Fuel 181 (2016) 310–318

Contents lists available at ScienceDirect

Fuel

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

Full Length Article

Effect of dual-fuel combustion strategies on combustion and emission characteristics in reactivity controlled compression ignition (RCCI) engine

Su Han Park [a], Seung Hyun Yoon [b,*]

[a] School of Mechanical Engineering, Chonnam National University, 77 Yongbong-ro, Buk-gu, Gwangju 61186, Republic of Korea
[b] Division of Automotive Engineering, Yeungnam University College, 170 Hyeonchung-ro, Nam-gu, Daegu 705-703, Republic of Korea

HIGHLIGHTS

- The dual-fuel combustion (DFC) is applied to diesel engine to reduce emission.
- In this study, diesel–gasoline and diesel–biogas DFC are introduced.
- NO_x and soot can be simultaneously reduced by DFC with particle number.
- The early in-cylinder injection and DFC allowed low emission and high IMEP.

ARTICLE INFO

Article history:
Received 13 November 2015
Received in revised form 25 April 2016
Accepted 26 April 2016
Available online 6 May 2016

Keywords:
Dual-fuel combustion
Biogas
Indicated mean effective pressure (IMEP)
Reactivity controlled compression ignition (RCCI)
Gasoline
Exhaust emissions

ABSTRACT

The purpose of this investigation is to reduce the exhaust emissions in a diesel engine without any penalty in the combustion performance using a dual-fuel combustion strategy. The in-cylinder direct injection for diesel and the port injection for gasoline and biogas were applied in a single cylinder diesel engine. The diesel used as the in-cylinder injection source was injected at a very early injection timing (before top dead center (BTDC) 40°), and the biogas and gasoline were injected around the top dead center (TDC).

Based on the experimental results, it was revealed that the increase of the port injection ratio caused the increase of IMEP in dual-fuel combustion with very early in-cylinder injection timing. In particular, the high rate of port injection can achieve the level of the single combustion of the conventional diesel (e.g., BTDC 5° injection timing). The increase of the port injection ratio caused the increase of the ignition delay. In addition, the increasing width of the ignition delay in diesel–biogas DFC is higher than diesel–gasoline DFC. The NO_x and soot emission can be simultaneously reduced by the application of dual-fuel combustion as well as the reduction of the total particle number. The HC and CO emissions in DFC are higher than the conventional single diesel combustion but it is lower than early injection diesel combustion.

1. Introduction

Aggravated environmental problems including global warming and air pollution from automobiles, have led to strengthened emission and fuel economy regulations in the US, Europe, and Japan. Vehicle manufacturing companies have tried to find a solution to these serious problems with high performance and nearly zero emission characteristics. During the last few decades, many researchers have studied the use of renewable and alternative fuels in vehicles as potential solutions. Based on numerous studies, representative alternative fuels replacing gasoline and diesel, while maintaining the current vehicular performance, are biodiesel, bioethanol, dimethyl-ether, and hydrogen (H_2). Specifically, biodiesel and dimethyl-ether with a high cetane number and oxygen are the most attractive alternative fuels in a compression ignition diesel engine [1–4].

Recently, many technical approaches such as new combustion strategies with high thermal efficiency and a very low emission level have been proposed such as the homogeneous charge compression ignition (HCCI) [5,6], the reactive controlled compression ignition (RCCI) [7,8], the premixed controlled compression ignition

* Corresponding author.
E-mail address: shyoon@ync.ac.kr (S.H. Yoon).

http://dx.doi.org/10.1016/j.fuel.2016.04.118

Nomenclature

AHR	accumulated heat release	LHV	lower heating value
BTDC	before top dead center	NAHR	normalized accumulation heat release
CA	crank angle	NO_x	nitrogen oxides
CA*xx*	crank angle at *xx*% of the normalized accumulation heat release	P_{max}	maximum combustion pressure
CO	carbon monoxide	ROHR	rate of heat release
DFC	dual fuel combustion	r_p	port injection ratio
HC	hydrocarbon	SOI	start of ignition
IS-	indicated specific-	SOE	start of energizing
ISFC	indicated specific fuel consumption	SFC	single fuel combustion
IMEP	indicated mean effective pressure		

(PCCI) [9,10], and the dual-fuel combustion [11–13]. The HCCI and PCCI combustion technologies have numerous advantages such as the simultaneous reduction potential of the exhaust emission and the high thermal efficiency, while their challenges include the control of the ignition timing, the limited power output, and the weak-cold start capability [14]. Furthermore, both HCCI and PCCI combustion technologies generally suffer from high level HC and CO emissions. On the other hand, the RCCI technology is a variant of HCCI combustion technology using dual-fuel combustion. Reitz [15] reported that this concept can provide better combustion control and higher thermal efficiency approaching 60% compared to other technologies such as HCCI and PCCI.

In this study, the dual-fuel combustion technology that is close to the RCCI concept was applied to the investigation. The dual-fuel combustion technologies are also applied to CI diesel engines to improve the fuel economy and reduce the exhaust emission. Ma et al. [16] studied the effect of diesel injection strategies on gasoline (port)–diesel (in-cylinder) dual-fuel combustion. Through the experimental study, they reported that the lowest ISFC can be achieved by the early second injection timing in dual-fuel combustion with very low NO_x and soot emissions. Sarjovaara and Larmi [17] used E85 and diesel as the dual-fuel concept in heavy-duty diesel engine. From their results, it was revealed that E85 is suitable for dual-fuel combustion, and a large proportion of the diesel substitution rate can be achieved at medium load conditions. In addition, they reported that the E85-diesel dual-fuel combustion has a benefit in regard to NO_x, while the THC and CO emissions significantly increased. Sarjovaara and Larmi [18] also reported the effect of charges in air temperature on the E85 dual-fuel combustion. It revealed that the air temperature at a lower charge allowed the reduction of NO_x and the increase of the E85 rate even though both CO and THC increased in their results. Park et al. [12] compared the effect of the port injection fuel on the combustion and emissions characteristics in biodiesel dual-fuel combustion. They revealed that bioethanol premixing dual-fuel combustion caused longer ignition delay and higher IMEP than gasoline premixing dual-fuel combustion. In addition, they reported that both bioethanol and gasoline premixing induced the increase of HC and CO emissions, and that gasoline premixing had a lower HC emission than bioethanol premixing dual-fuel combustion.

The purpose of this investigation is to find a way to improve the combustion performance, such as the use of IMEP with the simultaneous reduction of the exhaust emissions that may include, for example, NO_x and soot. Specifically, the in-cylinder direct injection timing was fixed at BTDC 40° (very early injection timing), and the way to improve the IMEP was then studied through the dual-fuel combustion by changing the port injection fuels and the port injection ratio.

2. Experimental setup and procedure

A schematic diagram of an experimental apparatus is shown in Fig. 1(a). A single-cylinder diesel engine was used for this study, that has a common-rail (high-pressure) injection system for diesel, the port injection systems for gasoline and biogas, 373.3 cm^3 (cc) of displacement volume, a 17.8:1 compression ratio, and a re-entrant piston bowl shape as shown in Fig. 1(b). The detailed specifications and dimensions of the test engine are summarized in Table 1. In order to control the engine speed, a DC dynamometer (55 kW h) was used. The injection timing and injection quantity of the direct injection fuel injector were controlled by a timing pulse generator (Blue Planet, TPG-28MP) and an injector driver (TEMS, TDA-3300) synchronized with two signals from the crank angle and the camshaft angle sensor with a sampling crank angle (CA) interval of 0.1° to ensure accurate ignition timing and phasing of heat release. A piezoelectric transducer (Kistler 6057A80) was mounted on the cylinder head at the position of the glow plug to acquire the in-cylinder (combustion) pressure. The measured in-cylinder pressure data were averaged, and were utilized to calculate the rate of heat release (ROHR), the accumulated heat release (AHR), the indicated mean effective pressure (IMEP), and the start of ignition (SOI) for each test fuel condition. The intake system of the test engine was modified for a dual-fuel (gasoline and biogas) combustion engine. Specifically, for the mixture of biogas as the port injection fuel with air intake, the biogas supply system consisted of a mixing chamber, a direct injection gasoline injector, an injector controller, a biogas flow meter (GFM 57, Aalborg) with a rated 0–200 L/min flow range, an accuracy of ±1.0%, and a repeatability of ±0.5% at a given pressure, and a fuel temperature control system as shown in the dotted frame of Fig. 1(a). The injection pressure of the premixed fuel was adjusted using nitrogen gas and a pressure regulator. The injectors for biogas and gasoline injection were installed into the mixing chamber. The mixing ratio of biogas and gasoline were adjusted by changing the quantity of the injected premixed fuels using the injector driver (TEMS, TDA-3300), and the injection pressure of biogas and gasoline were fixed at 0.4 MPa and 3 MPa, respectively. In this study, the total energy supplied by the diesel and biogas was approximately 470 J/cycle, and the injection quantity of diesel was gradually reduced by increasing the mixing ratio of biogas or gasoline in order to maintain the total energy supply. The port injection ratio is defined as the ratio of the energy input of the biogas or gasoline fuel to the total energy input. The port injection ratio was varied from 0.2 to 0.8. In this study, the injection timing of the in-cylinder fuel (diesel) was fixed at BTDC 40°.

Exhaust emissions from diesel–gasoline and diesel–biogas dual fuel combustions were measured and analyzed using different analyzers, including a HC, a CO, a NO_x analyzer (Horiba,