Fuel 211 (2018) 837–849

Contents lists available at ScienceDirect

Fuel

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

Full Length Article

Experimental comparative study on combustion and particle emission of n-butanol and gasoline adopting different injection approaches in a spark engine equipped with dual-injection system

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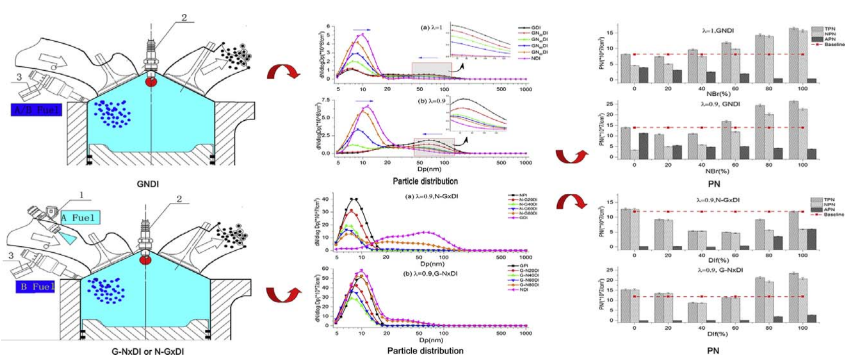
GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
N-butanol
Dual-injection engine
Injection approach
Particle number
Particle matter
Particle distribution

ABSTRACT

N-butanol, as a biofuel, could be one kind of engine fuel to relieve energy crisis and reduce particle emission. In this paper, n-butanol was applied to a spark-ignition engine equipped with dual-injection system. Three different fuel injection approaches were tried, including direct injection of gasoline and n-butanol with different volume mixing ratio (GNDI), n-butanol intake port injection combined with gasoline direct injection (N-GxDI) and gasoline intake port injection combined with n-butanol direct injection (G-NxDI), and finally the best method was recommended based on combustion and particle emission characteristics. Experiments were conducted under stoichiometric and rich mixture (excess air coefficient was at 0.9) condition to obviously present particle emission characteristics, including particle number (PN), particle matter (PM) and particle distribution. The results indicated that with the rising of n-butanol blending volume ratio (NBr) for GDNI, indicated mean effective pressure (IMEP) increased firstly and decreased afterward, total particle matter (TPM) decreased constantly, however, total particle number (TPN) and nucleation mode particle number (NPN) dropt first and then rose, accumulation mode particle number (APN) increased continuously. 20% was regarded as the best NBr, because it had the highest IMEP, TPN could be decreased by 8.63%, and TPM could be decreased by 30.88% compared with GDI under stoichiometric condition; With the increasing of fuel (gasoline or n-butanol) direct injection ratio (DIr) for G-NxDI and N-GxDI, IMEP decreased constantly, TPM increased continually, however,

Abbreviations: APN, accumulation mode particle number; BTDC, before top dead centre; CA, crank angle (0° CA refers to top dead center of compression stroke); DIr, fuel (gasoline or n-butanol) direct injection ratio; Dp, diameter parameter; DMF, dimethyl formamide; GDI, gasoline direct injection; GNDI, direct injection of gasoline and N-butanol with different volume mixing ratio; G-NxDI, gasoline intake port injection combined with N-butanol direct injection; GPI, gasoline port injection; NBr, n-butanol blending volume ratio; NDI, n-butanol direct injection; NPI, n-butanol port injection; NPN, nucleation mode particle number; N-GxDI, n-butanol intake port injection combined with gasoline direct injection; Pd, indicated mean effective pressure decreased percentage; PM, particle matter; PN, particle number; TPM, total particle matter; TPN, total particle number; λ, excess air coefficient

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http://dx.doi.org/10.1016/j.fuel.2017.09.108
Received 29 May 2017; Received in revised form 13 August 2017; Accepted 27 September 2017
0016-2361/ © 2017 Published by Elsevier Ltd.

TPN and NPN both decreased firstly and increased afterward, APN increased endlessly. There was also one best DIr to achieve the lowest TPN; Comparing three injection approaches, N-GxDI with 40% DIr was the best, because it owned the lowest TPN which was decreased by 51.07% and TPM could almost be ignored compared with GDI under stoichiometric condition. However, this approach had to sacrifice 1% decrease of IMEP compared with pure gasoline intake port injection, while the value was still above GDI.

1. Introduction

With the gradual exhaustion of fossil fuel and the aggravation of environment pollution, it is vital to find clean and renewable energy in the world wide. As automotive industry is important content of energy consumption, to obtain alternative fuels and reduce gaseous and particle emission is becoming a hot spot of worldwide countries. And foremost, alternative fuel characteristics and fuel injection approaches will play a crucial role in the performance of engine, which is worthy to be investigated.

Alternative fuels include gaseous fuels such as natural gas, hydrogen and propane; liquid fuels such as alcohols (ethanol, methanol, and butanol), DMF, vegetable and waste-derived oils and so on [1]. Among them, ethanol has been obtained a great deal of investigations and widely used as an alternative fuel addition to gasoline, such as E10 (a blend of 10% ethanol and 90% gasoline), E15, and even E85 [2–4]. Butanol is also one of the biomass-based fuels similar with ethanol, although, most n-butanol produced today is synthetic and derived from a petrochemical route, the theoretical feedstock costs of bioprocessing are much lower, and the lowest of which were estimated at $0.97/kg and $0.11/kg n-butanol, respectively [5]. Although there are still many challenges about the industrialization of bioprocessing, with the increasing attention of the Government on the utilization of renewable and even waste resources, as well as the progress of the process technology, the biomass-based n-butanol promises to have a competitive edge.

Compared to gasoline, the use of corn-derived butanol gains higher energy benefits and reduces greenhouse gas emissions more effectively [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 gasoline and butanol can be blended more easily and enduringly without phase separation, which could make it more cost-effective with the existing infrastructure [7]. In addition, butanol has higher energy density and lower latent heat of evaporation than ethanol, which will promote coefficient of fuel utilization and engine cold-start performance [8].

n-Butanol, which has a straight-chain structure with the OH at the terminal carbon, is one of four isomers of butanol. Investigations of n-butanol usage as engine fuels have been conducted for many researchers, and most investigations about n-butanol used as engine fuels could be divided into two parts, involving n-butanol blended with diesel and n-butanol blended with gasoline.

In port fuel injection (PFI) spark ignition (SI) engines, the majority of studies on n-butanol have been performed either as pure fuel or blend fuel. Gopinath Dhamodaran et al. [9] made investigations of n-butanol as fuel in a four-cylinder MPFI engine, blends comprising n-butanol (10%, 20% and 30%), results indicated that the use of n-butanol blends produced lower HC and CO, but higher NOx, and the peak in-cylinder pressures and heat release rates for the blends were higher than for unleaded gasoline, and the coefficient of variation of gasoline was higher than that of n-butanol blended with gasoline. Szwaja and Naber [10] 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 was similar to that of PON (pump octane number) 87 gasoline. Alasfour [11] 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 [12] also investigated the effect of 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. [13] 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 [14] 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 gasoline direct injection (GDI) engine, researchers have conducted many experiments to investigate the influence of n-butanol–gasoline blends on GDI engine. Zheng et al. [1] investigated the impact of higher n-butanol addition on combustion and performance of a turbocharged GDI engine, their results indicated that n-butanol/gasoline blends increase brake specific fuel consumption and higher brake thermal efficiency, moreover, higher n-butanol addition significantly decreases NOx emissions, but increased CO emissions obviously. Wallner et al. [15] 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. [16] investigated the combustion and particle number (PN) emissions of GDI engine fueled with gasoline blends with10% and 20% butanol, and reported that gasoline blending n-butanol show degraded anti-knock ability, but n-butanol addition is beneficial for the reduction of PN emissions.

Coordinating with exploitation of alternative fuels, fuel injection approaches play a vital role in the performance of engine, gasoline direct injection (GDI) engine has obvious advantages over the conventional PFI engine such as fuel economy, transient response and cold-start emission [17]. However, the mass particle emission of GDI can hardly satisfy strict emission regulations, that is why its usage is being restricted, therefore, decreasing particle emission of GDI engine becomes more significantly, many methods are being experimented, among which, the combination of alternative biochemical fuels containing oxygenated content with dual-injection, effectively combining the benefits of fuel injection methods and fuel characteristics, can be seen one most potential method to obtain low particle emission and constantly energy suppling [18].

There are many investigations concerning gasoline blended with biochemical fuels containing oxygenated content in dual-injection engine. Wang et al. [19] investigated alcohol and gasoline dual-fuel spark ignition combustion for knock suppression and higher engine efficiency, results showed that these injection approaches obtained improvement in engine efficiency and knock suppression, and gasoline-alcohols dual injection exhibited better potentialities. Zhuang et al. [20] investigated the economical efficiency and gaseous emission of ethanol and gasoline dual-injection, and observed that volumetric efficiency was improved, however, CO and total hydrocarbon (THC) emissions increased when the amount of ethanol was higher than 36.3% of the total fuel energy used. Kim et al. [21] made a similar investigation using gasoline DI and ethanol port injection in an SI engine, compared to the GDI engine, the compression ratio of dual-fuel engine was increased from 9.5 to 13.3 and achieved better engine

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