Effect of Fuel Physicochemical Properties on Spray and Particulate Emissions

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ABSTRACT: To investigate the effect of fuel physicochemical properties on spray and particulate emissions, fuel spray characteristics were tested on a constant volume chamber (CVC) test rig using a high-speed camera method to investigate the effect of different injection and ambient pressures on spray characteristics. In the engine bench tests, the effects of particulate emissions from five different diesel fuels with different physicochemical properties were analyzed under low-, medium-, and high-load steady-state conditions and 5 s transient loading conditions. The test results showed that the spray tip penetration of different CNs results from the combined effect of the fuel properties. The spray cone angle of the five fuels increased with the increase of injection and ambient pressure, and the impact of ambient pressure on the spray cone angle was more prominent. Spray tip penetration and spray projection area increase with increased injection pressure and decrease with increased ambient pressure; compared with spray tip penetration, the spray cone angle has more influence on spray projection area, especially near-field spray cone angle as the primary influence factor. Fuels with different ignition characteristics have other effects on particulates at different loads. At low loads, choosing CN = 55.3 fuel improved the number and mass of particulates; at medium and high loads, choosing CN = 51 fuel reduced the number of particulate emissions. Fuels with different volatilities have different effects on particulates at other loads. At low loads, CN = 54.9 fuel was chosen with moderate volatility and aromatic content. At medium and high loads, the volatility of the fuel had a lower weight on particulates, and the aromatic content had a higher weight. Under the transient loading condition of 5 s, using fuel with a higher CN, good volatility, and lower aromatic content can appropriately reduce the number of particulate emissions.

1. INTRODUCTION

The diesel engine spray and the combustion process can affect diesel engines’ power, economy, and emission characteristics. The atomization process is the premise and fundamental of combustion, and the completion of atomization determines good or bad combustion. The atomization process itself is dynamic, and the flow and evaporation characteristics of the whole process are very complex. For a long time, to meet the emission regulations, achieve minimum fuel consumption, and understand the change process in the engine cylinder, people have conducted a lot of research on diesel spray and formed different methods to study the change process in the engine cylinder; one is to simulate the fuel injection and combustion, and another is the use of optical diagnosis to visualize the process of in-cylinder engine changes. The visual approach is also used to verify the correctness of the simulation results.

Diesel vehicle emissions are closely related to the engine’s technology level on one hand, while on the other hand, fuel quality is also a critical factor in achieving emission control goals. Diesel fuel characteristics parameters such as CN and volatility significantly impact diesel engine performance. After the diesel fuel enters the cylinder, a multi-phase mixed spray field consisting of the fluid column, liquid droplets, and the air is formed due to the swirling motion of ambient gases. The spray field is thermodynamically and dynamically transient and extremely unevenly collapsed dynamic flow field. The fuel spray characteristics directly affect the combustion in the engine cylinder and the generation and emission of hazardous substances, so it is helpful to explore the spray characteristics of diesel fuel in depth. Among them, microscopic features include droplet diameter distribution, droplet number density, droplet temperature, droplet velocity distribution, etc.

The performance of the engine has long been improved by increasing the CN of diesel fuel. Studies have shown that for combustion processes involving large exhaust gas recirculation, lowering the fuel's CN and extending the ignition delay time can...
effectively reduce carbon soot and NO\textsubscript{X} emissions and improve the engine’s brake thermal efficiency.\textsuperscript{1,2} It was also shown that volatility directly affects the in-cylinder atomization and mixing rate of fuel. Fuels with low boiling points and easy volatility can improve the fuel−air mixing during the ignition delay time, which is beneficial to reduce the smoke level at high loads.\textsuperscript{3} Sluder et al. also found in the literature that highly volatile fuels have better emission results in low-temperature combustion.\textsuperscript{4} Kim\textsuperscript{5} and Musculus\textsuperscript{6} studied the macroscopic characteristics of the gas−liquid distribution in the spray field during diesel engine combustion using techniques including planar laser-induced fluorescence (PLIF), etc. The tests show that the penetration of the liquid spray tip in high-temperature and high-pressure environments is significantly less than that in ambient temperature and pressure environments and that quasi-stable values exist. The spray cone angle is also different from the experimental results in the ambient temperature and pressure environment. Naber and Siebers\textsuperscript{7} showed that the difference in spray cone angle could be up to 30% for ambient temperatures of 300−450 and 600−1400 K, respectively.

Numerical simulation is one of the effective tools to study diesel spray. Mohan et al.\textsuperscript{8} explored the macroscopic spray properties of fuel at high-ambient density conditions and validated the macroscopic spray properties through experiments and numerical simulations. The experiments showed that as the ambient gas density decreases and the incident pressure increases, the spray momentum flux increases, and the higher the incident pressure, the more air is mixed in the fuel. Xie et al.\textsuperscript{9} conducted a detailed experimental study of the macroscopic spray characteristics parameters, proving the previous conclusions. Wang et al.\textsuperscript{10} investigated the macroscopic and microscopic spray characteristics of diesel sprays under fractional injection using techniques such as ultrahigh-speed imaging.

To reduce the local overconcentration area of in-cylinder fuel and solve the current problem of diesel particulate emission to the environment, five types of petrochemical diesel produced by oil companies with different physical and chemical properties such as ignition and evaporation were selected in this paper with the aim to reduce the local overconcentration area of in-cylinder fuel by improving the fuel mixture uniformity through fuel properties. First, the spray characteristics of these five diesel fuels were studied by a high-speed camera in a CVC to analyze the effect of spray patterns on fuel evaporation and mixture formation. Then, the impact of the particulate emission of these five diesel fuels with different physicochemical properties was analyzed by engine bench test under low, medium, and high load conditions and transient loading conditions, respectively, to reduce the particulate emission of diesel engines further and to provide oil companies with the opportunity to refine better-quality fossil diesel fuels. The effects of particulate emissions on these five types of diesel fuel with different physicochemical properties were analyzed under low, medium, and high load conditions and transient loading conditions.

2. EXPERIMENTAL SECTION

2.1. Test Platform. Before the experiment starts, the optical quartz glass on the viewable window of the CVC needs to be cleaned to ensure the permeability of the light path, and the seal of the viewable window and the top cover needs to be checked to prevent air leakage. After the test preparation, the inlet valve of the CVC is opened, the exhaust valve is closed, nitrogen is flowed from the high-pressure gas cylinder through the high-pressure steel pipe into the CVC, and the real-time pressure in the CVC is displayed by the pressure gauge. When the pressure is about to reach the required ambient pressure, the inlet valve is closed. When the pressure comes to the set value, the rail pressure is adjusted to the target injection pressure, the injection control module on the control panel is clicked to send out the injection signal, and the spray development process in the CVC is recorded. When the fuel is replaced at the end of each test, the oil circuit is flushed well. The air is swept after each injection to exclude the interference of environmental factors and ensure a good seal of the CVC.

The test is conducted using a high-speed camera method on the CVC test platform. The intake and exhaust device of the CVC can achieve a maximum pressure of 16 bar in the vessel. Since the xenon lamp light source is also a point light source, a paper diffuser is added between the xenon lamp light source and the CVC to produce a scattered light source of uniform brightness. The test platform arrangement of the CVC is shown in Figure 1.

![Figure 1. Schematic diagram of the test platform layout.](image)

2.2. Test Conditions and Test Fuel. Three common rail pressures and two ambient pressures were selected for cross-testing, as shown in Table 1. In addition, the diesel fuel injector used in this paper is an electronically controlled single-hole solenoid valve type injector manufactured by Bosch with a 0.45 mm injection hole diameter. The relevant parameters of the injector are as follows: the number of injection holes is 1, the circulating mass is 10 mg, and the relative oil beam angle is 40°. The tests were repeated five times under each experimental condition. Table 2 summarizes the resolution and uncertainty of the main instruments used in this study.

The high-speed camera used in this study to record the spray images of the fuel spray process using the high-speed camera method is the Phantom v611 high-speed camera from AMETEK, USA, and the lens model is Nikon AF-S VR Micro-Nikkor 105 mm f/2.8G. The main parameters of the high-speed camera used in the test are as follows (Table 3).

The high-speed camera method is an efficient test for recording transient, high-speed spray processes using a high-speed camera. This method’s principle is that the spray liquid
obstructs the background scattered light to obtain the spray pattern, and the spray characteristics can be obtained by image processing. Different refining processes such as catalytic cracking, hydrocracking, and hydro refining are first used to blend and formulate different cetane fuels to ensure representative properties of diesel fuel. Diesel engine CN is measured by a third-party authority based on a standard process, and a report is issued. The percentage of alkanes and cyclic aromatic hydrocarbons is the mass content. The main fuel characteristics are shown in Table 4; other parameters of fuel can be found in Wu et al.12

### 2.3. Spray Image Processing

After acquiring the spray image using high-speed photography, the spray image needs to be processed to obtain parameters such as spray tip penetration, spray cone angle, and spray projection area. Image processing is performed using software that first pre-processes the spray image to enable further analysis. The main pre-processing is image background removal and image cropping. The methods for removing the image background are

\[ I_n = I_{\text{init}} - I_{\text{bg}} \]

where \( I_{\text{init}} \) is the original image and \( I_{\text{bg}} \) is the background image; to exclude the interference caused by the change of background light during the test, the previous image of the spray is used as the background. \( I_n \) is the final background-free image.

The specific parameters were obtained as follows.

1. **Spray tip penetration force:** Usually, the greater the penetration of the spray tip, the better the atomization effect in the cylinder, which can make full use of the cylinder space so that the mixture is evenly distributed, reducing the formation of local over-concentrated mixing area in the cylinder and reducing the generation of carbon smoke. However, too much spray tip penetration will make fuel contact with the lower temperature cylinder wall, resulting in carbon buildup, insufficient combustion, and other adverse effects.

\[ S = \frac{(x_{\text{end}} - x_0)}{N} \]

where \( x_0 \) is the number of lines at the beginning of the spray in the image, \( x_{\text{end}} \) is the number of lines at the lowest point at the end of the spray in the picture, and \( N \) is the number of pixels per unit length of the calibration.

2. **Spray cone angle:** The spray cone angle is sprayed transverse diffusion degree. Fuel volatility and ambient density can affect the spray cone angle. Figure 2 shows that the number of pixels is small at the beginning of the spray, and the calculated angle is significant; at the same time, the fuel starts to atomize twice in the middle and later part of the spray and is affected by the surface vibration waves in an asymmetric structure. The calculated angle regularity is different from the first half. Therefore, this paper divides the cone angle into near and far-field cone angles. The near-field cone angle is calculated as follows.

\[ \theta_i = \frac{1}{n} \sum_{x=n_0}^{n} \left[ \arctan \left( \frac{y_0 - y_i}{x - x_0} \right) + \arctan \left( \frac{y_i - y_0}{x - x_0} \right) \right] \]

where \( n \) is the total number of rows of spray image pixels within 1/5 to 1/2 of the spray tip penetration, \( n_0 \) is the number of rows of image pixels at 1/10 of the spray tip penetration, the coordinates of the start point of the spray image are \((x_0, y_0)\), the coordinates of the left boundary point of the spray image are \((x_l, y_l)\), and the coordinates of the right boundary point of the spray image are \((x_r, y_r)\).

The far-field cone angle is calculated as follows.
Figure 3. Spray development images at different injection pressures.

Figure 4. (a, b) Effect of CN on spray tip penetration.

Figure 5. (a–d) Effect of CN on the spray cone angle.
where $n_1$ is the number of rows at 1/2 of the spray tip penetration and $n_2$ is the number of rows at the end of the spray tip penetration.

(3) Spray projection area: The calculation method can be found in Liu.$^{15}$

3. RESULTS AND DISCUSSION

3.1. Effects of Different Experimental Variables on Spray Parameters. 3.1.1. Effect of Fuel Properties on Spraying. As seen in the spray development image, the surface wave amplitude grows gradually as the spray process develops, prompting the conical spray to split the atomization by oscillating progressively from side to side. The first half of the spray is influenced by the initial fuel velocity. It maintains a better conical shape during the spray duration, almost unaffected by the surface waves. However, the second half of the spray is visible as a spray profile affected by surface waves on both sides of the liquid during the fuel injection duration. Figure 3 shows the spray development images at different injection pressures for fuel CN = 57.4, where the time interval between two adjacent images is 0.01 ms.

In the early spray stage, the fuel is ejected from the injector’s spray hole, and the initial atomization mainly occurs. The amount of fuel ejected from the spray hole in this period is small, and the fuel is not fully developed. In this period, the fuel is not fully developed, the spray tip penetration and spray cone angle are relatively small, the oil mist area is dense, and the physicochemical properties of the fuel that affect the fuel crushing process appear to be insignificant. At the beginning of
the spray, the spray shape of diesel fuel with different CNs does not differ much. As the spray continues, the kinetic energy of the oil beam becomes more significant, and the spray intensifies the cooling effect with the ambient gas. Small vortex structures appear at the edges of the spray. Compared to higher-viscosity fuels, less viscous fuels are easier to atomize, mix more evenly with ambient gases, and have a more substantial vortex effect. This results in a more irregular spray head shape and a more expanded head for higher-viscosity fuels.

Figure 8. Effect of injection pressure on the spray near-field cone angle.

Figure 4a,b shows the curve of spray tip penetration force with time. The spray tip penetration of the fuel varies with increasing CN, which is due to the physicochemical properties of the fuel. The magnitude of the growth rate of spray tip penetration with time was CN = 59.3 > CN = 57.4 > CN = 55.3 > CN = 53.9 > CN = 51, but the difference was not very significant in the later stages of spraying. As seen in Figure 4b, the average spray tip penetration (t > 0.04 ms) of CN = 51 fuel adds a minimum of 155.25 mm, which is 3.09, 5.99, 6.91, and 0.31 mm less than the...
**CN** = 53.9, **CN** = 55.3, **CN** = 57.4, and **CN** = 59.3 fuels, respectively. Under the test conditions studied in this paper, the viscosity of the fuel plays a dominant role. The diesel fuel with a high density of movement makes it more difficult for the inertial force to break it up, and the jet-breaking effect of the oil mist is not ideal. At the same time, the initial kinetic energy is the same. The oil droplets with lower viscosity are less likely to stick together, which makes the flow resistance of the fuel at the nozzle lower and the initial velocity of the jet higher, which provides sufficient inertial force and thus leads to the spray tip penetration force being increased. In addition, the density of the five fuels is relatively close to each other, which has little effect on the spray tip penetration. Moreover, the spray tip penetration increase can be divided into two phases from 80 mm from the spray hole. The slopes of the curves of the two phases are different, and the growth rate of the spray tip penetration in the first phase is more significant than that in the second phase. This is due to the gradual decrease of the spray velocity due to the

**Figure 10.** Effect of injection pressure on the spray projected area.

**Figure 11.** Effect of ambient pressure on spray tip penetration.
fuel’s resistance to the ambient gas and the increase of the surface wave amplitude in the middle and rear of the spray, which also has a hindering effect on the increase of the spray tip penetration. Therefore, in the following analysis of the spray cone angle, it is necessary to divide the spray cone angle into the near-field cone and far-field cone angles.

In the middle and late stages of spray (0.04–0.16 ms), the curves were interspersed up and down, but the fluctuations were

Figure 12. Effect of ambient pressure on the spray near-field cone angle.

Figure 13. Effect of ambient pressure on the spray far-field cone angle.
small. This may be due to the slight surface tension when the oil beam is not entirely broken atomized, resulting in an insignificant difference in the atomization situation. Still, as the spray continues to develop, the front end of the oil beam strengthens with the ambient gas coiling motion. The physical and chemical parameters of the fuel undergo positive performance, and the atomization situation can return to normal.  

Figure 5a–d shows the curve of spray cone angle with time. Figure 5a shows that the spray near-field cone angles of the five fuels reach a stable value of around 0.03 ms and are maintained for a time, and then the spray near-field cone angles gradually decrease in the later period. This is due to the high penetration speed of the droplets at the beginning of the spraying period, and the spraying cone angle increases rapidly due to the rapid development of the spray in the axial direction and reaches the maximum value of around 0.02 ms. The droplets then evaporate into the gaseous state and diffuse with the ambient gas. In the late stage of the spray, the oil beam moves forward, and the oil beam becomes less within 1/5 to 1/2 of the

| property           | resolution | uncertainty |   |   |
|--------------------|------------|-------------|---|---|
| dynamometer (speed)| 1 rpm      | ±0.3%       |   |   |
| dynamometer (torque)| 0.01 N m  | ±0.2%       |   |   |
| pressure transducer| 0.01 MPa   | ±0.3%       |   |   |
| gas analyzer       |            |             |   |   |
| CO measurement     | 0.01%      | <0.2%       |   |   |
| HC measurement     | 2 ppm      | <0.2%       |   |   |
| NOx measurement    | 1 ppm      | <0.2%       |   |   |
spray tip penetration, resulting in a lower near-field cone angle. From Figure 5b, the far-field cone angle increases with time, which is opposite to the trend of the near-field cone angle. As the spray continues to develop, the front end of the oil beam intensifies with the ambient gas coiling motion, causing the far-field cone angle to increase. This can be verified from Figure 5c,d.

With time, the magnitude of the spray cone angle growth rate is $CN = 59.3 > CN = 57.4 > CN = 55.3 > CN = 53.9 > CN = 51$. This pattern of variation can be seen in Figure 5c,d. The different physicochemical properties among the fuels cause the various degrees of fuel diffusion in the ambient gas, where the $CN = 59.3$ and $CN = 57.4$ fuels have better evaporation. The oil bundle breaks into smaller droplets during the spray development process, strengthening the disturbance of the surrounding air and the winding section. It increases the speed of the radial expansion of the oil bundle. Due to the ambient pressure, the fixed threshold value set in the software will not be recognized.
when the droplets become gas phase, reducing the spray cone angle.

The change curve of the spray projection area can evaluate the fuel spraying process from two aspects: (1) A giant spray projection indicates that the sprayed liquid can be dispersed to a broader scope, a phenomenon of good atomization effect, and (2) a faster change rate of spray projection suggests that the fluid can be split and atomized more quickly, which is also a phenomenon of a good atomization effect. The experimental results in this paper can reflect these two aspects. Figure 6a,b shows the curves of the projected area of the spray with time for five different CN fuels. The spray projection area increases linearly and rapidly with time, reaching a maximum value at about 0.04 ms, and then decreases gradually. The difference between the rate of change of the spray tip penetration and the rate of change of the spray projected area is that the spray tip penetration reflects the longitudinal velocity of the fuel spray,

Figure 18. Effect of volatile and aromatic content on the distribution of particle number concentration (left) and mass concentration (right).

Figure 19. Effect of volatility and aromatic content on the total number of particles under transient loading conditions.
and the size of the spray projected area is influenced by the combination of the longitudinal acceleration and the lateral width. If the spray is idealized as a cone, then the spray flung area is proportional to the product of the spray cone angle and the spray tip penetration. At the maximum spray projection area, both also reach a maximum of around 0.04 ms, respectively. From Figure 6a, it is seen that the spray area increases and then decreases as time increases, and combined with Figure 4a and 5a, b, it can be concluded that the near-field cone angle accounts for the primary influence on the spray projection area.

As the CN increases, the spray projection area also increases. This is because the spray projection area mainly depends on the variation of the spray cone angle, which is CN = 59.3 > CN = 57.4 > CN = 55.3 > CN = 53.9 > CN = 51. The maximum spray projection areas of the five fuels are shown in Figure 6b, and the maximum spray projection area for CN = 51 fuel is 2026.24 mm², which is reduced by 188.48, 350.06, 768.71, and 1060.16 mm², respectively, compared to the CN = 53.9, CN = 55.3, CN = 57.4, and CN = 59.3 fuels.

3.1.2. Effect of Injection Pressure on Fuel Spray Characteristics. Figure 7a–d shows the curves of spray tip penetration with time for different injection pressures. As shown in Figure 7a–c, the trend of spray tip penetration for the five fuels is consistent throughout the curves, showing a similar linear increase in the early stage of spraying and a gradual decrease in the rise after the spraying stabilizes. In addition, the spray tip penetration force of the five fuels increased significantly with increasing injection pressure. As shown in Figure 7d, CN = 51, CN = 53.9, CN = 55.3, CN = 57.4, and CN = 59.3; when the injection pressure was 120 MPa, the average spray tip penetration increased by 4.62, 4.78, 3.49, 6.81, and 5.75 mm, respectively, compared with the injection pressure of 80 MPa. In addition, the increase in injection pressure increased the spray tip penetration at a greater slope to its maximum value. This is because the increase in fuel injection pressure provides more incredible turbulent energy and a higher rate of droplet forward motion.

In addition, the spray tip penetration of the fuel fluctuates more when the spray pressure is at 80 and 100 MPa, as seen from the late spray (after 0.12 ms) curve. It may be because the ambient medium enhances the initial velocity and kinetic energy of the fuel at low injection pressure and high ambient pressure; the first sprayed bundle has a more significant hindering effect on the continued development of the later injected fuel, and the penetration rate decay in the spray development process is accelerated. The situation is improved when the injection pressure is further increased.

In addition, the spray characteristics exhibited by different CNs at different injection pressures are also different. The spray tip penetration of CN = 59.3 fuel is greater than that of CN = 57.4 fuel because CN = 59.3 fuel has a smaller kinematic viscosity and smaller surface tension. Droplets with less viscous force are less likely to stick together, leading to a more significant initial velocity of the jet, which is more favorable to the broken atomization of the oil beam.

Figure 8 shows the variation curve of the spray near-field cone angle with time for different injection pressures. As the spray develops, the near-field cone angle first increases and decreases. As the spray pressure increases, the near-field cone and peak angles also increase, which means that increasing the injection pressure can split more fuel with a larger cone angle to atomize simultaneously, and the atomization effect is improved. The average growth of the spray near-field cone angle for CN = 51, CN = 53.9, CN = 55.3, CN = 57.4, and CN = 59.3 is 19.82, 9.32, 6.85, 3.41, and 2.53% for each 20 MPa increase in injection pressure, respectively. Among them, the average near-field cone angle value of CN = 51 fuel may be due to the fluctuation of the common rail tube pressure, causing instantaneous instability of the injection pressure, which affects the experimental results.

Increasing the injection pressure enhances the internal push of the jet, which promotes the fragmentation and atomization of the oil droplets and catalyzes the diffusion of the gases found inside the constant volume combustion chamber, so the spray cone angle increases accordingly. In the pre-spray period (0–0.03 ms), the spray cone angle changes more significantly due to the development of rapid diffusion of the spray as a result of the initial atomization of the fuel and the high axial velocity and radial momentum. In the middle and late stages of spraying (0.03–0.06 ms), the spray cone angle tends to be stable, the droplets on the cone surface of the oil beam and the ambient medium are rigorously rolled and absorbed, and the secondary atomization is evident; because the sprayed fuel and the surrounding gas form a stagnation to the spray cone angle of the renewed fuel later, the spray cone angle remains in a stable range. At the end of spraying (t > 0.14 ms), the spread oil volume and kinetic energy are nearly exhausted, the spray pattern is gradually broken, and the oil beam is sparsely distributed in space; at the same time, the fuel is affected by the ambient temperature, "evaporative cooling", and vaporization phase change (from the liquid phase to the gas phase). The high-speed camera cannot capture the gas-phase oil beam, so the spray near-field cone angle gradually becomes smaller.

The spray far-field cone angles in the early and middle sprays and the spray near-field cone angle's development trend is similar to that shown in Figure 9, and the analysis of the reasons is identical to the above. The far-field cone angle gradually increases with the increase of injection pressure. The flow speed of fuel in the spray hole is increasing. The turbulent motion is enhanced and increases the speed of radial expansion of the oil beam.

As can be seen in Figure 10, the spray projected area increases rapidly with time, first along with the linearity, reaches the maximum value at about 0.03 ms, and gradually decreases. The growth curve of the spray projection area is different from that of the spray tip penetration force and spray cone angle, which indicates that the spray projection area results from the combined effect of the spray tip penetration force and spray cone angle. The spray projection area increases with increased CN at 120 MPa compared to 80 MPa, and the maximum spray projection area increases by 521.24, 553.72, 682.74, 451.68, and 521.23 mm², respectively.

3.1.3. Effect of Ambient Pressure on Spray Characteristics. Figure 11 shows the curve of spray tip penetration with time for different ambient pressures. The overall trend of the spray tip penetration force did not change at different ambient pressures. At an ambient pressure of 5 MPa, the spray reached a steady state after about 0.04 ms, while at an ambient pressure of 10 MPa, the spray reached a constant state after about 0.06 ms.

As the CN increased, the average spray tip penetration at an ambient pressure of 5 MPa increased by 9.92, 6.11, 7.49, 0.19, and 7.33 mm, respectively, compared to that at an ambient pressure of 10 MPa. This is because as the ambient pressure increases from 5 to 10 MPa, the ambient gas density then becomes more extensive, and in the oil beam, in the process of forwarding motion with the ambient medium of the increased coiled suction, the kinetic energy loss is more significant; the
cavitation flow inside the spray hole is inhibited, and the initial flow rate obtained by the fuel at the nozzle outlet is reduced.

Figure 12 shows the curves of the spray near-field cone angle with time for different ambient pressures. It can be seen that the trend of the near-field cone angle of the fuel spray is approximately the same for different CNs, with a high peak at the early stage of spraying and then decreasing. The spray near-field cone angle is smaller for a 10 MPa ambient pressure spray. This is because the presence of the injection pressure will move the oil beam forward, the droplet evaporates into a gaseous state with the ambient gas to occur in the volume of suction and diffusion, and with the development of time, the spray continues to develop axially and the spray near-field cone angle tends to reduce. The far-field cone angle increases at the late stage of spraying, as shown in Figure 13. The higher ambient pressure promotes the fragmentation and atomization of oil droplets. It catalyzes the diffusion of gaseous fuel inside the CVC, so the spray cone angle increases accordingly. The average spray far-field cone angles for CN = 51, CN = 53.9, CN = 55.5, CN = 57.4, and CN = 59.3 increased by about 9.2, 9.9, 10.6, 9.8, and 10.3° compared to the average spray near-field cone angles for an ambient pressure of 5 MPa.

The average spray near-field cone angle of the fuel increases with increasing CN from 5 to 10 MPa by approximately 3.8, 4.9, 4.7, 3.4, and 3.9°, and the average spray far-field cone angle increases by about 4.3, 3.5, 3.1, 1.9, and 1.3°. This is because the increase of ambient back pressure accelerates the transformation of droplets from a large-volume form to a small-volume form and increases the jet fragmentation effect and a more substantial roll-suction effect occurs at the outer contour edge of the spray. The increase of ambient pressure can promote the diffusion of gaseous fuel to the surrounding area inside the CVC.24

Figure 14 shows the curves of the projected area of the spray with time for different ambient pressures. As time increases, the spray projection area increases and then decreases, and at t < 0.02 ms, the spray projection area of the fuel does not differ much. In the late stage of spraying, the spray projection areas of the fuels change more obviously with the ambient pressure. It takes about 0.03 ms to reach the peak when the ambient pressure is 5 MPa, while it takes about 0.04 ms to get the peak area when the ambient pressure is 10 MPa. CN = 51, CN = 53.9, CN = 55.5, CN = 57.4, and CN = 59.3 have different degrees of increase in the maximum spray projection area at an ambient pressure of 5 MPa compared to 10 MPa ambient pressure, respectively. At t < 0.02 ms, the pressure increases from 5 to 10 MPa, and although the cone angle can be increased, the spray tip penetration decreases, resulting in a similar projected area. At t > 0.02 ms, the spray tip penetration force difference becomes smaller and smaller for five fuels at two pressures. At the same time, the value change of the cone angle increases, and it can be verified that the size of the cone angle is the main factor affecting the area.

In the previous section, the effect of the rail and ambient back pressures on the spray characteristics was investigated by the spray characteristic test of CVC. To further investigate the impact of fuel ignition, volatility, and aromatic content on the particulate emission characteristics of diesel engines, this section analyzes the particle size distribution and particulate emission patterns based on the study of fuel spray characteristics using fuels with different ignition and volatility, as shown in Table 4, at a speed of 1600 r/min and under steady-state conditions of low, medium, and high load and 5 s transient loading conditions of 5–95%. The particle size distribution, particle number, and mass emission patterns were investigated.

3.2. Test Apparatus and Research Methods. 3.2.1. Test Platform. Figure 15 shows the schematic diagram of the engine test and control platform used in this study, which mainly consists of a 2.8 L four-cylinder four-stroke supercharged diesel engine, eddy current dynamometer, and control system, intake boost system, fuel supply system, pollutant emission measurement system, and cylinder pressure and data acquisition and analysis system. During the test, the CW160 Nanfeng eddy current dynamometer controls and records the engine speed and load. The intake airflow was measured by the SENSYYCON Sensy air flow meter. The diesel and gasoline consumption per unit of time was measured by the TOCEIL-CMF025 and Ono SOKKI DF-2420 fuel consumption meters, respectively. A BOSCH LSU4.9 lambda sensor and an ETAS lambda meter monitored the in-cylinder mixture concentration.25 An uncertainty analysis of the experimental instruments is seen in Table S.

3.2.2. Test Fuel and Experimental Method. The physicochemical parameters of the fuel used in the test are shown in Table 4. The typical speeds of 1600 rpm was selected and tested at 25, 50, and 75% load conditions corresponding to a brake mean effective pressure (BMEP) of 0.267, 0.535, and 0.802 MPa, respectively. For the following narrative, the following definitions are made: fuel with CN = 51 is defined as fuel no.1, fuel with CN = 55.3 is defined as fuel no. 2, fuel with CN = 59 is defined as fuel no. 3, fuel with CN = 54.9 is defined as fuel no. 4, and fuel with CN = 56.4 is defined as fuel no. 5.

3.2.3. Ignition Properties. In general, as the CN of fuel increases, it has better ignition, which can effectively shorten the stall period, reduce the premixed gas formed during the stall period, and generate better NVH performance of the diesel engine. However, too high CN makes the combustion stall period too short; the premixed combustion of fuel is too small, and the later diffusion combustion volume increases sharply, aggravating the particulate emission.25 This study investigated the particle size distribution, particle number, and mass emission of fuels no. 1, 2, and 3 in steady-state tests at low, medium, and high loads at 1600 r/min.

Figure 16a–c shows the particle number and mass emission size distributions for different fuel loads and cetane values. It can be seen that the number of particles is distributed in a single-peaked structure, and the mass of the particles is distributed in a double-peaked design, with the first peak being the largest. The number of particles and mass concentration peak size of the no. 1 fuel is the largest among the three fuels. At low loads, as the CN increases, the number and mass concentration of the particles decreases and then increases slightly and the particle size at the peak decreases; at medium and high loads, the CN increases, the particle size at the peak decreases, and the mass concentration of the particles decreases because the particle size becomes smaller. This is because the fuel combustion quality is poor due to the low thermal atmosphere in the cylinder at a low load. The increase of the CN improves the ignition of the fuel and makes it burn relatively well, while when the CN is too high, it can be seen from Figure 16b,c that the stall period is reduced. The combustion duration is shortened so that it may increase the local over-concentration area, reduce the mixture premixing combustion volume, and also increase the diffusion combustion and number of particles.26 The lower CN of fuel increases the stall period at medium and high loads. It improves premixed combustion, which reduces the number of particles and reduces
the particle size due to the easier nucleation of particles in the premixed combustion stage. Therefore, using no. 2 fuel at low loads improved the number and quality of particulates. In contrast, using the no. 1 fuel at medium and high loads reduced the number of particulate emissions. In contrast, using no. 2 and no. 3 fuels with higher CNs improved the number of particulate emissions more significantly.

Figure 17 shows the change in total particle number concentration of different fuels with different CNs under transient loading conditions of 5 s. It can be seen that during the loading process, the deterioration of the total particle number is the most serious for fuel no. 1, with the lowest CN. In contrast, with higher CNs, fuel no. 2 and fuel no. 3 have slightly improved the particle number concentration, and their peak number concentrations are reduced. However, there was little difference in the peak number concentration and the trend of particle deterioration throughout the loading process. Therefore, it can be concluded that using a higher CN fuel can reduce the particulate number emissions during the transient load change from 5 to 95% load.

3.2.4. Volatility and Aromatic Content. The fuel volatility can directly affect the degree of mixing of the combustible mixture, which in turn contributes to combustion and particulate emissions. In this section, fuels with fuel numbers 2, 4, and 5 in Table 4 were selected, with volatilities ranging from low to high in the order of 5, 4, and 2 and aromatic hydrocarbon contents ranging from low to high in the order of 5, 4, and 2. The laws of fuel volatility and aromatic hydrocarbon content on the number, mass emission, and particle size distribution of the particulates were investigated.

Figure 18 shows the particle number and mass emission particle size distributions of different volatile fuels at different loads. It can be seen that the number of particles is distributed in a single-peak structure, and the peak particle size is about 50 nm. In contrast, the mass concentration of the particles is distributed in a double-peak design at medium and large loads, and the peak of the first peak is the largest. The maximum mass concentration is around 100 nm. At small loads, the particles’ number and mass concentration decreased and then increased as the volatility of the fuel increased. The aromatic content increased, while at medium and large loads, the particles’ number and mass concentration gradually increased as the fuel volatility increased and the aromatic content is increased. The number of particles and peak mass concentration reached the minimum value when fuel no. 5, the least volatile fuel with the lowest aromatic content, was used. Therefore, it is recommended to use no. 4 fuel with moderate volatility and aromatic content at low load and no. 5 fuel with less volatility and aromatic range at medium and high loads to reduce the number and mass of particulate emissions. Therefore, it can be concluded that at low loads, fuel volatility and aromatic content significantly affect particulate emissions. In contrast, at medium and high loads, fuel volatility has a lower weight on particulate emissions, and aromatic content has a higher weight.

Figure 19 shows the effect of fuel volatility and aromatic content on the total number of particulate concentrations under transient loading conditions; from the figure, it can be seen that there is not much difference between the three fuels in terms of the degree of particulate deterioration and the peak number of particulate concentration under transient loading conditions.

4. CONCLUSIONS

In this paper, five types of petrochemical diesel fuel with the different characterizations of ignition and evaporation properties were selected, and first, the spray characteristics of these five types of diesel fuel were studied qualitatively by a high-speed camera in a fixed volume cartridge to analyze the effect of their spray patterns on fuel evaporation and mixture formation. The analysis was carried out to provide data reference for the further reduction of diesel particulate emissions and refinement of better-quality petrochemical diesel by oil companies. The conclusions are as follows.

(1) The development of spray tip penetration is a combined effect of the physical and chemical properties of the fuel. The near-field cone angle plays a critical role in developing the spray area, while spray tip penetration has no significant effect on the spray area.

(2) The trend of the spray parameters with time was consistent for different CNs. The spray tip penetration showed a linear increase at the beginning of the spray development and then remained in a stable value range. The spray near-field cone angle and far-field cone angle maintained a consistent trend at the beginning of the spray development, but by the late stage of spraying, the trend of development is diametrically opposite.

(3) Fuels with different ignition properties affect particulates at different loads. For small loads, choosing the no. 2 fuel (CN = 55.3) improved the number and mass of particulates; for medium and large loads, no. 1 fuel (CN = 51) reduced the number of particulate emissions; however, no. 2 and no. 3 fuels with higher CN improved the mass of particulate emissions more significantly.

(4) Different volatile fuels affect particulate emissions at different loads. At low loads, no. 4 fuel was selected with moderate volatility and aromatic content. At medium and high loads, the volatility of the fuel had less weight on particulate emissions, and the aromatic content had more weight, so no. 5 fuel, with the worst volatility but the lowest aromatic content, was selected to reduce particulate emissions in both number and mass. Under the transient loading condition of 5 s, using fuel with a higher CN, good volatility, and lower aromatic content can reduce particulate emissions.

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Notes
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REFERENCES
(1) Kalghatgi, G. T.; Risberg, P.; Ångström, H.-E. Advantages of fuels with high resistance to auto-ignition in late-injection, low-temperature, compression ignition combustion. SAE Trans. 2006, 623–634.
(2) Northrop, W. F.; Bohac, S. V.; Assanis, D. N. Premixed low temperature combustion of biodiesel and blends in a high speed compression ignition engine. SAE Int. J. Fuels Lubr. 2009, 2, 28–40.
(3) Kitano, K.; Nishiumi, R.; Tsukasaki, Y.; Tanaka, T.; Morinaga, M. Effects of fuel properties on premixed charge compression ignition combustion in a direct injection diesel engine. SAE Tech. Pap. 2003, 9.
(4) Sluder, C. S.; Wagner, R. M.; Lewis, S. A.; Storey, J. M. Fuel property effects on emissions from high efficiency clean combustion in a diesel engine. SAE Tech. Pap. 2006, 12.
(5) Kim, T.; Beckman, M. S.; Farrell, P. V.; Ghandhi, J. B. Evaporating spray concentration measurements from small and medium bore diesel injectors. SAE Tech. Pap. 2002, 17.
(6) Musculus, M. P. B. Effects of the in-cylinder environment on diffusion flame lift-off in a DI diesel engine. SAE Trans. 2003, 314–337.
(7) Musculus, M. P. B. Multiple simultaneous optical diagnostic imaging of early-injection low-temperature combustion in a heavy-duty diesel engine. SAE Trans. 2006, 83–110.
(8) Naber, J. D.; Siebers, D. L. Effects of gas density and vaporization on penetration and dispersion of diesel sprays. SAE Trans. 1996, 82–111.
(9) Mohan, B.; Yang, W.; Tay, K. L.; Yu, W. Macroscopic spray characterization under high ambient density conditions. Exp. Therm. Fluid Sci. 2014, 59, 109–117.
(10) Xie, H.; Song, L.; Xie, Y.; Pi, D.; Shao, C.; Lin, Q. An experimental study on the macroscopic spray characteristics of biodiesel and diesel in a constant volume chamber[J]. Energies 2015, 8, 5952–5972.
(11) Wang, Z.; Xu, H.; Jiang, C.; Wyszenski, M. L. Experimental study on macroscopic and microscopic characteristics of diesel spray with split injection. Fuel 2016, 174, 140–152.
(12) Wu, H.; Xie, F.; Han, Y.; Zhang, Q.; Li, Y. Effect of cetane coupled injection parameters on diesel engine combustion and emissions. Fuel 2022, 319, No. 123714.
(13) Liu, Y.; Li, F.; Fu, W.; Jiang, X.; Song, Z.; Zhu, Z.; Lin, Q. Experimental investigation of effects of Di-N-butyl ether addition on spray macroscopic characteristics of diesel-biodiesel blends. J. Energy Eng. 2019, 145, No. 04019028.
(14) Deshmukh, D.; Madan Mohan, A.; Anand, T. N. C.; Ravikrishna, R. V. Spray characterization of straight vegetable oils at high injection pressures. Fuel 2012, 97, 879–883.
(15) Ejim, C. E.; Fleck, B. A.; Amiri, A. Analytical study for atomization of biodiesels and their blends in a typical injector: surface tension and viscosity effects. Fuel 2007, 86, 1534–1544.
(16) Shangxue, W.; Guifeng, R.; Jing, C. Experimental study on macroscopic spray characteristics of coal to liquids. Chin. Intern. Combust. Engine Eng. 2016, 37, 67–71.
(17) Kook, S.; Pickett, L. M. Liquid length and vapor penetration of conventional, Fischer–Tropsch, coal-derived, and surrogate fuel sprays at high-temperature and high-pressure ambient conditions. Fuel 2012, 93, 539–548.
(18) Du, H.; Zhang, Z.; Liu, J.; Li, M.; Wang, Z.; Xu, B. Influence of changed fuel injection pulse width and pressure on discharge coefficient in diesel engine. Trans. Chin. Soc. Agric. Eng. 2015, 31, 71–76.
(19) Crua, C.; Shoba, T.; Heikal, M.; Gold, M.; Higham, C. High-speed microscopic imaging of the initial stage of diesel spray formation and primary breakup. SAE Tech. Pap. 2010, 2247.
(20) Wang, X.; Huang, Z.; Kuti, O. A.; Zhang, W.; Nishida, K. Experimental and analytical study on biodiesel and diesel spray characteristics under ultra-high injection pressure. Int. J. Heat Fluid Flow 2010, 31, 659–666.
(21) Huang, H. Z.; An, Y. Z.; Su, W. H.; Mao, L. W.; Liang, Y. F.; Dai, Y. L. Investigation on the influence of injection pressure and nozzle diameter on the spray of blended fuel in diesel engine. Trans. Chin. Soc. Intern. Combust. Engines 2013, 31, 200–207.
(22) Prescher, K.; Astachow, A.; Krüger, G.; Hintze, K. Investigation of the atomization and evaporation of Diesel fuel and heavy fuel sprays using optical measurement techniques. SAE Tech. Pap. 1999, 14.
(23) He, X.; Liu, H.; Zeng, W.; Yu, H.; Thomas, B.; Tian, G.; Li, X.; Liu, F. Effect of fuel temperature and injection pressure on spray characteristics of sunflower oil and diesel. Trans. Chin. Soc. Agric. Eng 2014, 30, 75–82.
(24) Shao, Z.; Wang, J.; Han, Y.; Xu, L.; Tian, J. The synergistic effect of fuel aromatic components refinement and ignition timing on GDI engine performance and emissions. Fuel 2021, 298, No. 120800.
(25) Liu, H.; Ma, J.; Dong, F.; Yang, Y.; Liu, X.; Ma, G.; Zheng, Z.; Yao, M. Perimential investigation of the effects of diesel fuel properties on combustion and emissions on a multi-cylinder heavy-duty diesel engine. Energy Convers. Manage. 2018, 171, 1787–1800.
(26) Han, M. The effects of synthetically designed diesel fuel properties-cetane number, aromatic content, distillation temperature, on low-temperature diesel combustion. Fuel 2013, 109, 512–519.
(27) Wu, H.; Xie, F.; Han, Y. Effect of cetane coupled with various engine conditions on diesel engine combustion and emission. Fuel 2022, 322, No. 124164.