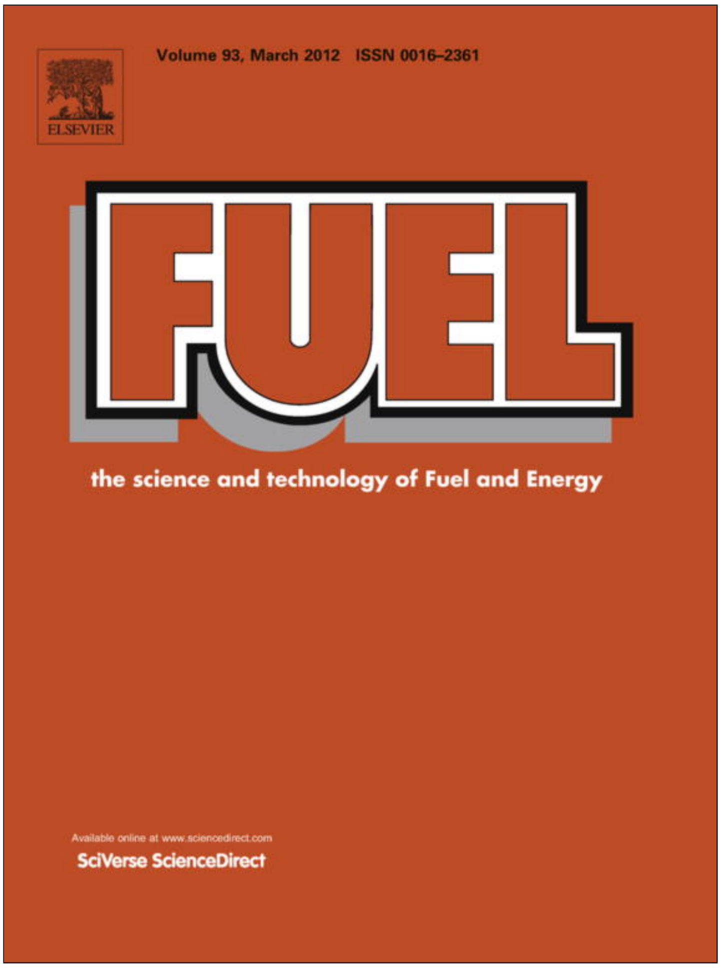
Volume 93, March 2012 ISSN 0016-2361
ELSEVIER
FUEL
the science and technology of Fuel and Energy
Available online at www.sciencedirect.com
SciVerse ScienceDirect

Fuel 93 (2012) 611–617

Contents lists available at SciVerse ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Emission characteristics of a spark-ignition engine fuelled with gasoline-*n*-butanol blends in combination with EGR

Xiaolei Gu [a], Zuohua Huang [a,*], Jian Cai [a], Jing Gong [a], Xuesong Wu [a], Chia-fon Lee [b]

[a] State Key Laboratory of Multiphase Flow in Power Engineering, Xi'an Jiaotong University, Xi'an 710049, People's Republic of China
[b] Department of Mechanical Science and Engineering, University of Illinois at Urbana–Champaign, Urbana, IL 61801, USA

A R T I C L E   I N F O

Article history:
Received 25 January 2011
Received in revised form 28 March 2011
Accepted 15 November 2011
Available online 2 December 2011

Keywords:
Gasoline-butanol blends
Emissions
EGR
Spark timing
Spark-ignition engine

A B S T R A C T

An experimental study was conducted in a port fuel-injection, spark-ignition engine fuelled with blends of gasoline and *n*-butanol at different spark timings and EGR rates. The effect of spark timing, blend ratio and EGR rate on the emission characteristics (unburned hydrocarbon (HC), carbon monoxide (CO), nitrogen oxide (NO_x) and particulate size and distribution) was analyzed. BSFC (Brake specific fuel consumption) and MBT (maximum brake torque timing) at full load were also discussed. Results show that the blends of gasoline and *n*-butanol decrease engine specific HC, CO and NO_x emissions compared to those of gasoline. Pure *n*-butanol increases engine specific HC and CO emissions and decreases NO_x and particle number concentration compared to those of gasoline. *n*-Butanol addition can decrease particle number concentration emissions compared with that of gasoline. Advancing spark timing increases engine specific HC, NO_x emissions and particle number concentration while it decreases engine specific CO emissions. EGR can reduce engine specific NO_x emissions and particle number concentration simultaneously in spark-ignition engine fueled with gasoline and *n*-butanol blends.

1. Introduction

With the increasing concern on the shortage fossil oil supplying and the need for environmental protection, more and more attentions have been paid to the alternative fuel utilization in engines. *n*-Butanol, as a promising fuel candidate, has attracted more attention recently. *n*-Butanol has several advantages over methanol and ethanol, including high tolerance to water contamination which allows the use of the existing distribution pipelines, less corrosive to aluminum or polymer components in fuel system, ability to blend in gasoline or diesel at high fraction without modifying vehicles and better fuel economy due to higher energy density [1]. The fuel properties of the base fuels are summarized in Table 1.

Indeed, there are many investigations on methanol, ethanol and butanol utilization in gasoline engines. Conney et al. [2] investigated knock-limited compression ratios and combustion characteristics for various ethanol-gasoline blends. Dernotte et al. [3] conducted extensive studies on *n*-butanol-gasoline blends in a port fuel injection, spark ignition engine and presented the influence of *n*-butanol addition on the emission of unburned hydrocarbon, carbon monoxide, and nitrogen oxide. Liu et al. [4] showed that if spark ignition timing is advanced, engine power and torque can be improved under wide open throttle (WOT) conditions in a port fuel injection engine fuelled with methanol-gasoline blends. Szwaja and Naber [5] investigated the effect of spark timing, *n*-butanol percentage, compression ratio and load on combustion process of a spark ignition engine fuelled with the blends of gasoline and *n*-butanol.

Alasfour [6] studied engine efficiency at different equivalence ratios with a 30% butanol-gasoline blend in a single cylinder engine. Their results showed 7% decreasing in power compared to the same engine fuelled with pure gasoline. Gu et al. [7,8] measured the laminar burning velocities of butanol isomers using the outwardly propagating flame. Wallner et al. [9] investigated the unburned hydrocarbon (HC), carbon monoxide (CO) and nitrogen oxides (NO_x) emissions with pure gasoline, 10% ethanol, and 10% *n*-butanol blends in a modern direct injection four cylinder spark-ignition engine. Their results showed little difference in HC, CO and NO_x emissions between pure gasoline and 10% *n*-butanol. This is because the engine is operated at the stoichiometric air/fuel ratio for each specific fuel blend, thus excess oxygen is not available. Rice et al. [10] conducted experiment in a spark-ignition engine fuelled with iso-butanol-gasoline, ethanol-gasoline and methanol-gasoline blends and their results gave lower CO and NO_x emissions for the alcohol blends compared with gasoline.

However, laws and regulations of particulate matter emissions from spark-ignition engine have not been set up. Spurred by epidemiological observations of a correlation between ambient particulate levels and health effects [11,12] and the enactment of a new

* Corresponding author. Tel.: +86 29 82665075; fax: +86 29 82668789.
E-mail address: zhhuang@mail.xjtu.edu.cn (Z. Huang).

0016-2361/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.fuel.2011.11.040

Nomenclature

BTDC	before top dead center	θ_{ig}	spark timing
EGR	exhaust gas recirculation	°CA	degree crank angle
CO	carbon monoxide	ELPI	electric low-pressure impactor
HC	hydrocarbon	λ	excess air ratio
NO_x	oxides of nitrogen	BTE	brake thermal efficiency
PM	particulate matter	WOT	wide opening throttle
RON	research octane number	BSFC	brake specific fuel consumption
rpm	revolutions per minute	MBT	maximum brake torque timing

$PM_{2.5}$ particulate matter standard by the Environmental Protection Agency, an interest in characterizing particulate matter number and size distribution has drawn attention in recent years. Particle size influences the environmental impact in several ways: it influences the atmospheric residence time of the particles, the optical properties of the particles, the particle surface area and ability to participate in atmospheric chemistry, and the health effects of the particles. A number of studies were reported on particulate matter number and size distribution in diesel engines [13–15]. However, there were few reports on number and size distribution of particulate matter in spark-ignition engines fuelled with gasoline-*n*-butanol blends. For future utilization of the blends of gasoline and *n*-butanol in spark-ignition engine, the study on engine emissions fuelled with the blends of gasoline and *n*-butanol is indispensable.

The objective of this paper is to investigate CO, HC, NO_x and particulate matter emissions for various *n*-butanol-gasoline blends in combination with EGR in a spark-ignition engine, especially to focus on the number and size distribution of particulate matter emissions under varying blend percentages and spark timings.

2. Experimental setup and procedure

The engine used in this study is a three-cylinder, port fuel injection, spark-ignition engine with compression ratio of 9.6. The specifications of the test engine are listed in Table 2. An electronic control unit system was used to control the air–fuel ratio and spark timing. An ECM EGR5230 analyzer was used to measure the EGR rate [16]. A Horiba MEXA-700λ instrument was used to measure the air–fuel ratio with an accuracy of 5%. Three different loads (low, part and full loads) were operated in this engine at engine speed of 3000 rpm. Stoichiometric air–fuel ratio was maintained under all operations.

Table 1
Typical properties of base fuels.

	Gasoline	Ethanol	*n*-Butanol
Chemical formula	C4-C12	C2H5OH	C4H9OH
Composition (C, H, O) (mass%)	86, 14, 0	52, 13, 35	65, 13.5, 21.5
Lower heating value (MJ/kg)	42.9	26.8	33.0
Density (kg/m^3)	736	790	810
Octane number (R + M)/2	97	100	89
Boiling temperature (°C)	25–215	78	118
Latent heat of vaporization (kJ/kg)	380–500	904	716
Self-ignition temperature (°C)	~300	420	343
Stoichiometric air/fuel ratio	14.7	9.0	11.2
Stoichiometric calorific value (MJ/kg)	2.73	2.68	2.70
Laminar flame speed (cm/s)[a,b]	~33	~39	–
Adiabatic flame temperature (K)	2370	2310	2340
Solubility in water at 20 °C (ml/100 ml H_2O)	<0.1	Fully miscible	7.7

[a] T = 325 K and p = 100 kPa.
[b] Stoichiometric mixture, standard temperature and pressure (STP).

Five tested fuels were used in the study. The pure commercial 97# gasoline (*Bu*0) which is used as the base fuel, three *n*-butanol and gasoline blends denoted as *Bu*10, *Bu*30, *Bu*40 (Bux means the volume fraction of *n*-butanol in the blend is *x*), and pure *n*-butanol with a purity of 99.99%.

Experiments were conducted on a fully warmed engine. A Horiba MEXA-554JA analyzer was used to measure the exhaust HC, CO, and CO_2 concentration with an accuracy of 12 ppm for HC, 0.06% for CO, and 0.5% for CO_2. NDIR (Non-dispersive infrared) analyzer was used to measure the concentrations of CO, unburned HC, and CO_2 in the engine exhaust. A Horiba MEXA-720 NO_x analyzer with an accuracy of 30 ppm was used to measure the exhaust NO_x concentration. In this experiment, the exhaust gases were measured when the engine operates under the steady conditions.

Particulate number and size distribution was measured by an electrical low-pressure impactor (ELPI) (Dekati Ltd., Finland) with an extra filter stage which covers the particle cut sizes from 7 nm to 10 mm (as detailed in Table 3). The ELPI was designed for real-time monitoring of the aerosol particle size distribution. The detailed principle and process have been well described by many researchers [17,18]. In addition, a two-stage diluter was employed. Furthermore, to prevent nucleation, condensation, and particulate losses, the first diluter was heated in advance.

3. Results and discussion

3.1. Brake specific fuel consumption (BSFC) and brake torque

Fig. 1a gives the relationship between BSFC, brake torque and spark timing at full load condition. Brake specific fuel consumptions of *Bu*10, *Bu*30, *Bu*40 and *Bu*100 are higher than that of *Bu*0. The higher fuel consumption for *Bu*100 and its blends is primarily related to the low heating value of *n*-butanol. The lowest BSFC is presented at around 25 °CA BTDC for all blends. Fig. 1b shows that the maximum brake torque timing (MBT) is presented at about 25 °CA BTDC for all blends.

3.2. CO, HC and NO_x emissions

3.2.1. Effect of spark timing

The specific unburned hydrocarbon emissions versus spark timing for different blends at different loads are shown in Fig. 2. When

Table 2
Engine specifications.

Type	HH368Q spark-ignition engine
Bore (mm)	68.5
Stroke (mm)	72
Displacement (cm^3)	796
Compression ratio	9.4
Ignition sequence	1–3–2
Rated power (kW)	26.5
Rated speed (r/min)	5500

Table 3
ELPI specifications.

Stage	$D^{*}_{50\%}$ (μm)	D^{+}_{i} (μm)	Number (cm^{-3})	
			Minimum	Maximum
12	3.97			
11	2.46	3.1061	0.36	4×10^4
10	1.61	1.9657	0.8	8×10^4
9	0.99	1.2393	1.6	2×10^5
8	0.637	0.7672	3	3×10^5
7	0.393	0.4874	5	5×10^5
6	0.255	0.3188	9	9×10^5
5	0.165	0.2036	15	2×10^6
4	0.101	0.1208	26	3×10^6
3	0.057	0.0715	50	5×10^6
2	0.029	0.0392	90	9×10^6
1	0.007	0.0208		

$D^{*}_{50\%}$ represents the particle size with 50 percent collection efficiency.
D^{+}_{i} represents the geometric mean of the $D_{50\%}$ values.

retarding the spark timing, HC emissions are decreased for all blended fuels. This is because retarding the spark timing will increase the average cylinder temperature of post-flame and exhaust gas temperature, resulting in the promotion on unburned hydrocarbon oxidation in-cylinder. In addition, as spark timing is postponed, the peak cylinder pressure will decrease and the mass fraction of HC trapped in the crevice volumes is reduced [19].

Fig. 2 shows that small *n*-butanol blending (less than 40%) can reduce HC emissions at different loads compared to that of gasoline. The addition of butanol decreases the fraction of hydrocarbons, leading to the decrease of HC formation. However, pure *n*-butanol fuel gives higher HC emission compared to that of gasoline, and this will be due to the cylinder gas temperature dropping as butanol evaporation, decreasing HC oxidation during expansion and exhaust processes. The decreasing in HC emissions is consistent to the results in previous study [3].

Fig. 3 shows the specific carbon monoxide (CO) emissions versus spark timing for different blends at different loads. CO emissions show little variation as spark timing retards from 40 °CA BTDC to 20 °CA BTDC. However, when further retarding the spark timing, CO emissions increase remarkably. Retarding the spark timing will increase the cylinder temperature in the expansion and exhaust processes, and this will facilitate the unburned HC converted to CO. Blends of gasoline and *n*-butanol give the lower specific CO emissions compared with that of gasoline, which results from combustion improvement. However, pure *n*-butanol gives high specific CO emissions. Decreasing in both CO post-flame oxidation and engine power output is responsible for this.

Fig. 4 gives the specific nitrogen oxides (NO_x) emissions versus spark timing for different blends at different loads. Spark timing significantly affects NO_x emission levels. Advancing the spark timing makes early combustion and increases the cylinder peak pressure. Combustion temperature and local oxygen concentrations are also the major factors affecting NO_x formation. An increase in-cylinder peak pressures corresponds to an increase in-cylinder peak temperature, leading to an increase in NO_x emissions [20]. *n*-Butanol gives the lowest value in specific NO_x emissions, and this is due to the low adiabatic temperature and heat value when engine operates on *n*-butanol indicated in Table 1. The results obtained in the study agree with those in Ref. [3] but differ to that in Ref. [21] which gave 50% reduction in NO_x emissions for the stoichiometric mixture of 70% gasoline/30% iso-butanol blends.

3.2.2. Effect of EGR rate

Fig. 5 shows the specific emissions (CO, HC, NO_x) versus EGR rate for different blends at full load. Variation of HC and CO emissions with EGR rate shows the similar trend at different *n*-butanol fractions. NOx emission is decreased as blending of *n*-butanol. Specific HC emissions increase with the increase of EGR rate. This can be explained by the following interpretations. Increasing EGR rate decreases the in-cylinder gas temperature, which decreases HC oxidation in the expansion and exhaust processes. Increasing EGR will decrease the flame propagation speed and decreases engine power. Thus, specific HC emissions increase with the increase of EGR rate.

Specific CO emissions increase with the increase of EGR rate and CO emissions increase remarkably at high EGR rate. The decreasing in CO oxidation in the expansion and exhaust processes is responsible to this. At high EGR rate, besides the effect of the decreased oxidation rate in CO, EGR will greatly dilute the oxygen concentration, and this will increase the CO formation in the cylinder. Meanwhile, engine power will decrease remarkably at large EGR rate. All these lead to a remarkable increase in specific CO emissions with the increase of EGR rate at large EGR rate.

Specific NO_x emissions are decreased with the increase of EGR rate. Three factors are responsible to this phenomenon. EGR decreases the cylinder gas temperature which decreases NO formation [23]. The introduction of EGR will decrease the fresh air and fuel, and this will decrease the amount of heat release and engine power. The presence of EGR will increase the ignition delay time, which in turn postpones the combustion phase and decreases engine power.

3.3. Particulate number and size distribution emissions

3.3.1. Effect of EGR rate

Fig. 6 shows engine particulate number and size distribution of exhaust gas fuelled with gasoline-*n*-butanol blends at different EGR rates. The number-size distribution curves are all in unimodal

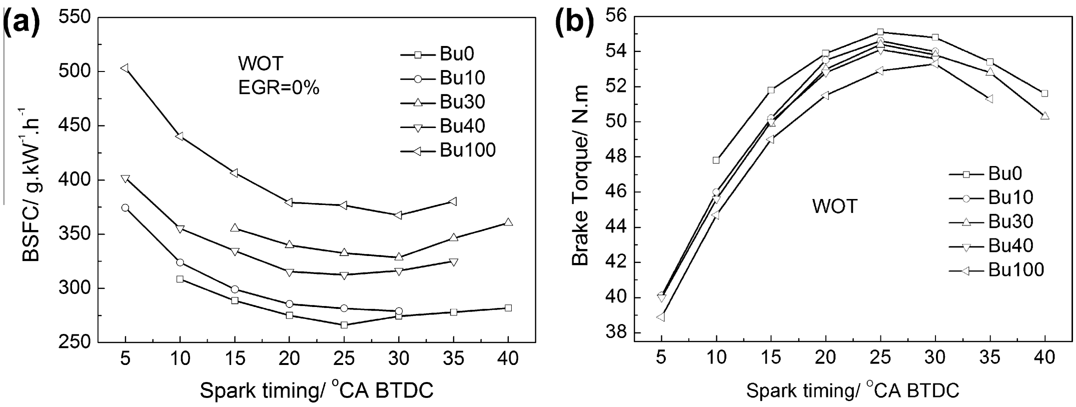

Fig. 1. BSFC and brake torque versus spark timing.

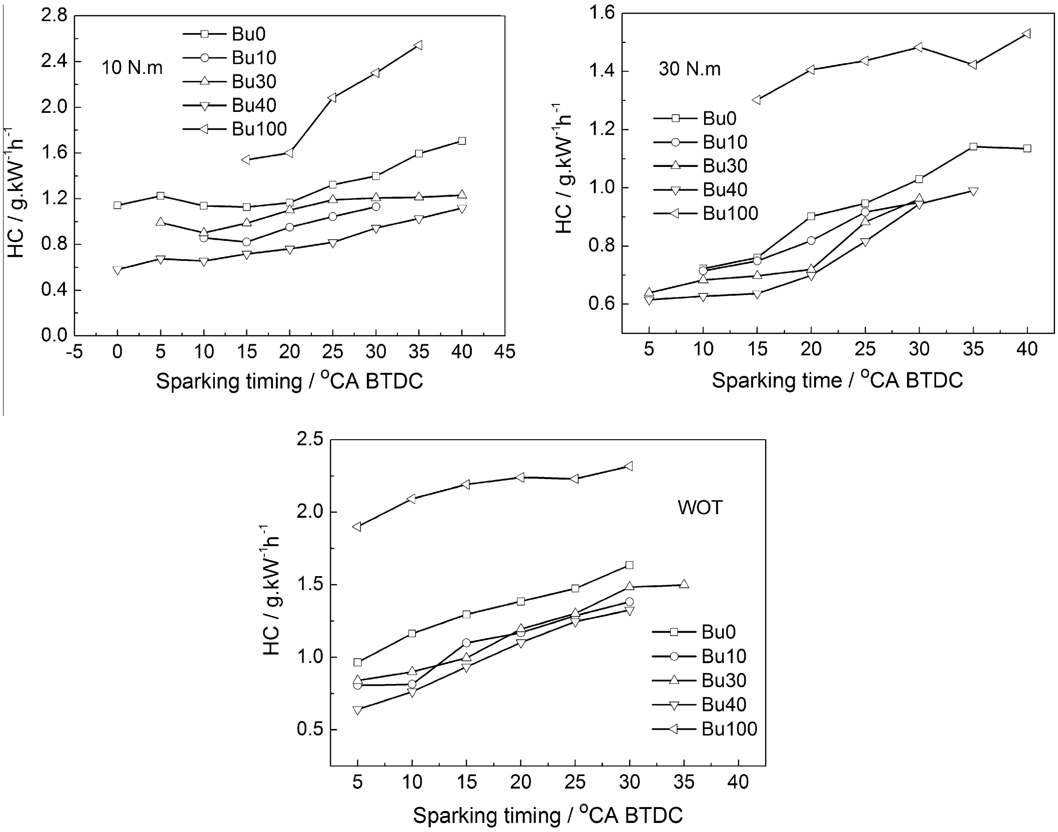

Fig. 2. Specific HC emissions at different loads.

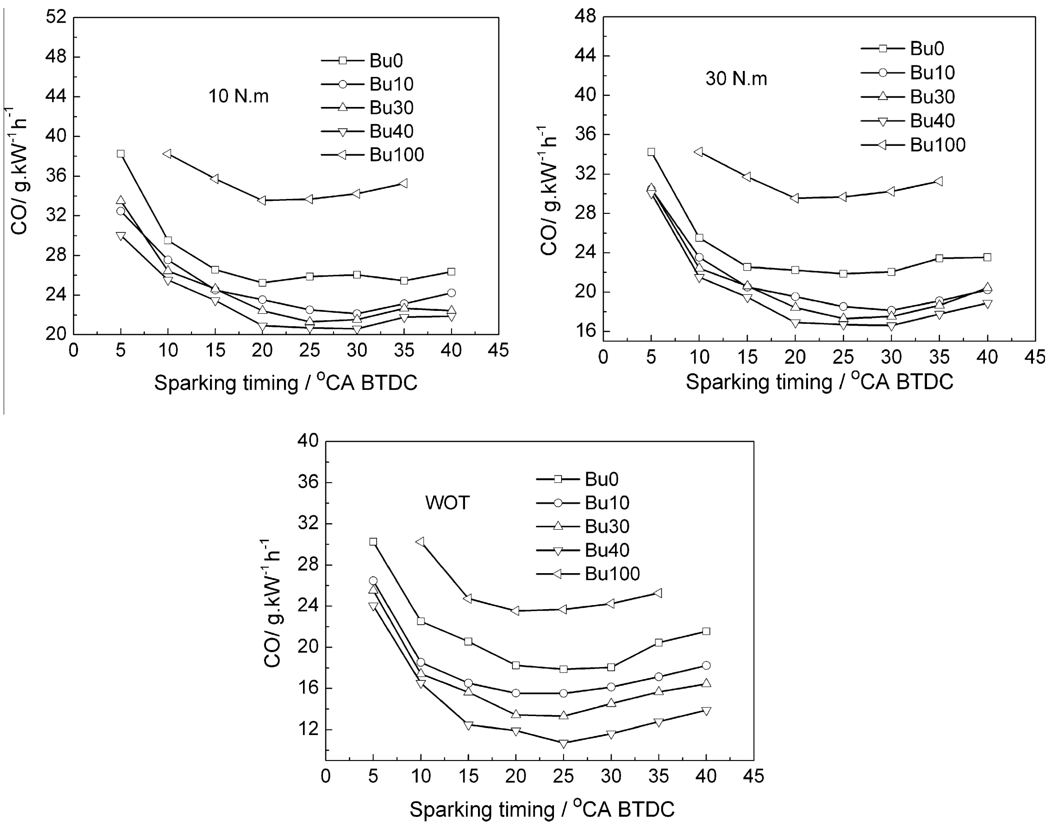

Fig. 3. Specific CO emissions at different loads.

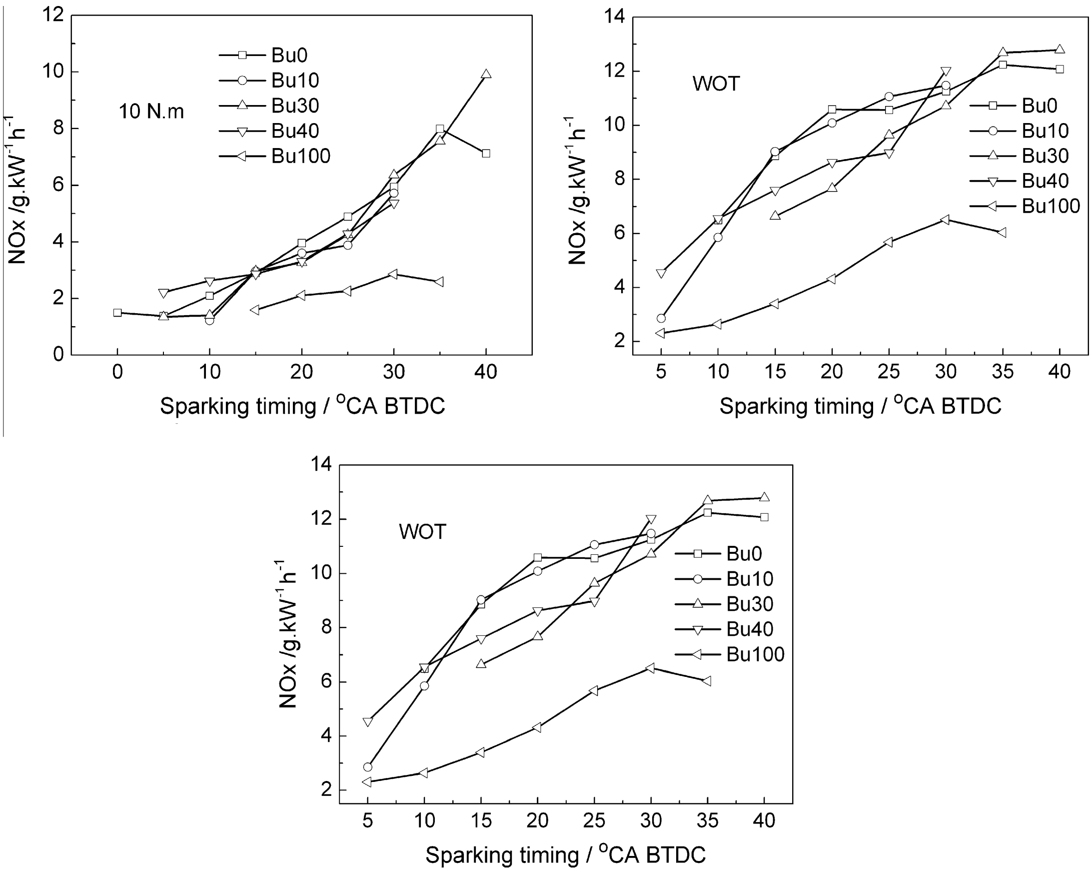

Fig. 4. Specific NO_x emissions versus spark timing at different loads.

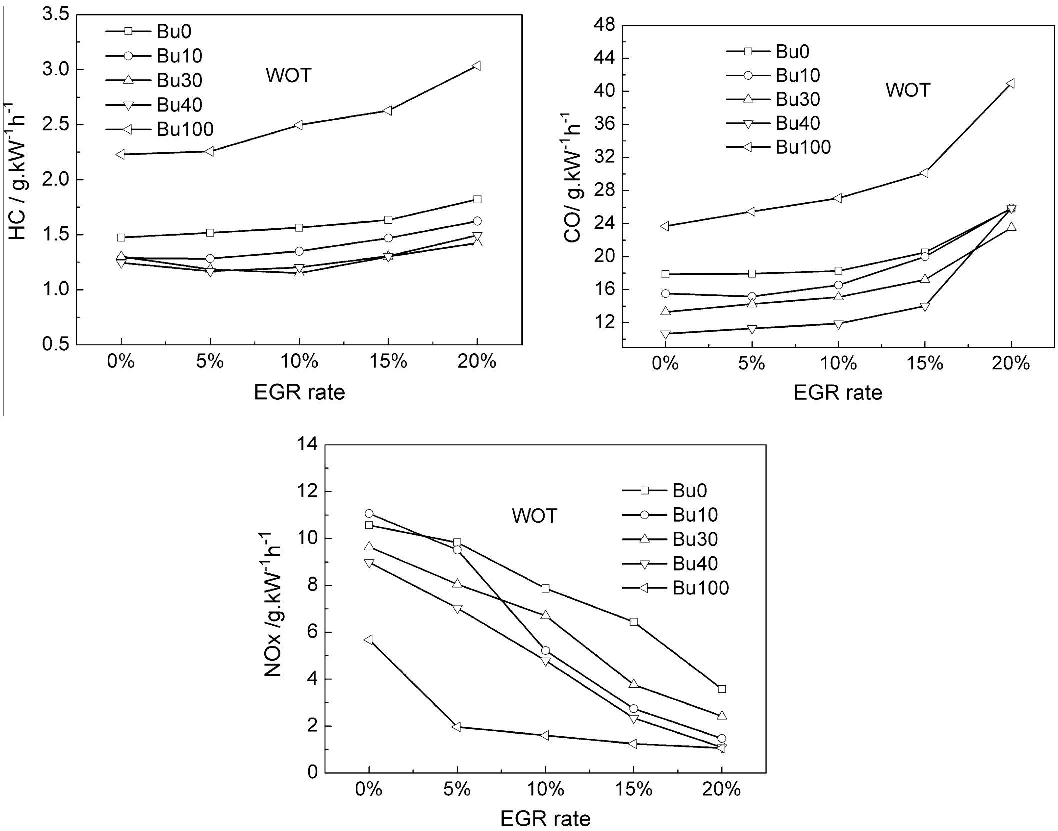

Fig. 5. Specific emissions (CO, HC, NO_x) versus EGR rate at full loads.

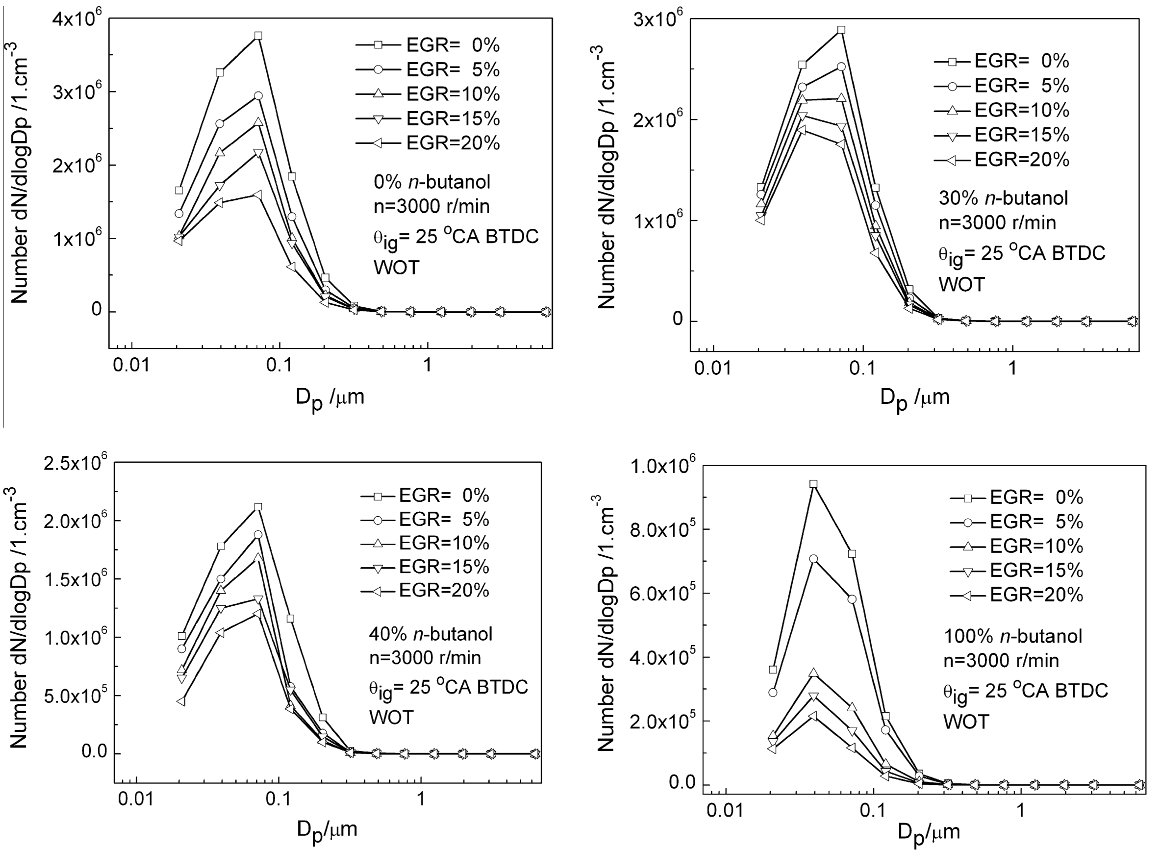

Fig. 6. Particulate number and size distribution at different EGR rates.

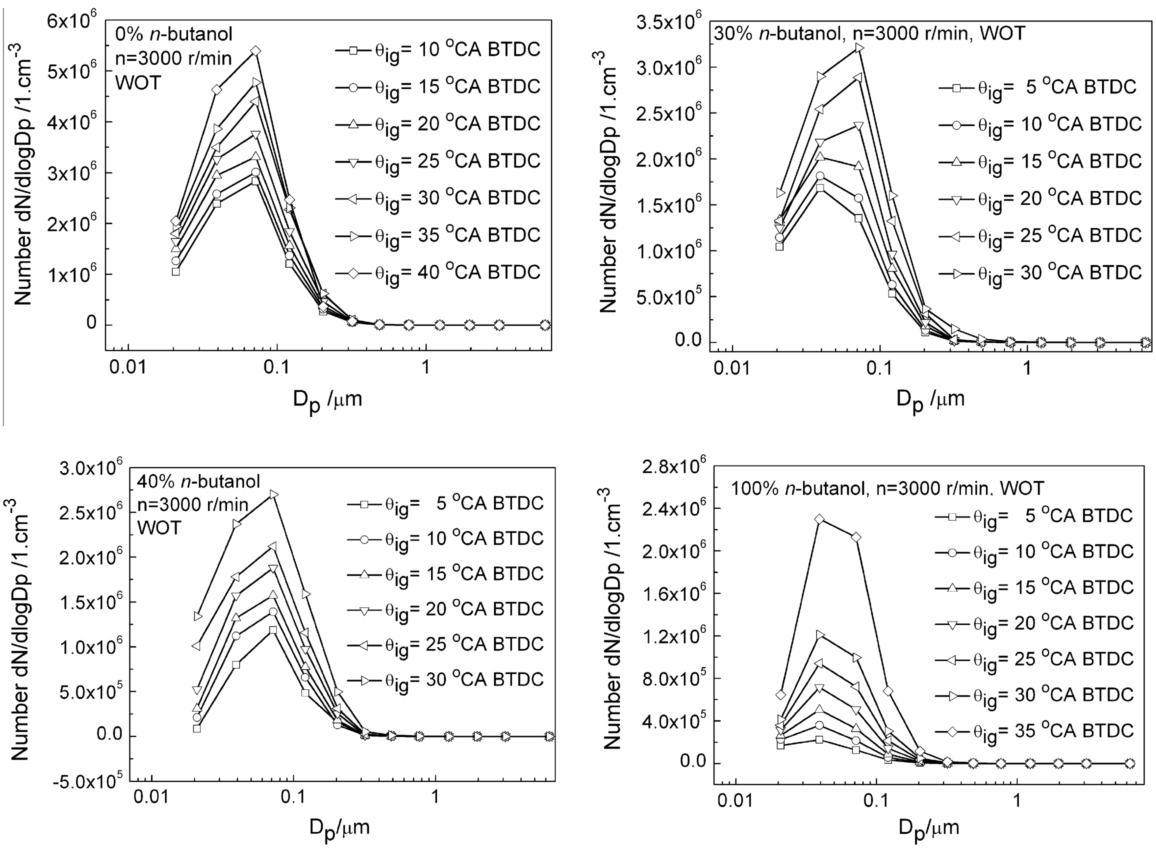

Fig. 7. Particulate number and size distribution at different EGR rates.

pattern. Particulate number concentration decreases with the increase of *n*-butanol fraction in the bends, indicating that *n*-butanol addition can improve cylinder combustion and reduce particulate emissions. As particulate emissions are strongly related to the aromatic hydrocarbons, and blending butanol in gasoline will decrease the fraction of aromatic hydrocarbons. Experimental results show that hot EGR can decrease the particulate number concentration for all blends. This is differs to particulate emissions on diesel engines, which gave an increase in particulate emissions with introduction of EGR [22,23]. In gasoline engine, the mixture is homogeneous, and flame propagation consumes the fuel–air mixture, which differs to the diffusion combustion in diesel engine. For homogeneously premixed mixture, particulates are formed at high temperature combustion. Hydrogen atom is consumed by H-abstraction reaction at high temperature combustion. The hydrogen atom is consumed by H-abstraction and later forms the particulates. EGR addition decreases the combustion temperatures, leading to the decreasing in particulate formation. EGR will lower the fuel fraction in the charge and this will decrease particulate number concentration as the fraction of particulate to total charge is decreased. Hot EGR will help the fuel evaporation and contributes to decreasing particulate formation. The combined effect of EGR on particulates leads to the decreasing of particulate number concentration with the increase of EGR rate in gasoline engines.

3.3.2. Effect of spark timing

Fig. 7 shows the particulate number and size distribution at different spark timings. Particulate number concentration increases with advancing spark timing. Advancing spark timing increases gas peak temperature and raises the rate of Arrhenius-dependent particulate matter nucleation (soot formation) rate [24]. Advancing spark timing will also decrease cylinder gas temperature in the expansion and exhaust processes, which decreases particulate oxidation rate in the expansion and exhaust processes. The effect of spark timing on particulate number concentrations becomes remarkably with the increase of engine load. This indicates an increased influence on cylinder gas temperature as load is increased.

4. Conclusions

An experimental study on emissions of a spark-ignition engine fuelled with *n*-butanol–gasoline blends combined with EGR was conducted. The main results are summarized as follows:

1. Specific HC, CO and NO_x emissions fueled with gasoline and *n*-butanol blends are lower than those of gasoline. Pure *n*-butanol increases the specific HC and CO emissions while decreases the specific NO_x emissions compared to those of gasoline. *n*-Butanol addition can decrease particle number concentration emissions compared with that of gasoline.
2. Advancing spark timing increases engine specific HC, NO_x emissions and particulate number concentration while it decreases engine specific CO emissions.
3. EGR addition increases engine specific HC and CO emissions slightly in the spark-ignition engine fueled with blends of gasoline and *n*-butanol. However, EGR can simultaneously reduce engine specific NO_x emissions and particle number concentration.

Acknowledgment

The study is supported by the National Natural Science Foundation of China (50636040 and 50581064).

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