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The Particle Number Emission Characteristics of the Diesel Engine with a Catalytic Diesel Particle Filter

Jia Qiang LI[1], Yan Yan WANG[1], Shu Chao HE[2], Huang Bin YAN[2] and Chao HE[1,a]

[1] *School of Mechanical and Traffic Engineering, Southwest Forestry University, Kunming 650224, China.*
[2] *Kunming Yunnei Power Co., LTD., Kunming 650224, China*

Abstract. Due to their adverse health effects and their abundance in urban areas, diesel exhaust ultrafine particles caused by the aftertreatment devices have been of great concern in the past years. An experiment of particles number emissions was carried out on a high-pressure, common rail diesel engine with catalytic diesel particle filter (CDPF) to investigate the impact of CDPF on the number emission characteristics of particles. The results indicated that the conversion rates of CDPF is over 97%. The size distributions of particles are bimodal lognormal distributions downstream CDPF at 1400 r/min and 2300 r/min. CDPF has a lower conversion rates on the nucleation mode particles. The geometric number mean diameters of particles downstream CDPF is smaller than that upstream CDPF.

1 Introduction

Particulate matter and nitrogen oxide (NOx) emissions from diesel engines are being recognized as the pollutants having adverse effects on the environment as well as on human health[1]. Many pathophysiological researches suggest that exposure to DEP, especially ultrafine particles, is associated with increased respiratory disease, cardiopulmonary mortality and other potential health effects [2]. Over the past few years, researches have begun to address the questions of the number concentration of DEP [3, 4] and regulations have been made to the number emissions of DEP in Euro V and VI emission standards. Among these after-treatment units, catalytic diesel particle filter (CDPF) has proved to be a very effective and promising technology for the abatement of particulate matter (PM) emissions from diesel engines. This technique not only reduces PM mass, but also provides good control over the number of ultrafine particles.

Maricq et al. studied the impact of DOC and sulfur content on the size distribution of DEP [5]. The results indicated that the nucleation mode particles would increase and the bimodal size distribution would appear only when the DOC and diesel with high sulfur were used together. Otherwise, the mono-modal distribution of the accumulation mode would occur. Biswas et al. investigated the size distributions , volatility, and agglomeration of particles from a heavy-duty diesel engine with DPF and SCR [6]. The advanced aftertreatment can decrease the mass of PM by 90%, but the number emissions of particles did not decrease on the stead modes and the nucleation mode particles increased. In this study, an experiment was carried out to investigate the number emission characteristics of particles emitted by the diesel engine with catalytic diesel particle filter (CDPF).

2 Experimental setup

2.1 Test devices

The test engine is a direct injection, high pressure common-rail, turbocharged diesel engine (WeiChai Power WP5, China), whose characteristics are shown in table 1. The engine with CDPF was tested on an engine test bench based on an AC dynamometer (Schenck HT350, Germany) with emission measurement system. An engine exhaust particle sizer (EEPS 3090, TSI, USA) was used for the investigation of particle matter (PM). To prevent the particle condensation and nucleation, two stages of ejector diluter (ED) upstream EEPS were used for sampling from raw exhaust stack (Burtscher, 2005). The fuel used in this study was locally available commercial low sulfur (50 ppm) diesel.

2.2 Measurement methods

The exhaust pollutant, temperature and pressure measurements were performed at the upstream and downstream of the after-treatment device. The results of emissions, fuel consumption and relevant engine parameters were recorded by the dynamometer control system. The stationary operation points (OPs), so called steps-tests were performed. The engine was operated at

[a] Corresponding author: hcsmile@aliyun.com

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10%、20%, 30%, 40%, 50%, 60%, 70%, 80%, 90% and 100% of full load at seven engine speeds (1000, 1200, 1400, 1600, 1800, 2000 and 2300 r/min). All operation points were performed with a warm engine and for each esearch task always in the same sequence.

A portion of the exhaust gas emitted from the engine was extracted from the tailpipe and quickly diluted by two ejector dilutors (Dekati Ltd.) in series. The dilution air is preconditioned to remove the water and volatile organic compound (VOC). The dilution air and diluted exhaust in the first dilutor are heated to 200°C in order to prevent condensation. The second ejector dilutor is at room temperature to cool the sample prior to distribution into the EEPS. The dilution ratio during test procedure is around 64, which essentially inhibits all post-dilution particle dynamics such as coagulation and adsorption [7]. The dilution factor (DF) was found with the following expression:

$$DF = (C_e - C_a)/(C_t - C_a) \quad (1)$$

where C_e, C_t and C_a respectively denote the CO_2 concentration in the engine-out exhaust gas, in the dilution tunnel and in the air.

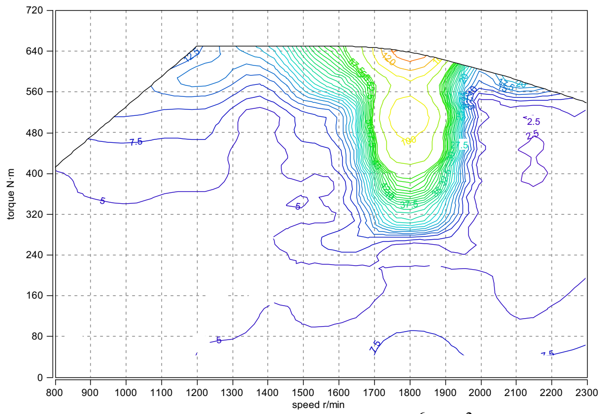
Table 1. Specification of the test engine.

Parameter	Feature/Size
Engine type	4-stroke, 4-cylinder, in-line
Bore×Stroke (mm)	108×10
Displacement (L)	4.76
Compression ratio	18
Fuel system	High pressure common rail
Max. Power (kW @ r/min)	132 (2300r/min)

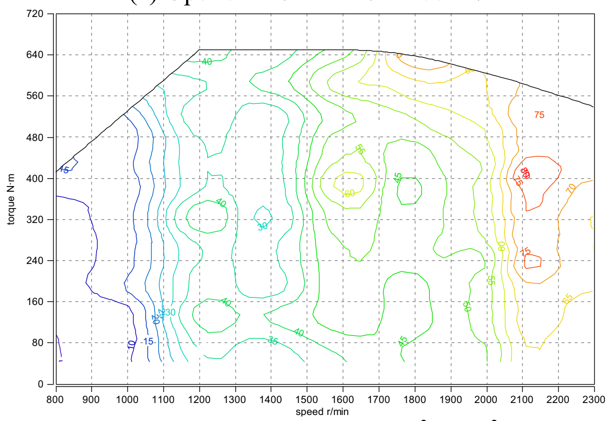
3 Results and discussions

3.1. The total particle number emissions of DEP

Figure 1 show the total number emissions of DEP unstream and downstream CDPF. The total particle number emissions is about 2.8×10^6-1.8×10^8 1/cm^3 upstream CDPF. The emission peak of engine-out particles is at the full load of medium speeds. Because CDPF increased the backpressure of diesel engine, the total particle number upstream CDPF was higher than that upstream CDPF, especially at the heavy loads of medium speeds. The total particle number emissions downstream CDPF increased with the incresing engine speed, and is about 4.6×10^3-7.96×10^4 1/cm^3, which is reduced by 3 order of magnitude compared with that upstream CDPF. The emission peak of particles downstream CDPF is at the heavy loads of high speeds. CDPF has the high conversion rates on the particle number emission with the minimum value of 97% at high speeds and heavy loads. The conversion rates of CDPF can reach 99.9% at the heavy loads of medium speeds.



(a) Upstream CDPF （$\times10^6$/cm^3）



(b) Downstream CDPF（$\times10^3$ 1/cm^3）

Figure 1. The total number emissions of DEP unstream and downstream CDPF.

3.2 The size distributions of DEP

Figure 2 showed the size distribution of DEP upstream and downstream CDPF and the conversion rates of CDPF at 1400 r/min. It can be seen that the size distribution of DEP upstream CDPF is mono-modal at 1400 r/min, and the peak concentration are at the diameter of 39-70nm at 10%-80% of full load, but 9-16nm at full load. The particle number concentration decreased firstly and then increased with the increasing engine loads. The maximum number concentration appeared at the full load, which is 5.8×10^7 1/cm^3, and the minimum number concentration is 5.8×10^6 1/cm^3 at the 60% of full load. Downstream CDPF, the size distribution is bimodal and the peaks are at the 7~10nm and 29~39nm. The conversion rates of CDPF keep over 99% except at the 20% of full load. CDPF has a lower reduction effect on the nucleation mode particles, that is 6nm~10nm.

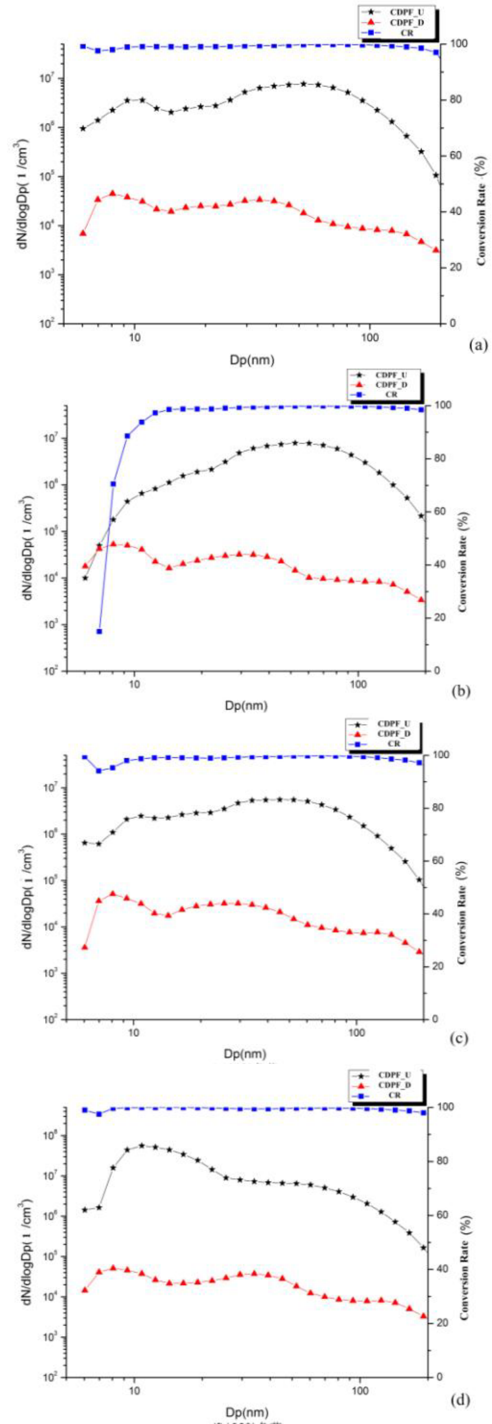


Figure 2. the size distribution of DEP upstream and downstream CDPF and the conversion rates of CDPF at 1400 r/min. engine load: (a) 10%, (b) 40%, (c) 80%, (d) 100%.CDPF_U: upstream CDPF, CDPF_D: downstream CDPF; CR:conversion rate

Figure 3 showed the size distribution of DEP upstream and downstream CDPF and the conversion rates of CDPF at 2300 r/min. At every load, the size distributions of particles are bimodal lognormal distributions upstream and downstream CDPF. The two peak concentrations upstream CDPF are at 6-9nm and 29-52nm, while at the diameter of 7-10nm and 29-39nm downstream CDPF. The conversion rate of CDPF decreased with the increasing particle diameter at the low load. The conversion rates of CDPF keep over 98%. CDPF has a lower reduction effect on the nucleation mode particles, that is 10nm~19nm.

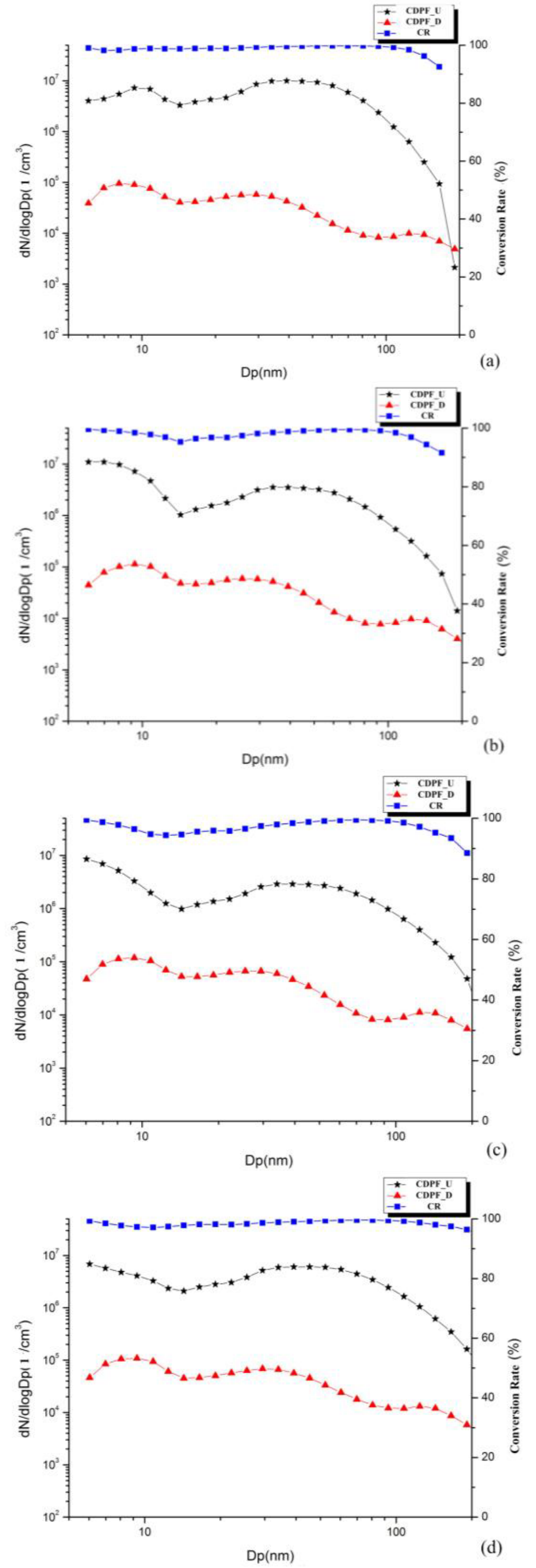


Figure 3. the size distribution of DEP upstream and downstream CDPF and the conversion rates of CDPF at 2300 r/min. engine load: (a) 10%, (b) 40%, (c) 80%, (d) 100%. CDPF_U: upstream CDPF, CDPF_D: downstream CDPF; CR:conversion rate

3.3 GMD of exhausted particles

Many literatures report that the experimentally measured size distribution of diesel exhausted particle can be fit to the lognormal form as following:

$$\frac{dN}{d\ln D_p}=\frac{N}{\sqrt{2\pi}\sigma}\exp\left[\frac{-(\ln D_p-\ln\mu)^2}{2\sigma^2}\right] \quad (2)$$

N is the number of particles, μ is the geometric number mean diameters (GMD) and σ is the corresponding geometric standard deviation (GSD).GMD and GSD are two important parameters regarding particle size. Table 2 gave the GMD and GSD of particles upstream and downstream CDPF. It can be seen that the GMD downstream CDPF is smaller than that upstream CDPF. The GMD of engine-out particles are about 38-58nm, and the GMD of particle downstream CDPF are about 17-30nm.

Table 2. The GMD and GSD of particles upstream and downstream CDPF.

Engine speed (r/min)	**Engine load (%)**	**Upstream CDPF**		**Downstream CDPF**	
		CMD （nm）	GSD	CMD （nm）	GSD
1400	20	42	1.94	29	2.53
	40	48	1.79	21	2.48
	60	40	1.88	21	2.43
	80	34	2.06	22	2.40
	100	16	1.83	22	2.43
2300	20	24	2.29	18	2.33
	40	15	2.41	17	2.26
	60	14	2.38	17	2.27
	80	18	2.56	18	2.29
	100	26	2.47	20	2.39

4 Conclusions

(1) The total particle number emissions of diesel engine is 2.8×10^6-1.8×10^8 1/cm^3 upstream CDPF and 4.6×10^3-7.96×10^4 1/cm^3 downstream CDPF. CDPF has the high conversion rates on the particle number emission with the minimum value of 97% at high speeds and heavy loads. The conversion rates of CDPF can reach 99.9% at the heavy loads of medium speeds.

(2) The size distributions of particles are bimodal lognormal distributions downstream CDPF at 1400 r/min and 2300 r/min. CDPF has a lower conversion rates on the nucleation mode particles.

(3) The geometric number mean diameters of particles downstream CDPF is smaller than that upstream CDPF. The GMD of engine-out particles are about 38-58nm, and the GMD of particle downstream CDPF are about 17-30nm.

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