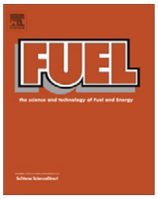
Fuel 94 (2012) 348–355

Contents lists available at SciVerse ScienceDirect

Fuel

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



Comparative study of engine control strategies for particulate emissions from direct injection light-duty vehicle fueled with gasoline and liquid phase liquefied petroleum gas (LPG)

Cha-Lee Myung, Juwon Kim, Kwanhee Choi, In Goo Hwang, Simsoo Park *

School of Mechanical Engineering, Korea University, 1, 5-Ga, Anam-dong, Sungbuk-gu, Seoul 136-701, Republic of Korea

ARTICLE INFO

Article history:
Received 25 April 2011
Received in revised form 19 October 2011
Accepted 19 October 2011
Available online 13 November 2011

Keywords:
Gasoline direct injection
Liquid phase LPG direct injection
Particle concentration
Split injection
Catalyst heating logic

ABSTRACT

To evaluate the potential of a dedicated direct injection liquefied petroleum gas (LPG-DI) vehicle, we investigated several engine control parameters that are closely related to the characteristics of mixture preparation and nano-particle emissions. The fuel supply circuit for the direct injection of LPG in liquid form was modified into a return-type system comprised of a three-way high pressure pump, a low pressure regulator, a brushless direct current (BLDC) pump, and an LPG tank. Particulate number (PN) and size distribution measurements were performed in FTP-75 and HWFET modes, and also using an engine test bench. The experimental results showed that significant PN emissions were produced during the cold start and the transient warm-up operations of the gasoline direct injection (GDI) vehicle; this production of particle emissions was due to application of split injection and catalyst heating function. A bimodal particle size of $10 < d_p < 100$ nm was formed in the GDI vehicle, whereas a sub 30 nm nuclei mode was mainly formed in the LPG-DI vehicle. Excessive particle formation during sudden acceleration of the GDI vehicle in the HWFET mode was improved with LPG fuel. The reduction rate of the PN concentration with LPG application reached approximately 98% (FTP-75 mode) and 99% (HWFET mode) compared to the GDI vehicle. The total PN concentration in the LPG-DI vehicle was significantly improved to 1.6×10^{10} (N/km) for the FTP-75 mode and 3.4×10^{9} (N/km) for the HWFET mode.

1. Introduction

Due to the challenge of meeting carbon dioxide (CO_2) and fuel economy targets, as well as stringent emission regulations in the transportation sector, global automotive manufacturers are focusing on the development of low carbon fuels, energy efficient gasoline direct injection (GDI) engines, and clean diesel powertrains with turbochargers [1–5]. Technical breakthroughs in advanced gasoline powertrains have resulted in new combustion concepts, such as continuously variable valve timing (VVT) and lift (VVL) control devices, and boosting and exhaust aftertreatment systems [1,5–8].

The major advantages of GDI engine include higher specific power, increased fuel efficiency and lower emissions due to the fact that the fuel can be sprayed directly into the combustion chamber. However, the GDI combustion mechanism inherently produces excessive particle emissions because of a non-uniform mixture preparation and wall wetting on the surface of combustion chamber during the cold start phase and transient operation [9,10]. Therefore, several parametric studies have been performed in order to reduce the particulate emissions from the GDI engine, in conjunction with the optimization of the engine control strategy, mixture preparation with high injection pressure, modification of the combustion chamber, and implementation of particulate filters [6,11–22].

Considering the widespread introduction of GDI vehicles, nano-particle number standards currently applied to light duty diesel engines (6.0×10^{11} N/km) could also be applied to GDI engines in the Euro-6 emissions standards in the European Union (EU). In the USA, the California Air Resource Board (CARB) is debating future particle emission regulations for the low emission vehicle-III (LEV-III) standards. Based on their researches, the particle number concentration would likely be 1.2×10^{12} N/mile (7.46×10^{11} N/km) for a GDI vehicle without a particulate filter [23–25].

Liquefied petroleum gas (LPG) has been widely adopted as an automotive fuel because of its potential for reducing emissions, relatively low fuel price, and CO_2 advantages. The nano-particle concentration of the port fuel LPG injection engine, classified into gaseous and liquid phase LPG types, is much lower than that of the port fuel injection (PFI) gasoline engine [26,27]. In an LPG-DI engine, as the liquid LPG fuel vaporizes in a very short time during

---

* Corresponding author. Tel.: +82 2 3290 3368; fax: +82 2 926 9290.
E-mail address: spark@korea.ac.kr (S. Park).

0016-2361/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.fuel.2011.10.041

the intake stroke, the amount of homogeneous mixture in the combustion chamber is substantially increased [28–30]. Therefore, an LPG-DI engine has better cold start performance than a GDI engine because it does net need excessive enrichment of the air–fuel ratio (A/F) at low coolant temperatures, which plays a key role in limiting the amount of particle formation for the gaseous fuels [26,31–33].

The goal of our study is to evaluate the particle number concentration and size distribution characteristics for GDI and dedicated LPG-DI vehicles in emission certification modes, in addition to other relevant parametric effects of DI engine control during the cold transient operating phase.

2. Experimental apparatus

2.1. Engine, fuel supply system, and test fuels

Detailed engine and vehicle specifications are provided in Table 1. We tested a side-mounted direct injection engine equipped with a dual continuously variable valve timing (DCVVT) device and dome shaped pistons, with a compression ratio of 11.3:1. Two brick under-floor catalytic converter (UCC) combined with a double split injection (DSI) strategy were applied to effectively lower vehicle emissions during the cold start phase.

Table 1
Specifications of test vehicle.

Engine type	In-line, stoichiometric direct injection
Displacement	2.359 cm^3
Bore × stroke	88 mm × 97 mm
Compression ratio	11.3:1
Valve train device	Dual continuously variable valve timing Camshaft-driven high pressure pump
Fuel system	Side mounted injector Split injection during cold start
Exhaust system	Under-floor catalytic converter
Transmission	Six speed automatic transmission

Table 2
Properties of gasoline fuel.

RON	93.2	Benzene (vol.%)	0.49
Vapor pressure @ 37.8 °C (kPa)	70.9	Low heating value (J/g)	41.120
Density @ 15 °C (kg/m^3)	718	Distillation temperature (°C)	
Sulfur content (mg/kg)	5	10 vol.%	49
Oxygen (wt.%)	2.02	50 vol.%	74
Aromatic (vol.%)	15.7	90 vol.%	144

Table 3
Properties of LPG fuel in Korea.

Fuel	Summer	Winter
Component (mol%)		
C_3	6.62	31.62
C_4	93.14	67.95
Olefin	0.73	0.52
1,3-butadiene (mol%)	Below 0.1	Below 0.1
Sulfur content (wt. ppm)	13.6	11.3
Vapor pressure @ 40 °C (MPa)	0.41	0.74
Density @ 15 °C (kg/m^3)	571.3	556.8

Fig. 1 shows a schematic diagram of the 2.4L DI engine and fuel supply system for gasoline and LPG fuel. The camshaft-driven high pressure pump pressurized the liquid fuel to a maximum of 15.0 MPa. The major difference between the gasoline engine and LPG-DI engine was the low pressure fuel supply system of the returnless or return type. In contrast to a direct current (DC) pump of 0.45 MPa for gasoline, a brushless DC (BLDC) pump with a low pressure regulator of 0.7 MPa was installed for the LPG system in order to shorten the pressure build-up time in the fuel-rail and to eliminate the vapor-lock in the fuel supply line.

A peak and hold type fuel injector controlled by a programmable electronic control unit (ECU) was used for the two types of fuel. In the case of the LPG fuel, the injection pulse width was modified to match the target air-to-fuel ratio (A/F), spark timing, and injection timing for transient operation of the test vehicle. Various

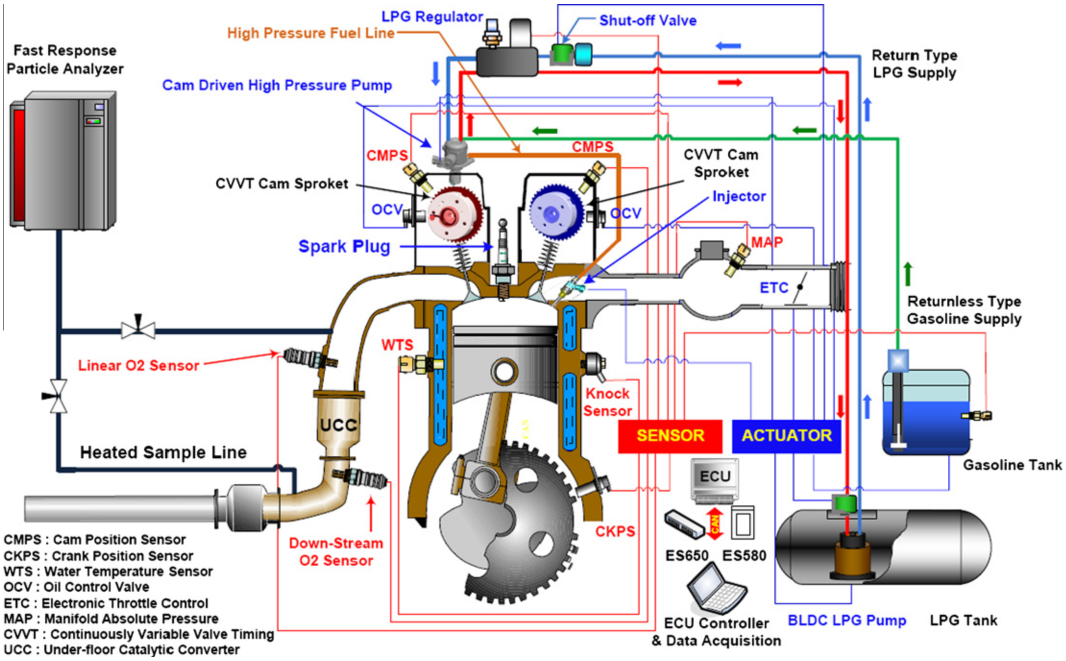


Fig. 1. Schematic diagram of the 2.4L DI engine and fuel supply system for gasoline and LPG fuel.