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Ultrafine particle emission characteristics of diesel engine by on-board and test bench measurement

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Abstract

This study investigated the emission characteristics of ultrafine particles based on test bench and on-board measurements. The bench test results showed the ultrafine particle number concentration of the diesel engine to be in the range of (0.56–8.35) × 10^8 cm^{-3}. The on-board measurement results illustrated that the ultrafine particles were strongly correlated with changes in real-world driving cycles. The particle number concentration was down to 2.0 × 10^6 cm^{-3} and 2.7 × 10^7 cm^{-3} under decelerating and idling operations and as high as 5.0 × 10^8 cm^{-3} under accelerating operation. It was also indicated that the particle number measured by the two methods increased with the growth of engine load at each engine speed in both cases. The particle number presented a "U" shaped distribution with changing speed at high engine load conditions, which implies that the particle number will reach its lowest level at medium engine speeds. The particle sizes of both measurements showed single mode distributions. The peak of particle size was located at about 50–80 nm in the accumulation mode particle range. Nucleation mode particles will significantly increase at low engine load operations like idling and decelerating caused by the high concentration of unburned organic compounds.

Key words: ultrafine particle emission; emission factor; diesel engine; on-board emission measurement; TSI EEPS

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Introduction

Diesel vehicles have greatly developed in the past decade due to their advantages of energy savings and low carbon potential. However, particle emission from diesel engines has been the focus of debate due to its environmental impact (Lloyd and Cackette, 2001; Robinson et al., 2007) and adverse health effects (Reed et al., 2004; Nel et al., 2005; Pope et al., 2006). Therefore, particle emission characteristics, especially for ultrafine particle emission, have attracted more and more attention in these years. Particle emissions in diesel engine exhaust have been shown to consist of ultrafine particles mainly smaller than 0.1 μm. The particle size distributions have often been measured to be bimodal in previous studies, and are composed of nucleation and accumulation modes (Kittelson, 1998). Based on some test bench studies, particles in the nucleation mode have been found to usually be smaller than 50 nm in diameter and in liquid form (Shi et al., 1999, 2000; Harris and Maricq, 2001). Nucleation mode particles are formed by the nucleation of semivolatile organic and sulfur compounds during the dilution and cooling processes (Wong et al., 2003; Giechaskiel et al., 2005; Rönkkö et al., 2006). Sakurai et al. (2003) further reported the composition of organic compounds and sulfur acid in the nanoparticles and indicated that sulfur contents in fuel and lube oil play important roles in the formation of nanoparticles, which has been confirmed by other researchers (Maricq et al., 2002; Lehmann et al., 2003). Accumulation mode particles in the diameter range of 50–100 nm consist of solid carbonaceous agglomerates with adsorbed and condensed semivolatile species.

The test bench is the major method for emission measurement due to its accuracy and repeatability. However, real-world emission testing based on on-board emission measurement systems has been gradually adopted as an important supplement to the test bench, especially for heavy duty vehicle emission measurement, in recent years (Chen et al., 2007; Durbin et al., 2007; Zhang and Frey, 2008). Some studies have shown that the bench test cycle has large differences compared with real-world driving conditions (Bergmann et al., 2009; Liu et al., 2011).

To control the particle emissions from diesel vehicles, more stringent emission standards on diesel engines are gradually being implemented in most countries. With the implementation of Euro V and Euro VI standards, ultrafine particle number concentration measurement is currently of great concern. The emission characteristics of ultrafine particles from in-use diesel vehicles still remain unclear in

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real-world situations, especially for nanoparticles. For this purpose, this study conducted particle number emission measurements using both a portable emission measurement system and test bench in Shanghai, China. The ultrafine particle emission characteristics of a diesel engine in bench test cycle and real-world driving conditions will be discussed in this paper.

1 Materials and methods

1.1 Tested engine and vehicle

The test engine was a common rail direct-injection inline 4 cylinder diesel engine turbocharged intercooler, equal to Euro III emission standard. The test bus was an in-use vehicle meeting the requirement of Euro IV emission standard. The bus was randomly selected from the bus fleet in Shanghai. The cumulative mileage reached 53,550 km. Table 1 shows the technical specifications of the tested engine and bus.

The diesel fuel used in the test was obtained directly from the market. The fuel quality met the requirement of the local standard equal to Euro IV. The sulfur content should be controlled below 50 ppm.

1.2 Test cycles

The test cycle for the engine was operated on the external characteristic curve. The speeds were in the range from idle speed (700 r/min) to the rated speed (2300 r/min). Each 200 r/min set one test point. At maximum torque speed (1500 r/min) and rated speed (2300 r/min), the engine loads of 10%, 25%, 50% and 75% were tested, respectively. Each test point was operated for 1 min to measure the ultrafine particle number concentration and size distribution.

The driving route for on-board measurement was designed in real traffic covering elevated roads, arterial roads, and residential roads. The total distance of the route was approximately 22 km. The length of elevated roads, arterial roads and residential roads represented 26%, 38%, and 35%, respectively. The tested bus ran 2 times a day, once in the peak hour during 7:00 to 9:00, and another in the non-peak hour at noon.

Based on the real-world driving cycle data of the on-board measurement system, we simulated the engine map of the test bus. The methodology of engine operation simulation is referenced from the vehicle dynamics analysis, including rolling resistance, grade resistance, aerodynamic resistance, and acceleration resistance, as shown in the following equation.

$$P_t = F_t \cdot v = \left(F_f + F_w + F_i + F_j\right) \cdot v = \left[M \cdot g \cdot f + \frac{C_D \cdot A \cdot \rho_{air} \cdot v^2}{2} + M \cdot g \cdot \sin(\alpha) + \delta \cdot M \cdot a\right] \cdot v$$

where, P_t (kw) represents vehicle traction power; F_t (N) is the traction of a vehicle; F_f (N) is rolling resistance; F_w (N) is air resistance; F_i (N) is slope resistance; F_j (N) is acceleration resistance; M (kg) is the total mass of the bus; V (m/sec) for speed; a (m/sec^2) is acceleration; G (9.81 m/sec^2) is the acceleration of gravity; A (m^2) is the frontal area of bus; ρ_{air} (1.207 kg/m^3) represents air density (20°C); α is the road slope angle (this study assumed that flat topography was 0); C_D is the air resistance coefficient, which for a heavy duty bus generally is 0.65; f is vehicle rolling resistance coefficient, which can be calculated by vehicle speed. The engine speed and torque also can be simulated according to the transmission ratio of the bus. See the detailed calculation method from the reference of

Table 1 Technical specifications of the test engine and vehicle

Parameter	Engine	In-use bus
Engine type	Common rail direct-injection inline 4 cylinder diesel engine turbocharged intercooler	Common rail direct-injection inline 4 cylinder diesel engine turbocharged intercooler
Displacement	5.308 L	7.1 L
Maximum power at r/min	132 kW at 2300 r/min	213 kW at 1800–2100 r/min
Maximum torque at r/min	660 N·m at 1400–1600 r/min	1200 N·m at 1050–1650 r/min
Emission level	Euro III	Euro IV
After treatments	None	Selective catalytic reduction (SCR)

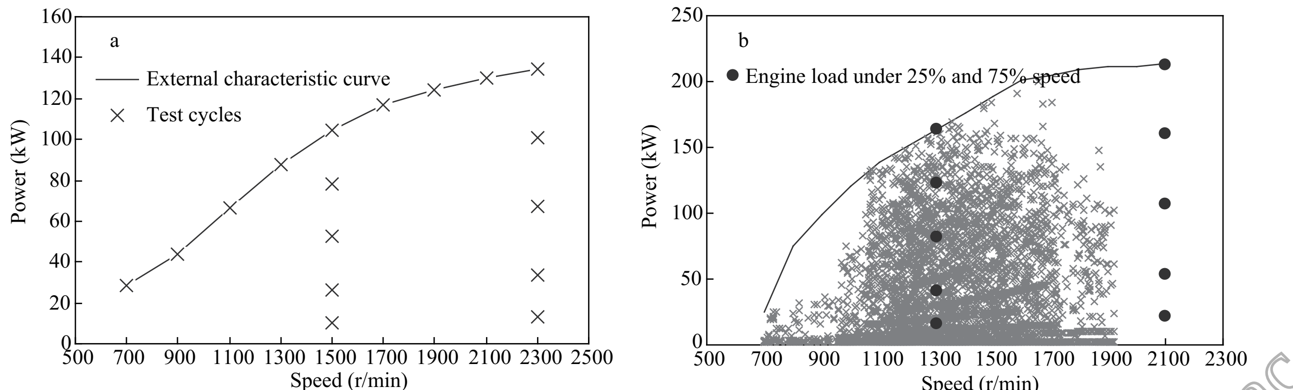

Fig. 1 Comparison of the engine performance of test bench (a) and on-board measurement (b).

Huang et al. (2010). Figure 1 shows the comparison of engine performance between the test bench and on-board measurement studies. It is indicated from Fig. 1b that the engine performance in the real-world driving condition has large differences compared with the bench test cycle. The engine was mainly operated on medium and low engine speed and load in real-world driving conditions, as discussed by Liu et al. (2011).

1.3 Emission measurement system

With the growing attention on the particle number and size distribution from diesel engines, various kinds of real-time particle measurement devices have been employed in both test bench and on-board measurement (Vogt et al., 2003; Durbin et al., 2007; Liu et al., 2009; Johnson et al., 2011). In this study, a fast scanning particle size spectrometer (EEPS 3090, TSI Inc.) was used during the test. The EEPS system has been successfully applied in previous on-board measurement studies (Bergmann et al., 2009; Merkisz et al., 2009). In order to simulate the actual dilution process of engine exhaust in real-world situations, a rotating disc and thermo-diluter was installed before the EEPS system to remove the large particles above the instrument's size range and dilute the sample flow 500 fold. The EEPS spectrometer counts particles in the range from 5.6 to 560 nm at a 10 Hz data collection frequency and operates over a wide particle concentration range down to 200 particles/cm^3, and at ambient pressure to prevent evaporation of volatile and semi-volatile particles. The equipment was installed around some buffers to reduce the vibration during the real-world test.

The on-board measurement system was installed in the bus and warmed up before each test. A barometer was also mounted to measure ambient humidity and temperature. Vehicle speed, altitude, latitude, and longitude were logged continuously by a GPS device. A water tank was loaded to simulate a heavy load condition. The total weight of the devices, batteries, and water tanks accounted for approximately 60% of the GVWR of the bus. The condensation of water and high molecular weight hydrocarbons was prevented by heating the sampling tube up to 190°C during the test. Figure 2 shows the schematic diagram of the installation of the on-board measurement system.

2 Results and discussion

2.1 Ultrafine particle emission characteristics of diesel engine by bench test

Figures 3a and 3d shows the ultrafine particle number and size distribution of each speed on the external characteristic curve. The particle number concentration under full load conditions was in the range of (2.00–8.35) × 10^8 cm^{-3} and showed a "U" shape distribution. The particle number concentration under low speed (700–1100 r/min) and maximum power speed (2300 r/min) achieved the highest levels, while the particle number under medium speed (1500–1900 r/min) reached the lowest. The particle size for each speed exhibited a single mode distribution. The peak size was about 50 nm in the accumulation particle range. Figure 3b and 3e indicates the particle number and size distribution of different loads for the speed of 1500 r/min. The particle number concentration was in the range of (0.56–3.07) × 10^8 cm^{-3}. Except for 10% load, the particle number under other loads was at the same emission level. The particle size for loads from 25% to 100% also showed a single mode distribution. For 10% load, the particle size showed a bimodal distribution. The ratio of nucleation mode particle increased compared with other engine loads. The particle number for max. power speed (2300 r/min) generally showed a growth trend with increasing engine load. However, the particle size distribution under low load ($\leqslant$ 50%) conditions was significantly different from the high load condition. Nucleation mode particles increased to 3.0 × 10^8 cm^{-3} at 10 nm diameter.

Generally, ultrafine particle emission under medium speed was relatively low. Lower or higher speed operations promoted the formation of ultrafine particles. Particle number concentration showed a growth trend with load. In addition, the nucleation mode particles tended to occur under low engine load. Nucleation mode particles are formed by carbon particles and the nucleation of sulfuric acid or other gaseous precursors such as HC. Under low load conditions, HC and other gaseous precursors are relatively prone to promoting the generation of nucleation mode particles. Especially for high speed situations, a high concentration of carbon particles and unburned gaseous

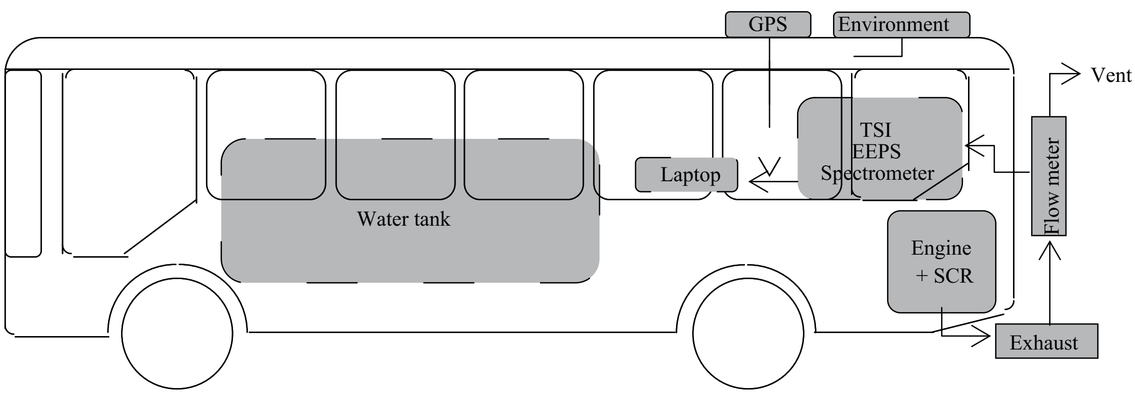

Fig. 2 Schematic diagram of the installation of on-board measurement system.

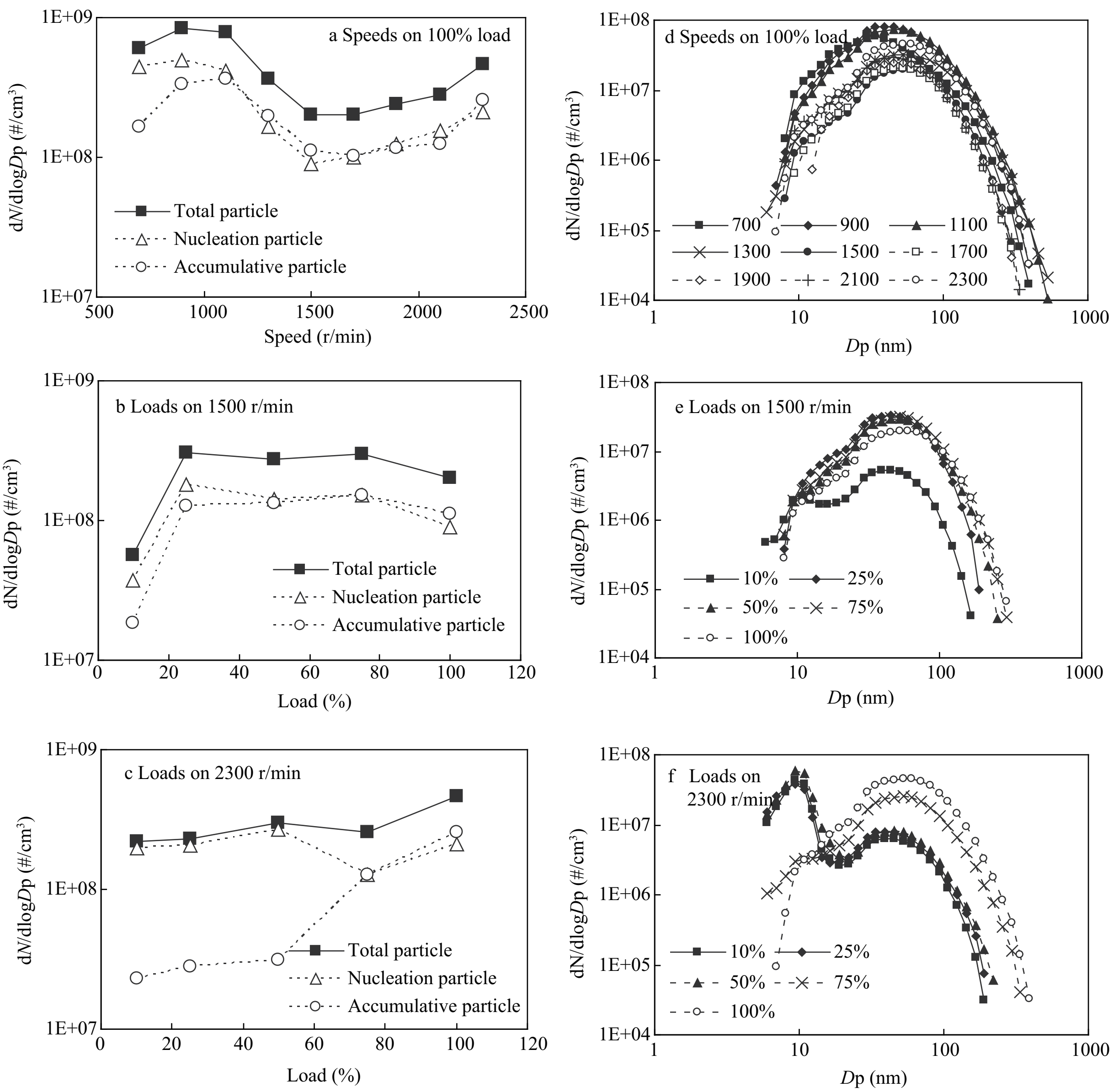

Fig. 3 Particle number (a, b, c) and size distributions (d, e, f) for different test cycle points in the bench test.

emissions contributes to the nucleation of nano-particles.

2.2 Instantaneous ultrafine particle emission change under on-road driving conditions

The ultrafine particle number emission factor of the whole real-world test cycle was about 7.6×10^{14} km^{-1}. The emission factor of ultrafine particle mass was 0.42 g/km based on the conversion of particle number in each size by assuming a density of 1 g/cm. In this study, we mainly focused on the emission characteristics of ultrafine particle number for the real-world driving cycles. Figure 4 shows a whole driving cycle fragment of the test bus in real-world driving conditions. Its engine power, nucleation and accumulation mode particle number, and size distribution are also described in the figure. Compared with the bench test, the particle emission under real-world driving conditions was more complex. The real time on-board measurement instrument could accurately capture the particulate emission characteristics with the change of driving cycles. The particle number concentration during idling operation remained at 2.7×10^7 cm^{-3}, and the particle size was mainly concentrated in the accumulation mode. During acceleration operation, the engine power sharply increased, and the particle number concentration simultaneously rose to 5.0×10^8 cm^{-3} or higher levels. Acceleration operation increased the fuel injection and decreased the air fuel ratio. High temperature and hypoxic conditions produced a higher amount of nanoparticles and also enhanced their chance of collision and conglomeration to form more accumulation mode particles. In the deceleration processes, the engine operated at low load condition and the particle number rapidly decreased to about 2.0×10^6 cm^{-3}, even lower than for idling operation, while the particle emission for deceleration operation was mainly composed of nucleation mode particles. The reason could be that more HC and other unburned organic compounds were emitted and were further nucleated to nanoparticles at low engine load condition (Mathis et al., 2004).

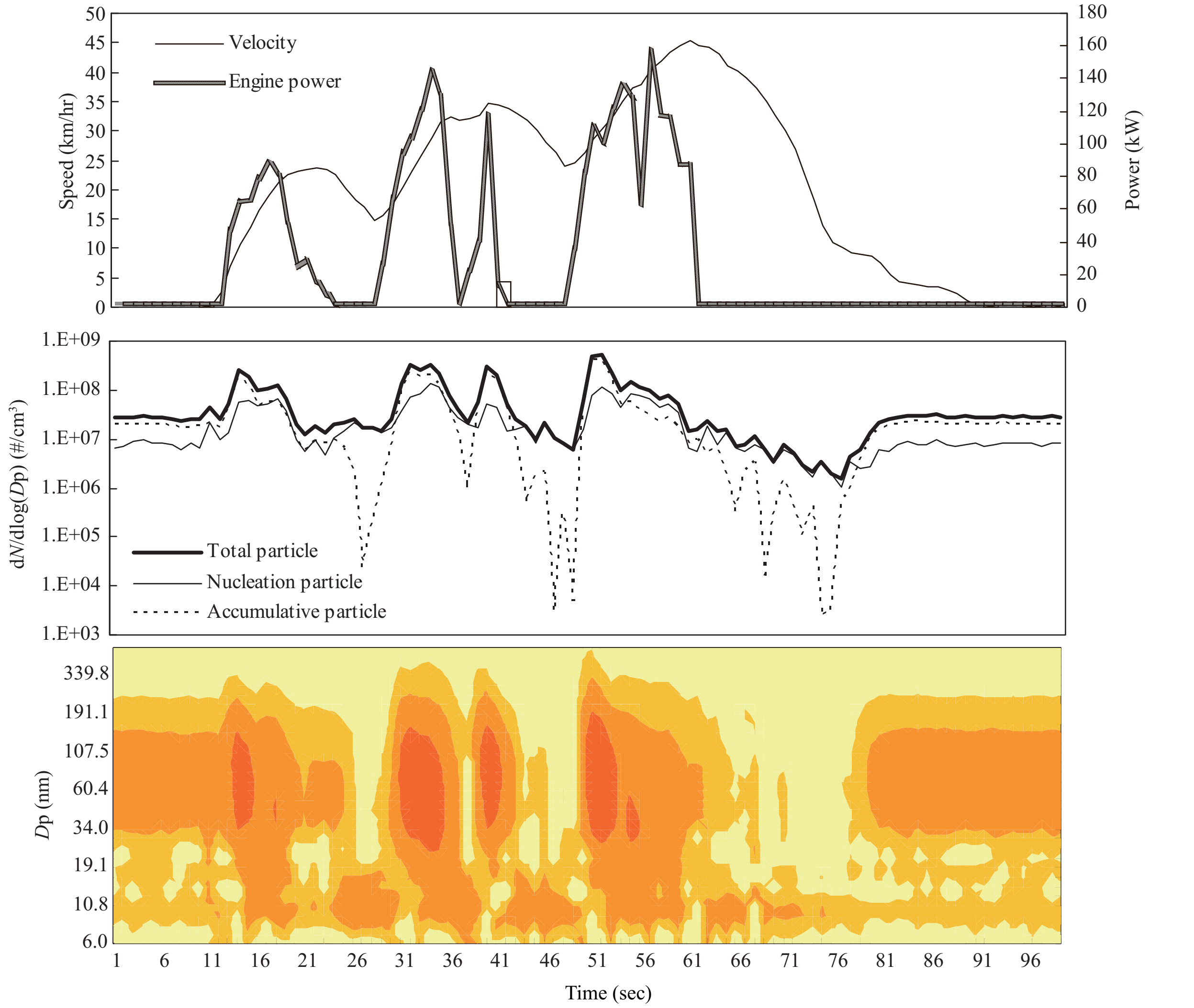

Fig. 4 Segments of instantaneous particle number and size distribution emission under variable driving conditions. Deeper color in the last chart means higher particle number.

2.3 Comparison of ultrafine particle emission characteristics from test bench and on-board measurements

According to the simulation results of engine performance in real-world driving conditions, the particle number concentration distribution under different engine speeds and loads of the test bus is shown in Fig. 5a. Figure 5b indicates the particle number concentration for each engine speed and load of the engine. By comparison, the ultrafine particle emission level of the test Euro IV bus was relatively lower than the Euro III engine. However, the distributions of particle number concentration with changing engine speeds and loads are basically consistent with each other. The real-world test results show that particle number generally increased with the growth of engine load at

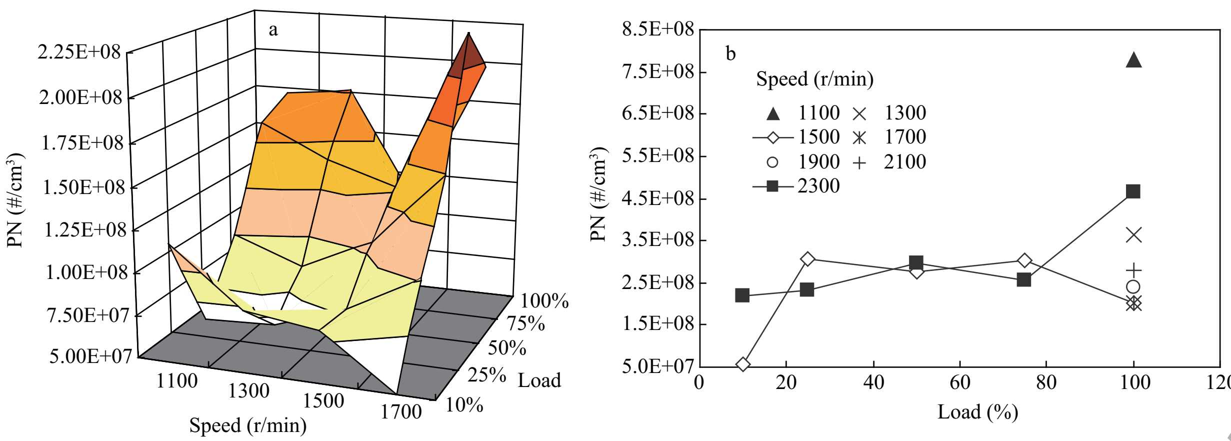

Fig. 5 Particle number (PN) concentration distribution of each engine speed and load based on real-world (a) and test bench studies (b).

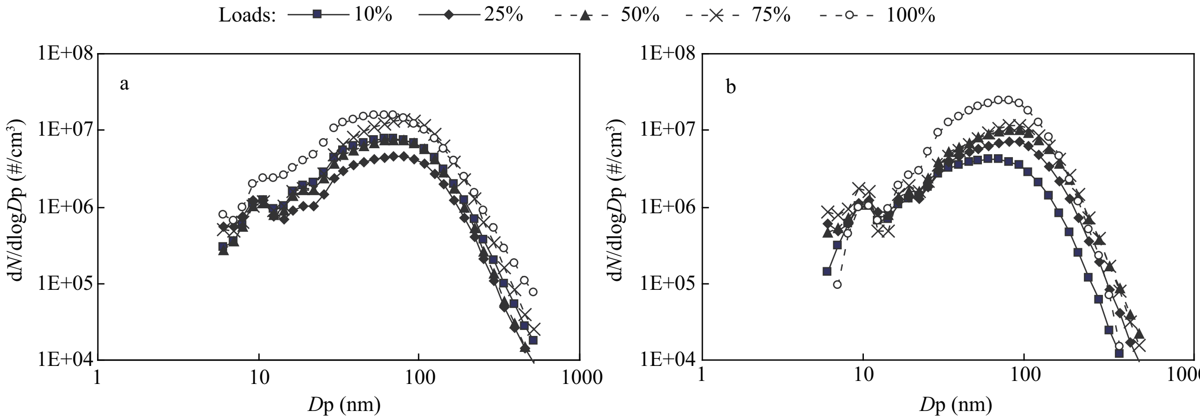

Fig. 6 Particle size distribution at different engine loads for the speeds of 1300 r/min (a) and 1700 r/min (b) based on real-world measurement.

each speed. At high load condition, the particle number concentration shows a “U” shape distribution with engine speed.

Figure 6 selects the particle size distribution of different engine loads at the maximum torque speed (1300 r/min and 1700 r/min). The particle size distribution under different engine conditions generally remains the same and shows a single mode distribution. This is similar to the engine bench test where nucleation mode particles were a low proportion of the total particles, which could be induced by the reduction of diesel sulfur content from 2009 in Shanghai. In addition, since we did not capture the max. power speed under real-world driving conditions, it cannot be proved if the nucleation mode particles would have increased a great deal under high engine speed operation.

3 Conclusions

This study discussed the ultrafine particle emission characteristics derived from engine bench and real-world diesel bus measurements, respectively. The bench test results showed the emission characteristics of ultrafine particles under different engine operations. Correspondingly, the on-board measurement results also illustrated that the ultrafine particle emission was strongly correlated with changes of the real-world driving cycle. In addition, the engine performance simulation results based on on-board measurement data presented great differences compared with the bench test cycle. However, the results both indicated that the particle numbers in the range of 5.6–560 nm measured for the diesel engine and on-road diesel bus were basically at the same level, about 10^7–10^8 cm^{-3}. The particle number concentration of the Euro III diesel engine was relatively higher than that of the Euro IV diesel bus. However, given the large differences in the experimental method and test cycle of the bench and on-board measurements, it is hard to accurately demonstrate the differences in particle emission levels between these two engine types. It can also be concluded that the distributions of particle number concentration under different engine speeds and loads are basically consistent between the test bench and on-board measurement. The particle number results measured by the two methods both showed a growth trend with increasing engine load at each engine speed. The particle number presented a “U” shape distribution with changing speed at high engine load driving conditions, suggesting that the particle number emission is relatively lower for medium speed operation. The particle sizes generally showed single mode distributions for both test methods possibly due to the reduction of diesel sulfur content in Shanghai. The peak of particle size was located at about 50–80 nm in the accumulation mode particle range. For low engine load operations like idling and decelerating, the proportion of nucleation mode particles was significantly higher than for the other driving conditions. However, the experimental sample in this study is relatively small and some analysis is based on simulation data, which introduces certain errors compared with the actual situation. Therefore, more experimental studies need to be carried out to accurately explain the ultrafine particle emission characteristics of diesel engine and associated impact factors.

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