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Combustion and particle number emissions of a direct injection spark ignition engine operating on ethanol/gasoline and n-butanol/gasoline blends with exhaust gas recirculation

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HIGHLIGHTS

- The addition of ethanol or n-butanol improves the combustion stability.
- Ethanol/gasoline blends show stronger anti-knock ability than gasoline and n-butanol/gasoline blends.
- The employment of EGR overcomes the negative effect of n-butanol on knock.
- Both EGR and alcohol addition are beneficial for the reduction of PN emissions.

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ABSTRACT

The combustion and particle number (PN) emissions of a direct injection spark ignition engine (DISI) operating on ethanol/gasoline and n-butanol/gasoline blends with exhaust gas recirculation (EGR) were studied in this paper. Firstly, the effect of EGR and fuel evaporation on charge cooling was investigated. The results indicate that both the addition of EGR and alcohol show evident charge cooling effect. The 0–10% mass fraction burned (MFB) combustion duration increases with increasing EGR rate and increasing charge cooling ability of fuels. As the EGR rate is increased from 0% to 20%, the 10–90% MFB combustion duration is prolonged by 25.5–38.9% for alcohol/gasoline blends, and 64.1% for gasoline. As alcohol is introduced, the 10–90% MFB combustion duration decreases. The addition of ethanol or n-butanol improves the combustion stability. The anti-knock ability mainly depends on the octane number and charge cooling effect of fuels, as well as EGR. Either ethanol/gasoline blends or EGR is beneficial to improve the anti-knock ability. However, n-butanol/gasoline blends show degraded anti-knock ability. Combined with EGR, it is possible to overcome the negative effect of n-butanol on knock. Furthermore, the effects of EGR rate and alcohol content on PN emissions were investigated. It is found that the peak particle number concentration gradually decreases and its distribution shifts toward smaller size with increasing EGR rate. Similarly, the increasing alcohol content in the blends results in decreased peak particle number concentration and higher proportion of finer particles.

1. Introduction

On the increasing demand of reducing fossil fuel consumption and greenhouse gases, the investigation of alcohols addition in spark ignition (SI) engines has become a hot spot [1,2]. The United States renewable fuel standard has made it a requirement to increase the production of ethanol and advanced biofuels to 36 billion gallons by 2022. Ethanol will be capped at 15 billion gallons, which leaves 21 billion gallons to come from other sources, such as butanol [3].

Both ethanol and butanol can be produced from the fermentation of the sugars in biomass. Recently, the use of genetically enhanced bacteria increases the fermentation process productivity [4,5]. It is expected that a sustainable and cost effective process for butanol production will be realized in the foreseeable future.

Ethanol shows some superior fuel properties compared to n-butanol, such as higher octane number and higher oxygen content. As well known, high octane number fuels can be used to extend engine knock limit. Moreover, high oxygen content in the fuel is beneficial for more complete combustion [6]. The higher Reid

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vapor pressure of ethanol is advantageous to cold start, while disadvantageous to pollutions, especially during hot summers. N-butanol also exhibits some superior fuel properties compared to ethanol, such as higher energy density, lower corrosivity to aluminium or polymer components in fuel system, higher tolerance to water contamination for long-time storage and better solubility in gasoline [7]. N-butanol can be used either as neat fuel or blend fuel in SI engines without any engine modification, due to its fuel properties are much closer to gasoline. Both ethanol and n-butanol have higher latent heat of evaporation compared to gasoline, realizing additional charge cooling benefit in direct injection spark ignition (DISI) engines.

Nowadays, particle number (PN) emissions have become an issue for SI engines since more stringent standard limits have been proposed in the United States and European Union. DISI engines typically emit higher PN emissions than port fuel injection (PFI) SI engines due to the difference in air–fuel mixture preparation. The PN emissions of a PFI SI engine fuelled with n-butanol/gasoline blends combined with hot EGR were studied by Gu et al. [8]. The results showed that particle number concentration decreased with increasing n-butanol content in the bends. The impact of air–fuel ratio and spark advance on PN emissions in a PFI engine was investigated by Arsie et al. [9]. A sharp decrease of number concentration was observed for lean mixtures compared to stoichiometric ones, and an increase of particles smaller than 20 nm was observed at advanced spark timing. Alger et al. [10] found that EGR had a beneficial effect on particle matter (PM) emissions of a PFI engine. However, it is worth noting that all above investigations focus on PFI engines, and more efforts should be paid to DISI engines.

In downsized SI engines, the rise of the compression ratio or turbocharger pressure ratio is strongly limited by engine knock. Knock has become an obstacle for the improvements of engine performance and thermal efficiency, and also results in potential engine damage. Some methods have been employed to avoid knock. The utilization of high octane number fuels allows higher thermal efficiency gains by the rising compression ratio or downsizing. Koç et al. [11] found that ethanol/gasoline blends enabled higher compression ratio without knock occurrence. Moreover, EGR can be applied to mitigate knock by reducing the tendency of end gas autoignition, and it is attracting the attention of researchers as a means of making engines comply with the increasingly stringent demands for lower fuel consumption and exhaust emissions [12–14].

One aim of this study is to investigate the effect of EGR on PN emissions of DISI engines, and the potential of PN reduction with alcohol addition. The other aim is to evaluate the anti-knock ability of EGR, ethanol/gasoline blends and n-butanol/gasoline blends.

2. Experimental setup

2.1. Engine and instrumentation

The engine used in this study is a four-cylinder DISI engine, and the detailed specifications are presented in Table 1. The experimental setup is schematically showed in Fig. 1. During the whole test, the air/fuel ratio was measured by a Robert Bosch LSU Broadband lambda sensor fitted in the inlet of the three way catalyst converter (TWC) and kept constant at stoichiometric. The combustion pressure was measured using a Kistler 6117BFD16 pressure transducer. The transducer output was amplified by a Kistler 5011 charge amplifier and recorded by a high speed data collecting card. For each test point, the pressure data from 250 consecutive cycles were recorded to investigate the combustion stability and knock behavior. Among these 250 cycles, 200 cycles (misfire cycles removed if any) were utilized to calculate the heat release rate.

Table 1
Engine specifications.

Engine type	Inline 4 cylinder
Combustion chamber	Pent roof/4 valves
Fuel injection	Direct injection
Bore (mm)	82.5
Stroke (mm)	84.2
Displacement (L)	1. 8
Compression ratio	9.6
Fuel	Gasoline (RON 93)
Air/fuel ratio	Stoichiometric
Coolant temperature (°C)	85 ± 1
Oil temperature (°C)	95 ± 1

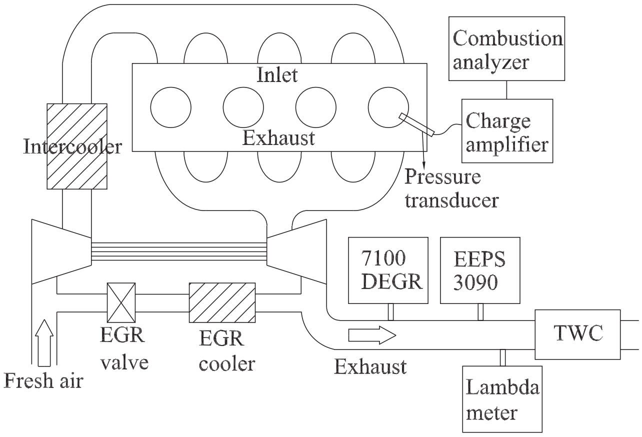

Fig. 1. Schematic diagram of experimental setup.

Gaseous emissions (such as hydrocarbon (HC), carbon dioxide (CO_2)) in exhaust pipe and CO_2 in intake pipe were sampled by a Horiba MEXA 7100DEGR analyzer. Particle emissions were measured by a TSI engine exhaust particle sizer spectrometer (EEPS3090). The particle size from 5.6 to 560 nm was measured with a sizing resolution of 16 channels per decade (a total of 32 channels). A rotating disk diluter model MD19-3E and an air supply thermal conditioner model ASET15-1 with an evaporating tube were coupled to the EEPS, as the primary and secondary diluters, respectively. The temperature of the rotating disk was 120 °C, as accepted by the particle measurement programme (PMP). The total dilution factor of the experimental setup used was 200. Both the gaseous emissions and particle emissions were taken upstream of the TWC as shown in Fig. 1.

A low pressure loop EGR system was employed, in which EGR gases were taken from the upstream of the TWC and then recycled to the upstream of the compressor. The low pressure loop EGR is also called the long route EGR due to the long distance between the position of EGR introduction and engine cylinders. The low pressure loop EGR system introduces a nearly ideal homogenous mixture of fresh air and EGR gases into the cylinders, thus the differences of the EGR repartition among the cylinders could be negligible [15]. In this study, EGR rate was swept from 0% to 20% with an interval of 4%.

As widely adopted, EGR rate is calculated from CO_2 concentrations in intake and exhaust pipes as defined in Eq. (1). The brake specific fuel consumption (BSFC) is defined as the ratio of the fuel consumption to the brake power as shown in Eq. (2). The brake thermal efficiency (BTE) is defined as the ratio of the brake power to the heat input as shown in Eq. (3).

$$\text{EGR rate}(\%) = \frac{[CO_2]_{intake} - [CO_2]_{ambient}}{[CO_2]_{exhaust} - [CO_2]_{ambient}} \times 100 \tag{1}$$