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Investigation into particle emission characteristics of partially premixed combustion fueled with high n-butanol-diesel ratio blends

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ABSTRACT

Based on a 4-cylinder turbocharged intercooler diesel engine fueled with n-butanol/diesel blends, this paper investigated the effect of various parameters on emissions under the early-injection partially premixed combustion (PPC) strategy and pre-injection PPC strategy. The potential for realizing PPC with different fuel reactivity and oxygen content was evaluated. The experimental results indicated that the peak value of heat release rate (HRR) increased and the heat release duration shortened after mixing the n-butanol under the same injection timing. The start of combustion (SOC) was advanced and the proportion of premixed combustion decreased as the growth of pre-injection ratio. The heat release process was delayed when the n-butanol ratio was increased. As the growth of n-butanol ratio, the peak value of the accumulation mode particles reduced and that of the nucleation mode particles increased sharply. The geometric mean diameter (GMD) of the particles was significantly reduced when the pre-injection timing was changed from −25 to −35° CA ATDC. As the growth of the pre-injection ratio, the GMD of the particulates had a tendency to decrease. Under the same pre-injection conditions, the total number and mass concentration of the particulates both reduced obviously with the increase of n-butanol ratio.

1. Introduction

Soot particulates emitted from the engine are great harmful to the environment and human health. So new emission regulations put forward higher requirements on the number and quality of particulate matter [1,2]. Moreover, people nowadays pay more attention to the environmental pollution and there will be more demanding regulations on the emission of particulate materials in the future with the increasing development of engine technology. "Euro VI" emission standards introduce the concept of particulate number (PN) and limit the mass and number of particulates. From fuel decomposition to combustion emissions, particulate matters go through six processes successively: pyrolysis, nucleation, surface growth, coalescence, agglomeration and oxidation [3,4]. According to the particle size, generated particulates are generally classified into the nucleation mode ($Dp < 50\,nm$) and accumulation mode ($50\,nm < Dp < 1000\,nm$), respectively [5]. Nucleation mode particulates consist of volatile organic compounds and sulfate, with a lower content of solid particles. Organic compounds and inorganic compounds are adsorbed on the surface of soot to form accumulation mode particulates [6–8].

The combustion of traditional diesel engines belongs to the diffusion combustion mode controlled by fuel injection and fuel-air mixing. To reduce both NO_x and soot emissions, researchers proposed a low-temperature combustion (LTC) concept model, including homogeneous charge compression ignition (HCCI) and partially premixed combustion (PPC), etc. Compared with the existing conventional diesel engine conceptual model, LTC concept model avoids the soot and NO_x emission generation region on Φ-T diagram by prolonging the ignition delay period, promoting the mixing of fuel and gas, descending the combustion temperature [9,10]. Compared with the traditional combustion mode, PPC mode has lower particulate emissions. Due to the stratification of the mixture, PPC model possesses a better combustion control compared with HCCI combustion model. This mixture stratification can be adjusted by modifying injection timing and fuel injection strategy to control the combustion phase.

Scholars have done a lot of researches on the realization method, emission characteristics and fuel consumption rate of PPC with pure diesel [9,10]. Under the condition of a single injection strategy, early-injection PPC can realize a high proportion of premixed combustion to get a cleaner combustion, since it has a longer period of premixing [12].

Abbreviations: GMD, geometric mean diameter; HRR, heat release rate; LTC, low temperature combustion; MEP, mean effective pressure; PM, particulate mass; PMD, particle mass distribution; PN, particle number; PPC, partially premixed combustion; PSD, particle size distribution; SOC, start of combustion; HCCI, homogeneous charge compression ignition

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Kalghatgi and Manente et al. [13,14] found that PPC combustion can realize high efficiency and low emissions under high load conditions. Price et al. [15] found that though PPC mode can reduce the emission of particulates, particulates from PPC mode are mainly concentrated in the accumulation mode. Therefore, soot problems of PPC mode cannot be ignored. In addition, the multi-injection strategies can also realize the PPC mode by adjusting the injection timing and fuel ratio at each injection stage [16] flexibly. Fang et al. [17] found that the combustion of mixture was subject to premixed combustion mode when the earlier pre-injection and lower fuel injection quantity were used. Horiber et al. [18] revealed that under appropriate injection strategy, EGR conditions and two-stage combustion mode can significantly improve the emission of the engine and keep a small pressure rise rate.

Oil resources are facing an increasingly depleted crisis and countries around the world are working on clean, low-polluting and renewable biofuels. Commonly used biofuels are methanol, ethanol, butanol and biodiesel. To date, ethanol and biodiesel have been widely studied and applied and butanol is gaining more and more attention due to the advantages of reserves.

Compared with methanol and ethanol, butanol has higher calorific value, higher energy density and lower latent heat of vaporization. Moreover, it can be mixed with gasoline and diesel in a higher proportion and it is less corrosive and there is no need to modify the structure of the fuel supply system of the original engine, so butanol/diesel blends get more popular in scholars. Rakopoulos et al. [19,20] conducted a detailed study on butanol/diesel blends and found that the moderate addition of butanol could reduce the soot and CO emissions. Feng et al. [21] found that the addition of butanol can effectively decrease the soot emission, while the change of NOx is determined by the butanol blending ratio and operating condition. Yao et al. [22] also conducted a test of butanol/diesel blends to investigate the effect of multiple injections. The results show that, while maintaining NOx substantially constant, the blending of butanol will increase the soot and CO, although it has a slight impact on the fuel consumption rate. Siwale et al. [11] investigated the engine characteristics of n-butanol/diesel blends on a light supercharged diesel engine under high load conditions. The results show that the emission of soot and CO decreases with the increase in the proportion of n-butanol, but the NOx emissions increased gradually. After blending n-butanol, combustion stability in the cylinder is improved, while the effect indicating pressure does not change much. Compared with the naturally aspirated diesel engine, the emission characteristics are improved. Zhang et al. [23] studied the effects of butanol/ultralow-sulfur-diesel blends on the physical and chemical properties of particulates emissions. The results show that the content of organic carbon increases with the higher proportion of butanol, and the amount of particulates and element carbon in the combustion products is reduced. Compared with low sulfur diesel, the concentration of volatile matter and nonvolatile particles in the combustion of mixed fuel is greatly reduced and the GMD is reduced. Under low load conditions, the number of small-size particles has increased. On the other hand, when the proportion of butanol is higher than 10%, the soot precursor would increase. Chen et al. [24] found that a longer ignition delay period results in a higher HRR and in-cylinder pressure when blended fuels are used. Lower local equivalence ratios led to a lower soot emission. Meanwhile, more high-temperature oxygen-rich areas lead to the increasing in NOx emissions.

N-butanol/diesel blends can be used without modifying the original engine structure. It can improve the fuel atomization and evaporation process and prolong the ignition delay period effectively. The property is conducive to the expansion of the PPC operating range of the diesel engine [25,26]. In addition, compared with methanol and ethanol, n-butanol can be miscible with diesel in any proportion at normal atmospheric temperature; the low heat value is higher, and the viscosity is appropriate, so that the engine operating conditions are stable. Thus, n-butanol is more suitable for adding to diesel to achieve PPC. Leermakers et al. [27] investigated the PPC in different proportions of N-butanol/diesel blends. Experiments show that even with less injection pressure, the use of n-butanol/diesel blends can significantly reduce the soot emissions. The proportion of diffusion combustion will increase under high loads and diesel engines have higher thermal efficiency under moderate blending ratios. Valentino et al. [28] studied how to perform premixed low temperature combustion by reasonably optimizing the injection timing as well as the injection pressure by using the n-butanol/diesel blends in a high pressure common-rail diesel engine. The results show that a longer ignition delay period can still be obtained when a blended fuel is used even injection pressure is lower, so that the fuel/air can be mixed more homogeneous before the SOC, thereby improving the emission characteristics. The higher volatility of the blended fuel results in increasing of the dispersion of the fuel/air mixture.

Previous studies have demonstrated that PPC mode can reduce soot emissions from diesel engines fueled with pure diesel or n-butanol/diesel blends, but most of these studies qualitatively examined the total amount of soot generated. Under the PPC mode, there are still no clear conclusions on the changing rules of PSD and GMD. However, these studies become much more important because of environmental problems and requirements of emission regulations. This study, based on a 4-cylinder turbocharged intercooler diesel engine fueled with n-butanol/diesel blends, investigated the influence of various injection parameters on engine characteristics under the early-injection PPC strategy and pre-injection PPC strategy, evaluating the potential in realizing PPC with different fuel reactivity and oxygen content, and this paper focused on the particulate characteristics. Accordingly, this study further provides a reference to reduce emissions through optimizing injection strategies and puts forward thoughts and directions to abide by higher emission standard requirements.

2. Experimental setup and materials

As shown in Fig. 1, the experiment was carried out on a 4-cylinder turbocharged intercooler diesel engine, and Table 1 lists the main technical parameters of the test diesel engine. The emission data were recorded during the experiments included the gaseous and particulate emissions. In this study, PM emissions were investigated by DMS500 MKII fast particulate spectrometer (Cambustion Ltd.) in terms of PSD, PMD and GMD of particles.

2.1. Fuel characteristics

Three kinds of fuels were used: commercially available 0# diesel oil (B00), two n-butanol/diesel blends. The blending ratios are 7:3 and 5:5 (diesel: n-butanol) by volume denoted as B30 and B50 respectively. During the trial, a higher proportion (60%, 70%) of the butanol blended was attempted, but the engine was extremely unstable and the combustion deteriorated, which was of little significance in the study.

2.2. Particulate matter measurements

The PSD is presented by dN/dlogDp, where N is the particle number concentration and Dp is the particle diameter. The PMD can be calculated as follows [29]:

$$\frac{dM}{d\log D_p} = \frac{dN}{d\log D_p}\cdot\rho_p\cdot S\cdot(D_p)^{d_f} \tag{1}$$

where M is the particle mass concentration. ρ_p is the particle density, S is a shape factor and df is the particulate fractal dimension. Those values were assumed to be 1.2 g/cm^3, 0.524 and 3.19, respectively. The particles mass concentration measured by DMS was calculated from a particles density of 1.2 g/cm^3 as follows:

$$Soot\ mass\ (\mu g) = 1.53\times10^{-16}\cdot(D_p)^{d_f}\ (nm) \tag{2}$$