Effect of Fuel Ignitability and Volatility on Ultra-Fine Particulate Emissions in Diesel Engine

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Abstract. The effects of fuel components on particulate matter emissions were studied on a high pressure common rail diesel engine fuelled with different diesel fuels. Six kind of diesel fuels with various volatility and ignitability were selected in this test. Particle number, composition and morphology were studied with various physicochemical property diesel fuels. The results show that lower ignitability fuel and stronger volatility fuel could reduce the accumulation mode particle number, while the nucleation mode particle number would increase. Meanwhile, the proportion of DS might reduce with the SOF increase. With the decrease of the fuel cetane number, the number of large cluster particles in the exhaust decreased obviously.

1. Introduction
Energy shortage and environmental pollution have become the focus of global attention. Despite the great development of new clean fuel vehicles, traditional gasoline and diesel vehicles will remain the mainstream of development for a long time in the future. Diesel engine is widely used in automobile, transportation, agriculture and construction machinery because of its high compression ratio, small adiabatic loss and pump air loss, good power and economy. However, due to the high viscosity, poor volatility of diesel oil and the difficulty in the formation of mixed gas, the traditional diesel engine combustion process inevitably has local high temperature and over concentration area, which makes the NOx and carbon smoke emission of diesel engine have a competitive relationship, which restricts the development of diesel engine. In recent years, the application of a large number of new technologies has greatly reduced the quality of diesel particulate emissions, but it has led to a higher degree of ultrafine particles generated by combustion, a corresponding increase in the number of exhaust particulate composition is more complex, greater harm to the environment and human body. Therefore, the research on the particle size distribution of diesel PM emission has been paid more and more attention.

The combustion and emission of engine are closely related to the physical and chemical properties of fuel. Fuel evaporation, mixing and chemical reaction are the main factors that determine the combustion process of the engine. The fuel cetane number is an important index to measure the flammability of fuel. The higher the fuel cetane number, the better the ignition, the shorter the ignition delay period, the more likely to catch fire, the less mixture formed during the diesel engine work soft; However, if the cetane number is too high, the ignition delay period will be too short, the premix and combustion amount will be reduced in the early stage, and the diffusion combustion amount will be
increased in the later stage. A large number of studies have shown that the particle morphology, composition and particle size distribution characteristics are closely related to the combustion boundary conditions of the engine and the physical and chemical characteristics of the fuel.

Commercial diesel oil is composed of a variety of diesel components in different proportions. In this study, direct run diesel, hydrogenated diesel, kerosene and other blending components with significant differences in flammability and volatility were selected as the basic fuels, and different flammability and volatility fuels were obtained by mixing them in different proportions. At the same time, the exhaust particle size spectrometer of TSI 3090 EEPSTM engine was used to test and study the particle size distribution of particulate emission under different steady-state load conditions of the engine and particle mass emission under heavy load conditions.

2. Experimental Section

2.1. Experimental engine and test equipment

A four-stroke, four-cylinder, direct injected turbocharged diesel engine with a displacement of 2.771 L was used for the investigation. Table 1 shows the key specifications of this engine.

| Item                                | Value          |
|-------------------------------------|----------------|
| Bore×Stroke/mm×mm                   | 93×102         |
| Intake Type                         | TC&Inter-cooler|
| Compression Ratio                   | 17.5           |
| Displacement/L                      | 2.771          |
| Rated Power/ kW                     | 80             |
| Idle Speed                          | 850            |
| Rated Speed/r·min⁻¹                 | 3400           |
| Max. Torque/ N·m                    | 260            |
| Speed@Max. Torque/r·min⁻¹           | 1800           |
| Injector Holes                      | 6              |
| Injector Hole Diameter/mm          | 0.124          |
| Injection Pressure/ MPa             | 160            |

CW160 dynamometer was used to control the engine running process in this study, and the air inlet temperature was maintained around 35°C by the self-built air inlet cooling system. The fuel consumption was measured by Onno-Sokki DF20 series fuel consumption meter, and the exhaust composition and air combustion were determined by Horiba 7100DEGR. At the same time, the AVL Dismoke 4000 smoke meter was used to monitor the exhaust smoke, so as to ensure that the engine emissions were within a reasonable range and the particle size analyzer could work normally.

As ultrafine particles are unstable and prone to change in physical and chemical characteristics during exhaust, a secondary dilution system of exhaust particles was designed for the measurement requirements of ultrafine particles in this study, and the dilution ratio was adjusted to ensure that no further reaction of the particles during exhaust flow would affect the measurement results. In the experiment, the dilution ratio was controlled at about 200, and the test results showed good repeatability, which could meet the needs of research. Filter paper was used to collect and analyze the composition and morphology of particulate matter.

2.2. Test fuels

In this experiment, hydrogenated diesel, straight-run diesel and kerosene were selected as the basic blending components to obtain test fuels with different ignitability and volatility. In the research of different ignition fuels, the fuel is named by its hexadecane number, and is defined as CN44, CN55 and CN60 respectively. In the study of different volatilization, the fuel was named by the medium average boiling point of the fuel, which was defined as T264, T271 and T281 respectively. The physicochemical properties and preparation ratios of different fuels are shown in table 2. Figure 1 shows the comparison of C10-C16 alkanes in diesel fuel with different physical and chemical
properties. The test results are obtained by SHIMAZU-GC2014 gas chromatographic analyzer. It can be seen from the results that in the fuel with high hexadecane number, the content of long chain alkane with carbon number above 13 is relatively high. Straight-chain alkanes tend to break chains with the increase of carbon number, so when the temperature and pressure conditions are appropriate, chemical reactions are more likely to occur, and the whole exothermic process is triggered.

![Figure 1](image1.png)

**Figure 1.** Alkane series in various fuels

2.3. Test Conditions and Analysis Method

The typical medium load condition (2000r/min, equivalent ratio 0.4) of the maximum torque and rotation speed of diesel engine was selected for the test. In order to avoid the influence of sediment in exhaust pipe on the measurement of ultrafine particulate matter quantity, for different test fuels, the measurement of particulate matter quantity and filter paper collection were carried out after the engine ran steadily for more than 30min under test conditions. For the collected filter paper samples, the collected filter paper was dried in a muff furnace at a high temperature of 400℃ to separate DS and SOF components. By measuring the mass of filter paper before and after drying, the proportions of DS and SOF in particulate matter were obtained. In order to further analyze the influence of fuel characteristics on the emission of ultrafine particles, ultrafine particles with particle size smaller than 100nm are defined in this paper as ultrafine particles, nuclear particles with particle size smaller than 30nm and accumulated particles with particle size larger than 30nm.

| NO. | Straight-run Diesel | Hydrogenated Diesel | Kerosene | Centane Number | Density /g.L-1 | Distilling Range /℃ |
|-----|---------------------|---------------------|----------|----------------|----------------|---------------------|
| CN44 | 0                   | 100                 | 44       | 44             | 853.5          | 208                 |
| CN55 | 54                  | 46                  | 55       | 55             | 835.0          | 230                 |
| CN60 | 75                  | 25                  | 60       | 60             | 831.5          | 239                 |
| T264 | 40.5                | 34.5                | 25       | 55             | 831.6          | 217                 |
| T271 | 48.6                | 41.4                | 10       | 55             | 826.5          | 222                 |
| T281 | 54                  | 46                  | 0        | 54             | 835.0          | 230                 |

3. Results and Discussion

3.1. Effect of Auto-ignitability on PSD

Fig.2 shows the particle size distribution characteristics of the particulate emission when the engine burns different burning fuels under medium and small load conditions. As can be seen from the figure, the emission curves of ultrafine particulate emission from the exhaust of different fuels show an irregular single-peak distribution, in which the peak concentration of nuclear particles is around 10nm, and there is no obvious peak interval in the accumulated particle area. As for the particle volume concentration distribution curve, the peak value of the volume concentration distribution curve is mainly located in the interval of accumulated particles, about 100nm, which is different from the
quantity concentration distribution curve due to the large particle size proportion in the volume. With the increase of hexadecane number, the ignitability of fuel increases and the peak concentration of nuclear particles decreases. The main reason is that, with the improvement of ignitability, the content of high-carbon straight-chain alkane in the fuel increases, and the chemical reaction is easy to occur. Macroscopically, the lag period is shortened, the mixing time of fuel and air is relatively insufficient, and there are more oil-gas over-concentrated areas in the cylinder, and the carbon smoke generation tendency increases in the combustion process. As the accumulated particles are mainly porous carbon particles adsorbed by unburned hydrocarbons and other substances and formed by collision and agglomeration, there is a certain correlation between the amount of carbon smoke generated and the number of accumulated particles. It can be seen from figure 2d that the total number of particles in different modes increases monotonically with the increase of hexadecane value, while the total number of nuclear particles gradually decreases. When the hexadecane value increases to 55, the total number of particles and the number of ultra-fine particles do not change significantly when the number of particles continues to increase. When the fuel with high cetane value was burned, the proportion of nuclear particles in the total number of particles decreased significantly, but the proportion of ultra-fine particles in the total number of particles changed little.

![Particle Size Distribution with Various Fuels](image)

Figure 2. Particle Size Distribution with Various Fuels

To further analyze the influence of fuel characteristics on particulate matter composition, filter paper was used to collect exhaust particulate matter and separate DS and SOF components from particulate matter. As can be seen from Fig.3, the total mass of particles collected by filter paper decreases first and then increases with the increase of cetane value. But for DS, there is a monotonic increase, and SOF decreases. Low hexadecane number fuels have poor ignitability, long ignition delay period, sufficient oil and gas mixing, and low carbon smoke generation tendency. However, too low hexadecane can lead to too long ignition delay, excessive thinning of parts of the cylinder, an increase in the amount of unburned hydrocarbon, and an increase in the proportion of SOF. Based on the above analysis, it can be concluded that in the selected operating conditions, the fuel with hexadecane value of 55 can obtain better particulate mass emission characteristics, and the particulate mass
concentration can be reduced by about 28% compared with the fuel with hexadecane value of 44 and 60.

Figure 3. Particle Composition of Different Fuels

3.2. Effect of Fuel Volatility on PSD
In this section, different ratios of kerosene, straight-run diesel and hydrogenated diesel are used to produce different volatile fuels in different proportions, and the cetane values of various fuels are ensured to be similar. Fig.4 shows the results of particle emission size distribution when different volatile fuels are burned. It can be seen from the figure that, when the engine burns different volatile test fuels under medium load, the characteristic curve of emission particle number concentration distribution appears obvious nuclear particle peak near 10nm. When the fuel with an average boiling point of 281℃ is burned, due to its relatively poor volatility, the mixture takes more time to form, and it is prone to uneven mixing, leading to high-temperature pyrolysis of fuel molecules in local oil-rich areas in the combustion process to generate carbon smoke particles, and the number of accumulated particles increases. For the medium boiling point of 264℃ and 271℃ fuels, the particle size distribution characteristics are not significantly different. It can also be seen from figure 4d that the proportion of ultra-fine particles is more than 97% when different volatile fuels are burned, among which the proportion of nuclear particles is more than 80%. It can be seen from the figure that, under medium and small load conditions, the number and concentration of particles in base fuel T281 were relatively low, and the number and concentration of nuclear particles were increased by adding a small amount of volatile components compared with T281. The proportion of nuclear particles in ultra-fine particles increased by about 8 percentage points when the more volatile fuel (T264) was burned compared with the T281 fuel. This is because volatile fuels promote in-cylinder mixing, reduce the number of locally concentrated areas, improve combustion conditions, and reduce the number and concentration of nuclear particles.

(a) Particle Number Size Distribution (b) Particle Volume Size Distribution
Fig. 5 shows that the variation trend of DS ratio in particles has a certain correspondence with the number of accumulated particles. When the number of accumulated particles increases, the proportion of DS in particles will increase, and the total particle mass will increase when T281 fuel is burned compared with the fuel with good volatility.

3.3. Effect of Fuel on Particulate Micromorphology

Fig. 6 shows the comparison of micromorphology of particulate matter from fuel exhaust with different physical and chemical characteristics. In the experiment, glass fiber filter paper was used to collect particulate matter from exhaust, and the collected samples were placed in the scope of scanning electron microscope. In the figure, the long straight columns interspersed in space are the amplified glass fiber morphology, and the bright spots on the surface of the columns are the particulate matter components after collection. As can be seen from the figure, the fuel with lower hexadecane value has relatively poor ignitability, the delay period of fuel spray cylinder is prolonged, the fuel and air have more sufficient time to form oil-gas mixture, and the number of accumulated particles with large particle size is significantly reduced. For CN60 fuel, due to the shorter ignition delay period, the amount of mixed gas in the cylinder is too concentrated, and the number of accumulated particles increases relatively. It can be found that the improvement of fuel volatilization performance can effectively promote the formation of homogeneous mixture and reduce the tendency of particle formation. As can be seen from figure (f), when the less volatile fuel is burned, the micro morphology of exhaust particles is mainly in the form of group flocculation, and the particle size is relatively large. It can be seen that, by reducing the ignition of fuel or improving the volatility to promote the mixing of oil and gas, the number of accumulated particles with large particle size can be reduced, and the exhaust particles all develop to small particle size.
4. Conclusion
(1) For the high-pressure common-rail diesel engine, the particle size distribution curve when burning fuels with different physical and chemical characteristics is roughly single-peak structure, and the peak value is around 30nm, and both fuel volatility and ignition will have an impact on the particle size distribution characteristics.

(2) Increasing hexadecane number and improving ignitability of the fuel will shorten the ignition delay period, reduce the amount of premix combustion, increase the proportion of diffusion combustion, and increase the number of accumulated particles and the proportion of DS in particles.

(3) Improving fuel volatility is conducive to promoting oil and gas mixture, improving the overall homogeneity of mixture, reducing the number of accumulated particles with large particle size, and reducing the proportion of DS mass.

(4) From the perspective of micromorphology, burning fuels with strong ignitability and poor volatility will increase the number of large particle size in exhaust, and decrease the number of small nuclear particle size.

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