Applied Thermal Engineering 103 (2016) 399–410

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

Enabling dual fuel sequential combustion using port fuel injection of high reactivity fuel combined with direct injection of low reactivity fuels

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HIGHLIGHTS

- Three stages of heat release can be found.
- Port injected n-heptane has high impacts on combustion parameters.
- NOx and soot emissions are all kept at low levels for the experimental conditions.
- Ethanol has lower NOx and soot emissions than with n-butanol and n-amyl alcohol.

ARTICLE INFO

Article history:
Received 17 December 2015
Revised 31 March 2016
Accepted 22 April 2016
Available online 23 April 2016

Keywords:
DFSC
n-Heptane
Ethanol
n-Butanol
n-Amyl alcohol
Combustion and emissions

ABSTRACT

This paper presents a preliminary experimental study on the combustion and emission characteristics of Dual Fuel Sequential Combustion (DFSC) mode, in which port fuel injection of n-heptane combined with in-cylinder, directly injected ethanol, n-butanol and n-amyl alcohol are used in a single-cylinder engine at fixed directly injection timing. The results show that the heat release can be divided mainly into three stages: low temperature reaction, high temperature reaction of n-heptane and the directly injected fuel combustion stage. The amount of port injected n-heptane plays a key role in the maximum in-cylinder pressure (Pmax), maximum in-cylinder mass averaged temperature (Tmax) and the maximum pressure rise rate. For the high overall lower heating values (LHVs) per-cycle, the CO emissions decrease with the increase of the premixed ratio. By contrast, the CO emissions increase with the premixed ratio when the overall LHVs per-cycle are kept at medium and low levels. The NOx and soot emissions are all kept at low levels for the experimental conditions. In particular, the higher latent heat, lower cetane values and the shorter carbon chains associated with ethanol lead to lower NOx and soot emissions than those of n-butanol and n-amyl alcohol. When directly injection of n-butanol and at low loads, with optimized premixed ratio, the indicated thermal efficiency can be higher than 46% meanwhile maintaining low emissions.

1. Introduction

To address global energy problems and increasingly stringent emission regulations, biomass-based alternative fuels and new combustion modes are being widely developed [1,2]. As alternative fuels, biomass-based fuels, which are commonly known as biofuels, possess many advantages over fossil fuels [3]. First, biofuels are easily available from common biomass sources. Second, the application of biofuels enables carbon circulation between the air and fuel, meaning problems such as greenhouse gas emissions and energy shortages can be solved together. Third, most biofuels, such as biodiesel and ethanol, have suitable physicochemical properties that permit effective combustion in internal combustion engines with or without minor modifications.

Ethanol is the only large-scale renewable fuel used currently [4–7]. Because the physical and chemical properties of ethanol are similar to that of gasoline, ethanol is added to gasoline in the United States, Canada, China and many other countries. A large number of studies have focused on the application of gasoline mixed with ethanol in a spark ignition (SI) engine [8–10]. Meanwhile, to realize the high efficiency of ethanol, and to find a solution to the problem of high NOx and soot emissions from traditional diesel engines, many scholars have studied using ethanol

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http://dx.doi.org/10.1016/j.applthermaleng.2016.04.122
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in a diesel engine [11–13]. He et al. [14] studied the mixing proportion of ethanol in diesel fuel blends and noted that as the proportion of ethanol mixed with diesel increases, the density, cetane number, kinematic viscosity, higher heating value and aromatic fractions of the blends decrease. Ignition improvement is needed to enhance the cetane number. Lu et al. [15] studied the combustion of diesel/ethanol blends and found that the combustion efficiency can be improved. For higher ethanol blending ratios, NOx and soot amounts decrease, whereas CO emissions increase. Li et al. studied the combustion and emissions characteristics of diesel/ethanol blends with 5%, 10%, 15%, and 20% ethanol/diesel ratio blends [16]. They found that the brake specific fuel consumption and brake thermal efficiency increased with the ethanol content for the overall operating conditions.

Diesel blended with ethanol can reduce soot emissions [17,18], improve combustion efficiency [19,20] and under certain conditions, can also decrease NOx emissions [21,22]. However, this decline has not achieved a breakthrough, and NOx emissions are still at high levels [23,24]. In addition, because ethanol and diesel oil is difficult to stabilize, additives or solvents are required to make diesel/ethanol blends fuel stable miscible [25]. However, diesel/ethanol blends have not yet gone into commercial applications or large scale production.

In recent years, butanol fermented from sugar, starch, or lignin converted from crops has drawn significant attention [26,27]. Szwaja and Naber [28] studied the combustion characteristics of n-butanol with an SI engine and found that the optimal ignition timing and antiknock properties of butanol are similar to gasoline with an octane number of approximately 87. Gu et al. [29] researched the effects of EGR on the emissions from n-butanol/gasoline blends in a gasoline engine. Studies show that when using an n-butanol/gasoline mixture, the HC, CO and NOx emissions can be reduced. EGR helps to reduce NOx emissions when using n-butanol/gasoline blends. Rakopoulos et al. [30] studied the combustion properties of n-butanol/diesel blends in a diesel engine. Their study found that mixing butanol into the blend can effectively reduce soot emissions and slightly decrease NOx emissions. Yao et al. [31] studied the effect of n-butanol as a diesel additive on engine performance and emissions for a heavy duty diesel engine. They found that while the NOx emissions are roughly the same, n-butanol can effectively improve the soot and CO emissions. Doğan [32] studied the effects of n-butanol/diesel blends on engine performance and emissions and found that as the volume percentage of butanol increases, the soot, CO and NOx emissions decrease. However, the HC emissions increase. Rakopoulos et al. [27] studied the effects of n-butanol/diesel blends on engine performance and emissions in a high-speed diesel engine. Their results showed that as the volume percentage of n-butanol increased, the soot and CO emissions decreased gradually and that NOx emissions decreased slightly. However, HC emissions increased with the volume percentage of butanol.

Besides the exploration of new clean renewable alternative fuels and to optimize combustion efficiency and emissions limits for diesel traditional compression ignition engines, different modes of combustion have also been researched. In recent years, many scholars have performed studies on the homogeneous charge compression ignition (HCCI) combustion mode. These studies have produced a series of achievements, but for the existing technical conditions and control system, the full load range and variable operating conditions for HCCI combustion are still very difficult to control [33,34]. To achieve high efficiency and low emissions for different operating conditions, reactivity controlled compression ignition (RCCI) combustion mode is proposed [35,36]. The internal combustion is well controlled by high EGR ratios and two stage fuel injection strategies [37,38]. Recently, Lu et al. proposed a dual fuel sequential compression combustion (DFSC) mode [39,40]. DFSC introduces a well-mixed, lean fuel/air mixture into the cylinder by injecting a high cetane number fuel at the intake port, followed by the direct injection of a high-octane number fuel near top dead center (TDC).

In the DFSC mode, the port injected fuel, which has a high cetane value, burns first and combusts in the HCCI low temperature combustion mode. Meanwhile, the combustion of high cetane value fuels provides a suitable temperature and releases a large number of active radicals, which is beneficial to the combustion of directly injected fuels. In addition, the lower cetane value of direct injected fuel results in a delayed burn, which is beneficial to the mixing of the directly injected fuel. Furthermore, a direct injection fuel gasification process may lead to temperature drops in the cylinder, which effectively inhibits the generation of NOx.

Based on these reasons and considering the alcohol fuel properties, which generally include a high latent heat, high fuel oxygen content, and a low cetane value, an experimental study was conducted on the combustion and emissions characteristics of DFSC in a single-cylinder engine applying port injection of n-heptane combined with in-cylinder direct injection of ethanol, n-butanol and n-amyl alcohol, respectively. The combustion characteristics and emission properties are analyzed in detail.

2. Experimental setup

2.1. Engine and instrumentation

The experiments were performed on a modified single-cylinder, direct-injection, 4-stroke, water-cooled, naturally aspirated diesel engine, as shown in Fig. 1. The main engine specifications are listed in Table 1. A port fuel injection system was employed to supply n-heptane into the intake manifold to form the homogeneous charge. The injector for this system was mounted approximately 0.45 m upstream from the intake valve, with an injection pressure of 5 bar and port fuel injection timing of 340°CA BTDC. A direct injector (DI) with a cone angle of 154° was used to inject different alcohols directly into the cylinder. The DI timing can be held constant by maintaining the fuel supply advance angle at 25 °CA BTDC.

The in-cylinder gas pressure was measured using a pressure transducer (Kistler mode 6125B). The charge output from this transducer was converted to an amplified voltage using an amplifier (Kistler mode 5015A) and recorded at a resolution of 0.5°CA. The exhaust gas components of the CO, UHC (unburned hydrocarbon), and NOx emissions were measured by a gas analyzer (AVL Digas 4000). The smoke opacity was measured by a smoke meter (AVL Dismoke 4000). The measured parameters and their accuracy are summarized in Table 2. For all data presented, 0°CA is defined as TDC (top dead center) for the compression stroke. In consideration of the accuracy of g/kW h is highly relied on the accurate measurement of inlet air mass. For single cylinder engine, uneven intake flow leads to difficult accurate measurement of inlet air mass. In this work, ppm is used to discuss the gas emissions.

2.2. Test fuels

To compare the ignition and combustion characteristics of the DFSC fueled with n-heptane/alcohols fuels, high purity n-heptane, ethanol, n-butanol and n-amyl alcohol are used. The properties of these fuels are listed in Table 3.

2.3. Experimental procedure

Before the tests start, the engine is warmed up until the lubrication oil and coolant fluid temperatures are 85 °C. The engine speed is set to 1500 rpm. The test cylinder is fired in the HCCI mode with