Applied Energy 194 (2017) 123–135

Contents lists available at ScienceDirect

Applied Energy

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

Evaluation of injection and ignition schemes for the ultra-lean combustion direct-injection LPG engine to control particulate emissions

Keunsoo Kim [a], Junghwan Kim [b], Seungmook Oh [a,*], Changup Kim [a], Yonggyu Lee [a]

[a] Department of Engine Research, Korea Institute of Machinery and Materials, 156 Gajeongbuk-Ro, Daejeon 305-343, Republic of Korea
[b] Department of Energy System Engineering, Chung-Ang University, 84 Heukseokro-Ro, Dongjakgu, Seoul, 06974, Republic of Korea

HIGHLIGHTS

- Particulate emission characteristics of ultra-lean LPG combustion were analyzed.
- Various ultra-lean LPG combustion strategies were analyzed and compared.
- Lean strategies reduced NOx and CO along with increasing 18% thermal efficiency.
- Multi-charge ignition lowered particle concentration; increased the particle number.

ARTICLE INFO

Article history:
Received 4 October 2016
Received in revised form 24 February 2017
Accepted 2 March 2017

Keywords:
Liquefied petroleum gas (LPG)
Lean-burn
Direct-injection
Spark-ignition
Emission characteristics
Particulate matter (PM)
Multi-charge ignition

ABSTRACT

The high level of particulate emission in ultra-lean combustion direct injection engine was obstacles for real application and satisfying the further upcoming regulation. The use of LPG (liquefied petroleum gas) in lean direct injection engines has the potential to reduce carbon-related emissions owing to its simple structure, and it can become an easily stratified mixture because of its higher vapor pressure. In this respect, the effects of the injection and ignition schemes on combustion and emission characteristics, including particle emission of ultra-lean combustion through LPG, were investigated. Four different injections schemes in order for forming stratified mixture and two ignition schemes (single charge ignition and multi-charge ignition) were employed to achieve simultaneous harmful emissions and fuel consumption reduction.

The experimental results reveal that the fully stratified injection strategies indicate an improvement of approximately 18% in thermal efficiency, but combustion fluctuation was observed owing to stratification. Moreover, simultaneous reductions in the NO_X (Nitric Oxides) and CO (Carbon monoxide) emissions were observed (when compared to homogeneous stoichiometric combustion) while increasing the particulate matter emission. In order to stabilize the combustion and reduce the level of soot, a multi-charge ignition was introduced to the selected injection strategies (LBM1 and LBM2). Multi-charge ignition successfully reduces particulate mass by about 10% and secures the combustion stability slightly; however, it increases the particle number concentration.

1. Introduction

Owing to awareness of environmental issues related to fossil fuels, human beings make an extraordinary effort to reduce both its consumption and its harmful exhaust emissions. Since the United Nations established the "Framework Convention on climate change" to formally address greenhouse gas reduction [1,2] and the European Union has introduced regulations for reducing CO_2 emission [3], concerns regarding CO_2 emission have increased. In response to this, automobile companies have focused on hybrid and diesel vehicles to meet emission regulations and improve fuel economy at the same time. On the other hand, many different types of combustion strategies and post-treatment systems have been researched recently for the development of spark-ignition engine [4]. Among clean fuel candidates for spark ignition engine, Liquefied Petroleum Gas (LPG) has been regarded as a promising alternative fuel and its properties have been well researched for application to the gasoline spark ignition engine [5–7]. The high-octane rating and high vapor pressure accompany reasonable combustion stability and improved thermal efficiency. Especially, the spray-guided LPG homogeneous stoichiometric combustion

* Corresponding author at: Department of Engine research, Korea Institute of Machinery & Materials (KIMM), 156, Gajeongbuk-Ro, Yuseong-Gu, Daejeon, 34103, Republic of Korea.

E-mail addresses: jkim77@cau.ac.kr (J. Kim), mook@kimm.re.kr (S. Oh).

http://dx.doi.org/10.1016/j.apenergy.2017.03.012
0306-2619/

exhibited a significant reduction of particulate matter emissions compared to gasoline application as its easily premixed characteristics and low carbon content result in decreased carbon emissions and a lowered possibility of wall-wetting [8]. Therefore, liquid LPG injection combustion systems based on driving cycle and/or cold starting mode have been largely researched under stoichiometric operation [9–13] and also LPG engines has been available in the EU and Asian countries for many years.

Although most internal-combustion engines use stoichiometric combustion schemes, which enables the use of a three-way catalyst, the pumping loss limits their thermal efficiency. On the other hand, lean combustion results in a high-efficiency engine and it also provides low levels of NO_X emissions [14–16]. This is possible because the overall combustion cylinder of lean-burn scheming is an air-dominant condition which can suppress NO_X formation during the combustion process. These factors bring the recent research of automotive industries in lean-burn combustion for internal combustion engine, especially for spark ignition engine.

There are two ways in which spark ignition engines can implement lean-burning combustion, with regard to mixture states: premixed mixture and stratified mixture. In the early stages of lean-burning combustion development, premixed mixture schemes were dominant. These schemes depended upon on the flammability limit of the fuel under a normal ignition system. Consequently, various types of ignition systems, including a plasma jet, high current and multi-ignition system have been employed to improve the flammability of the air-fuel mixture by means of introducing powerful ignition energy [17,18]. Nevertheless, its low excess air ratio leads to the emergence of a novel lean-burning mixture strategy, called the stratified mixture strategy, according to Toyota's suggestion. Toyota's first lean-burn engine adopted aerodynamically designed intake ports and swirl control valves in order to generate a stratified mixture [19]. The direct-injection spark ignition concept was first created by BMW and Mercedes-Benz [20–22]. This concept involved directly injecting the fuel into the combustion chamber. It is widely used for fuel-air mixture stratification. In this scheme, a locally stratified fuel-rich region is ignited by the spark plug, which mediates stabilized combustion with a small amount of fuel and an excessive amount of air. In order to form a well-stratified air-fuel mixture, lean combustion's quick mixture formation and fuel atomization are needed according to computational simulation results [23–27]. In a direct injection combustion system, highly pressurized fuel is directly injected into the combustion cylinder. A direct injection system can improve the volumetric efficiency by means of fuel vaporization, which increases the charge density [28,29]. One of a direct injection system, the spray-guided injection system is the system in which the fuel injection is centrally located in the chamber. It is a method that not only prevents the fuel wall wetting phenomena, but also induces a well-established air-fuel mixture [30–33].

Despite the upcoming stringent particulate matter regulations, the particle emission characteristics of the stratified direct-injection lean combustion strategy has not been explored. The significance of the particle emissions lies in the fact that the efficiency gain by the lean combustion strategy could diminish if the particulate level requires additional aftertreatment devices, such as a particulate filter. Several researches showed that the fuel economy improvement of stratified lean combustion with gasoline and natural gas would be reduced due to substantial particulate formation, which likely leads to an additional aftertreatment for soot removal [33–38].

The present study provides a thorough investigation on the number- and mass-based particulate emissions of the stratified LPG lean combustion. A variety of injection and ignition strategies was evaluated to determine the fuel consumption level of the optimal injection and ignition strategy that can achieve an acceptable level of particulate emission in the lean combustion regime. Injection and ignition strategies are critical in the lean combustion regime to achieve a proper stratification [39–44]. The experimental LPG engine, a 4-cylinder, center-mounted, direct-injection engine, was operated at an engine speed and torque of 1500 rev/min and 40 N m, respectively, which is known to be one of the most common operating conditions in the urban driving.

2. Experimental setup

Fig. 1 shows the experimental facilities and Table 1 lists the engine specifications. The engine is a 4-cylinder, and the bore and stroke of each cylinder is 86 mm. The compression ratio of the cylinder is 10:1. The engine was converted from a 2.0 L multi-point port fuel injection engine to a spray-guided direct injection engine as [24]. In order to construct the spray-guided direct injection system, the injector and spark plug were relocated on the head of the redesigned engine head. This can be applicable for the spray-guided system according to the LPG spray visualization results [45,46]. To be specific, the injector was centrally mounted on chamber and the spark plug was installed near the injector. An outwardly opening piezo-injector (Continental, Germany) which sprays in a hollow cone-shape by piezo-electric effect was introduced for fuel injection; and multi-charge ignition spark plug (Delphi, UK) which enables to fire multiple times increasing spark energy was used for ignition. A current probe was mounted on the spark plug and was used to measure the real spark timing by inferring the actuating voltage.

There are two stages of pressurization. The first is accomplished with a low-pressure electric pump installed in the fuel tank, and the second is accomplished with a high-pressure plunger type pump. The first stage increases the fuel pressure to 0.5 MPa, and the second increases it to 20 MPa. According to the previous studies [23,24], the fuel injection pressure had an insignificant effect on both the fuel economy and the combustion stability of LPG combustion. Meanwhile, high injection pressure is required to allow longer injecting penetration length as LPG's higher vapor pressure attenuates the spray momentum. Besides, using the highest possible injection pressures secures the mixture formation period as short as possible [47]. In this sense, the present study decided that the fuel injection pressure should be 20 MPa, considering the pump performance and durability.

The fuel-recirculating system and common-rail system were established to retain the high-fuel pressure. A modified universal engine ECU system (Motohawk, Woodward) controlled the fuel injection and spark timing, and a direct current dynamometer controlled the engine speed and torque load. In the present study, the engine operating condition was set to 1500 rpm and the torque was 40 N m, which reflects the common operating conditions for passenger vehicle engines.

The exhaust emissions were sampled downstream from the exhaust manifold. The sampled gases were analyzed by an exhaust gas analyzer (AVL AMA i60, AVL), which allows for the measurement of total hydrocarbon (THC), carbon monoxide (CO), carbon dioxide (CO_2), and nitrogen oxides (NO_X). The opacimeter (4390G004, AVL) measured the opacity of the sampled gases in order to weigh the PM mass. The measured opacity was converted into mass per volume using the formula suggested by the AVL [48,49]. In addition, the detailed particulate matter analysis was conducted using a scanning mobility particle sizer (SMPS, GRIMM) which consists of a Dynamic Mobility Analyzer (DMA) and a condensation particle counter with diluted sampled gases after passing through a diluter (DEED-100, DEKATI). The measured emissions are described in brake specific terms in accordance with [48]. To measure the excess air ratio of each cylinder, wideband