Future Regulation-based Particle Number Emission Characteristics for a Heavy-duty Diesel Engine

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Abstract: In this paper, a 7.8L heavy-duty diesel engine was selected to run WHSC (World harmonized Steady-State Cycle), Hot and Cold WHTC (World harmonized Transient-State Cycle) and CHTC (China Engine Transient-State Cycle) on the engine test bed. The particle emissions were measured by using a particle counter which can simultaneously measure PN10 (number of particles above 10nm) and PN23 (number of particles above 23nm) and other equipment. The results show that the transient emission of PN10 and PN23 have basically the same trends under different cycles. The brake specific emission of PN10 is 21%-105% higher than that of PN23. The brake specific emission of PN for CHTC is higher than that for WHTC. After weighting of cold and hot cycle, the brake specific emission of PN10 of CHTC is 91.16% higher than that of WHTC, and the brake specific emission of PN23 of CHTC is 154.66% higher than that of WHTC. The correlation coefficient between PM and PN23 is 0.995, while the correlation coefficient between PM and PN10 is 0.895. The correlation between PM emissions and PN23 is stronger.

Key words: Heavy duty diesel engine, WHSC, WHTC, CHTC, PN10, PN23.

1. Introduction

The government issued the "Limits and Measurement Methods for Pollutant Emissions from Heavy Duty Diesel Vehicles (China's Sixth Phase)" [1]. This regulation required to change the test cycles from ESC (European Steady State Cycle) and ETC (European Transient Cycle) to WHSC (World Unified Steady State Cycle) and WHTC (World Unified Transient Cycle). Additionally, the number of particulate matter (PN) with a particle size between 23nm-2.5 μm must be counted and limited in the test cycles.

However, with the in-depth study of the emission of particulate matter, it was found that the emission of particles smaller than 23nm is also very serious [2-3]. Moreover, because these fine particles have a higher deposition efficiency in the respiratory system and can be transferred to other human organs such as the brain, such fine particles are more harmful to the human body [4]. Studies have shown that 30%-
50% of GDI (gasoline direct injection) engine particulate matter, and 50%-100% of PFI (port fuel injection) engine particulate matter, are not controlled under the current particulate matter testing methods[5-6]. The European Union has set up a DTT (Down to Ten) working group, which is discussing extending the range of particulate matter size measurement from the current above 23nm to above 10nm (also called sub-23nm). The Pollutant Monitoring Center of the Ministry of Ecology and Environment of China also set up a working group to carry out related pre-research work.

At present, the research on particulate matter with size above 10nm is mainly concentrated on light gasoline vehicles and light diesel vehicles [5-7], and there is less attention to heavy diesel engines. However, due to the increase in the pressure of the high-pressure common rail of heavy-duty diesel engines, the finer diesel spray causes the generated particle size to continue to decrease. In this context, a 7.8L heavy-duty diesel engine was selected to run WHSC (World harmonized Steady-State Cycle), Hot and Cold WHTC (World harmonized Transient-State Cycle) on the engine test bed. The particle emissions were measured by using a particle counter which can simultaneously measure PN10 (number of particles with size above 10nm) and PN23 (number of particles with size above 23nm) and other equipment. Meanwhile, as future regulations may also adopt CHTC(China Engine Transient-State Cycle) [8], a particulate matter emission test under CHTC has also been carried out to compare and analyze the differences between PN10 and PN23 under different test cycles.

2. Experimental Setup

2.1. Experimental test equipment

Two sets of AVL particle counters were used to measure the particle number in this paper. 1# particle counter that meets the China VI regulation was used to measure PN23. The equipment first removes volatile particles through a volatile particle remover (VPR), and then counts particles above 23nm through a particle counting unit (CPC). 2# particle counter was the latest particle counter developed by AVL against future regulations which can measure both PN10 and PN23. Compared with the 1# particle counter, 2# particle counter adds a catalyst in the VPR to oxidize vaporized hydrocarbons and store sulfides to minimize the impact on particle number testing. At the same time, the CPC was upgraded. The counting efficiency of PN10 of 2# particle counter is greater than 50%, and the counting efficiency of PN15 (the number of particle size above 15nm) is greater than 90%. The sampling positions of the two particle counters are as close as possible to eliminate the influence of pipeline deposition on the particles, as shown in Figure 1.

![Figure 1. Sampling position of the Two particle counters](image)

In addition to particle counters, the equipment used in this article also includes AVL electric dynamometer, gas emission analyzer, particle quality sampling equipment AVL 472, fuel consumption meter, etc. The main test equipment is shown in Table 1.
Table 1. Test equipment

| Equipment name                          | Equipment Type and Manufacturer |
|----------------------------------------|--------------------------------|
| AC Dynamometer                         | AVL INDY P44                   |
| Test bed control system                | AVL PUMA Open V1.5.3           |
| Intake air temperature conditioning    | AVL Air Conditioning System 2400 |
| Gaseous emission measurement          | AVL Emission Bench AMA i60     |
| Fuel consumption measurement          | AVL 753C/735S                 |
| 1# particle counter                    | AVL 489                       |
| 2# particle counter                    | AVL APC<sup>plus</sup> ADVANCED with AVL CPC option for sub-23nm |
| particle quality sampling equipment    | AVL SPC 472                   |
| Weighing balance                       | CPA2P-F                       |
| Weighing chamber                       | RXCH-500                      |

2.2. Tested engine
The engine used in this paper was a heavy-duty diesel engine with a displacement of 7.8 liter which meets the China VI emission legislation. The specific parameters of the engine are shown in Table 2.

Table 2. Main parameters of tested engine

| Parameter                          | Value                  |
|------------------------------------|------------------------|
| Engine capacity                    | 7.8 L                  |
| Bore×Stroke                        | 115 mm×125 mm          |
| Compression ratio                  | 17.5                   |
| Rated power/speed                  | 228 kW/2400 rpm        |
| Maximum torque/speed               | 1130 Nm/1400 rpm       |
| Idle speed                         | 525 rpm                |
| Emission Control Technology Route  | EGR+DOC+DPF+SCR+ASC    |
| Emission Standards                 | China VI               |

2.3. Test plan
WHSC, Cold WHTC(WHTC-C), Hot WHTC (WHTC-H), Cold CHTC(CHTC-C) and Hot CHTC (CHTC-H) were separately run on the engine test bed. The Particle mass (PM), PN10 and PN23 were all measured for each tests.

3. Results and Discussions

3.1. Impact of PN test equipment
The results of measuring PN23 emissions using 1# particle counter and 2# particle counter are shown in Figure 2. It can be seen from the figure that the maximum deviation of the PN23 measured by the two particle counters is 3.15% under the cold WHTC cycle, and the minimum deviation is 1.38% under the hot CHTC cycle, indicating that although the two particle counters have different pre-processing devices, it has little effect on the measurement results of PN23. This conclusion is basically consistent with the conclusions of previous studies [9-10]. The particulate matter number emissions of steady state WHSC, hot and cold WHTC, hot and cold CHTC are all lower than the limit of 6×10<sup>12</sup> #/kW.h required by regulations. And the value of PN23 of 2# particle counter is all higher compared with the 1# particle counter. This may be because the sampling position of the 2# particle counter is in the front of the 1# particle counter. A part of the exhaust particles will be deposited in the exhaust pipe and cause a certain
loss. Since the PN23 emissions of the two devices are not much different, the PN23 emissions refer to the measured value of the 2# particle counter in the subsequent comparative analysis.

![Figure 2. PN23 emissions tested by two particle counters](image)

3.2. **PN10 and PN23 emission characteristics under the WHSC cycle**

Figure 3 shows the transient emission values of PN10 and PN23 under the WHSC cycle. Under steady-state conditions, the trends of PN10 and PN23 are basically the same, and the emissions of PN10 are higher than those of PN23. In transitional conditions, such as the transition from the first operating condition to the second operating condition, the emissions of PN10 and PN23 will increase to a certain extent.

![Figure 3. PN transient emission under WHSC cycle](image)

WHSC is a steady-state test cycle consisting of thirteen working conditions. From this test, the variation of PN emission with engine speed and load is extracted, as shown in Figure 4. The changing trends of PN10 and PN23 are the same. For 35% of engine speed, when the load increases, the brake specific emissions of PN10 and PN23 gradually decrease. For 45% of engine speed, the brake specific emission of PN10 and PN23 gradually increases with load increases. At 55% of engine speed, the brake specific emissions of PN10 and PN23 first increasing, then decreasing and then increasing with load increases. The PN emission inconsistent variation trend with load at different speed may be due to the inconsistent filtration efficiency of the particulate filter (DPF) at different exhaust flow rates.
Figure 4. PN transient emission under WHSC cycle

Figure 5 shows the brake specific emissions of PN10 and PN23 under the WHSC cycle. The brake specific emission of PN10 is $4.84 \times 10^{11}$ #/kW.h, and of PN23 is $3.13 \times 10^{11}$ #/kW.h, respectively. The brake specific emission of PN10 is 54.61% higher than that of PN23, but they all meet the limitation of current emission regulations.

Figure 5. Brake specific emissions of PN10 and PN23 under the WHSC cycle

3.3. PN10 and PN23 emission characteristics under the WHTC cycle

Figure 6 shows the brake specific emissions of PN10 and PN23 of cold WHTC, hot WHTC and weighted WHTC. The brake specific emissions of PN10 of the cold and hot WHTC are $3.82 \times 10^{11}$ #/kW.h, $2.42 \times 10^{11}$ #/kW.h, respectively. The brake specific emissions of the PN23 of the cold and hot WHTC are $2.82 \times 10^{11}$ #/kW.h, $1.18 \times 10^{11}$ #/kW.h, respectively. The PN10 of cold WHTC is 35.34% higher than that of PN23, while the PN10 of hot WHTC is 105.42% higher than that of PN23. The conclusions of this paper are consistent with Khan et al. [10] who studied two diesel engines with DOC+DPF+SCR and found that the brake specific emissions of PN10 are 40%~137% higher than those of PN23 under multiple cycles. PN10 and PN23 of cold WHTC are 58.09% and 139.91% higher than PN10 and PN23 of hot WHTC, respectively. The brake specific emissions of PN10 and PN23 of weighted WHTC are $2.61 \times 10^{11}$ #/kW.h and $1.41 \times 10^{11}$ #/kW.h, respectively, which all meet the limitation of current emission regulations.
Figure 6. Brake specific emissions of PN10 and PN23 of cold WHTC, hot WHTC and weighted WHTC

Figure 7 shows the transient emissions and cumulative emissions of PN10 and PN23 of cold WHTC. The trends of PN10 and PN23 are very consistent, with a higher peak around 75 seconds and 375 seconds. In the last 300 seconds of the cycle, the emission increase of PN10 was more obvious than that of PN23.

Figure 7. Transient emissions and cumulative emissions of PN10 and PN23 of cold WHTC

Figure 8 shows the transient emissions and cumulative emissions of PN10 and PN23 of the hot WHTC. Similar to the cold WHTC, the trend of PN10 and PN23 is very consistent, with a higher peak around 75 seconds and 375 seconds. The growth rate of PN10 in the last 300 seconds of hot WHTC is higher than that of PN23.
3.4. PN10 and PN23 emission characteristics under the CHTC cycle

Figure 9 shows the brake specific emissions of PN10 and PN23 of cold CHTC, hot CHTC and weighted CHTC. The brake specific emissions of PN10 of the hot and cold CHTC are $4.5 \times 10^{11} \#/\text{kW.h}$, $5.08 \times 10^{11} \#/\text{kW.h}$, and the brake specific emissions of the PN23 of the cold and hot CHTC are $3.74 \times 10^{11} \#/\text{kW.h}$, $3.56 \times 10^{11} \#/\text{kW.h}$. The PN10 of cold CHTC is 20.38% higher than that of PN23, while the PN10 of hot CHTC is 42.67% higher than that of PN23. The PN10 of the cold CHTC is 11.42% lower than the PN10 of the hot CHTC and the PN23 of the cold CHTC is 4.97% higher than the PN23 of the hot CHTC. The brake specific emissions of PN10 and PN23 of weighted CHTC are $5.0 \times 10^{11} \#/\text{kW.h}$ and $3.59 \times 10^{11} \#/\text{kW.h}$, respectively, which all meet the limitation of current emission regulations.

Figure 8. Transient emissions and cumulative emissions of PN10 and PN23 of hot WHTC

Figure 9. Brake specific emissions of PN10 and PN23 of cold CHTC, hot CHTC and weighted CHTC.

Figure 10 shows the transient emissions and cumulative emissions of PN10 and PN23 of cold CHTC. The trends of PN10 and PN23 are very consistent, with a higher peak around 358 seconds and 426 seconds. And in the first 1500 seconds of the cold CHTC cycle, the cumulative emissions of PN10 and PN23 are not much different. Only in the last 300 seconds of the cycle, the emission increase of PN10 is more obvious than that of PN23.
Figure 10. Transient emissions and cumulative emissions of PN10 and PN23 of cold CHTC.

Figure 11 shows the transient emissions and cumulative emissions of PN10 and PN23 of the hot CHTC. Similar to cold CHTC, the trend of PN10 and PN23 is very consistent, and there are two higher peaks around 358 seconds and 426 seconds. In the last 300 seconds of the cycle, the emission increase of PN10 was more obvious than that of PN23. In addition, compared with cold CHTC, PN10 and PN23 emissions are very low in hot CHTC before 358 seconds. Cold CHTC has two smaller peaks before a larger peak appears at 358 seconds. This is mainly due to the incomplete combustion under cold conditions leading to increased particulate matter production.

Figure 11. Transient emissions and cumulative emissions of PN10 and PN23 of hot CHTC.

3.5. Impact of test cycle on PN10 and PN23 emissions

Figure 12 shows the PN brake specific emissions under different test cycles. For PN23, the hot WHTC cycle PN brake specific emission is the lowest, followed by cold WHTC, hot CHTC and cold CHTC. For PN10, the hot WHTC PN brake specific emission is also the lowest, followed by cold WHTC, cold CHTC and hot CHTC. The brake specific emission of PN under CHTC is higher than that of WHTC. After weighting, the brake specific emission of PN10 under CHTC is 91.16% higher than that of WHTC, while brake specific emission of PN23 under CHTC is 154.66% higher than that of WHTC.
Although the load rate of CHTC is lower than that of WHTC, the exhaust temperature is also lower, which will affect the entire after-treatment system, especially the DPF system, and thus affect the final PN emission.

![Graph showing PN brake specific emissions under different test cycles.](image)

**Figure 12.** PN brake specific emissions under different test cycles.

### 3.6. Correlation of PM and PN emissions

Figure 13 shows the emission distribution data of PM, PN10 and PN23 for five cycles including hot and cold WHTC, hot and cold CHTC and WHSC. It can be seen from the figure that the correlation coefficient between PM and PN23 is 0.995, while the correlation coefficient between PM and PN10 is 0.895. The correlation between PM emissions and PN23 is stronger, indicating that larger particulate matter has a greater contribution to the quality of particulate matter.

![Graph showing correlation of PM and PN emissions.](image)

**Figure 13.** Correlation of PM and PN emissions.

### 4. Conclusion

The particulate matter emission test results of this diesel engine under different test cycles indicated that:

1) The transient emission of PN10 and PN23 have basically the same trends under different cycles. The brake specific emission of PN10 is 21%-105% higher than that of PN23. The cold state CHTC has the smallest gap, and the hot state WHTC has the largest gap.

2) The PN brake specific emission of CHTC is higher than that of WHTC. After weighting, the brake specific emission of PN10 under CHTC is 91.16% higher than that of WHTC, while brake specific emission of PN23 under CHTC is 154.66% higher than that of WHTC.

3) The correlation coefficient between PM and PN23 is 0.995, while the correlation coefficient between PM and PN10 is 0.895, and the correlation between PM emissions and PN23 is stronger.
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