Applied Energy 111 (2013) 721–730

Contents lists available at SciVerse ScienceDirect

Applied Energy

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

# Effects of pilot injection timing on the combustion and emissions characteristics in a diesel engine using biodiesel–CNG dual fuel

Kyunghyun Ryu *

*School of Mechanical & Automotive Engineering, Kunsan National University, 558 Daehak-ro, Kunsan, Jeonbuk 573-701, South Korea*

## HIGHLIGHTS

- Injection timing of pilot fuel in dual fuel combustion affects the engine power and exhaust emissions.
- BSEC of DFC improves with advanced pilot injection timing at low load and with delayed pilot injection timing at high loads.
- The ignition delay in DFC is 1.6–4.4 CAD longer than that of the diesel single fuel combustion.
- Smoke is decreased and NOx is increased with advanced pilot injection timing in the biodiesel–CNG dual fuel combustion.

## ARTICLE INFO

*Article history:*
Received 8 February 2013
Received in revised form 13 May 2013
Accepted 17 May 2013
Available online 14 June 2013

*Keywords:*
Dual fuel combustion (DFC)
Single fuel combustion (SFC)
Biodiesel
CNG
Alternative fuel
Pilot injection timing

## ABSTRACT

Combustion and emissions characteristics of a compression ignition engine with a dual fuel (biodiesel–CNG) combustion system were investigated in this study. This experiment utilized a biodiesel pilot injection to ignite a main charge of compressed natural gas (CNG). The pilot injection pressure was maintained at approximately 120 MPa while the pilot injection timing was varied across the range 11–23 crank angle degrees (CAD) before top-dead-center (BTDC) to investigate the characteristics of engine performance and exhaust emissions in a single cylinder diesel engine. Results show that performance can be optimized for biodiesel–CNG dual fuel combustion (DFC) by advancing the pilot injection timing for low loads and delaying the injection timing for high loads. However, overall performance of diesel single fuel combustion (SFC) still exceeds that of biodiesel–CNG DFC. Slight cycle-to-cycle variations are observed when dual fuel is used, but remains less than 1.3% at all conditions. The combustion of biodiesel–CNG begins at a later CAD compared to that of diesel SFC due to the increase of ignition delay of the pilot fuel. The ignition delay in DFC is 1.6–4.4 CAD longer than that of the diesel SFC. Ignition delays are reduced with the increased engine load. BSEC of biodiesel–CNG DFC improves with advanced pilot injection timing at low load and with delayed pilot injection timing at full load. Smoke is decreased and NOx is increased with advanced pilot injection timing in the biodiesel–CNG DFC. Compared to the diesel SFC, however, smoke emissions are significantly reduced over the range of operating conditions and NOx emissions are also reduced except for the full load condition. DFC yields lower $CO_2$ emissions compared to diesel SFC over all engine conditions. Biodiesel–CNG DFC results in relative high CO and HC emissions at low load conditions due to the low combustion temperature of CNG but no notable trend of HC emissions with variations of pilot injection timing were discovered.



## 1. Introduction

Due to increased greenhouse gases and the worldwide shortage of fossil fuels, various studies on internal combustion engines using alternative fuels to protect the global environment and to conserve energy have been undertaken in recent years [1–4]. Research has particularly focused on diesel engines, utilizing high thermal efficiency to improve both performance and emissions [5–9]. However, diesel engines still have a major problem with the simultaneous reduction of NOx and smoke due to governing combustion mechanisms. Many studies [6–9] have developed new methods for reducing the exhaust emissions by avoiding the combustion regions where NOx and smoke are mainly generated.

For conserving energy and protecting the global environment natural gas is a promising alternative, demonstrating higher hydrogen-to-carbon ratio than gasoline and diesel thus resulting in

*Abbreviations:* ATDC, after top-dead-center; BSEC, brake specific energy consumption (MJ/kW h); BSFC, brake specific fuel consumption (g/kW h); BTDC, before top-dead-center; CNG, compressed natural gas; COV, coefficient of variations; $CO_2$, carbon dioxide; DFC, dual fuel combustion; IMEP, indicated mean effective pressure; NOx, oxides of nitrogen; SFC, single fuel combustion; HC, unburned hydrocarbons; WOT, wide-open throttle.

* Tel.: +82 63 469 4871; fax: +82 63 469 4727.
*E-mail address:* khryu@kunsan.ac.kr

0306-2619/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.apenergy.2013.05.046

reduced carbon dioxide emissions. Given the current market conditions, compressed natural gas (CNG) is a cheaper alternative to gasoline and diesel fuels for transportation vehicles due to vast natural gas deposits throughout the world. CNG is composed primarily of methane, which results in lower greenhouse gas emissions and inherently cleaner exhaust gas emissions than gasoline and diesel fuels as a result of short carbon chains [10,11]. CNG is non-toxic, much lighter than air, and diffuses quickly if released, which provides an advantage in safety over gasoline and diesel fuels that pools on the ground. Additionally CNG has a higher octane number giving higher resistance to knock which allows it to be utilized in high compression ratio engines.

Although natural gas has various advantages to use in automobile engines there are many challenges in using natural gas in diesel engine application due to a very high auto-ignition temperature which requires a high energy source such as spark plug or pilot injection to achieve ignition. Thus CNG has been mainly used in spark ignition engine applications, however, based on the properties of CNG it is best utilized in high compression ratio engine applications [12]. Therefore, CNG would be best utilized in diesel engine applications.

CNG presents a promising prospect in duel fuel combustion (DFC) operation with pilot injection as an ignition source to increase thermal efficiency while simultaneously reducing exhaust emission in diesel engines. DFC systems are particularly promising because no cylinder chamber modifications are necessary in the implementation process. Dual fuel engines are capable of reducing both PM and NOx to levels significantly lower than that of traditional diesel engines. Various studies [13–17] have previously been conducted to characterize the combustion and exhaust emission of dual fuel compression ignition engines with diesel fuel and CNG. The peak cylinder pressure in DFC was lower when compared to the diesel single fuel combustion (SFC). Smoke emissions were lower in DFC than in the diesel SFC. Equivalent thermal efficiencies were also achieved for the majority of operating conditions while some cases higher efficiency was achieved with duel fuel modes [18].

However, dual fuel engines suffer from poor low load characteristics [19]. This is mainly because of the flammability limit of the lean homogenous charge which leads to incomplete combustion or in the worst case absence of combustion. When the main fuel is premixed with the intake air during the induction stroke, an increase in HC emissions are also seen due to the impact of air/fuel mixture trapped in crevices in the combustion chamber during the compression stroke. There are several ways of improving these poor low load characteristics, for example throttling, EGR, increase of inlet air temperature, or switching over to diesel mode as a last resort.

Abdelghaffar [20] showed that brake thermal efficiency in diesel-CNG DFC is lower than its value in the diesel SFC at part and low torque with a modified diesel engine for operation under dual fuel conditions. Wong et al. [8] reported that the exhaust emissions could be reduced without unstable ignition in DFC systems with a micro-pilot injector.

However, most of studies on DFC systems have been conducted with diesel fuel as a pilot fuel to ignite CNG as a main fuel. It is necessary to study biodiesel fuel as a pilot fuel in the DFC systems, but few studies using biodiesel fuel as a pilot fuel have been reported [21–23].

Biodiesel has great potential as an alternative fuel for compression ignition engines due to its properties, which are similar to diesel fuel. Biodiesel has a higher specific gravity and higher kinematic viscosity than diesel; the higher cetane number of biodiesel can shorten the ignition delay, reducing the NOx emissions during the initial combustion process. In addition, biodiesel is easy to handle because its boiling point is higher than that of diesel and it is an environmentally friendly fuel with low smoke emissions as it contains 10% oxygen. Exhaust emissions such as hydrocarbons, CO, particulate matter, polycyclic aromatic hydrocarbons, $SO_2$, and smoke are also reduced with biodiesel when compared to diesel [24–27].

In this study, based on these preceding studies, the effects of pilot injection timing on combustion and exhaust emissions characteristics were investigated with a biodiesel–CNG DFC system in a single cylinder diesel engine. Biodiesel produced from used vegetable oil was used as a pilot injection fuel to ignite the CNG, which was the main fuel charge used in this study.

## 2. Experimental apparatus and method

In order to investigate the effects of pilot injection timing in a diesel engine with a biodiesel-CNG DFC system, a single cylinder diesel engine coupled with a dynamometer was used in this study. The detailed experimental system and test conditions are given as follows.

### 2.1. Test engine

A Daedong ND 130DI unmodified water-cooled, single-cylinder, 4-stroke, direct-injection diesel engine (Table 1) was used to evaluate the effect of pilot fuel injection timing on the performance and exhaust emissions in this study. Engine loads and speeds were controlled manually by a 110 kW eddy current engine dynamometer (W130; Schenck, Darmstadt, Germany).

The engine required a few modifications to the injection system to be compatible with DFC. Fig. 1 shows the test engine, equipped with a high pressure common-rail injection system and a CNG supply system, used in this study. The original injection system was replaced by a high pressure common-rail injection system in order to inject the pilot fuel. A specially fitted common-rail fuel pump for high pressure injection supply was equipped to and driven by the engine. To inject the diesel fuel for the SFC or to inject the biodiesel fuel as a pilot fuel for the DFC, a 7-hole common-rail solenoid injector with a spray angle of 153° was installed in the engine using the pre-existing injector port. And a Bosch fuel injector designed for use in CNG dedicated engines was installed at the intake port in order to supply CNG.

### 2.2. Fuel and fuel supply system

In this study, diesel and biodiesel were used as a pilot injection fuel and CNG was used as the main fuel. Biodiesel used in this study was produced from used vegetable oil by a biodiesel production company (Eco Solution Co., S. Korea). Table 2 shows the properties of the fuels used in this study. Diesel fuel containing small amount of biodiesel fuel was also used as a reference fuel to compare the combustion modes between SFC and DFC. Lower heating

**Table 1**
Specifications of test engine.

| Description | Specification |
|---|---|
| Engine model | ND 130DI |
| Type | Single-cylinder DI engine |
| Bore × stroke (mm) | 95 × 95 |
| Displacement volume (cc) | 673 |
| Compression ratio | 18 |
| Intake value open | BTDC 340° |
| Intake value close | ATDC 136° |
| Exhaust value open | ATDC 136° |
| Exhaust value close | BTDC 340° |
| Combustion chamber | Open chamber |
| Max. hose power (ps/rpm) | 13/2400 |
| Max. torque (N m/rpm) | 42/2000 |
| Coolant temperature (°C) | 70 ± 2 |