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Impact of higher n-butanol addition on combustion and performance of GDI engine in stoichiometric combustion

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ABSTRACT

An experimental study was carried out on a turbocharged gasoline direct injection (GDI) engine fueled by n-butanol/gasoline blends. Effects of n-butanol percents (15%, 30%, and 50%) on combustion and performance of the engine operating on stoichiometric combustion condition were discussed and also compared with pure gasoline in this paper. The results indicate that n-butanol/gasoline blends increase combustion pressure and pressure rise rate, fasten burning rate, and shorten ignition delay and combustion duration, as compared to pure gasoline. Moreover, these trends are impacted more evidently with increased n-butanol fraction in the blends. In addition, higher n-butanol percent of gasoline blends increase combustion temperature but decrease the temperature in the later stage of expansion stroke, which contributes to the control of exhaust temperature at high-load. With regards to engine performance, higher n-butanol percent in the blends results in increased brake specific fuel consumption (BSFC) and higher brake thermal efficiency (BTE). However, higher n-butanol addition helps to improve combustion stability but shows slightly higher knock possibility in high-load. In that case, the knock trend could be weakened by retarding ignition timing. Moreover, higher n-butanol addition significantly decreases NOx emissions, but it increases CO emissions obviously.

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1. Introduction

With the gradual exhaustion of fossil fuel and the environment pollution, the exploitation of renewable energy has developed quickly in the world wide. Especially to the automotive industry, to find renewable alternative fuels and reduce the dependence on fossil fuel is becoming a hot spot of worldwide countries. Represented by the United States, the original Renewable Fuel Standard (RFS) program was created in 2005, and required 7.5 billion gallons of renewable fuel to be blended into gasoline by 2012. In 2007, the RFS program was revised and expanded to include diesel, in addition to gasoline, and increased the volume of renewable fuel required to be blended into transportation fuel to 36 billion gallons by 2022 [1].

Alternative fuels include gaseous fuels such as hydrogen, natural gas, and propane; alcohols such as ethanol, methanol, and butanol; vegetable and waste-derived oils; and so on. Among them, ethanol has been widely used as an alternative fuel addition to gasoline, such as E10 (a blend of 10% ethanol and 90% gasoline) [2], E15, and even E85 [3], which cannot be used in a conventional gasoline-only engine, but only used in flex fuel vehicle (FFV) running on E85, gasoline, or any blend of the two.

As similar with ethanol, butanol is one of the biomass-based renewable fuels. It can also be produced by a similar alcoholic fermentation process to ethanol [4]. Similarly, butanol, like ethanol, can blend with gasoline as fuel for a series engine working without great modification to the control parameters of an engine electronic control unit (ECU) [5]. Compared to gasoline, the use of corn-derived butanol achieves energy benefits and reduces greenhouse gas emissions [6]. What is more, butanol has a number of advantages over ethanol in the field of transport. It is less corrosive and has better intersolubility than ethanol, so it can be blended more easily with gasoline without phase separation [7], which could make it more cost-effective with the existing infrastructure [8]. In addition, butanol has higher energy density than ethanol [9].

Abbreviations: AFR, air fuel ratio; ATDC, after top dead center; BMEP, brake mean effective pressure; BTE, brake thermal efficiency; BSFC, brake specific fuel consumption; CA50, 50% mass fraction burned; CO, carbon monoxide; COV, coefficient of variation; CR, compress ratio; ECU, electronic control unit; FFV, flex fuel vehicle; GDI, gasoline direct injection; HC, hydrocarbon; HCCI, homogeneous charge compression ignition; HRR, heat release rate; IMEP, indicated mean effective pressure; KI, knock intensity; MON, motor octane number; NOx, nitrogen oxides; PFI, port fuel injection; PON, pump octane number; PN, particle number; RON, research octane number; SI, spark ignition; TWC, three way catalyst.

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n-Butanol, which has a straight-chain structure with the OH at the terminal carbon, is one of four isomers of butanol. Investigation of n-butanol usage as the engine fuel has been conducted for some researchers. In diesel engines, especially, the research groups, represented by Yao et al. [10,11], Liu et al. [12,13], Rakopoulos et al. [14,15], and the author [16,17] have investigated the characteristics of n-butanol blended with diesel combusted in diesel engines. On conventional port fuel injection (PFI) spark ignition (SI) engines, on the other hand, the majority of studies on n-butanol have been performed either as pure fuel or blend fuel due to its high octane number. Szwaja and Naber [18] tested the blends of n-butanol to gasoline with 0%, 20%, 60%, and neat n-butanol in a PFI engine, and found that the behavior of neat n-butanol with respect to combustion knock is similar to that of PON (pump octane number) 87 gasoline. Alasfour [19] studied the effect of using 30 vol.% n-butanol blended with gasoline in a PFI engine, and showed that the engine efficiency had a reduction by 7% compared to pure gasoline fuel. Sayin and Balki [20] also investigated the effect of CR (compression ratio) on the emission, performance and combustion characteristics of a gasoline engine fueled with iso-butanol (10%, 30% and 50%) blended gasoline fuel. Pechout et al. [21] studied the effects of 30% and 50% of n-butanol blends with gasoline on combustion and emissions of a naturally aspirated PFI spark ignition engine on stoichiometric operation and found that flame propagation was faster with higher butanol content, as well as with lower HC, comparable CO, and higher NOx. Venugopal and Ramesh [22] compared the effects of 50% n-butanol–gasoline adopting simultaneous port injection of two injector and pre-blended on performance, combustion and emission characteristics of a spark-ignition engine.

In addition, the emission characteristics of n-butanol–gasoline blends were also investigated in PFI SI engine by Feng et al. [23], Singh et al. [24], Elfasakhany [25], Gu et al. [26], and Arsie et al. [27]. Moreover, n-butanol and its blend with gasoline were also tested in PFI engine with new concept like Homogeneous Charge Compression Ignition (HCCI) by He et al. [28,29]. Furthermore, Raviteja and Kumar [30] even investigated the effects of hydrogen addition (5% and 10% by volume) on the performance and emission parameters of an SI engine fueled with 10%, 20%, and 30% butanol/gasoline blends at stoichiometric conditions.

Parallel to the exploitation of alternative fuels, the development of gasoline direct injection (GDI) engine is an important worldwide innovation of the automotive industry [31]. GDI engine has apparent advantages over the contemporary PFI engine such as fuel economy, transient response and cold-start emission. Considering higher latent heat of evaporation of n-butanol, researchers have conducted a small amount of experiments to investigate the influence of n-butanol–gasoline blends on GDI engine. Wallner et al. [8] investigated the emissions with pure gasoline, 10% ethanol (E10), and 10% n-butanol blends (B10) in a modern GDI engine. Their results showed little difference in HC, CO and NOx emissions between pure gasoline and 10% n-butanol due to stoichiometric air/fuel ratio combustion, while brake specific fuel consumption (BSFC) increased by 3.4% for B10 compared with gasoline. Zhang et al. [32] investigated that the combustion and particle number (PN) emissions of GDI engine fueled with gasoline blends with 10% and 20% butanol, and reported that n-butanol/gasoline blends show degraded anti-knock ability, but n-butanol addition is beneficial for the reduction of PN emissions.

As can be seen from the above literatures, however, the majority of investigations with n-butanol/gasoline blends focus on PFI engines, and more efforts should be paid to GDI engines due to their potential of energy saving and emission reduction. Therefore, the present study concentrates more on the influence of butanol addition, especially higher butanol fractions, on combustion, fuel efficiency and emission characteristics of a GDI engine running on stoichiometric combustion.

2. Experimental setup and approaches

2.1. Experimental setup

Experiments were conducted on a four-cylinder turbocharged gasoline direct injection (GDI) engine. The engine specifications are shown in Table 1. The schematic of experimental setup is shown in Fig. 1. During the whole test, the relative air/fuel ratio (lambda) was measured by Bosch LSU broad-band oxygen sensor and lambda meter, kept at stoichiometric ratio by closed-loop feedback control.

The cylinder pressure was measured in one of the cylinders using an AVL spark plug pressure sensor (GH13Z-31) with the corresponding charge amplifier and data acquisition system. The pressure data from 200 continuous cycles, which were taken every 0.5 °CA, were averaged and furthermore analyzed by using a single-zone heat-release model. In the model, a spatial uniformity of pressure, temperature, and composition in the combustion chamber, at each instant of time or during a crank angle step, is assumed. By combining the first law of thermodynamics and the ideal gas law, the net heat release (HRR) rate with respect to crank angle can be derived as [33]

$$\frac{dQ_n}{d\varphi} = \frac{dQ_{ch}}{d\varphi} - \frac{dQ_{ht}}{d\varphi} = \frac{\gamma}{\gamma - 1} p \frac{dV}{d\varphi} + \frac{1}{\gamma - 1} V \frac{dP}{d\varphi} \quad (1)$$

The net HRR, $dQ_n/d\varphi$, which is the difference between the gross HRR, $dQ_{ch}/d\varphi$, and the heat transfer rate to the walls, $dQ_{ht}/d\varphi$, equals the rate at which work is done on the piston plus the rate of change of sensible internal energy of the cylinder contents [33].

In the above equation, γ is the ratio of specific heats at constant pressure and volume, c_p/c_v, which is assumed to be a constant value without variation with the cylinder temperature. p is the measured cylinder pressure. The cylinder volume V and its rate of change with respect to crank angle $dV/d\varphi$ are calculated by standard expressions [33].

The original engine gas emissions before three-way catalyst (TWC) were measured by using AMA I60 exhaust analyzer made by AVL, in which carbon monoxide (CO) and carbon dioxide (CO_2) were analyzed by a non-dispersive infra-red (NDIR) analyzer, hydrocarbon (HC) determined by a flame ionization detector (FID) analyzer, and total oxides of nitrogen ($NO + NO_2$, NOx) measured by a chemiluminescent analyzer (CLA).

2.2. Test fuels

A commercial gasoline (RON 93) was used as a base fuel for the preparation of all the blends. The n-butanol (butanol hereafter) with a purity of 99.5% (analytical grade), purchased from local commercial representatives, was chosen as an alternative fuel addition to the base fuel. The properties of the base fuels are listed in Table 2. Mixtures of 0%, 15%, 30%, and 50% by volume fraction of butanol with the base fuel were tested in this study, expressed as Bu00, Bu15, Bu30, and Bu50. Bu00 represents pure gasoline fuel which was used for all baseline runs, while Bu15, Bu30 and Bu50 were used to investigate the influence of butanol fraction (concentration) on combustion and performance of the GDI engine. Those

Table 1
Engine specifications.

Engine type	Inline 4 cylinders, 4 valves
Displacement	1.4 L
Compression ratio	11:1
Intake system	Turbocharged, intercooled
Fuel system	Direct injection
Air/fuel ratio	Stoichiometric

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