Applied Energy xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

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

Impact of intermediate ethanol blends on particulate matter emission from a spark ignition direct injection (SIDI) engine

Jaeho Cho, Woosung Si, Wonwook Jang, Dongyoung Jin, Cha-Lee Myung, Simsoo Park *

School of Mechanical Engineering, Korea University, Republic of Korea

HIGHLIGHTS

- SIDI engine with intermediate ethanol blends was evaluated under steady and cold start conditions.
- Size-resolved particle number emissions were investigated using differential mobility spectrometer.
- Combustion analysis with various ethanol blends were studied.
- High fraction of ethanol caused significantly lower PN emission than pure gasoline fuel.
- Combustion and particle emissions of the E10 fuel were affected by the azeotropic characteristics in the SIDI engine.

ARTICLE INFO

Article history:
Received 4 May 2015
Received in revised form 24 July 2015
Accepted 5 August 2015
Available online xxxx

Keywords:
Spark ignition direct injection (SIDI)
Ethanol–gasoline blend
Particulate matter (PM)
Azeotrope

ABSTRACT

The purpose of this study was to investigate particle emission characteristics from a spark ignition direct injection (SIDI) engine fueled with ethanol–gasoline blends. Particulate matter (PM) from internal combustion engine is a complex mixture of substances deemed harmful for the human body. Consequently, they are regulated by stringent legislation. According to the Euro-6 regulation, the standard for particle number (PN) emissions of SIDI vehicles is 6.0×10^{11} N/km. Recent studies have reported that SIDI engines, renowned for their feasibility in reducing CO_2 emissions, could produce excessive amounts of PM due to its structural characteristics. For this reason, there have been many studies on reducing PM emissions from SIDI engines to satisfy strict emission standards. Because ethanol contains an oxygen atom in each molecule, it has a significant influence on combustion performance and characteristics of vehicular discharge, including PM. This study focused on the effect of intermediate ethanol blends from E0 (pure gasoline fuel) to E20 (gasoline fuel with 20% volume of ethanol) on engine performance, size-resolved particle emissions, and engine startability. Particle emission characteristics including particle number and size distribution at part-load test and start performance were investigated with operation points, fuel pressure and injection timing.

1. Introduction

As air pollution caused by automotive emissions has become a global issue, enhancing fuel economy has become one of the most important challenges in the automotive industry. To address this issue, the spark ignition direct injection (SIDI) engine has been recognized for its feasibility of enhancing fuel economy and reducing CO_2 emissions. The SIDI engine can achieve higher fuel economy and power output close to that of the compression ignition (CI) engine with improved volumetric efficiency and various engine control strategies. Moreover, it is able to increase the compression ratio and lean air-fuel mixture composition of the SIDI engine. Therefore, a downsized SIDI engine with a turbocharger has become a global research trend and has been able to rapidly penetrate the passenger car market [1–3].

However, a relatively non-homogeneous air-fuel mixture formation in the combustion process of the SIDI engine rather than the conventional port fuel injection (PFI) engine leads to an increase of particle number (PN) emission. Due to the structural theory behind direct injection technology, wall-wetting phenomena in the combustion chamber, especially for the cylinder wall and piston head, occurs frequently during fuel enrichment procedure in SIDI engines [3–13]. Therefore, there have been many studies conducted on reducing the particulate matters (PM) emissions by optimizing the engine management system, shape of

* Corresponding author at: School of Mechanical Engineering, Korea University, 145, Anam-ro, Sungbuk-gu, Seoul 136-713, Republic of Korea. Tel.: +82 (2) 3290 3368; fax: +82 (2) 926 9290.

E-mail address: spark@korea.ac.kr (S. Park).

http://dx.doi.org/10.1016/j.apenergy.2015.08.010
0306-2619/

Nomenclature

BTDC	before top dead center	LHV	lower heating value
CI	compression ignition	MBT	minimum spark advance for best torque
CVVT	continuously variable valve timing	SIDI	spark ignition direct injection
COV	coefficient of variance	PFI	port fuel injection
degCA	degree of crank angle	PM	particulate matter
DVPE	dry vapor pressure equivalent	PN	particle number
EMS	engine management system	PMP	particulate measurement program
FUP	fuel pressure	SOI	start of injection
GPF	gasoline particulate filter	UN ECE	united nations economic commission for Europe
KPMP	Korea particulate measurement program	WOT	wide open throttle

combustion chamber, fuel supply system, and installing a gasoline particulate filter (GPF) at the exhaust tail pipe [14].

A PM is known as a deleterious substance for the human body, and thus, requires regulation by stringent legislation. Studies on levels of acceptable particle emission from SIDI engines and improving PN emission characteristics have been conducted by numerous investigators. The Particulate Measurement Program (PMP) was established by the United Nations Economic Commission for Europe (UN–ECE) to support this and establish standards on a particle measurement system [9,10]. In Korea, the Korea Particulate Measurement Program (KPMP) has also been following these research trends. As part of these efforts, plenty of research has been conducted on ethanol–gasoline blend SIDI engine to reduce injurious nanoparticle emissions. Because ethanol contains an oxygen atom at each molecule instead of heavy hydrocarbon chains, ethanol–gasoline fuel blends can affect air-fuel mixture formation, and spray characteristics, which in turn can affect regulated (THC, CO, NO_X, and PM) as well as unregulated discharges (polycyclic aromatic hydrocarbons, volatile organic compounds) [15–40].

In general, an ethanol fueled direct injection engine emits lower particle emissions, especially a large size of PM, due to the oxygen content in the ethanol fuel in place of the heavy hydrocarbon chains. However, the fuel consumption and the level of alcohol and aldehyde emissions increase with ethanol content. The result of using intermediate ethanol blends, ranging from 0% to 20% volume of ethanol in gasoline fuel, is still controversial. There were inconsistent PN results from E10 blend that some researches demonstrated reducing tendency of PN emissions as increasing ethanol content, while the others indicated exceptional or opposite results [27–36]. Therefore, a study on PM characteristics for the E0 to E20 range is needed to identify these odd trends.

The purpose of this study is to analyze the particle emission characteristics of the SIDI engine with ethanol–gasoline fuel blends in various proportions. Throughout this study, combustion performance and PM emission characteristics were investigated under part-load operating conditions to elucidate consistent trends in particle number. Additionally, an engine startability test focused on particle emissions was conducted at a cold start condition, to verify the amount of PN emissions discharged within few seconds after engine start which was able to account for a large proportion of total particle emissions during the vehicle mode test.

2. Experimental apparatus and instruments

The combustion performance, particle number concentration, and size distribution characteristics of the engine were analyzed. Fig. 1 shows the schematic diagram of the engine test apparatus. The test engine was a 2.4 L in-line four cylinder wall-guided SIDI engine equipped with a double overhead camshaft and a dual continuously variable valve timing (CVVT) device. A pent-roof type of combustion chamber with a side mounted six-hole injector was also used. The engine operation strategy of the SIDI engine was focused on the complete vaporization of fuel droplets and homogeneous formation of air-fuel mixture with proper injection timing during the intake stroke. The vaporization of the fuel injected during intake stroke was able to affect the temperature of the air-fuel mixture, resulting in an improved charging efficiency of the SIDI engine. The highly pressurized fuel reached a maximum of 150 bars during the wide open throttle (WOT) condition and was supplied by a camshaft driven high-pressure pump. Detailed engine specifications are given in Table 1. Particle emission characteristics including PN concentration and particle size distribution were investigated via a differential mobility spectrometer (DMS500, CAMBUSTION Co.) directly connected before the three-way catalyst. The combustion performance was analyzed with a spark-plug-integrated piezoelectric type pressure sensor and combustion analyzer.

The five test fuels used in this study were 0%, 5%, 10%, 15%, and 20% ethanol by volume in gasoline fuel named as E0, E5, E10, E15, and E20, respectively. Physicochemical characteristics of the fuels are analyzed at the Korea petroleum quality and distribution authority (K-Petro), which are shown in Table 2. In general, latent heat of the ethanol fuels have been shown to be higher than that of gasoline fuel [41]. Thus, it is possible that this has positive effects on the volumetric efficiency of the same combustion chamber. The lower stoichiometric air-fuel ratio of ethanol blends can be related to its lower chemical reaction ratio demand, with more fuel input necessary to produce the same amount of energy required.

3. Experimental results and discussion

3.1. Part-load engine operation results

Part-load swing tests with reference engine mapping of the ECU was conducted for various operation points, with engine speeds ranging from 1250 to 2000 rpm and loads ranging from 1.5 to 2.0 bar of BMEP. The peak pressure of the combustion chamber was lowered and the combustion phase delayed with increasing of ethanol content due to a lower heating value and higher latent heat of the ethanol blends than that of pure gasoline fuel, as shown in Fig. 2. Thus, at the same spark timing, the time required for the entire combustion process was prolonged and maximum heat release crank timing could be retarded. A boundary condition was set the test as 3.0% of the coefficient of variance (COV) of IMEP, which indicated combustion stability. All of the COV values of ethanol blends for each operation point were measured. The default condition was set at 2000 rpm and 2.0 bar of BMEP, which yielded the best COV values. Ignition timing was kept constant in each operating conditions for knock limited spark advance (KLSA)

Please cite this article in press as: Cho J et al. Impact of intermediate ethanol blends on particulate matter emission from a spark ignition direct injection (SIDI) engine. Appl Energy (2015), http://dx.doi.org/10.1016/j.apenergy.2015.08.010