

A Comparative Study of Emission Characteristics of Propanol Isomers/Gasoline Blends Combined with EGR

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ABSTRACT

Propanol isomers are oxygenated fuels and have higher octane number and energy density compared to methanol and ethanol. In recent years, with the development of fermentation method, propanol isomers have gained more attention as engine additive to reduce the emission and the consumption of traditional fossil fuels. In this study, Hydrocarbon (HC), carbon monoxide (CO) and particulate matter (PM) emission characteristic of propanol isomers/gasoline blends were comparatively investigated at different blending ratios (0, 10, 20, 40 and 100) combined with exhaust gas recirculation (EGR) in a spark-ignition engine. The number distribution of particulate matter emission is mainly studied in addition to the particulate matter mass distribution. Results show that pure propanol isomers yield significantly different emission characteristics compared to the other blends. With the increase of blending ratio, CO emission shows a decreased trend while unidentified HC emissions are observed except pure propanol isomers. And particulate matter number concentration is increased as the increase of propanol isomers proportion. With the introduction of EGR, particulate number concentration and CO emissions decrease. Moreover, n-propanol/gasoline blends produce higher CO and particulate matter number concentration compared to iso-propanol/gasoline blends at the same blending ratio due to their distinctive molecular structures and properties. The experimental results suggest that iso-propanol is more suitable than n-propanol as a gasoline additive within the scope of present experimental condition.

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INTRODUCTION

With the environmental deterioration and fossil fuel shortage, the demands on clean and renewable alternative fuels have been attracting more and more attention. Oxygenated fuels, such as alcohols, carbonates, ethers, and acetates, have been used due to their potential of reducing emissions [1, 2, 3]. Alcohols can be produced through bio-chemical processes, and they are promising alternatives for gasoline and diesel engines [4, 5]. Previous investigations mainly focused on methanol and ethanol to improve combustion and decrease emissions [6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18]. Since large alcohols, such as propanols, have higher energy density and research octane number (RON), thus they are more advantageous than methanol and ethanol in practical use. With respect to alcohols, especially propanol isomers, some study has been done previously. Kelkar et al. [19] reported that the addition of alcohols (methanol, ethanol, iso-propanol and butanol) caused no discernible difference of thermal efficiency in a spark-ignition engine. Yacoub et al. [20] showed that the addition of methanol, ethanol and propanol to gasoline would improve the knock resistance. Gautam et al. [21, 22] investigated the combustion characteristics of higher alcohol

(C₃-C₅)/gasoline blends and reported that the gasoline/alcohol blends had significantly lower brake specific emissions of CO, CO₂, NO_x and organic hydrocarbon compared with neat gasoline in a spark ignition engine. This differs from the observation of Keskin and Gürü [23] stating that the addition of alcohols (ethanol and iso-propanol) brought lower CO and HC emissions, but higher NO_x and CO₂ emissions. Additionally, Lü et al. [24] found that cold EGR in a homogeneous charge compression ignition (HCCI) engine could reduce the combustion rate and increase CO and HC emissions, especially for large iso-propanol addition. Recently, Gravalos et al. [25] reported that the addition of higher alcohols (C₃-C₅) increased HC, CO₂ and NO_x emissions, but reduced CO emissions.

From a practical point of view, propanol isomers can be produced commercially through the fermentation of starch sugars [26]. Recently, the method of producing n-propanol from glucose using *Escherichia coli* was suggested [27, 28]. Moreover, in 2012 Dai et al. [29] developed the method to convert acetone into iso-propanol based on the previous study and switched from the traditional ABE (Acetone-butanol-ethanol) fermentation to IBE (iso-propanol-butanol-ethanol) fermentation.

fermentation. Since the mixture of iso-propanol, butanol and ethanol can be used as biomass inherently, IBE fermentation is more valuable. These further extend and accelerate the possibility of propanol utilization in internal combustion engines as additives. However, previous studies on the emission of propanol isomers as gasoline additives are still limited, especially on the particulate matter emissions. Thus, the present study mainly focuses on the engine emission characteristics of propanol isomers as gasoline additives, including HC, CO and particulate matter emissions. The effects of blending ratios and EGR rates on emissions are clarified and the emissions between n-propanol and iso-propanol/gasoline blends are compared.

EXPERIMENTAL SETUP

A three-cylinder, port-injection, spark-ignition engine was employed in this study. The specifications of the engine are given in Table 1. To investigate the effect of EGR, an EGR system was installed on this engine. The exhaust gas went through an intercooler and mixed with fuel and air in the mixer before it was introduced to the cylinder. The rate of water flow in the intercooler could be adjusted according to the EGR rate and exhaust gas temperature to ensure the consistency of EGR intake temperature during all the experiments. The ECM EGR5230 analyzer was used to monitor the EGR rate with an accuracy of 0.5% based on the volumetric percentage of EGR rate. EGR rate is defined as $\text{EGR (\%)} = V_{\text{EGR}} / (V_i + V_{\text{EGR}})$, where V_{EGR} presents the volume flow rate of EGR and V_i indicates the volume flow rate of intake air-fuel mixture. Moreover, EGR rates were regulated by the valve opening, which was controlled by a self-designed EGR control system. Excess air ratio, λ , and ignition timing were controlled by an Electronic Control Unit (ECU). Horiba MEXA-7001 was employed to monitor the excess air ratio with an accuracy of 5%. Horiba MEXA-554JA analyzer was employed to measure the emission of HC and CO with accuracies of 12 ppm and 0.06%, respectively. Aerosol particulate matter number and size distributions were detected by an electrical low-pressure impactor (ELPI) covering the size from 7 nm to 10 μm in aerodynamic diameter. In order to prevent the overload of the measurement system, a two stage-diluter was used to dilute the exhaust gas samples to an appropriate ratio and the dilution ratio was fixed in all experimental cases to eliminate the dilution effect. The first diluter was heated to prevent the possible nucleation, condensation, and PM loss. More details of this experimental facility and principle can be found in Ref. [30, 31, 32]. All experiments were carried out under stoichiometric condition (excess air ratio $\lambda = 1.0$) and the engine was operated at full load (wide-open throttle, WOT) with a speed of 3000 r.min⁻¹. PM emissions were sampled at

maximum brake torque timings (MBT) and the data collected here is the average value of 200 cycles. In the experiment, blending ratios were $x = 0, 10, 20, 40$, and 100 and EGR rates were 0 and 10, respectively. The blending ratio, x , indicates the volume fraction of propanol isomers in the propanol/gasoline blends. The properties of propanol isomers and gasoline are tabulated in Table 2.

Table 1. Engine specifications.

Type	HH368Q spark-ignition engine
Stroke	75 mm
Bore	68.5 mm
Displaced volume	796 cc
Compression ratio	9.4:1
Ignition sequence	1-3-2
Rated power	26.5 kW
Rated speed	5500 r. min ⁻¹

RESULTS AND DISCUSSIONS

Gaseous Emissions of Propanol Isomers/Gasoline Blends

Effect of Blending Ratio and Spark Timing

Figures 1 and 2 show the brake specific emissions of HC and CO in terms of spark timing at different blending ratios for propanol isomers/gasoline blends without EGR, respectively. Both propanol isomers/gasoline blends show similar trends.

Table 2. Properties of propanol isomers and gasoline (97#).

	gasoline	<i>n</i> -propanol	<i>iso</i> -propanol
Typical formula	C ₄ -C ₁₂	CH ₃ (CH ₂) ₂ OH	(CH ₃) ₂ CHOH
Lower heat value [MJ/L]	30~33 ^a	24.7 ^a	24.1 ^a
Density (20°C) [kg/m ³]	746	804	785
Oxygen content [wt. %]	< 2.7	26.6	26.6
Sulfur content [wt. %]	< 0.005	0	0
Benzene content [vol. %]	< 1.0	0	0
Olefin content [vol. %]	< 25	0	0
Boiling point [°C]	27-225	97.2	82.3
Heat of vaporization (25°C) [kJ/kg]	~351 ^a	792.1 ^a	756.6 ^a
Adiabatic flame temperature [K]	--	2257 ^b	2245 ^b
RON	97 ^a	104 ^a	106 ^a

^a All lower heat value, heat of vaporization and research octane number (RON) are from Christensen et al. [33].

^b Calculated by the models from Curran's group [34], at stoichiometric mixture, standard temperature and pressure.

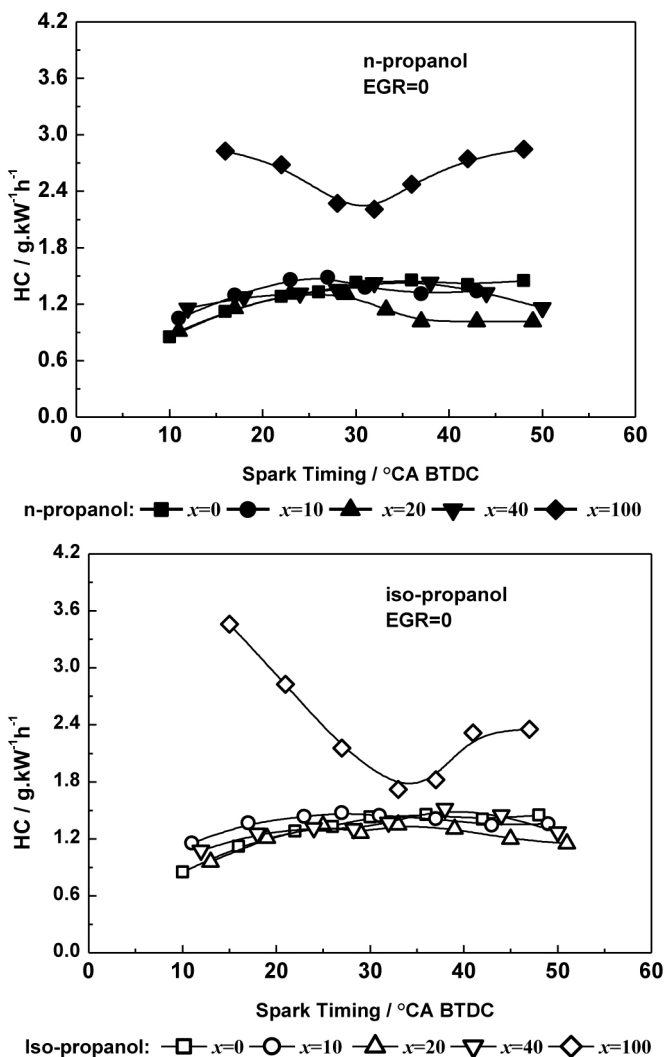


Figure 1. Brake specific HC emissions in terms of spark timing at different blending ratios without EGR.

When blending ratios are small (0, 10, 20, 40), HC varies slightly and CO reduces with the increase of propanol isomers proportion. It can be ascribed to the combination of two competitive effects, increased oxygen content and reduced heat release rate, on the oxidation of HC and CO. Pure propanol isomers generate higher HC and CO emissions than propanol isomers/gasoline blends because the significant reduction of heat release weakens the flame and post-flame oxidation. Lü et al. [24] reported that HC emission would increase substantially for the fuel blends containing more than 50% iso-propanol in HCCI engine. This behavior is also consistent to that of n-butanol [35]. Noteworthy, HC emission of pure propanol isomers decreases first and then increases with the increase of spark timing. In the case of pure propanol isomers, the advancement of spark timing improves the combustion and enhances the oxidation of HC in the expansion process, lowering HC emission. However, large advancement of spark timing, which brings higher cylinder pressure,

increases the possibility of wall quenching and the unburned fuel trapped in the crevice volumes, leading to the increase of HC emission.

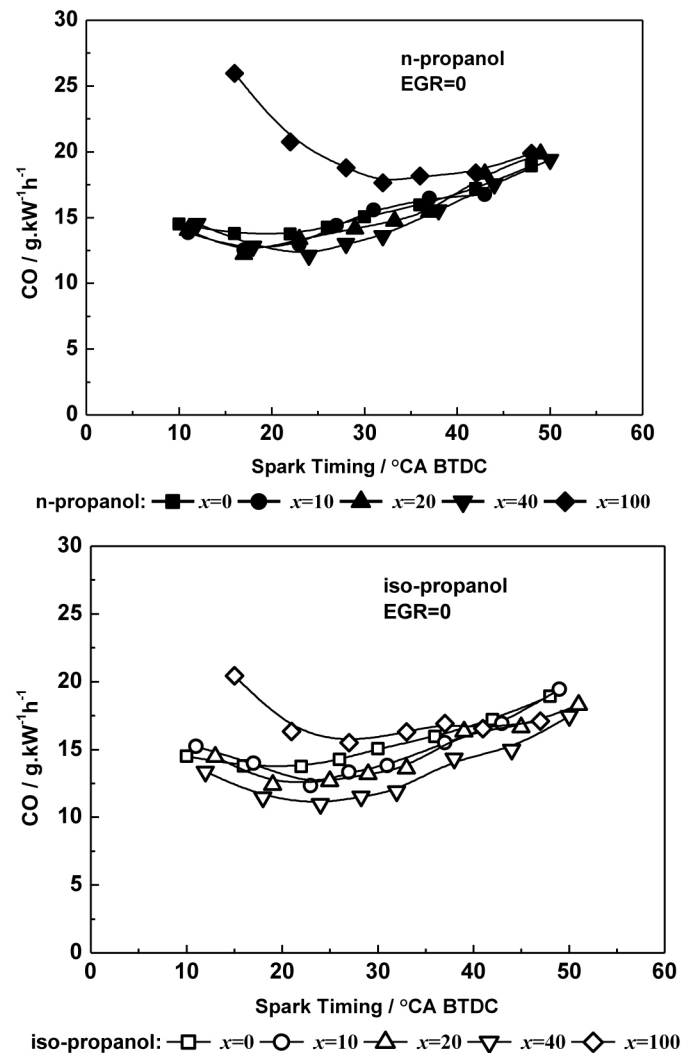


Figure 2. Brake specific CO emissions in terms of spark timing at different blending ratios without EGR.

Effect of EGR

Figure 3 shows the comparison of HC and CO emissions between n-propanol/gasoline blends and iso-propanol/gasoline blend at different EGR rate.

Brake specific HC emission shows unidentified difference between with and without EGR. Since engine is operated at stoichiometric condition, HC emission is intrinsically low. Thus, the effect of EGR introduction on HC emission is insignificant. Hu et al. [36] also reported that the increase of brake specific HC emission is not obvious when the EGR rate is less than 15% for the natural gas/hydrogen blends. Little variation of HC emissions at small EGR rates are also observed for n-butanol/gasoline blends [35].