Comparative Study of Sub-23nm Particle Number Emission Characteristics for Non-road Diesel Engine on RMC and NRSC Test

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Abstract. A non-road diesel engine meeting China IV emission regulation was selected, the RMC and NRSC test procedures of the EU non-road Stage V emission regulation were run on the engine test bench. The emissions of particle number (PN) with particle sizes above 23 nm and 10 nm were tested simultaneously using direct exhaust sampling and full-flow dilution channel CVS dilution sampling equipment. The results showed that the emission characteristics of particulate matter above 23 nm and above 10 nm in the RMC test had the same trend, and the cumulative PN emissions were 1.9×1012 and 2.3×1012 for the whole test cycle, respectively. The PN23 values of dilution sampling were higher than those of direct sampling. The main reason for the difference in PN emission values at the same working modes in RMC and NRSC is the change in DPF capture efficiency caused by the different order of working modes and conditions.

Keywords: Non-road diesel engine, Sub-23nm, Particle number (PN), RMC, NRSC.

1. Introduction

Sub-23 nm particles are classified as exhaust particulate matter with a geometric mean diameter (GMD) smaller than 23 nm[1]. A growing number of studies have found that the prevalence of sub-23 nm particles in the exhaust and their volatile, as well as solid nature [2-3], pose even stronger harms to human health than the legislated due to larger surface/volume ratio and higher reactivity [4-5].

Focusing on the internal combustion engine sector, along with the commercialization of advanced combustion concepts, emission reduction technologies, and renewable fuels, sub-23 nm particles in the total particle number (TPN) could further climb [6-7].

According to the "China Mobile Source Environmental Management Annual Report (2022)" released by the Ministry of Ecology and Environment [8], China's PM emissions from non-road mobile sources will be 234,000 tons in 2021, much larger than the 64,000 tons of PM emissions from automobiles, so particulate matter emissions from non-road mobile machinery need to be controlled urgently.

EU stage V regulation introduced a new limit for particle number emissions. The PN limit is designed to ensure that a highly efficient particle control technology—such as wall-flow particulate filters—be used on all affected engine categories. The Stage V regulation also tightened the mass-based PM limit for several engine categories, from 0.025g/kWh to 0.015g/kWh. Adopting particle number (PN) emission limits for several categories of CI engines between 19 and 560 kW.The regulation of "Limits and measurement methods for exhaust pollutants from diesel engines of non-road mobile machinery(China's Fourth Phase)" [9] was revised and updated in 2020, which not only sets limitation on particulate matter quality, but also requires to count the particle number with a particle size above 23nm(PN emission) for 37-560kW diesel engine. The limitation of PN emission is 5×10^{12}#/kWh at the non-road steady cycle(NRSC) and the non-road transient cycle (NRTC), respectively.

However, laboratory tests reveal that particles from vehicle engine in sub-23nm region should not be neglected[10].Particle filter in current exhaust aftertreatment units may have to improve the efficiency of trapping fine particles smaller than 23 nm. However, there are few studies on PN10 for non-road diesel engines, and none of them consider the adaptability of non-road diesel engines meeting China emission regulations to EU regulation cycles and the differences in test cycles.

In this study, the PN10 and PN23 emission characteristics of non-road diesel engine running the RMC test meeting the China IV regulation was comparatively studied, and the PN emissions at each operating point of the RMC and NRSC test cycles were compared and analyzed.

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2. Test bench and method

2.1 Test bench

The following is a schematic diagram of the engine full-flow emission test bench, which contains a non-road diesel engine, an electric dynamometer, an intake air conditioner, an intake flow meter, a fuel flow meter, a full-flow dilution channel, two particulate counters, and a test control and data logging system.Our testing system includes two particle counters, the first (PN#1) is sampled directly through the exhaust line and the second (PN#2) is sampled through the CVS dilution.

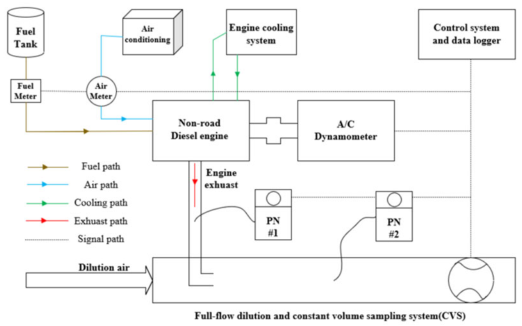

Fig. 1. The schematic diagram of test bench

2.1.1 Test engine

The tested engine was a non-road diesel engine with a displacement of 8.71 liter with a rated power of 305 kW and a maximum torque of 1850 Nm. The specific parameters of the engine can be seen in Table 1.

Table 1. Main parameters of tested engine

Parameter	Value
Engine capacity	8.71L
Cylinder number-Bore×Stroke	6-117mm×135mm
Compression ratio	15.9
Rated power/speed	305kW/2000rpm
Maximum torque/speed	1850Nm/1300-1400rpm
Idle speed	900±100rpm
Emission Control Technology Route	DOC+DPF+SCR+ASC
Emission Standard	China Non-road IV

2.1.2 Test equipment

The main test equipment is summarized in Table 2, including the equipment type, manufacturer and accuracy.

Table 2. Test equipment

Equipment name	Equipment Type and Manufacturer	Accuracy
AC Dynamometer	Horiba HD600	Torque: ±0.3%F.S. Speed: ±1rpm
Intake air conditioning	CAC4000-C	Temperature: ±1K Humidity:±3(%RH)
Air flow meter	Sensyflow FMT700-P	±1%
Fuel meter	Horiba FQ-3100DP	±0.1%
Full-flow dilution sampling system(CVS)	CVS DLT-24150W	±1%
Particle counter #1 (for CVS dilution sampling)	MEXA-2000SPCS	±10%
Particle counter #2 (for exhaust pipe direct sampling)	AVL APC^{Plus} ADVANCED with AVL CPC option for sub-23nm	±8%

2.2 Test procedure and analysis method

2.2.1 Test cycle

According to Non-road EU V emission regulation, at the choice of the manufacturer, a steady-state test cycle may be run as a discrete-mode cycle or a ramped-modal cycle. Based on the engine category, we select the C1 steady-state test cycle, which consists of 8 speed and load modes. Ramped Modal non-road steady-state test Cycle (“RMC”) test sequence, which is hot running cycle where emissions shall be started to be measured after the engine is started. The engine shall be continuously controlled by the test bed control unit during the RMC test cycle. The gaseous and particulate emissions shall be measured and sampled continuously during the RMC test cycle in the same way as in a transient cycle. An RMC is intended to provide a method for performing a steady-state test in a pseudo-transient manner.

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Table 3. RMC-C1 test modes

RMC mode number	Mode time[s]	Engine speed	Torque[%]
1a Steady-state	126	Idle	0
1b Transition	20	Linear transition	Linear transition
2a Steady-state	159	Intermediate	100
2b Transition	20	Intermediate	Linear transition
3a Steady-state	160	Intermediate	50
3b Transition	20	Intermediate	Linear transition
4a Steady-state	162	Intermediate	75
4b Transition	20	Linear transition	Linear transition
5a Steady-state	246	100 %	100
5b Transition	20	100 %	Linear transition
6a Steady-state	164	100 %	10
6b Transition	20	100 %	Linear transition
7a Steady-state	248	100 %	75
7b Transition	20	100 %	Linear transition
8a Steady-state	247	100 %	50
8b Transition	20	Linear transition	Linear transition
9 Steady-state	128	Idle	0

Each RMC consists of a series of steady state modes with a linear transition between them. The relative total time at each mode and its preceding transition match the weighting of the discrete mode steady state cycle("NRSC"). The change in engine speed and load from one mode to the next one has to be linearly controlled in a time of 20±1 seconds. The mode change time is part of the new mode (including the first mode). In some cases modes are not run in the same order as the discrete model steady state cycles or are split to prevent extreme changes in temperature.

2.2.2 Analysis method

This section describes data processing and calculation methods for exhaust direct sampling and CVS dilution sampling.
For direct sampling through the exhaust pipe:

$$T_{PN} = G_{\text{exh}} \cdot c_{PN} / \rho_{exh} / 0.0036$$

$$G_{\text{exh}} = G_{fuel} + G_{air}$$

Where: TPN is the instantaneous particle number(#/s), Gexh, Gfuel, Gair are the exhaust, fuel and intake air mass flow rates respectively (kg/h), cPN is the PN concentration(#/cm^3) measured by the direct sampling equipment, PN#1 , ρexh is the exhaust density (as 1.2943 kg/m^3)

$$N_{PN} = \int_0^t T_{PN} dt$$

Where: NPN is the cumulative particle number(#).
For dilution sampling through CVS :

$$T_{PN-CVS} = 10^6 \times Q_{CVS} \cdot c_{PN-CVS}$$

Where: TPN-CVS is the instantaneous particle number(#/s), QCVS is the dilution channel CVS volume flow rate (m^3/s), cPN-CVS is the PN concentration (#/cm^3) measured by the dilution sampling equipment, PN#2.

$$N_{PN-CVS} = \int_0^t T_{PN-CVS} dt$$

Where: NPN-CVS is the cumulative particle number(#).
Particle number per unit cycle work, PN(#/kWh):

$$PN = \frac{N_{PN}}{W} = \frac{N_{PN}}{\int n \cdot T / 9550}$$

Where: W is the cycle work(kWh), n is the engine speed(r/min), T is the engine torque(Nm).
In the calculation, it should be noted that the RMC test is a full process including the integration of steady-state and transient transition conditions, while the NRSC test is only the calculation of steady-state conditions and does not include the part of transient transition conditions.

3. Results and discussions

3.1 PN10 and PN23 results under RMC test

Comparative analysis of PN10/PN23 recorded by the direct particle counter and PN23 recorded by the CVS dilute particle counter during the RMC test, results showed that the concentration and cumulative emission changes of PN10 and PN23 in the RMC test had the same trend, with cumulative PN emissions of 2.3×10^{12} and 1.9×10^{12} for the whole cycle, respectively. At the transition of switching between each working mode of RMC, such as the 5th to 6th working mode for the sudden drop of 100% load to 10% load under rated speed condition, the PN emission sudden increase changes obviously, and the PN emission rate of the 6th working mode is the largest. In addition, the PN emission is generally higher in the transition condition of the working mode switching.

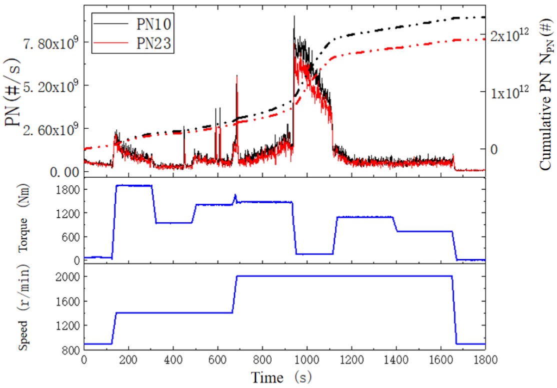

Fig. 2. Instantaneous and cumulative PN10 and PN23 under RMC test

The ratio of direct sympling PN10 to PN23 for each operating mode of the RMC is between 1.05 and 1.29, and the overall cycle PN10 emission is about 1.2 times of PN23, among which the 5/6/7/8 operating modes are rated speed, and their multiples are above 1.2, indicating that the percentage of 10-23 nm particulate matter is relatively high under high speed operating conditions. In the idle and intermediate speed low load conditions, the ratio of PN10 to PN23 is smaller, which indicates that the percentage of 10-23nm particles generated under these conditions is relatively low.

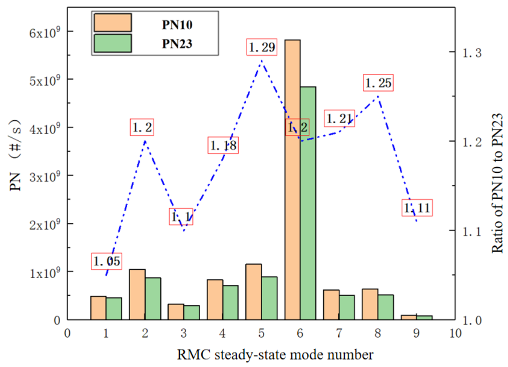

Fig. 3. Ratio of PN10 to PN23 under RMC modes

From the test results, the exhaust pipe direct sampling PN10/PN23 and CVS dilute PN23 have the same trend, and the specific emissions of the whole cycle are 2.721×10^{10}, 2.265×10^{10} and 2.741×10^{10}#/kWh, respectively. Compared with the direct PN23, the overall value of dilute PN23 is high, which may be related to the mixing process of dilute air and exhaust causing large particulate matter breaking down into smaller particles.

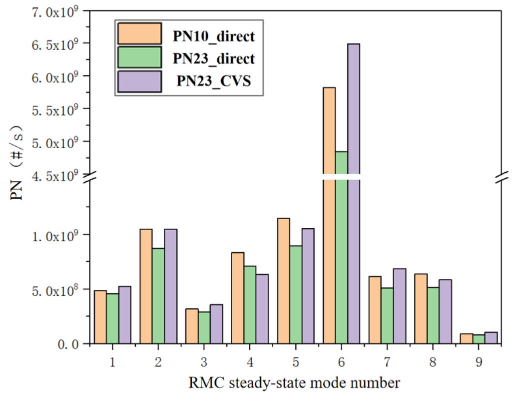

Fig. 4. Direct exhaust PN10/PN23 and dilute CVS PN23 under RMC modes

3.2 PN comparison of RMC and NRSC

The speed and torque in the steady-state operating modes of RMC and NRSC are the same, both contain idle speed, 100%-75%-50% load at intermediate speed, and 100%-75%-50%-10% load at rated speed, but the operating sequence and duration of the modes are different. The RMC cycle is shown in the figure, following the 1-2-3-4-5-6-7-8-9 mode sequence, and the NRSC cycle carries out the test according to the 5-7-8-9-2-4-3-1 (a-b-c-d-e-f-g-h) mode sequence.

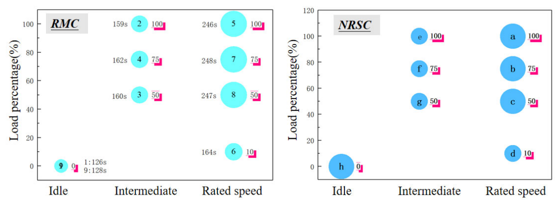

Fig. 5. Test cycle mode sequence of RMC and NRSC

The higher PN emissions in the first four operating modes and lower PN emissions in the last four operating modes in the NRSC test indicates that the PN emissions are higher in the high speed operating modes than in the low speed operating modes in the NRSC operating sequence, and the PN emissions increase with increasing load in the high speed condition.
Compared with NRSC, RMC has higher PN emissions at idle and intermediate speed operating modes, and lower emissions at high load operating modes at rated speed.The PN emissions were higher at 10% torque and 100% torque at rated speed, 100% torque at intermediate speed operating modes in the RMC test. The highest PN emissions at 10% torque rated speed may be due to the reduced capture efficiency with DPF carbon load reduction after the transition from rated condition modes with the high speed and high torque, where the high PN emissions at the first four condition points of NRSC are also influenced by this factor.

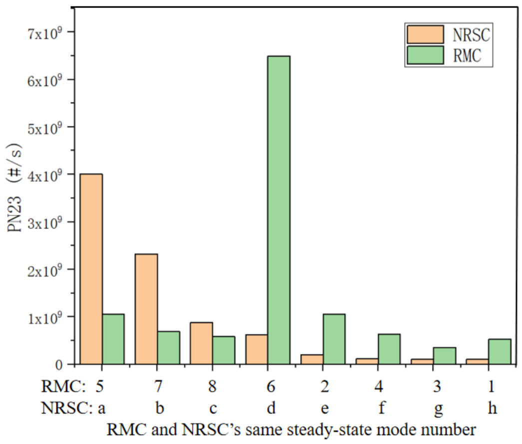

Fig. 6. PN23 comparation of RMC and NRSC

4. Conclusion

In this paper, PN tests based on RMC and NRSC were carried out on off-road diesel engines meeting China IV non-road emission regulations. The transient and each steady-state operating modes emission characteristics of PN10 and PN23 in the RMC cycle were investigated, and the PN23 emissions at each same operating mode in the RMC and NRSC cycles were compared and analyzed.

(1) The ratio of PN10 to PN23 for each working mode of RMC is between 1.05 and 1.29, and the overall cycle PN10 emission is about 1.2 times that of PN23. Particle with 10-23nm diameter accounts for a higher percentage under high speed working conditions, while the percentage of 10-23nm particle generated under idling and intermediate speed, low load working modes is relatively low.

(2) The exhaust direct PN10/PN23 and CVS dilute PN23 vary in the same trend, and the specific emissions of the whole cycle are 2.721×10^{10}, 2.265×10^{10} and 2.741×10^{10}#/kWh, respectively. Compared with PN23 in the direct exhaust extraction, the overall value of PN23 in the dilute extraction is higher, which may be related to the fragmentation of large particles caused by the mixing process of dilute air and exhaust decomposition into smaller particulate matter.

(3) The PN emissions at the same speed and torque operating modes are more affected by the sequence of the operating modes. Compared with NRSC, RMC has higher PN emissions at idle and intermediate speed operating modes, and lower emissions at high load operating moedes at rated speed.

(4) The high PN emissions at the 6th operating mode of RMC and the first 4 operating modes of NRSC may be caused by the reduced carbon loading of DPF after the transition from the high speed and high torque rated operating modes, which makes the capture efficiency lower.

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