Science of the Total Environment 472 (2014) 56–62

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Experimental study on the nitrogen dioxide and particulate matter emissions from diesel engine retrofitted with particulate oxidation catalyst

Xiangyu Feng, Yunshan Ge *, Chaochen Ma, Jianwei Tan, Linxiao Yu, Jiaqiang Li, Xin Wang

School of Mechanical and Vehicular Engineering, Beijing Institute of Technology, Beijing 100081, China

HIGHLIGHTS

- The ratios of NO_2/NOx increased 4.5 times on average with the POC.
- The abnormal particle emissions were observed under a steady engine mode with the POC.
- With the application of the POC, the PN concentrations tended to increase over time.
- The average reduction rate of PN with the POC was 61%.
- The issues of the NO_2 escape and the abnormal emissions should be addressed.

ARTICLE INFO

Article history:
Received 2 August 2013
Received in revised form 16 October 2013
Accepted 7 November 2013
Available online 28 November 2013

Keywords:
Diesel
Particulate oxidation catalyst
Particulate matter
Nitrogen dioxide

ABSTRACT

A particulate oxidation catalyst (POC) was employed to perform experiments on the engine test bench to evaluate the effects on the nitrogen dioxide (NO_2) and particulate matter (PM) emissions from diesel engine. The engine exhaust was sampled from both upstream and downstream of the POC. The results showed that the POC increased the ratios of NO_2/NOx significantly in the middle and high loads, the ratio of NO_2/nitrogen oxides (NOx) increased 4.5 times on average under all experiment modes with the POC. An engine exhaust particle sizer (EEPS) was used to study the particle number-weighted size distributions and the abnormal particle emissions with the POC. The results indicated that the average reduction rate of particle number (PN) was 61% in the operating range of the diesel engine. At the engine speed of 1400 r/min, the reduction rates of PN tended to decrease with the larger particle size. In the long time run under the steady mode (520N m, 1200 r/min), abnormal particle emissions after the POC happened seven times in the first hour, and the average PN concentration of these abnormal emission peaks was much higher than that in normal state. The particle emissions of peaks 1–5 equaled the particles emitted downstream of the POC in normal state for 1.9 h in number concentration, and for 3.6 h in mass concentration. The PN concentrations tended to increase over time in 5 h under the steady engine mode and the increase of the PN in the size range of 6.04–14.3 nm was more evident.

1. Introduction

Legislations worldwide have started imposing stringent emission standards for particulate matter (PM) and gaseous pollutants emitted by diesel engines because of their abundance and their adverse effects on the environment as well as on human health (Kinnunen et al., 2012; Liu et al., 2011, 2012; Wichmann and Peters, 2000). The biological effects of PM are attributed to the particle size and composition. The particle size determines how particles are deposited within the respiratory tract (Lehtoranta et al., 2009). Fine particles (with aerodynamic diameter < 2.5 μm), which covers a wide range of typical particulate emissions generated by internal combustion engines, can get into the alveolar region in the human lungs (Kinnunen et al., 2012). There are various types of after-treatment devices for the modern diesel engine. NOx emissions can be removed significantly by selective catalytic reduction (SCR), while diesel oxidation catalysts (DOC) are commonly used to oxidize carbon monoxide (CO) and hydrocarbon (HC) emissions as well as partial particles (Vaaraslahti et al., 2006). Diesel particulate filters (DPF) are widely used for reducing particle emissions, and its filtering efficiency can reach 90% or higher, but they need regeneration process periodically to avoid high back pressure in exhaust line (Kinnunen et al., 2012). The particulate oxidation catalyst (POC) is considered as an alternative PM reduction aftertreatment technology to the wall-flow DPFs

---

Abbreviations: POC, Particulate Oxidation Catalyst; EEPS, Engine Exhaust Particle Sizer; SCR, Selective Catalytic Reduction; DOC, Diesel Oxidation Catalyst; DPF, Diesel Particulate Filter; NO_2, Nitrogen Dioxide; NOx, Nitrogen Oxides; NO, Nitric Oxide; HC, Hydrocarbon; CO, Carbon Monoxide; PN, Particle Number; PM, Particulate Matter; ESC, Euro Steady-state Cycle.

* Corresponding author. Tel.: +86 152 1051 0075; fax: +86 10 6894 8486.
E-mail address: fengxy010@gmail.com (Y. Ge).

0048-9697/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.scitotenv.2013.11.041

(Zhan et al., 2012). There are two sections in POC, DOC section and DPF section, thus, the POC has the potential to remove HC, CO and particle emissions simultaneously. Furthermore, the POC has no risk of clogging because the DPF section of the POC introduces a honeycomb structure with open tortuous channels that are designed with several corrugated layers instead of alternately plugged channels with porous walls (Guangtao et al., 2011; Lehtoranta et al., 2007; Liu et al., 2012; Vakkilainen and Lylykangas, 2004). The structure of the POC forces the exhaust to follow the channels or pass through the corrugated substrate wall (Lehtoranta et al., 2007), by which the particles can be trapped then. However, the "blow-off" issues (Zhan et al., 2012) may occur due to the open channels of the POC. If this happens, it will cause the failure of the POC to reduce particle emissions and superfluous particles escaping into the atmosphere.

The POC can realize continuous regeneration for the particles through utilizing NO_2 to oxidize the particles collected in the filter (Cooper and Thoss, 1989; Murtonen et al., 2010). NO_2 is mainly from the conversion of nitric oxide (NO) to NO_2 in the DOC section of the POC. NO_2 is a more effective oxidant than O_2 in promoting low temperature oxidation of soot in the temperature range of 200–500 °C, which has also been postulated to play a synergistic role with O_2 in the combustion of diesel soot (Ehrburger et al., 2002; Setiabudi et al., 2004). Commonly, the proportion of NO_2 is lower than 15% of the total NOx in the diesel exhaust. However, oxidation catalysts like platinum could oxidize NO to NO_2 which can increase NO_2 concentrations to 50% of the total NOx in the temperature range of 300–350 °C (Ehrburger et al., 2002; Marques et al., 2004). The primary emission of NO_2 is a significant concern due to NO_2's having a higher toxicity compared to NO and would cause increased photochemical ozone production (Carslaw and Beevers, 2004).

In this study, a diesel engine retrofitted with particulate oxidation catalyst was employed to perform experiments on the engine test bench to evaluate the effects of the POC on the NO_2 and PN emissions of exhaust from diesel engine. The present work focused on the contributions of NO_2 to total NOx, the PN size distributions and abnormal particle emissions under steady mode.

2. Experimental method

2.1. Specifications of engine and the POC

The engine used in this study was a 4-cylinder, turbocharged, intercooled diesel engine with an electronically controlled Bosch common-rail fuel injection system, for which the specifications are listed in Table 1. The engine was fueled with locally available commercial diesel with properties and standards listed in Table 2. The specifications of the POC are shown in Table 3.

Table 1
Engine specifications.

Parameter	Feature/value
Engine type	In-line 4-cylinders, intercooled, turbocharged
Fuel supply system	Common-rail
Displacement	4.76 L
Bore	108 mm
Stroke	130 mm
Compression ratio	18
Rated power	132 kW at 2300 r/min
Maximum torque	650N m at 1200–1600 r/min
Emission target	Euro IV

Table 2
Properties of fuels.

Properties	Diesel	Test method
Sulfur content (%, by weight)	0.0032	SH/T 0689-2000
Heat value (MJ/kg)	42.77	GB/T 384-1988
Cetane number	53.1	GB/T 386-2010
Density at 20 °C	841 kg m^{-3}	GB/T 2541-1981(2004)
Viscosity at 20 °C (mm^2/s)	4 mm^2/s	GB/T 265-1988(2004)
Carbon content (%, by weight)	85.95	SH/T 0656-1998(2004)
Hydrogen content (%, by weight)	13.39	SH/T 0656-1998(2004)
Oxygen content (%, by weight)	<0.2	ASTM D5622-95(2000)

2.2. Test bench and instrumentation

The engine retrofitted with the POC was tested on a bench based on an AC dynamometer (Schenck HT350, Germany) and the emission measurement system. The AC dynamometer was employed to control the rotation speed and toque of the test engine. The resolution for engine speed and torque control was 1 r/min and 1N m respectively. Fig. 1 sketches the experimental system in this present paper. The engine exhaust was sampled from both upstream and downstream of the POC as described in Fig. 1. An exhaust analyzer (AVL AMA4000, Austria) was employed for gaseous pollutant measurement. It measured the HC by FID (flame ionization detector), NO_X by CLD (chemiluminescence detector), and CO and CO_2 by NDIR (non-dispersive infrared). The model 3090 engine exhaust particle sizer spectrometer (TSI EEPS 3090, USA) was used to investigate the PN size distributions. The EEPS is a high-performance electrical mobility instrument designed specifically for measuring particles emitted from internal combustion engines and vehicles. It measures particle size from 5.6 to 560 nm with a sizing resolution of 16 channels per decade (a total of 32 channels). Prior to the EEPS, two tandem ejector diluters (Dekati, Finland) were utilized to dilute part of the engine exhaust. The first stage is heated to 200 °C and the second stage is left at ambient temperature. The overall dilution ratio was 64, which essentially inhibited all post-dilution particle dynamics such as coagulation and adsorption (Abdul-Khalek et al., 1999). Concentration in engine out exhaust was calculated by multiplying the measured concentrations in diluted exhaust by the dilution ratio.

2.3. Test procedure

The experiment for regulated pollutant emissions was performed in accordance with Euro Steady-state Cycle (ESC) (Table 4). For comprehensively evaluating the NO_2 contribution to NOx after the POC was retrofitted, the universal characteristic tests (10%–100% of full load at 10% intervals, 800 r/min, 1000 r/min, 1200 r/min,1400 r/min, 1600 r/min, 1800 r/min, 2000 r/min, 2100 r/min, 2300 r/min) of the NO_2 and the total NOx emission as well as the PM emissions were performed. The number-weighted size distributions of PM upstream and downstream of the POC were measured under 20% and 80% of full loads, at an engine speed of 1400 r/min. A long time observation on the PM emissions was performed at 520N m, 1200 r/min for 6 h.

3. Results and discussions

3.1. Regulated pollutant emissions

Table 3
Specifications of POC.

Parameter	Feature/value
Substrate of DOC section	Cordierite
Cell density of DOC section (cell/in.^{2})	400
Diameter × length (mm × mm)	Φ174.6 × 140
Substrate of DPF section	Metal
Cell density of DPF section (cell/in.^{2})	380
Diameter × length (mm × mm)	Φ174.6 × 178

The results are shown in Table 3. The HC and CO emissions were reduced by 59.27% and 51.42%, respectively, with the POC. However, a