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Effect of DMDF on the PM emission from a turbo-charged diesel engine with DDOC and DPOC

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HIGHLIGHTS

- A new technical route on the reductions of smoke emissions and PM was introduced.
- Smoke emissions and PM from turbo-charged diesel engine with DMDF were measured.
- Interior relation on dry-soot, smoke opacity and PM was analyzed.
- Effects of DMDF, DDOC and DPOC on smoke emissions and PM were investigated.
- Particle number and mass concentrations and size contribution with DMDF were realized.

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ABSTRACT

This study is aimed to investigate the combined application of diesel methanol dual fuel (DMDF) and a simple after-treatment for reducing particulate matter (PM) emissions of a diesel engine. The effects of DMDF, a double diesel oxidation catalyst (DDOC) and a DOC closely coupled with a particulate oxidation catalyst (POC) in series (DPOC) on smoke emissions, particulate mass and number concentrations and size distributions were analyzed. Tests were conducted on a 4-cylinder turbo-charged, inter-cooling, mechanical in-line fuel injection pump diesel engine modified to DMDF combustion mode. Testing results showed that, before the DDOC and the DPOC, the dry-soot and smoke opacity efficiency decreases with the increase of substitution ratio of methanol at high engine load. There is a significant decrease of smoke opacity in DMDF mode after the DDOC, while the DPOC has a significant effect on the reduction in dry-soot emission. There is an average reduction in dry-soot by 25% in pure diesel fuel mode after the DDOC, while in DMDF mode, the average reduction is more than 60%, and the maximum reduction in dry-soot is up to 96%. There is a slightly reduction in PM emissions at low substitution ratio of methanol, while the high substitution ratio of methanol leads to more reduction in PM emissions. After the DDOC and the DPOC, particulate number and mass concentrations, especially nuclear particles, can be significantly reduced when the exhaust gas temperature is enough high.

1. Introduction

Particulate matter (PM) contains variety of carcinogenic substances, which are harmful to the people's health and lead to human diseases such as lung diseases, even cancer, asthma and elevated blood pressure with the corresponding complications [1–3]. World Health Organization (WHO) has recognized the emissions of diesel engine as the carcinogen in June 12, 2012. Since January 2013, most of areas in China have been affected by the haze. Several technologies have been investigated to reduce the PM emission such as ultra-high fuel injection pressure, low temperature combustion, and hybrid powertrains [4]. Moreover, many researchers have pay much attention to the development of cleaner alternative fuels, such as natural gas, bio-diesel and alcohols, for reducing the PM emission and decreasing the dependence on fossil fuels [5]. Due to its high oxygen content and high latent heat of vaporization, methanol is beneficial for reducing NOx and smoke emissions [6,7], and it can be easily synthesized from abundantly available materials such as coal, nature gas, and biomass [8,9]. Moreover, there are sufficient productive capacities of methanol in most of areas in China and methanol has been widely used as alternative fuel for petroleum oil. Methanol can be used in the diesel engine by direct mixture [10], double injection [11] and diesel/methanol duel fuel (DMDF) [12–14].

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Nomenclature

DMDF	diesel methanol dual fuel
PM	particulate matter
DOC	diesel oxidation catalyst
POC	particulate oxidation catalyst
SOF	soluble organic fraction
N	opacity
K	absorption coefficient
ECU	electronic control unit

As a new combustion scheme, DMDF is the approximate gaseous phase combustion by forming homogeneous mixtures while involving combustion in cylinder. Different with diesel–methanol blended fuel, there is a larger proportion of methanol which can be premixed with diesel fuel for stable operation in DMDF mode. On the other hand, there is no necessity to modify the diesel engine and methanol will be fumigated into the air intake using low-pressure fuel injectors at the engine manifold [15–17]. With DMDF, the engine operates on diesel fuel when starting and idling, while under conditions when the temperature of cooling water is above 65 °C, the engine operates on the DMDF mode in which methanol is a homogeneous air/methanol mixture and then ignited by pilot diesel fuel. When the amount of diesel fuel remains unchanged under different engine conditions, but the amount of methanol injected varies in accordance with the demand of engine power output. Additionally, DMDF also can be easily applied to in-use diesel vehicles such as trucks, buses, container transporters, and construction machineries. In particular, it is not only able to improve engine power output but also to reduce fuel cost since methanol cost is much cheaper than that of diesel fuel in China. Previous study has shown that the DMDF scheme has a significant reduction in NOx and PM but increase CO and HC.

In previous studies, there was rather low effect of particulate oxidation catalyst (POC) on the reduction of PM, and the efficiency was less than 30%. Thus the direct use of POC only was not considered to be as an effective technology route to reduce the PM emission. However, in the mode DMDF, the pressurized methanol was induced into the intake manifold with six injectors and mixed with boost fresh air to form homogeneous mixtures and then ignited by pilot diesel in the cylinder. It is the gas-phase combustion like gasoline engine, so the particulate matter emission would decrease significantly with the diesel/methanol dual fuel mode. However, former investigations focused on the emissions of the natural-aspirated diesel engine with DMDF and there were lack of investigations on the smoke emissions and PM of the turbo-charged, inter-cooling diesel engines with DMDF. Recently, the turbo-charged, inter-cooling diesel engines are widely used for in-use HD vehicle, especially for urban buses, which can lead to a large number of particles. Therefore there is a need to investigate the smoke emissions and PM of the turbo-charged, inter-cooling diesel engines. Some researchers also noticed that the behaviors of those engines for HD vehicles using DMDF in recent years [18]. But those previous studies are restricted in the following aspects, firstly, substitution ratio was rather low, usually 30% max; secondly, in DMDF mode, the effects of after-treatment such as DOC and POC on reduction of smoke emission and characteristic of PM were not complete, as well as on reduction of the soluble organic fraction (SOF) of the particulate [19]; thirdly, the previous studies were on the naturally aspirated diesel engines; finally, there are some differences of methanol injection between the previous researches and this study.

This study is aimed to give detailed experimental data on the combined application of diesel methanol dual fuel (DMDF) and a simple after-treatment (DDOC and DPOC) for reducing particulate matter (PM) emissions from an in-use diesel engine and the inherent relation on these emissions with the increase of the amount of methanol replacement at the high load. Besides smoke opacity and dry-soot, the particulate number and mass concentrations and size distribution are also measured.

2. Experimental setup

2.1. Test engine and fuels

Experiments were carried out on a four-cylinder turbo-charged, inter-cooling mechanical pump diesel engine, which is a common engine used in the in-service buses or coaches in China. Specifications of the engine are shown in Table 1. The engine has been modified for the new combustion scheme. The modification includes the installation of a methanol injection and control system to the air inlet manifold of the diesel engine, with three different spray range injectors for four cylinders. A fuel pump was used to inject methanol and the methanol injection pressure was about 0.35 MPa to form a lean air/fuel mixture. The amount of methanol injected was controlled by the electronic control unit (ECU). The engine was coupled with a hydraulic dynamometer and the engine speed and torque were controlled by the Bohao diesel engine test system that allows adjustment of engine speed at fixed engine load or adjustment of engine load at a fixed engine speed. The experimental setup is shown in Fig. 1. Two different after-treatments were installed respectively at the down-stream exhaust pipe. The one is DDOC with honeycomb structure, which consists of Pt and Pd as internal coating catalyst; the other one is DPOC, which consists of Pt, Pd and Rh as internal coating catalyst, and the material of its structure is ceramic. The detailed descriptions of the after-treatment systems in terms of the specific properties are shown in Table 2.

The fuels used include CHN III diesel fuel with less than 350-ppm by weight of sulfur and industrial methanol. Major properties of the test fuels are shown in Table 3. Fuel consumptions were measured using an electronic balance with a precision of 0.1 g.

2.2. Sampling and analysis

Smoke emissions were measured respectively using AVL 415S and 439 smoke meter. Dry-soot was measured by AVL 415S smoke meter, while smoke opacity was measured by AVL 439 smoke meter. The specifications of the equipment are shown in Table 6.

Table 1
Specifications of the test engine.

Model	YC4D140M-31
Type	Four-cylinder, turbo-charged, inter-cooling, in-line injection pump, diesel engine
Maximum power	103 kW/2800 r min^{-1}
Maximum torque	400 Nm/1800 r min^{-1}
Bore/stroke	115 mm/108 mm
Displacement	4200/cm^3
Compression ratio	17.1