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Research Article

EFFECT OF INJECTION PRESSURE ON THE PERFORMANCE OF A MARINE DIESEL ENGINE BLENDED WITH LOW-CARBON BIODIESEL

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Article Highlights

Efficient combustion organization;
Soot emissions have been significantly reduced;
Improves the turbulence intensity and flow rate.

ABSTRACT

In order to deeply study the performance of biodiesel blending in marine diesel engines, the effects of different fuel injection pressures on the oil-gas mixing, combustion and emission of the fuel blended with a small percentage of biodiesel were investigated using the CONVERGE simulation software. Based on the simulation software CONVERGE, the three-dimensional model of the combustion chamber of the test marine diesel engine was established, the RNG k-ε model and the correct biodiesel chemical reaction mechanism were selected, and the simulation results were compared with the test results to ensure the accuracy of the simulation results. The results show that: the increase of fuel injection pressure can enhance the average turbulence intensity in the cylinder as well as increase the relative flow rate between oil and gas, and also promote the flame propagation, thus increasing the maximum burst pressure and the average temperature in the cylinder; in terms of the emission, the generation of carbon soot is suppressed with the increase of injection pressure, but the emission of nitrogen oxides is deteriorated.

1. INTRODUCTION

In recent decades, in order to meet the increasingly stringent emission regulations, scholars in the shipping industry have conducted a series of studies, in which the diversification of ship-powered fuels has been developing rapidly, and the main research on alternative fuels include hydrogen, ammonia, LNG, methanol, biomass fuels and other alternative fuels (Paulauskiene, T *et al*., 2019). Biodiesel refers to the fatty acid methyl ester or ethyl ester formed by the processing of vegetable oils, animal oils, waste fats and oils or microbial fats and oils (Shahir, S.A *et al*., 2015). Biodiesel is a typical "green energy", with good environmental performance, good engine starting performance, wide source of raw materials, renewable and other characteristics (Chaudhari, V.D *et al*., 2021). In addition, the high oxygen content and high cetane number of biodiesel can effectively reduce the emission of sulfur oxides (SOx), hydrocarbons (THC), carbon fumes (soot) and other harmful gases (Mohd Noor, C.W *et al*., 2018), but due to the density and viscosity of biodiesel, it is prone to poor atomization and poor combustion, which results in a decline in the economic performance and emission performance of power machinery (Rahman, M.M *et al*., 2014).

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Meanwhile, scholars at home and abroad are gradually deepening their research on biodiesel. H. An et al (An, H *et al*., 2014) simulation study of pure biodiesel and ethanol blends with different proportions of ethanol was carried out using KIVA-CHEMKIN coupled code. It was found that as the percentage of ethanol was increased, the ignition delay time was lengthened, the peak cylinder burst pressure was decreased, CO emissions increased, carbon smoke emissions decreased under some load conditions, and NOx emissions decreased under all load conditions. Ambarish Datta et al (Datta, A. and Mandal, B.K, 2017) utilized the simulation software, Diesel-RK, to investigate the combustion and emission characteristics of biodiesel under 75% of operating conditions by using a single-cylinder, 4-stroke, naturally aspirated, direct-injection diesel engine as a simulation model to investigate the effects of palm stearin and ethanol addition in the preparation of biodiesel. The effect of ethanol addition in the preparation of biodiesel shows slightly higher brake specific fuel consumption and brake thermal efficiency as well as suppression of NOx emission as compared to pure biodiesel. Wenliang Qi et al (Qi, W *et al*., 2018) used a mixing and fragmentation model to consider the effect of turbulence within the nozzle to simulate the fuel combustion process using the backbone mechanism of diesel alternative fuel and biodiesel alternative fuel, which showed that due to the difference in the surface tension of the two oils, there is a significant difference in the size of the spray droplets.

Although there are more and more researches on biodiesel, there are fewer contents in the previous researches to explore the fuel injection pressure for biodiesel combustion in marine diesel engine. In this paper, for the biodiesel viscosity, density and flash point and other physicochemical properties of the large fuel atomization and evaporation performance degradation of the problem, select the propulsion characteristics of 75% of the rated load conditions, through the three-dimensional simulation of the CONVERGE software simulation analysis method, to explore different fuel injection pressure on the diesel combustion of biodiesel in the oil and gas mixing, combustion characteristics and emissions of the impact of the marine diesel combustion of biodiesel to provide theoretical references for the study. It provides theoretical reference for the research of biodiesel combustion in marine diesel engine.

2 BASIC PARAMETERS OF THE COMPUTATIONAL MODEL AND VALIDATION

In this paper, an inline six-cylinder inland marine diesel engine is modeled and simulated under 75% load condition by CONVERGE software to investigate the effects of different fuel injection pressures on the oil-gas mixing, combustion and emission of the fuel blended with a small percentage of biodiesel. The specific parameters of the diesel engine are shown in Table 1 below.

Table 1 Main engine parameters

parameters	Number
Model	6135G128Zca
Number of cylinders	6
Bore/stroke	135mm/150mm
displacement	12.88L
compression ratio	16.5
Rated power	184kW
Rated RPM	1500r/min
Rated torque	1000Nm
Number of holes × diameter	5×0.32mm
Spray opening pressure/ spray angle	24MPa/150^o

Through the measurement to get the real size of the diesel engine, and then the establishment of the combustion chamber model, due to the diesel engine's injector nozzle uniformly distributed in the combustion chamber axis, and the test diesel engine's injector consists of five injector nozzles, in order to simplify the calculation model and improve the calculation accuracy, this paper selected 1/5 combustion chamber as a Computational Fluid Dynamics (CFD) simulation model. The 3D model located in the piston bottom dead center (BDC) is shown in Fig 1.

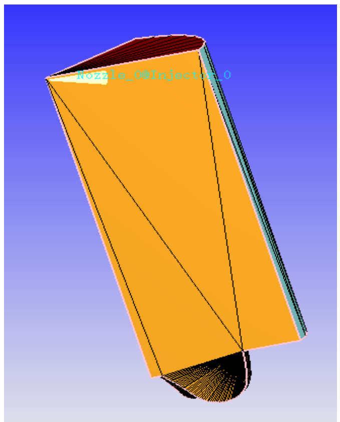

Figure 1 3D Engine model at BDC

The simulation calculates the starting and closing moments as the inlet valve closing moment (-130^o BTDC, before the top dead center) and the exhaust valve opening moment (130^o ATDC, after the top dead center), respectively. The experimental results yielded an initial pressure of 0.11 MPa in the cylinder, an initial temperature of 330 K in the cylinder, and the temperatures of the bottom of the cylinder head, the top of the piston and the cylinder wall were set to be 575K, 550K, and 475K, respectively. Initial conditions in the simulation included the turbulence kinetic energy (TKE), the turbulence dimension length (TLS) in the cylinder, and the cyclic oil injection volume of the combustion chamber model for a single time, which were calculated by the formulas of Eq. (1), Eq. (2), Eq. (3), Eq. (4), Eq. (5), and Eq. (6) shown.

In this test, B10 biodiesel was selected as the fuel, which was modulated by diesel and pure biodiesel at a volume ratio of 9:1, and it was calculated that the diesel engine injected 1.2×10-5kg per working cycle under 75% load condition in the simulation model, and in this paper, the mechanism consisting of 233 reactions and 75 components was selected as the simplified chemical reaction mechanism of diesel/biodiesel (Chang, Y *et al*., 2015), n-heptane was used instead of diesel fuel, and n-decane, methyl decanoate, and methyl 5-decenoate were used as components instead of biodiesel fuel, in which the percentage of each component was 0.9, 0.0351, 0.0032, and 0.0617, respectively, and the various types of models used in the simulation are shown in Table 2.

Table 2 Sub-models in the simulations

Model	Name
turbulence model	RNG k-ε
Combustion model	SAGE
Spray Evaporation Model	Frossling
Oil droplet collision model	NTC collision
Oil droplets hitting the wall model	Wall film
Spray Crush Model	KH-RT
NOx emission modeling	Extended Zeldovich
Soot emission model	Hiroyasu-NSC

Set the base mesh size of the model to 4 mm, set 3 levels of mesh encryption during the injector injection time period, and use adaptive 1 level of mesh encryption based on temperature and velocity.

$$TKE = (3/2) \times u^2 \quad (1)$$

$$u = 0.5 \times C_m \quad (2)$$

$$C_m = 2 \times h \times (n/\theta) \quad (3)$$

Where, u is the turbulent pulsation velocity, m/s; n is the engine speed for the test, m/s; Cm is the average piston speed, m/s; h is the cylinder stroke, m.

The turbulence dimension length is 1/2 of the maximum valve lift of the diesel engine, calculated as follows:

$$TLS = \frac{h_v}{2} \quad (4)$$

Where, hv is the maximum valve lift of the test diesel engine, m.

The formula for calculating the single cycle injection volume required by the simulated combustion chamber is as follows:

$$G_f = g_e \times N_e \quad (5)$$

$$g_f = \frac{G_f}{3600 \times i \times \left(\frac{n}{\theta}\right) \times \delta} \quad (6)$$

Where Gf is the hourly fuel consumption of the test engine, g; ge is the effective fuel consumption rate of the test engine, g/kW; Ne is the power of the test engine, kW; gf is the single-cylinder cyclic injection volume of the test engine, g; n is the rotational speed of the test engine, m/s; i is the number of cylinders of the test engine; and δ is the number of the stroke of the test engine.

Fig.2 show the comparison of the pressure experiment simulation of burning B10 biodiesel under 75% load condition, respectively. The experimental data come from the experimental results of the group's previous blending of B10 biodiesel, and it can be seen from the figure that the overall agreement of the pressure curves is better, and the error of the peak cylinder pressure is within 5%, so that we can use this calibrated model to carry out the related research of combustion and emission.

3 SIMULATION EXPERIMENT PROGRAM

The injection pattern of marine diesel engine is closely related to the thermal efficiency and emission characteristics of biodiesel. In order to investigate the effect of injection pressure on the combustion of B10 biodiesel in diesel engine in terms of oil-gas mixing, emission and combustion, the rated injection opening pressure of diesel engine 24MPa is taken as the basis and the injection opening pressure is increased to 28MPa and 32MPa under the condition of ensuring the injection volume, injection advance angle and the initial conditions of the simulation remain unchanged, and the duration of fuel injection is slightly shortened with the increase of the injection pressure, the specific simulation experiment program is shown in Table 3.

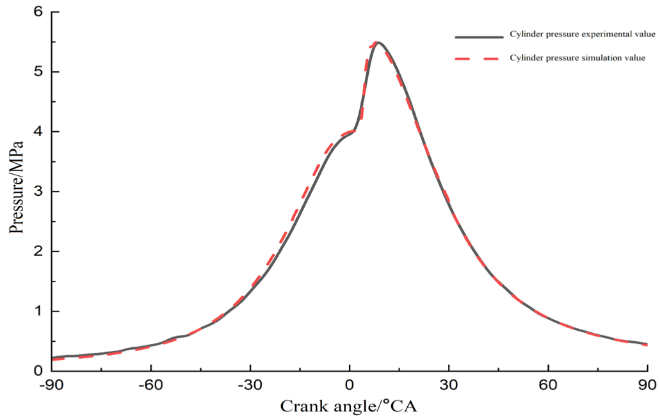

Figure 2 Comparison of experimental and simulated B10 biodiesel in-cylinder pressure at 75% load condition

Table 3 Simulation scheme settings

working condition	oils	Injection pressure/ MPa	Spray end angle /ATDC
75%load(1365r/min 、121.5kW)	B10	24	4.5
	B10	28	3.8
	B10	32	3.2

4 RESULTS AND ANALYSIS

4.1 Effect of Fuel Injection Pressure on Oil-Air Mixing

The size of the average turbulent kinetic energy in the cylinder plays a key role in the oil-gas mixing, and Fig.3 shows the variation of the average turbulent kinetic energy in the cylinder of B10 biodiesel under three different fuel injection pressures of 24MPa, 28MPa, and 32MPa.

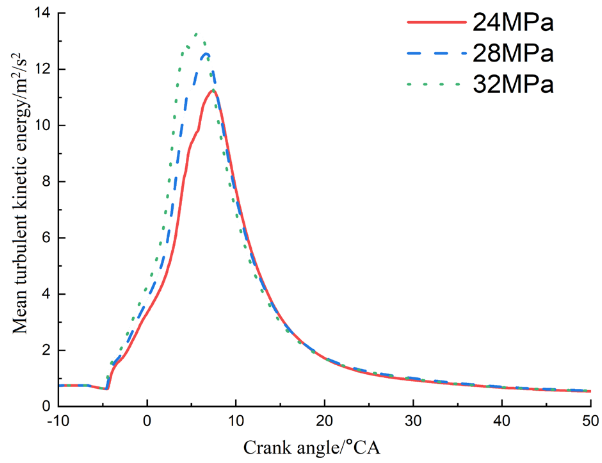

Figure 3 Effect of different fuel injection pressures on the mean turbulent kinetic energy in the cylinder

From Fig.3, it can be seen that the in-cylinder turbulent kinetic energy increases with the increase of fuel injection pressure, and the peak values of the average in-cylinder turbulent kinetic energy under three different fuel injection pressures are 11.02 m^2/s^2, 12.48 m^2/s^2, and 13.28 m^2/s^2, respectively, which is mainly due to the increase in injection pressure resulting in the increase of the injection velocity into the combustion chamber, which will lead to better fuel atomization and combustion which promotes the further development of in-cylinder turbulence and makes the internal disturbances become strong. Moreover, with the increase of injection pressure, the crankshaft angle corresponding to the peak of the average turbulent kinetic energy in the cylinder is advanced, corresponding to 7.6°, 6.8°, and 5.7° after the top stop, respectively, which is caused by the shortening of the fuel injection duration due to the increase of injection pressure, which contributes to the rapid mixing of oil and gas and improves the combustion quality.

Fig.4 shows the distribution of in-cylinder flow rate at the moment of combustion top stop at three different fuel injection pressures of 24MPa, 28MPa and 32MPa.

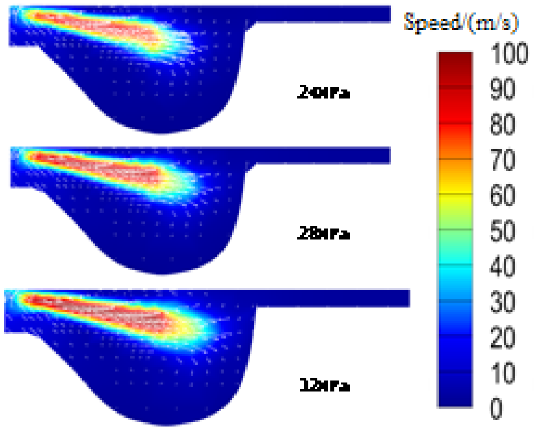

Figure 4 In-cylinder flow rate distributions at different fuel injection pressures

From Fig.4, it can be seen that with the increase of fuel injection pressure, the spray penetration distance of the fuel becomes longer, and the area of the high-flow velocity region in the combustion chamber expands, which will lead to an increase in the relative velocity of gas-liquid motion and enhance the gas perturbation, which is conducive to the reduction of the droplet particle size, and to promote the atomization of the sprayed oil bundles, as well as the oil-gas mixing (Wang, G *et al.*, 2022).

4.2 Effect of fuel injection pressure on combustion characteristics

Table 4 shows the effect of three different fuel injection pressures on the exothermic rate of the fuel combustion process, CA10, CA50 and CA90 represent the number of crankshaft rotation angles at which the percentage of exothermic heat of combustion of B10 biodiesel to the total exothermic heat reaches 10%, 50%, and 90%, respectively, for one operating cycle. Figure 3-3 shows the variation of in-cylinder pressure under three different fuel injection pressures.

Table 4 Effect of different fuel injection pressures on cumulative heat release rate

injection pressure/MPa	CA10/°ATDC	CA50/°ATDC	CA90/°ATDC
24	3.75	11.08	48.93
28	3.45	10.34	46.09
32	3.24	8.80	42.24

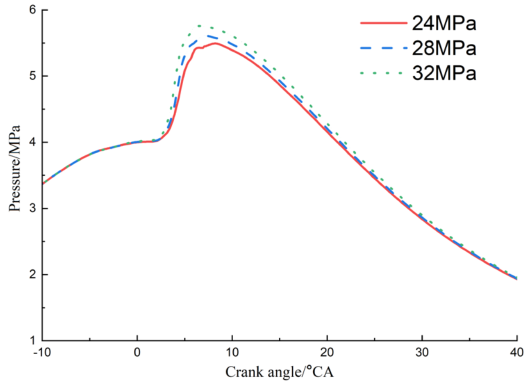

Figure 5 Effect of different fuel injection pressures on in-cylinder pressure

From Table 4, it can be concluded that the crankshaft angle angles corresponding to CA10, CA50 and CA90 are advanced with the increase of injection pressure, and compared with the CA10, CA50 and CA90 values at an injection pressure of 24 MPa, the CA10 value at an injection pressure of 28 MPa and 32 MPa decreases by 0.3° and 0.51°, the CA50 value decreases by 0.74° and 2.28 °, and CA90 values decrease by 2.84°, 6.69°. With the increase of injection pressure, the stagnation period of fuel is shortened accordingly, and at the same time, the time for fuel combustion to do work is also shortened, which leads to the full combustion of fuel. Higher injection pressure plays a certain role in fuel mixing, evaporation and atomization, and improves the fuel combustion rate; in addition, it also leads to an increase in the amount of fuel injected to the point where the combustion process is advanced. As can be seen from Fig.5, the effect of different fuel injection pressure on the maximum burst pressure in the cylinder and the angle corresponding to the maximum burst pressure is basically the same as the effect on the exothermic rate, indicating that increasing the injection pressure is conducive to improving the thermal efficiency of the diesel engine to enhance the power performance (Wang, G *et al.*, 2022), but at the same time also improves the possibility of rough combustion, in order to maintain the stability of the operation of the diesel engine to keep the fuel injection pressure in a reasonable zone.

Fig.6 shows the effect of three different fuel injection pressures of 24MPa, 28MPa and 32MPa on the average in-cylinder combustion temperature of B10 biodiesel. From Fig.6, it can be seen that with the increase of injection pressure, the peak of the average in-cylinder temperature increases, and the maximum average in-cylinder temperatures under three different fuel injection pressures are 1365K, 1372K, and 1399K, respectively, and the higher the temperature, the more fuel exothermic in the combustion stop position, and the high temperature is conducive to improving the diffusion of spray oil droplet particles and the mixing of oil and gas, which makes the combustion of fuel The higher the temperature, the more exothermic the fuel at the combustion upper stop position.

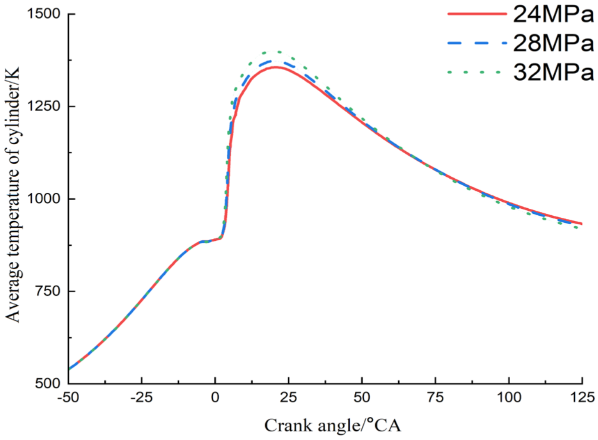

Figure 6 Effect of different fuel injection pressures on average in-cylinder temperature

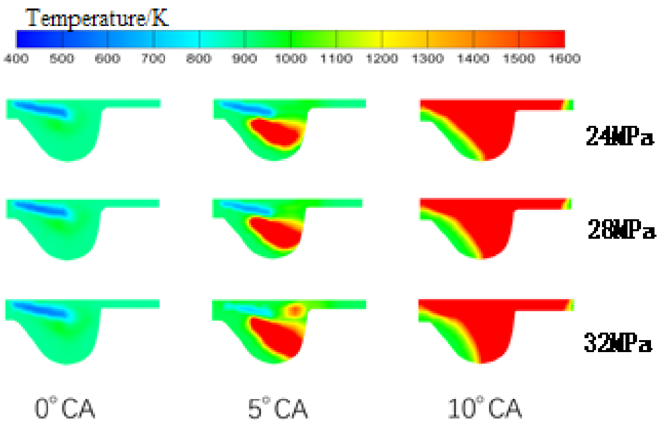

Figure 7 In-cylinder Temperature Distribution under Different Fuel Injection Pressures

Fig.7 shows the temperature distribution of the combustion chamber at the time of the combustion stop and 5° and 10° after the combustion stop. As can be seen from Fig.7, at the moment of combustion stopping point, the fuel is still in the stage of fuel injection and oil-gas mixing; at the moment of 5° after the combustion stopping point, with the increase of fuel injection pressure, the area of high temperature area in the combustion chamber gradually increases, and at this time the turbulence energy in the cylinder becomes larger, and the distance of spray penetration becomes longer, which accelerates the speed of oil-gas mixing, improves the quality of mixing, and facilitates combustion as well as the propagation of flame; at the moment of 10° after the combustion stopping point, at this time, the injection stage is already over 10° after the combustion stop, the oil spraying stage has ended, and the flame propagates toward the pit of the combustion chamber and the squeezing area (Zhao, W *et al.*, 2019).

4.3 Effect of Fuel Injection Pressure on Emission Characteristics

There are many pollutants generated in the combustion process of marine diesel engines, and this paper selects two pollutants, carbon soot and nitrogen oxides (NOx), to focus on. Fig.8 and Fig.9 reflect the generation of NOx and soot in the cylinder under different fuel injection pressures, respectively.

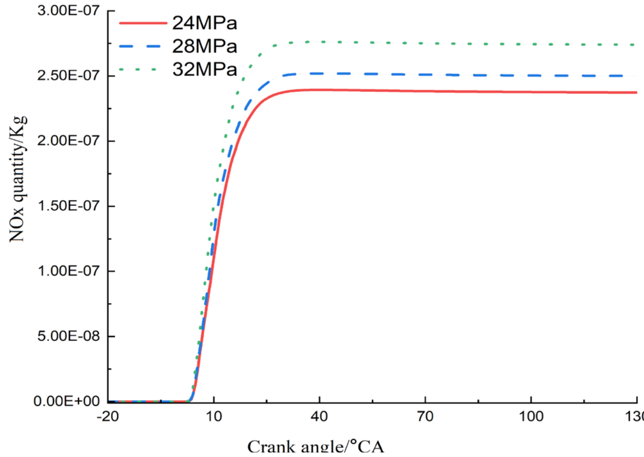

Figure 8 Effect of different fuel injection pressures on in-cylinder NOx generation

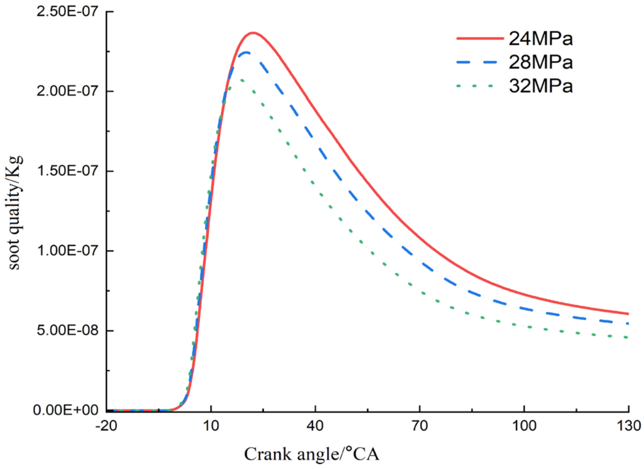

Figure 9 Effect of different fuel injection pressures on soot generation

As can be seen from Fig.8, the NOx generation per working cycle at injection pressures of 24MPa, 28MPa, and 32MPa is 0.237mg, 0.25mg, and 0.274mg, respectively. The conditions on which NOx depends are high temperature and rich in oxygen, and the temperature inside the cylinder will rise sharply due to the shortening of the combustion time and the speed due to the higher injection pressure; at the same time, due to the higher injection Higher pressure promotes the oil-gas mixing in the cylinder, thus the physicochemical properties of biodiesel with high oxygen content are utilized, so the NOx generation increases with the increase of injection pressure (Huang, J *et al.*, 2020). From Fig.9, it can be seen that the soot generation per working cycle at injection pressures of 24MPa, 28MPa, and 32MPa is 0.06mg, 0.054mg, and 0.045mg, respectively. soot generation decreases with the increase of injection pressure, which is opposite to the generation of NOx, forming a tendency of both sides of the equation. On the one hand, the increase of in-cylinder turbulence intensity reduces the gas mixture concentration zone in the combustion chamber; on the other hand, the shortening of the stagnation period and the acceleration of the combustion rate promote the surface oxidization of soot, which inhibits the generation of soot.

In order to deeply understand the generation of soot and NOx in the diesel engine under different injection pressures, the combustion chamber pollutant cloud maps under four degrees of crankshaft rotation angles of 5°, 10°, 20°, and 60° after the combustion stopping point were explored respectively, and the NOx generation cloud maps of two oils under different crankshaft rotation angles are shown in Fig.10, and the soot generation cloud maps of two oils under different crankshaft rotation angles are shown in Fig.11 soot generation cloud maps for two oils at different crankshaft angles.

Unit: kg

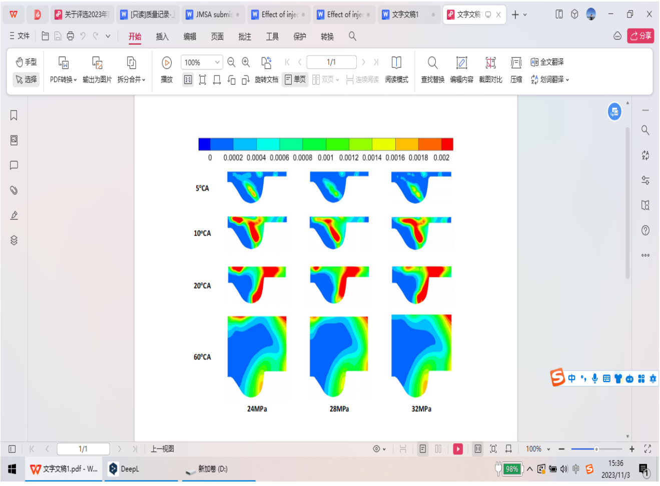

Figure 10 Clouds of NOx generation of two oils at different crankshaft angles with different injection pressures

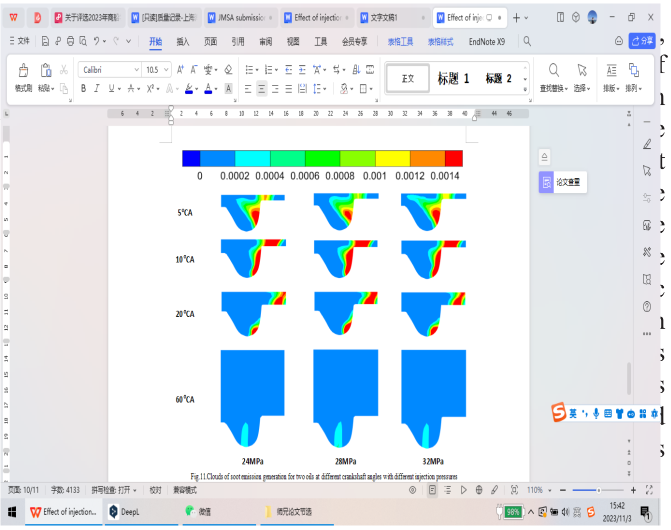

Figure 11 Clouds of soot emission generation for two oils at different crankshaft angles with different injection pressures

From Fig.11, it can be seen that at the moment of 5 degrees from the upper combustion stop, the area of the soot generation region becomes larger with the increase of injection pressure, and the additional area of carbon smoke generation is distributed in the region of the oil droplet injection. This indicates that increasing the injection pressure causes the fuel to burn earlier, but due to the high concentration of fuel just injected from the nozzle, the air content in the region of high concentration of oil and gas is not enough to support the complete combustion of the fuel, which makes the increase of soot generation. However, with the downward movement of the piston, the high injection pressure will continue to improve the quality of the oil-air mixture and the degree of atomization of the oil droplets, which will lead to a more complete combustion of the fuel, resulting in a decrease in soot generation.

5. CONCLUSION

In this paper, a three-dimensional simulation model of the combustion chamber of a marine diesel engine is established by CONVERGE thermodynamic simulation software, and numerical calculations are carried out for an inland waterway marine propulsion diesel engine fueled with a small proportion of blended biodiesel under different fuel injection pressures to study the effects of oil-gas mixing, combustion and emission characteristics of the diesel engine under different fuel injection pressures. The results are as follows.

1. With the increase of fuel injection pressure, the intensity of oil-gas turbulence in the diesel cylinder and the oil-gas flow rate in the combustion chamber can be improved, which effectively improves the phenomenon of insufficient oil-gas mixing of biodiesel due to high viscosity and high density.
2. (High injection pressure will lead to shorten the stagnation period in the combustion process of B10 biodiesel, increase the maximum burst pressure in the cylinder and the average temperature in the cylinder, so that the combustion and exothermic process is carried out quickly.
3. With the increase of fuel injection pressure, it will significantly reduce the emission of soot in the combustion process of B10 biodiesel, compared with the working condition of 24MPa, when the fuel injection pressure is increased to 28MPa and 32MPa, the emission of soot will be decreased by 10% and 25%, respectively; however, it will increase the emission of NOx, compared with the working condition of 24MPa, when the fuel injection pressure is increased to 28MPa and 32MPa, the emission of soot will be decreased by 10% and 25%, respectively; however, it will increase the emission of NOx, compared with the working condition of 24MPa. However, it will increase NOx emissions, compared with the case of 24MPa injection pressure, when the fuel injection pressure is increased to 28MPa and 32MPa, the NOx emissions increase by 5.5% and 15.6%, respectively.

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