Fuel 234 (2018) 227–237

Contents lists available at ScienceDirect

Fuel

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

Full Length Article

Effect of two-stage injection dwell angle on engine combustion and performance characteristics of a common-rail diesel engine fueled with coconut oil methyl esters-diesel fuel blends

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ARTICLE INFO

Keywords:
Diesel engine
NO_x
Injection timing
Dwell angle
Biodiesel

ABSTRACT

Diesel engine is widely used as prime mover due to its high thermal efficiency. Usage of renewable biodiesel in diesel engine is also widely studied due to its potential in reducing emission and as a replacement of conventional diesel. Biodiesel performance could be improved by blending it with petroleum diesel besides introducing appropriate injection strategies. In this experiment, the effect of percentage of biodiesel blends and injection strategies such as variations in start of injection (SOI) timing and dwell angle on diesel engine performance were investigated. The test engine used is four-stroke turbocharged direct injection diesel engine. Results show that exhaust emissions, engine performance and combustion characteristics are substantially affected by biodiesel blending ratio and SOI timing but slightly influenced by two-stage injection dwell angle. Biodiesel blends percentage could be raised to improve NOx and smoke emissions. Even though SOI performed at a later timing could reduce NOx emission, smoke emission increased. Dwell angle between two successive injections could be prolonged to lower the effect of the increase in smoke emission. It could also be inferred that by setting a proper SOI timing and dwell angle under two-stage injection scheme when suitable biodiesel blend is used, the engine performance could be optimized.

1. Introduction

Diesel engine is ubiquitously used as primary mover by virtue of its high efficiency. It has been used in many areas such as transportation, power generation, irrigation and construction equipment. However, the use of diesel fuel has posed two main problems – fossil fuel depletion and air pollution issues. The demand of liquid fuels is expected to increase in the near future as depletion problem may worsen. Besides, usage of diesel engine has caused emission of air pollutants. Nitrogen oxides (NO_x) (nitric oxide and nitrogen dioxide), carbon monoxide (CO) and unburned hydrocarbons (HC) are some of the main components of air pollutants produced when diesel engine is used [1]. The air pollutants may cause various health problems, formation of acid rain, destruction of ozone layer, etc. Steps have to be taken to overcome the problems due to the usage of diesel engine.

Biodiesel fuel is one of the alternatives to solve the diesel depletion problem. It can be derived from plants and animals such as coconut, rapeseed, soybean, animal fats, etc [2]. It is nontoxic, renewable and biodegradable [3]. Emission characteristics of biodiesel fuel are different from conventional diesel. Combustion of biodiesel emits a lower level of CO, smoke and particulate matter concentration due to the higher oxygen content in it [4]. According to Shivakumar et al. [5], NO_x emission of waste cooking oil biodiesel blends is higher than conventional diesel. However, the smoke emission of waste cooking oil biodiesel blends is less than conventional diesel. Ganapathy et al. [6] studied about the emission of Jatropha biodiesel. They found that Jatropha biodiesel always exhibits a higher NO_x emission compared to conventional diesel. The smoke density observed when Jatropha biodiesel is used is lower than conventional diesel. Brake thermal efficiency (BTE) of Jatropha biodiesel is lower than conventional diesel.

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https://doi.org/10.1016/j.fuel.2018.07.036
Received 7 April 2018; Received in revised form 4 July 2018; Accepted 7 July 2018
0016-2361/ © 2018 Published by Elsevier Ltd.

Raheman and Ghadge [7] investigated the performance of diesel engine when Mahua biodiesel was used. They showed that the brake specific fuel consumption (BSFC) increased while the brake thermal efficiency (BTE) decreased when the percentage of biodiesel blend increased. The NO_x and smoke emission trends are the same as what were observed when waste cooking oil biodiesel blend and Jatropha biodiesel were used.

In order to improve the performance and emission characteristics of diesel engine when biodiesel is used to replace conventional diesel, a more advanced injection strategies have to be carried out. Multiple-injection strategy has been proposed as one of the methods to reduce the air pollutants emitted by diesel engine. Generally, two kinds of multiple-injection schemes which are pilot injection and split injection are applied in diesel engine. Pilot and split injections are distinguished by the injection quantity of the first injection. Usually, in pilot injection, a relatively small quantity of first injection fuel is introduced before the second main injection. While in split injection, the injection of fuel is divided into two or more equal portions, where each portion is injected consecutively but non-continuously. One of the purposes is to ensure that before main combustion occurs, a highly premixed fuel can be formed. The benefits of multiple-injections, which includes pilot and split injections, have been studied by many researchers before [8–14]. Jafarmadar and Nemati [15] applied the split injection scheme in an indirect injection diesel engine to study the exergetic performance using three-dimensional CFD code. The first injection pulse was altered from 75% to 90% and the duration of the dwelling angle was maintained at 20° crank angle. As the results showed, with longer first injection pulse, the heat loss, work, and fuel burn exergies as well as the exergy efficiency increased. Besides, Choi and Reitz [16] noted the NOx suppression effects with both late and split injection strategies when using biodiesel in a single-cylinder heavy-duty diesel engine. In the case of double injection strategies, the first injection pulse and dwell time were fixed at 50% and 0.97 ms for low load and at 61% and 1.18 ms for high load conditions. The authors found that these injection schemes reduced the burning rate during premixed combustion phase, thereby lowered in-cylinder combustion temperatures. Another study [17] used neat biodiesel from soybean oil for the study of the effect of injection timing and exhaust gas recirculation (EGR) rate on the combustion and emissions. The results showed that biodiesel exhibited lower NOx with split injection strategy at retarded SOI timing. Also, the BSFC was slightly increased with retarded SOI. The testing was carried out with small fuel quantity of the first injection compared to the second injection (main injection) on the Ford Lion V6 DI diesel engine. This injection technique was rather common but no in-depth studies were conducted on the effect of same fuel injection quantities for the first and second injection. Kim et al. [18] experimentally assessed split injection on engine performance, exhaust emissions and soot particulates on single-cylinder common-rail injection diesel engine fueled with neat biodiesel derived from soybean. The results indicated that the split injection reduced NOx emissions remarkably without a significant increase in soot emissions. The benefits of split injection for NOx reduction were further affirmed by Stringer and co-worker [19] using an optical access research engine. Additionally, post injection applied during split injection serves to reduce the amount of smoke, particulate matter and unburned hydrocarbon [20]. The parameters in split injection can be changed and improved to produce a better effect on the performance and emissions characteristics of diesel engine. These parameters include injection timing, dwell angle between injections, mass injected, mass ratio of injections, number of injections, injection pressure and others. Recently, the authors of this paper [21] examined the effects of combining biodiesel blended fuels and split injection (i.e. single, double and triple injection) in a four-cylinder common-rail diesel engine at various SOI and reported simultaneous decrement of NOx and smoke emissions with a drop in performance. Besides, the outcomes also suggested that the dwell angle between consecutive injections for double injection scheme could be further optimized for obtaining a much cleaner exhaust emissions and engine performance. In this study, effect of different start of injection timing and dwell angle between injections in two-stage injection scheme on the performance and emission characteristics will be investigated and discussed.

Start of injection timing is one of the factors which greatly affect diesel engine performance and emission characteristics. Shivakumar et al. [5] found that NO_x emitted was reduced when waste cooking oil biodiesel blends were used when SOI is retarded while advanced SOI caused reduction in amount of smoke emitted. The same results were obtained by Sayin et al. [22] using $C_{18.08}H_{34.86}O_2$ biodiesel and Ganapathy et al. [6] using Jatropha biodiesel. According to Jeon and Park [23], when pilot injection was applied, the retardation of SOI of pilot injection caused higher emission of NO_x compared to single injection scheme. Adam et al. [24] used gasoline and soy methyl ester biodiesel in investigating engine performance and emission characteristics. They found that with retarded injection timing, gas temperature and HRR increased, leading to rise in NO_x emission amount.

Besides SOI, dwell angle is also an important factor. According to Cung et al. [25], when the dwell angle was reduced, the penetration rate was increased. However, a dwell angle which is too short will cause the soot to increase. With a longer dwell angle, the peak heat release rate (PHRR) and total heat released were increased. Rohani and Bae [26] found that longer dwell angle of about 30°CA produced a more premixed charge. In split injection with five times of injection, Mathivanan et al. [27] discovered that smoke level was the lowest when the dwell angle between the fourth injection and the last injection was the longest. Liu and Song [28] found that cylindrical pressure decreased with increasing dwell angle under constant fuel quantity in double injection scheme. When the post injection was retarded and the dwell angle was increased, NO_x emission could be reduced. A shorter dwell angle causes limitation in oxidation of CO and hydrocarbon (HC) due to insufficient mixing time. Using Karanja biodiesel as fuel, Dhar and Agarwal [29] found that NO_x emission decreased with retarding start of main injection timing for every start of pilot timing. However, at fixed start of main injection, NO_x emission was almost constant with the change in start of pilot injection.

Some studies about impacts of biodiesel blends, start of injection (SOI) timing and multiple injection dwell angle on efficiency and exhaust emission of diesel engine have been carried out as stated above. However, the study on the combination effect of these three factors is less. In fact, most of them have been carried out on single-cylinder research engine, which is not a practical representative of the production multi-cylinder engine adopted in commercial vehicles. This might be due to single-cylinder engine that essentially differs from multi-cylinder engine in term of rotational dynamics, gas intake dynamics, heat transfer dynamics, dynamic coupling between cylinders, and in other aspects [30]. For instance, the difference in gas intake dynamics arises especially in the case of turbocharged engines, which can significantly alter the in-cylinder intake air charge motion and momentum, thus impacting on in-cylinder emission production due to the differences in heat transfer. Consequently, there is a research gap existing in these disciplines. Hence, the topic will be explored in the present paper. In this study, effects of start of injection timing and dwell angle on diesel engine performance and characteristics emission will be investigated by using biodiesel blended fuels in multi-cylinder turbocharged diesel engine. Combination of different parameters will be carried out to understand the combination which can lead to optimum performance and emission characteristics of diesel engine.

2. Experimental apparatus and procedure

2.1. Apparatus setup

Table 1 shows the specifications of the engine used in this experiment. The experimental setup was the same as that described in [31]. Four-stroke diesel engine with turbocharger was used instead of single-

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