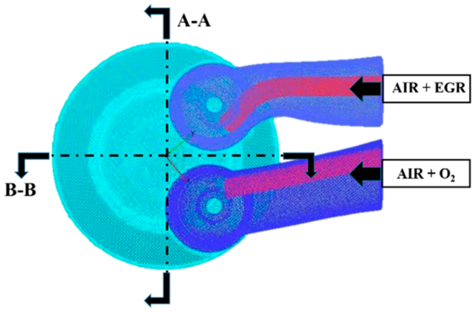

Figure 16. Intake gas introduction diagram.

study is shown in Figure 17, and the detailed specifications of the measurement analyzers are listed in Table 3. It mainly includes a Kaimai CW260 program-controlled eddy current dynamometer, a Japan Ono DF-2420 transient fuel consumption meter, a British Cambustion fast exhaust gas analyzer, and a DMS500 particle size spectrometer. The in-cylinder pressure of the engine has been collected with a Kistler 6052C cylinder pressure sensor. The sampling interval of Kistler 6052C is 0.1 °Crank Angle (CA), and in total, data from 50 cycles have been collected and averaged at each operating point to eliminate the measurement error.

4.3. Test Plan. The experiments are run at an engine speed of 1400 r/min with a common rail pressure of 100 MPa. The engine is fueled with ultralow sulfur diesel (ULSD), and the fuel injection pulse width and the fuel injection timing are adjusted in real time to keep the engine working at the fixed medium load (50% full load), at an indicated mean effective pressure (IMEP) of 8.5 bar. The crank angle of 50% cumulative heat release rate (CA50) is kept constant at 8.5 °CA ATDC. The total intake charge flow (sum of air flow, O_2 flow, and CO_2 flow) is controlled at 440 L/min to study the effect of different intake components on the pollutant emission of diesel engines. By adjusting the proportion of CO_2 in the intake air, different EGR rates including 10%, 15%, 18%, and 20% are achieved for testing. At the four selected EGR rates, the IOC is increased by 1% gradient until 22%. The upper limit of the IOC is 22% to avoid serious deterioration of NO_x emission at a too high O_2 mass fraction. All the tests are repeated three times, and the data used in this paper are the average of the three tests. Among them, the pure air flow is adjusted with the change of the CO_2 and O_2 flow to ensure that the total intake flow is constant. This study also uses the self-developed intake stratification system to test the two intake forms of homogeneous and stratified and explores the effects of intake component stratification on emissions from diesel engines. Homogeneous intake refers to the case where oxygen and EGR are introduced into the intake manifold, and

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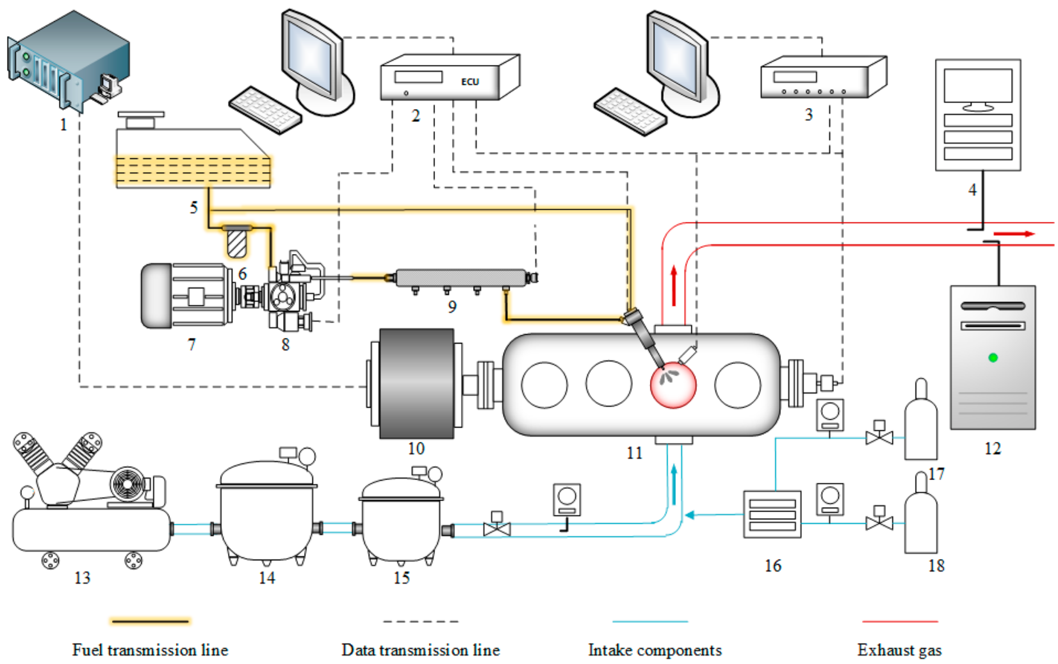

1: dynamo controller; 2: ECU (NI2106); 3: combustion analyzer; 4: CAMBUSTION fast exhaust gas analyzer; 5: fuel tank; 6: filter; 7: fuel pump motor; 8: high pressure fuel pump; 9: high pressure common rail; 10: dynamo meter; 11: test engine; 12: DMS500 particle size spectrometer; 13: air compressor; 14: primary regulator tank; 15: secondary regulator tank; 16: intake components control equipment; 17: high pressure O_2 cylinder; 18: high pressure CO_2 cylinder;

Figure 17. Schematic diagram of the test bench.

Table 3. Accuracies of the Main Measured Parameters

measured parameters	instrument	accuracy
NO_x emission	CLD500	<±1%
HC emission	HFR500	<±1%
CO emission	NDIR500	<±1%
CO_2 emission	NDIR500	<±1%
particle size distribution	DMS500	
in-cylinder pressure	Kistler 6052C	<±1%
transient fuel consumption meter	DF-2420	<±0.5%

the stratification intake refers to the case where EGR is introduced into the helical intake port and O_2 is introduced into the tangential intake port.

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Notes

The authors declare no competing financial interest.

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