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Research Article

A Study on the Combustion Performance of Diesel Engines with O_2 and CO_2 Suction

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Based on the chemical reaction mechanism of fuel combustion, NOx in the diesel emissions is mainly generated from N_2 inside the burning environment of engine cylinder. Taking the gas mixture, O_2 and CO_2, as the intake air, nitrogen-free intake is accessible, and through simulative calculations and experiments, researchers can make a study of the ignition and combustion performances of the engines. Taking a type of "4135ACa" diesel engine as the research object, the study suggested the following: in the environment of O_2 and CO_2, only when the volume fraction of O_2 reaches 45% can the engine be ignited and kept running; engine operation became more steady after its O_2 percentage increased to 50%. There is no NOx emission of engine's nitrogen-free combustion, despite some black particles in the exhaust gas. So, the bottleneck of "NOx-Soot" emission is successfully transformed into how to optimize the combustion performance of engines. Additionally, through simulative calculations, influences of the O_2 volume fraction on the nitrogen-free combustion performance have been researched; results suggested that it can help promote the burning efficiency with the increase of O_2. When it reached 60%, its heat output in the cylinder has been equal to that under the operation condition of air intake. Therefore, nitrogen-free combustion can be used in some NOx control area, especially to some power plant which worked underwater. The huge gas consumption can be recycled from exhaust gas by closed cycle.

1. Introduction

With the daily environment exacerbation and International Maritime Organization's increasingly stringent requirements on the emissions of vessel NOx and Soot, the emission performance of vessel engines has become the research focus both at home and abroad [1–3]. Currently, the performance is optimized mainly through after-engine, in-engine, and before-engine purification technologies. After-engine purification mainly includes lean NOx trap (LNT) and selective catalytic reduction (SCR); the core part of in-engine and before-engine purification is to take advantage of the optimization of the combustion process to control the generation of cylinder emissions like oxygen-enriched combustion, exhaust gas recirculation (EGR), optimization of fuel oil system, new burning technology, and so forth [4–10].

At present, the after-engine treatment technology of diesel engines is still in such an immature state that it is difficult to put into popular application [4, 5]. In-engine optimization technology, based on the air or oxygen-enriched condition, can improve the efficiency of combustion and lower down the emissions of carbides, but the increase of in-cylinder temperature will be favorable for the generation of NOx [6, 7]; EGR or air inlet humidification or any other measures will be in favor of the decrease of NOx emissions; however, this is at the cost of the economy of diesel engines [8, 9]. Even the most advanced in-engine purification technology cannot shake off the shackles of emission bottleneck curve of the "NOx-Soot" [10]. Based on the kinetic mechanism of combustion reaction, the generation of in-cylinder NOx is mainly decided by the following three aspects: in-cylinder temperature, concentration of reactants, and the length of high temperature duration of the reaction process [11, 12]. As long as there is nitrogen, it is inevitable that NOx will be generated. N_2-free inlet can effectively avoid the existence of N_2 in the burning environment; thus the emission of NOx is near to zero.

Table 1: Specifications of the 4135ACa engine.

Engine	Main parameters
Engine type	Inline 4-cylinder 4-stroke water-cooled
Bore and stroke	135 mm/150 mm
Capacity	8.58 L
Compression ratio	17
Rated power	66.2 kW/1500 rpm
Injection timing	18° before TDC
Inlet valve open/close timing	20° before TDC/48° after BDC
Outlet valve open/close timing	48° before BDC/20° after TDC
Shape of combustion chamber	ω shape
Intake air type	Naturally aspirated

Separating N_2 from air, which is necessary for nitrogen-free combustion, and mixing a proportion of non-N_2 gases into pure oxygen can prevent fuel oil from overdramatic combustion in high-density oxygen. The realization and optimization of the combustion itself are the key point in achieving nitrogen-free combustion. With the comprehensive consideration of diesel engine's running characteristics, the focus of the research is the feasibility and pertinent optimization measures in the environment of O_2 and CO_2. Many relevant studies on the combustion technologies have been made in such environment at home and abroad, but particular emphasis has been laid on how to realize the application of it to coal stoves which can improve the burning efficiency of many kinds of combustibles like pulverized coal and can reduce the emissions of many pollutants like NO*x* and dust [13–15]. The research object in [16, 17] is the type of "ZS195" one-cylinder diesel engine, and a steady running of single-cylinder engine can be made to come true in the environment of O_2 and CO_2. Based on the above study, a further simulative and experimental study on the combustion performance of vessel engines in the environment of O_2 and CO_2 has been made with such a research object as the type of "4135ACa" diesel engine.

2. Numerical Simulations of Diesel Engines in the Environment of O_2 and CO_2

2.1. Main Parameters of Diesel Engines. The research object is the engine of "4135ACa," which is a brand of *Dongfeng*, and its main technical parameters are shown in Table 1.

2.2. Establishment of Simulation Models. Researchers have set the structural parameters of the combustion chamber of 4135ACa engine and parameters of its operation condition in the FIRE ESE Diesel module of AVL-FIRE software, and the process of numerical simulation starts from the closure of intake valve and ends at the opening of exhaust valve. Its 3D grid model of the combustion chamber is shown in Figure 1. In the light of the particular traits of this burning process,

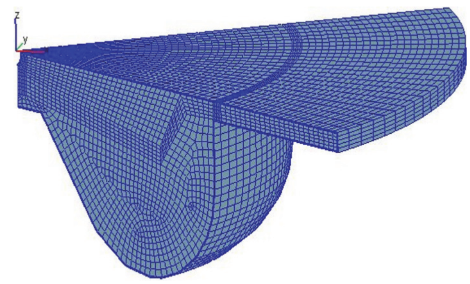

Figure 1: 3D grid model of the combustor of the 4135ACa engine.

it is necessary to couple its general gas phase reactions and the burning mechanism of external chemical reactions together to make calculation. Currently, there are not so many studies aiming at the burning reaction mechanism in the environment of O_2 and CO_2 that this model has adopted the simplified n-heptane burning reaction mechanism developed by Ra and Reitz [18]. Additional manipulation includes selecting general mode in the material transport module *Species Transport*, setting up the varieties of materials that may occur in the chamber, initializing the proportion of all kinds of intake gases, and using AVL-FIRE software to make simulative calculations on the in-cylinder pressure, temperature field distribution, and overall performance in order to make sure of the proportion of O_2/CO_2 needed for the engine's nitrogen-free combustion and to provide instructional opinion for the study of test-bed during the later stage.

2.3. Analyses of Simulation Results. Aiming at the 4135ACa engine's thermal parameters operating at the loading conditions of 800 rpm and 70 Nm, it is attainable to match calculating values (cylinder pressure curve and heat release rate curve) and experiment values through adjusting the burning module of simulation models. Figure 2 shows that the 3D combustion model is feasible and can be used to make relevant simulative calculating studies on the engines' combustion performance.

At the premise of invariant quantity of fuel injection, Figures 3–6 are, respectively, under the conditions of normal air intake as well as the environment of O_2 and CO_2, simulation calculation results of 4135ACa engine's in-cylinder average pressure, in-cylinder temperature, heat release rate, and the total heat release changing with the variation of crank angles. As can be seen from the figure, when the mole percentage of O_2 is 40%, indicator diagram curve is almost consistent with compression curve, and heat release curve shows that the fuel oil is not burnt to release heat, which indicates that the engine cannot be ignited normally under such intake condition. Though 40% O_2 intake has far exceeded that in the air which is only 21%, the compression pressure and temperature are lower than the normal intake running condition in the case of absorbing the same amount of external work during the compression process since the specific heat capacity of CO_2 is greater than nitrogen, so the ignition requirements cannot be achieved to make it burn normally under such intake condition.

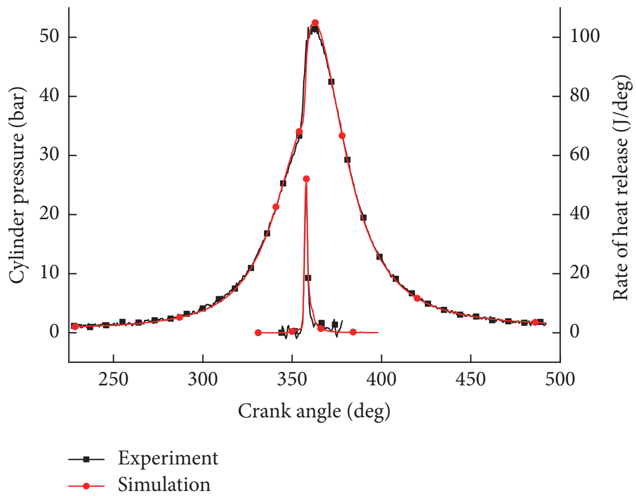

Figure 2: The adaptation verification for the 3D simulation models of the 4135ACa engine.

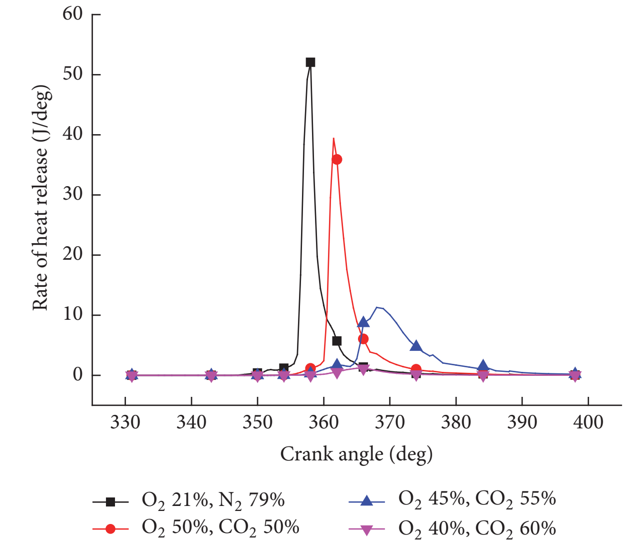

Figure 4: Curve of heat release rate under different O_2 volume fraction.

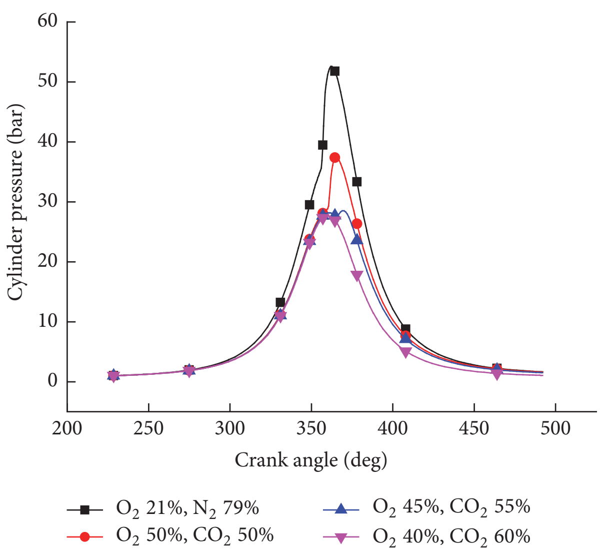

Figure 3: Curve of pressure under different O_2 volume fraction.

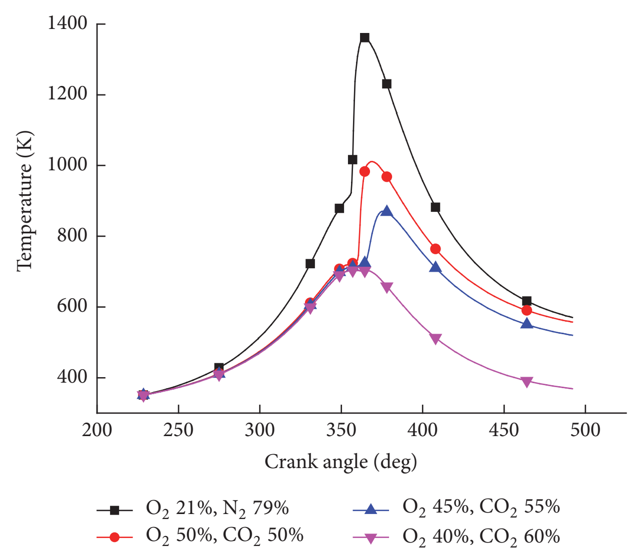

Figure 5: Curve of temperature under different O_2 volume fraction.

When O_2 density is increased to 45%, its compression pressure and temperature are basically consistent with the condition of 40% O_2, but the heat release curve shows that there appears combustion heat release caused by ignition, an obvious rising process of pressure and temperature curves and the pressure curve movement of expansion stroke towards upper right direction. The result suggested that the increase of O_2 density can effectively promote the ignition performance of engines, but the little heat release of fuel oil was mainly caused by large amount of CO_2 in the chamber that has seriously influenced the burning process. There are three reasons: firstly, the large specific heat capacity of CO_2 is not favorable for flame spread because the same heat release of it brings less temperature increase; secondly, other performances of CO_2 like heat radiation and coefficient of thermal conductivity and so on are not favorable for flame spread; finally, as a combustion product, CO_2 has a suppression effect on fuel combustion to a certain extent.

According to the heat release curve, when the O_2 density is increased to 50%, the ignition burning point will be brought ahead and the total heat release will increase substantially. In the environment of O_2 and CO_2, the increase of O_2 density will be favorable for decreasing ignition delay period, speeding up flame spread, and improving burning efficiency, while the participation of CO_2 will delay the ignition, impede the spread of flame, decrease the temperature, and cut down the duration of combustion. When the volume percentage of CO_2 is increased to 60% or so, ignition and combustion will not occur. Above all, the 3D simulation calculation demonstrates that the engine can be ignited and burn normally in the environment of O_2 and CO_2 with over 45% of O_2.

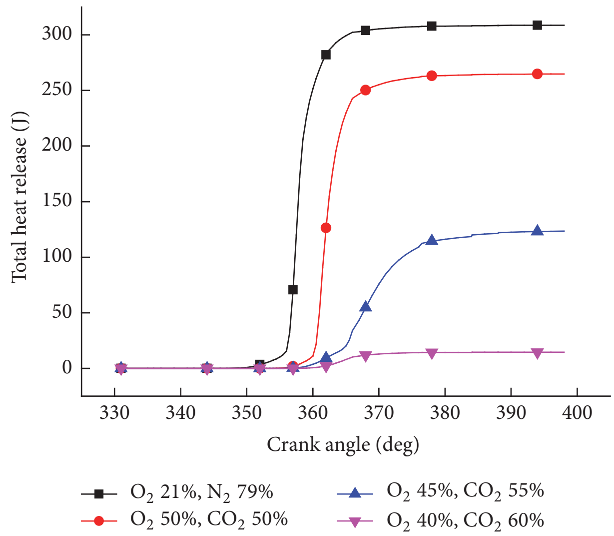

Figure 6: Curve of total heat release under different O_2 volume fraction.

3. An Experimental Study on Diesel Engines with O_2 and CO_2

3.1. Test-Bed. Figure 7 shows a tentative running test of 4135ACa engine with O_2 and CO_2 suction and hydraulic dynamometer bench. The gases in the test come from the following steps: firstly, liquid oxygen and liquid carbon dioxide are vaporized by the vaporizer, and, secondly, the proportion of each is distributed by servo gas mixer. The mixer can make online analyses on the density of O_2 and CO_2 of the mixture gas and automatically adjust the opening degree of the valve to adjust the density according to the gas consumption. In order to ensure that the test is comparable, an automatic constant-pressure valve is installed onto the intake airline between the mixer and the engine to ensure that intake pressure is in consistency with that under normal inlet running condition. The professional exhaust gas analyzer *Testo 350* is used to monitor the emissions of the engine. The cylinder pressure is collected by the sensor *Kistler 6613CG1* for the heat analyses of combustion analyzer. Also, thermal parameters of the engine are monitored and collected online for burning analyses.

3.2. Experimental Methods. High O_2 density will result in wildly dramatic combustion, thus giving rise to detonation. High CO_2 density may result in the failure of ignition and the sudden halt of diesel oil which are all extremely detrimental to the engine's safe operation. Therefore, in view of this tentative stage of combustion experiment and the above simulation calculation results, the following steps have been adopted: firstly, the engine is adjusted to the state of idle running in a natural intake manner; secondly, pure oxygen is added to the intake line in front of the mixer to increase the O_2 content of the mixture gas to 50% or so; thirdly, the airline valve is gradually closed while increasing the CO_2 content of the mixture gas so that the condition is steadily transferred into a 50% O_2 and 50% CO_2 nitrogen-free intake; finally, researchers have gradually decreased the proportion of O_2 and increased the CO_2 content to study the limit intake running condition to maintain the idling running of the engine's nitrogen-free combustion.

3.3. Analyses of Experiment Results. Based on the above test-bench and operational methods, the next step is to gradually reduce O_2 density if the inlet condition of 50% O_2 and 50% CO_2 has been successfully attained. The engine can still keep running with 45% O_2, but it will stop running after reducing to 40%. The cylinder pressure curve is shown in Figure 8 at the condition of normal inlet of 50% O_2 and 50% CO_2 or of 45% O_2 and 55% CO_2, which is basically in consistency with simulative calculation results. With the participation of CO_2, the triatomic gas, the physical property difference of it directly gives rise to the downward shift of pressure curve during the compression stage and the slackness of combustion, thus leading to the imperfectness and the decreasing efficiency of combustion with obvious carbon black material contained in the smoke. The existence of carbon black material would be extremely easy to block the analyzer, so the analyses on the emission components were not made. As is known from the combustion theories, no matter what the in-cylinder burning temperature is, the nitrogen-free combustion will absolutely reduce the emission of NO*x* to the greatest extent, and the only thing needed to do is to improve the combustion in the environment of O_2 and CO_2 and reduce carbide emissions. The successful nitrogen-free combustion has transformed the bottleneck of "NO*x*-Soot" emission into how to optimize the combustion performance of engines.

4. Optimization of the Engines' Combustion Performance under O_2 and CO_2

The realization of nitrogen-free combustion relies on the recycling of large amount of O_2 and CO_2 in the smoke to reduce operation cost. Based on the above studies, this paper has focused on studying the feasibility of optimizing the combustion performance by increasing O_2 density. Based on the former 3D burning model, simulation calculation has been made to study the burning performance of the engine with the O_2 density of the nitrogen-free inlet constantly changed.

As can be seen from the in-cylinder temperature distribution chart of the top dead center (Figure 9), when O_2 density is less than 50%, the high temperature mainly appears at the peripheral area, and, also, the highest temperature is under 800 K. While temperature distribution regularities are in consistency with those under the running condition of air intake with O_2 density surpassing 60%, high temperature zone is relatively small. The highest temperature value will increase along with the growth of O_2 density, and when it has reached 80%, the highest in-cylinder temperature is 3636 K, which is the highest temperature value under the air running condition. Also, it can be seen from Figure 10 that the final in-cylinder total heat release will reach the experiment value when O_2 density is 60%. With the growth of O_2 density, the ignition point will be brought ahead, and the final total heat release will increase. Furthermore, the burning of fuel oil is more perfect compared with the operation condition

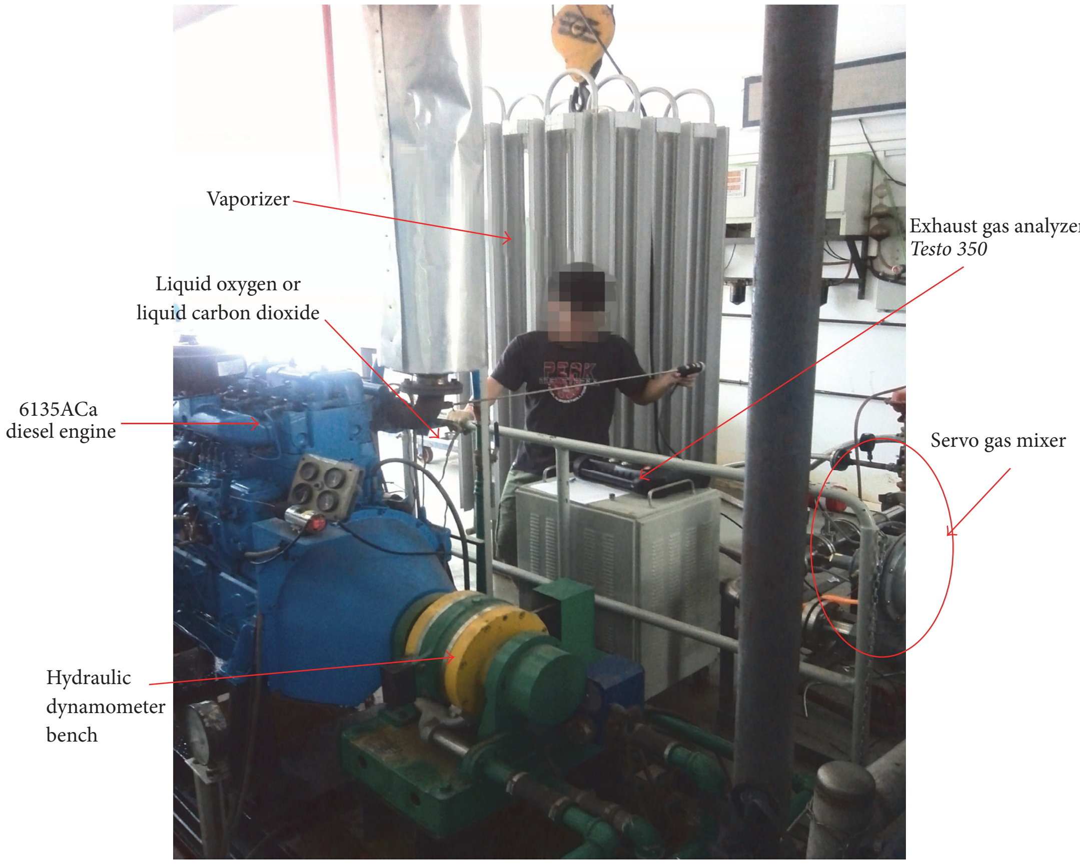

Figure 7: Test plant of the 4135ACa engine.

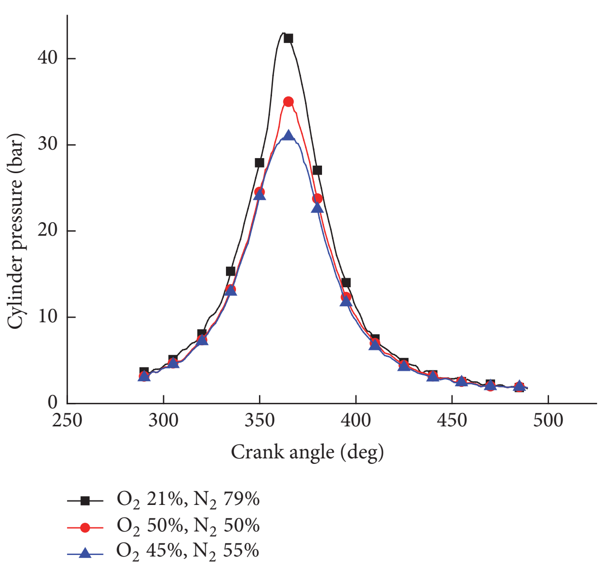

Figure 8: Cylinder pressure of diesel engine tests in the environment of O_2 and CO_2.

of air intake. With the growth of O_2 density, the cylinder pressure curve will gradually approximate to that of the air intake running condition (Figure 11), but that cannot be identical with the latter one mainly because of the different thermophysical properties of O_2, N_2, and CO_2.

The above simulative calculation study has shown that the burning efficiency of the engine in the environment of O_2 and CO_2 can be boosted through increasing O_2 density. The above information is only the simulative calculation result. Owning to the large consumption of gases and the inadequate preparation of O_2/CO_2 during the experiment process, the study aiming at the optimization of the engine's combustion performances affected by O_2 density was not carried out in the environment of O_2 and CO_2. Additional experiments will follow and at the same time other engine parameters will be changed to optimize its combustion performance.

5. Conclusions

We conclude the following:

(1) According to the experiments and simulation results, in the environment of O_2 and CO_2, when the density of O_2 reaches 45%, the engine can keep idle running, and when the density is increased to 50%, the operation becomes more steady; when the lowest emission of NO*x* is realized, there will be obvious black particles in the exhaust gas; the engine can run steadily in the environment of O_2 and CO_2, and the bottleneck of "NO*x*-Soot" emissions is successfully

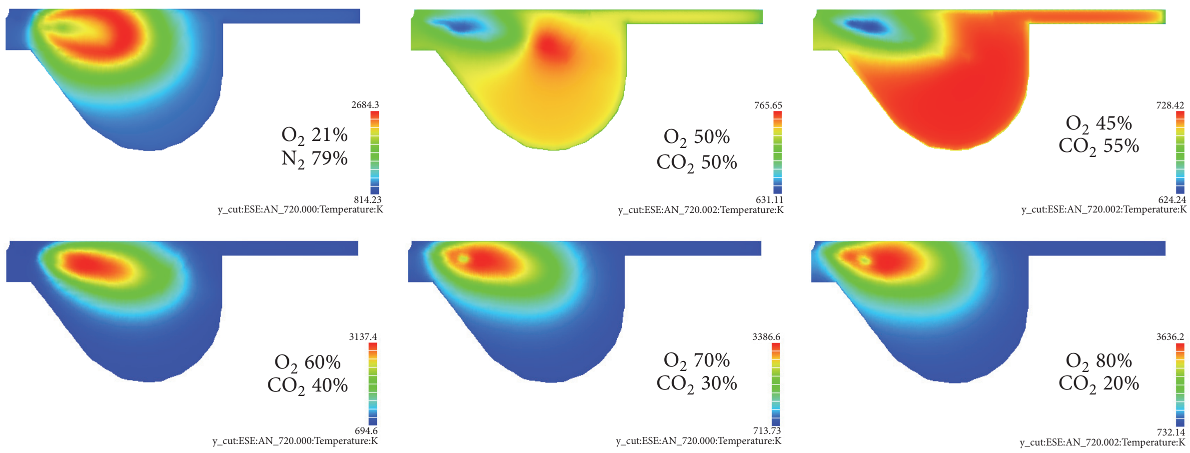

Figure 9: Temperature distribution of the engine's cylinder at top dead center positions in the environment of different high O_2 volume fraction.

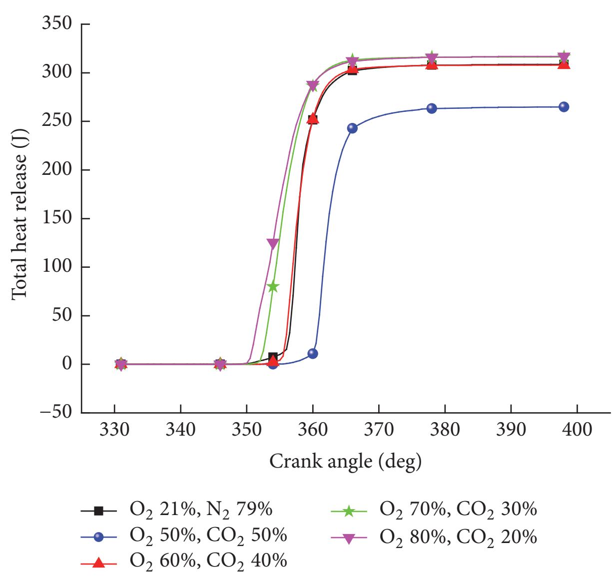

Figure 10: Heat release in the environment of different high O_2 volume fraction.

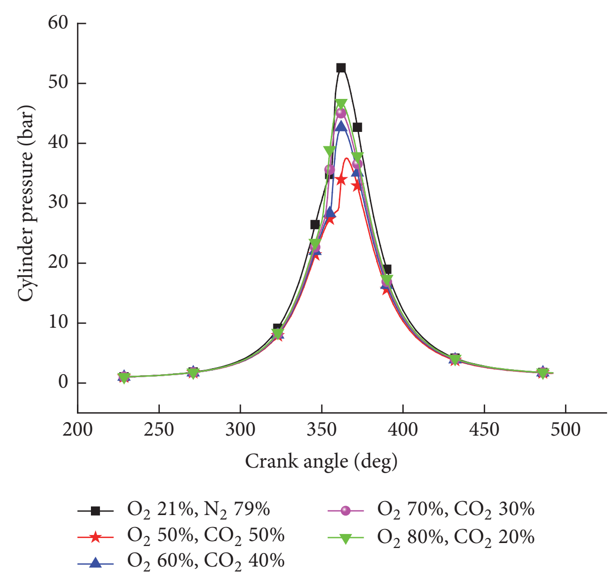

Figure 11: Cylinder pressure in the environment of different high O_2 volume fraction.

transformed into how to optimize the combustion performance of engines.

(2) According to the experiments and simulation results, the heat release with the operation condition of 50% O_2 has distinct advantages over that of 45% of O_2 in the environment of O_2 and CO_2, and the increase of O_2 density will be favorable for the optimization of combustion performance; when O_2 density is lower than 50%, the cylinder high temperature is relatively distributed around, and the highest temperature is lower than 800 K; when O_2 density is higher than 60%, the high temperature area is the center of the cylinder and the temperature distribution regularities are basically the same as those of the air operation condition, and the mere difference is a rather small range of high temperature.

(3) According to the simulation calculation results, when O_2 density is increased to 60%, the total combustion heat release reaches a level the same as that under the air operation condition in the environment of O_2 and CO_2, but the pressure and the temperature are still a bit low; when they are increased to 70% or 80%, there is not much difference in terms of total combustion heat release, but there is a little increase compared with the air operation condition; under the situation of little difference of total heat release, the temperature of top dead center with the running condition of 80% O_2 is apparently higher than the condition of 70% O_2 and is the same as that under the air operation condition.

Competing Interests

The authors declare that there are no competing interests in this paper.

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