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Particulate emissions from urban bus fueled with biodiesel blend and their reducing characteristics using particulate after-treatment system

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ABSTRACT

Particulate emissions from an urban bus fueled with B20 (20% biodiesel from waste cooking oil and 80% diesel by volume) were investigated using portable emissions measurement system (PEMS), then the effect of a catalyzed continuously regeneration trap (CCRT) on the particulate emissions of the B20-fueled bus were ascertained. Results show that compared with a D100 (pure diesel), B20 reduced particulate number (PN) and particulate mass (PM) emission rates of the bus by 13.9% and 24.3% under cruise control. Under transient condition, B20 reduced the PN and PM emission rates by 18.4% and 16.3%. B20 decreased the total PN concentration by 6.6% whereas increased the proportion of nucleation particles from 89.0% to 92.0%. Correspondingly causing a decrease in the GMD (geometric mean diameter) from 43.02 nm to 41.25 nm under cruise condition, and from 41.26 nm to 39.57 nm under transient condition. Using a CCRT exhibited an excellent filtration effect on both PN and PM from the B20-fueled bus. Both under cruise and transient conditions, CCRT could reduce more than 93% of the PN and PM. In addition, CCRT had a better filtration effect on accumulation particles. The use of CCRT also changed the particle size bimodal distribution of the B20 by removing the accumulation mode peak.

1. Introduction

According to statistics, China's urban food waste is no less than 60 million tons per year [1]. The food waste is the main source of waste oil which not only pollutes the environment but also brings risks to public health simply because cooking oil has no safeguards on disposal. A chemical process can convert the waste oil into biodiesel [2–4]. Diesel engines are highly favored in urban bus transportation due to their high thermal efficiency, good reliability, and fuel savings. However, the main problem encountered by diesel engines is the significant amount of particulate matter emitted into the environment [5–7]. The abundant particulate matter in the atmosphere can contribute to haze weather [8,9]. Moreover, several recent studies have found that particulate matter results in respiratory and immune system problems, even cancer, because nano-sized soot particles can penetrate human lungs during breathing [10–12]. A reduction in particulate matter emissions can be achieved through the application of biodiesel in diesel engines. This is due to biodiesel fuel's higher cetane number, which allows for a more complete combustion of the fuel [13]. Many studies have been conducted on the PM and total PN emissions when the engine is fueled with biodiesel [14–17]. Meanwhile, the application of biodiesel also resulted in a change of the particle size distribution of the emissions. Tan et al. [18] found that accumulation-mode PN of diesel engine decreased and nucleation-mode increased after using biodiesel blend and the similar conclusion was drawn by He [19]. As far as particle size distribution is concerned, Barrios et al. [20] reported that the GMD of the particle emissions from biodiesel was less than that from pure diesel. Armas et al. [21] further proved that biodiesel led to a reduction in both the number and size of accumulation-mode particles and a decrease in both total particle concentration and GMD. In terms of the effect of blending ratio of biodiesel on the engine emissions, Asokan et al. [22] concluded that B20 is the most suitable biodiesel blend for substitute of diesel with diesel-like performance and combustion characteristics but reduce 8.3% of the smoke emission. A similar conclusion was also drawn by Bari [23]. Although biodiesel as a renewable clean fuel can reduce particulate matter emissions to a certain degree, the particulate matter emission level of the engines that only using biodiesel has to go even lower to meet the increasingly stringent exhaust emission regulations [24–26]. Therefore, to reduce the particulate matter emissions substantially, it is necessary to use an after-treatment

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equipment for the diesel engine. The CCRT, composed of an upstream diesel oxidation catalyst (DOC) and a downstream catalyzed diesel particulate filter (CDPF), is recognized as the most efficient diesel particulate after-treatment system. The CDPF can trap the particulate matter emissions efficiently and then oxidize them by nitrogen dioxide (NO_2), which is created in DOC via nitric oxide (NO) oxidation [27–29]. The application of biodiesel in combination with CCRT to diesel vehicle not only alleviates the crisis of fossil fuel depletion, but also reduces pollutant emissions, especially particulate matter emissions. Some studies have focused on the effect of biodiesel coupling CCRT on the particulate matter emission characteristics. Rounce et al. [30] investigated particulate matter reduction by after-treatment based on a single cylinder research engine fueled with biodiesel and found that more than 99% of the solid particulate matter by mass and number was trapped by the CDPF. Cheng et al. [31] examined the effect of biodiesel and after-treatment on particulate emissions of a heavy-duty diesel engine and results showed that the use of CCRT yielded a 79–94% reduction of particulate matter. And in Mori's research, a more than 99.95% reduction of the PN concentration was observed after the biodiesel-powered engine used CCRT [32]. In addition to the significant decrease of the PN and PM, the after-treatment system also leads to remarkable change of the particle size distribution of the biodiesel-fueled engine. Tan et al. [33] found that the particle size distribution of a biodiesel-powered heavy-duty engine changed from double-peak distribution to multi-peak distribution after using CCRT. And he further proved that there was a peak at approximately 10 nm occurring when the B20-fueled engine was equipped with CCRT [34]. Millo's [35] results presented that the engine-out and DOC-out particle size distribution appeared to be extremely similar, while the downstream CDPF exhibited high filtration efficiency on PN also in the nanoparticles range. Although there have been many studies on the effect of after-treatment system on the particles size distribution of emission from biodiesel-fueled engine, few of them compared the effects of after-treatment system on particles with different sizes quantifiably. On the other hand, most the studies were conducted based on engine bench test in laboratory, which is difficult to reflect the real-world driving conditions of the vehicles. In general, the real-world driving conditions contain idle, cruise, accelerating and decelerating, significantly, they switch between each other frequently [36–38], which differ greatly from laboratory test conditions. On-board tests based on PEMS can measure vehicle emissions under various real-world driving conditions [39,40], offering an effective method for the study of the particulate emissions from urban bus fueled with biodiesel blend and their reducing characteristics using after-treatment system under real-driving condition. Consequently, this study used a PEMS system to make a comprehensive evaluation of the impact of biodiesel blend B20 on the particulate matter emission characteristics. PEMS was then used again to evaluate effect of CCRT on PN and PM emissions of the B20-fueled bus under cruise and transient conditions, including reducing efficiencies for particles with different sizes, as well as the particle size distributions.

2. Materials and methods

2.1. Test vehicles and fuels

The experimental study was conducted using an in-use diesel urban bus without exhaust after-treatment device. The test bus satisfied the Euro 3 emission standard. A commercial after-treatment system (CCRT) was then applied to retrofit the bus to investigate its beneficial effect on the particulate matter emissions in the second part of the experiment. In Table 1 the main specifications of the test bus are presented.

Table 1
Main specifications of the test bus.

Parameter	Value
Bus type	SUNWIN SWB6100V5
Curb weight (kg)	10100
Engine type	Deutz D7E240-EC01
Displacement (L)	7.146
Maximum velocity (km/h)	85
Rated power (kW/rpm)	177/2300
Maximum torque (N·m/rpm)	920/1700
Model year	2011
Emission standard	Euro 3

Table 2
Physical and chemical properties of test fuels.

Parameter	D100	B20	B100
Density at 20 °C (kg/m^3)	813.6	836.9	873.8
Viscosity at 20 °C (mm^2/s)	3.3	4.6	6.0
Cetane number	50.8	53.1	55.3
Low heating value (MJ/kg)	43.42	42.31	38.17
Fatty acid methyl ester (%)	/	21.6	>98.0
Sulfur content (mg/kg)	1.4	9.9	22.5
Carbon content (%, m/m)	85.49	83.74	76.2
Hydrogen content (%, m/m)	14.48	13.66	12.29
Oxygen content (%, m/m)	0	2.6	11.5
Stoichiometric relative air-fuel ratio	14.82	14.44	13.49

The test fuels included a premium low-sulfur diesel (D100) and a biodiesel blend referred to as B20, which contains 20% waste-cooking-oil biodiesel (B100) and 80% D100 by volume. The D100 was obtained directly from the commercial market, and the B100 was provided by a cooperation company—Zhongqi environment technology. The properties of the test fuels are given in Table 2. It notably shows that the biodiesel blend used in the study has higher sulfur content, which may be attributed to the extensive resources of waste cooking oil raw materials with organosulfur compound, in addition, the use of concentrated sulfuric acid in the producing process of the waste-cooking-oil biodiesel may also lead to a higher sulfur content [41].

2.2. After-treatment parameters

The after-treatment system CCRT was composed of an upstream DOC and a downstream CDPF in this study. The specifications of the DOC and CDPF are given in Table 3.

Table 3
Specifications of the DOC and CDPF.

Parameter	Feature/Value	
	DOC	CDPF
Diameter (mm)	295	285.8
Length (mm)	80	304.8
Cell density (cpsi)	300	100
Wall thickness (mm)	0.05	0.45
Porosity (%)	/	55
Average pore size (μm)	/	8–13
Carrier material	FeCrAl	Cordierite
Catalyst component	γ-Al_2O_3	γ-Al_2O_3
Precious metals (g/ft^3)	60	35
Pt:Pd:Rh	10:1:0	10:2:1
Adjuvant	Fe_2O_3+ZrO_2	Fe_2O_3+CrO_2
Coating	$Al_2O_3 \cdot H_2O$	$Al_2O_3 \cdot H_2O$