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Experimental study of the effect of heavy aromatics on the characteristics of combustion and ultrafine particle in DISI engine

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HIGHLIGHTS

- Heavy aromatics ($C \geq 9$) has more significant effect on PN emisson than that of total aromatics.
- Total aromatics as well as the heavy one has a limited influence on PN emission at cold condition.
- The effect of aromatics on PN increases with the decrement of excesive air coefficient.

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ABSTRACT

An experiment was carried out in a direct injection spark ignition (DISI) engine to research the effect of aromatics, especially the heavy aromatics (aromatics with $c \geq 9$) content on the characteristics of in-cylinder combustion and engine-out ultrafine particle. The results show that total aromatics and heavy aromatics content all have a limited effect on in-cylinder combustion. But the ultrafine particle, especially the nucleation mode particles, increases with the increment of aromatics content under warm engine operation condition. More importantly, higher total aromatics content does not always lead to more ultrafine particles and it is dependent on the content of heavy aromatics, which means that the heavy aromatics content has a more significant effect on ultrafine particles. On the contrary, total aromatics content as well as heavy aromatics content has a limited effect on ultrafine particles under cold engine operation condition which emits much more particle number (PN) than it emitted under warm condition. In addition, PN increase significantly with the increment of aromatics content at warm idle operation condition, but no matter total aromatics or heavy aromatics has a limited influence on PN at cold idle operation condition. And it also shows that the effects of aromatics on particle size distribution and PN are affected by excess air coefficient. The decrement of excess air coefficient would enhance the effect of aromatics on PN.

1. Introduction

Nowadays light-duty vehicles are universally used. In generally, they adopt port fuel injection (PFI) or direct injection spark ignition (DISI) engines. And compared with conventional PFI engines, DISI engines have been an important mean for these vehicles due to the promotion of fuel efficiency and the reduction of CO_2 emission which is one of the greenhouse gases [1]. However, DISI engines are known to emit more particle number (PN) than PFI engines [2,3]. And the increase in PN emission is mainly due to the fact that, compared with the PFI engines, less time is gettable for the fuel vaporization as well as mixture preparation [4]. Furthermore, it could results in liquid gasoline impinging onto the surfaces of piston and cylinder wall which leads to charge heterogeneity and pool fire.

At the same time, it is worth noting that over the past decades, evidences have been accumulated that ultrafine particle can have significant effect on human health [5,6]. Lately some studies have taken to explain the mechanisms behind these effects. And they demonstrate the ability of ultrafine particle to penetrate into the bloodstream [7,8] and even to cause genetic damage [9]. Anxiety about the effects of the ultrafine particle on human health have

Abbreviations: DISI, direct injection spark ignition; PN, particle number; PFI, port fuel injection; PM, particle matter; HEPA, high efficiency particulate air filter; DBE, double bond equivalent; PAHs, polycyclic aromatic hydrocarbons; EPA, environmental protection agency; bTDC, before top dead center; ECU, electronic control unit; PID, proportional-integral-derivative; λ, excess air coefficient.

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forced the European Union (EU) to issue PN emission standard, which limits the number of particle emitted from DISI engines over the certification New European Driving Cycle to 6.0×10^{12} particles/km in the year of 2014 and the number would be reduced to 6.0×10^{11} particles/km in the year of 2017 [10]. USA has not implemented PN standard for DISI engines, but it had adopted a federal particle matter (PM) mass FTP standard of 3 mg/mile for light-duty vehicles in the year of 2017 which is much stricter than that in EU (5 mg/km). In addition, California has even issued a 1 mg/mile standard for light-duty vehicles beginning with the year of 2025 [11]. The standard of China V implemented in the year of 2018 do not give the limitation of PN emitted from DISI engine, but it also gives the limitation of PM which is 4.5 mg/km.

In order to reduce PN emission and meet the increasingly stringent regulatory requirements, it is important to make it clear of the source of PN emitted from DISI engines. Over the past years, lots of studies had researched the effect of engine parameters as well as the gasoline component on PN emission, and the results shows that gasoline quality have a great effect on PN [12,13]. In light of the effect of gasoline component on PN emission and meeting engine emission regulations, gasoline regulations have been enacted in different countries and they are shown in Table 1 [14]. At present, China IV gasoline standard have been promulgated nationwide since the year of 2014, and the standard of China V is also promulgated in big cities and several provinces of East China. From Table 1 we can see that the limitations of aromatics content in China IV and China V are 5%v/v higher than it in Europe V. In addition, according to SGS gasoline survey data in the year of 2014, actually the average aromatics content of China V commercial gasoline (35–40%v/v) is much higher than U.S. (22%v/v) and Europe (30%v/v). And this value is even higher than the survey results of China IV (about 30%v/v) commercial gasoline [14]. And the commercial gasoline of China is abundant in aromatics for obtaining high octane number. But aromatic hydrocarbons are unsaturated compounds with benzene ring like structure and they are known to form polycyclic aromatic hydrocarbons (PAHs), which are the precursors of particles [15,16]. Several studies have shown an increase in PM emissions with increasing aromatics content in gasoline [17–22]. In addition, the US environmental protection agency (EPA) already made an all-around study of the influence of gasoline properties on light vehicle exhaust emissions which included an evaluation of gasoline aromatics content, while the study was only limited to PFI engines [22]. In addition to the total aromatics (including light aromatics and heavy aromatics) content, the heavy aromatics (aromatics with $c \geq 9$) content should also be taken into attention. But few studies were taken to research the effect of heavy aromatics content on PN emission as well as the combustion characteristic. And the objective of this work is to provide some experimental data and analysis on the effect of aromatics, especially the heavy aromatics content on PN emission and combustion characteristic in congested urban conditions of China. On the basis of better understanding of those impacts, it is desired to provide some suggestions and guidelines on how to improve gasoline quality to help effectively reduce PN emission in China.

2. Experimental apparatus and method

2.1. Test engine and instruments

The test engine was an in-line four-cylinder, turbocharged and inter-cooled, direct injection spark ignition engine, and the detailed specifications are presented in Table 2. Fig. 1 shows the layout schematic of test engine and instruments. Engine speeds and torques could be controlled by the dynamometer, which allowed changing the engine speeds and loads according to the needs of the experiments.

In order to trace the combustion process, the in-cylinder pressure was measured by a pressure transducer (Kistler 6117BFD16). And a charge amplifier (Kistler 5011) was used to amplify the transducer output which was then recorded by a data collecting card. 500 consecutive cycles of pressure data were recorded for each experiment point. The collected cycles were simultaneously averaged and yield cylinder pressure trace, it was used to calculate the heat release rate. PN and particle size distribution were measured with a fast particle spectrometer (DMS 500SKII, Cambustion, Inc.). It combines electrical mobility measurements of particles with sensitive electrometer detectors, allowing generation of particle size/number distributions in real-time. These outputs may be further processed to give simultaneous outputs of particle size, number. There is a built-in 2 stage dilution system in DMS 500SKII. The primary diluter is controlled by filtered compressed air, and the dilution ratio is 1–5. The secondary diluter is a rotating disc type, and the dilution ratio is 12–500. The parameters of DMS are shown in Table 3. In our experiment, the sampling position was taken after the turbo charger and the exhaust was then diluted by 2 stage dilution system (1st dilution ratio was set to 5, 2nd dilution ratio was set to 12; maintaining a good signal to noise ratio whilst extending instrument cleaning intervals, as suggested by the manufacturer). The sample line from the exhaust to the second dilution system was maintained at 150 °C [23] which is in order to avoid the condensation of the particles. The mass flow rate of air in the dilution system was controlled by using high efficiency particulate air filter (HEPA) filtered compressed air. Coriolis meter was used to measure the flow rate of gasoline. PT100 type thermal resistance and K type thermocouple were used to record intake air temperature, engine coolant temperature and exhaust temperature.

2.2. Engine operating method and test fuel

The important engine operating parameters such as torque, speed, injection timing, injection pressure, intake air temperature, coolant temperature were kept constant in the experiments to ensure test repeatability and comparability. Experiments were tested on both cold and warm engine operation conditions by maintaining the engine-out coolant temperature at 25 ± 2 °C and 80 ± 2 °C, respectively. Firstly, under warm engine operation condition, the engine was maintained at a constant speed of 1500 rpm which represents low speed adopted in congested urban conditions. Loads were set to 0.42 MPa and 0.85 MPa which represent the low and high engine load, respectively. Electronic control unit

Table 1
Specifications Comparison of current Europe, U.S. and China gasoline standards.

Specifications	EU V	U.S.	China IV	China V
Spec name	EN 228:2008	Conventional	GB 17930-2011	GB 17930-2013
Implementation year	2009 July	2012 January	2014 January	2017
RON grade	91/95	92/94/96 +	90/93/97	89/92/95
Sulfur (ppm, max)	10	30	50	10
Aromatics (vol%, max)	35	–	40	40