Energy Conversion and Management 103 (2015) 778–789

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Experimental investigation of n-butanol/diesel fuel blends and n-butanol fumigation – Evaluation of engine performance, exhaust emissions, heat release and flammability analysis

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ARTICLE INFO

Article history:
Received 17 March 2015
Accepted 30 June 2015
Available online 18 July 2015

Keywords:
Turbocharged diesel engine
n-Butanol/diesel fuel blends
n-Butanol fumigation
Heat release analysis
Flammability analysis

ABSTRACT

The aim of this paper is to investigate and compare the effects of n-butanol/diesel fuel blends (nBDFBs) and n-butanol fumigation (nBF) on the engine performance and exhaust emissions in a turbocharged automobile diesel engine. Also, evaluations based on heat release and flammability analysis have been done. Experiments have been performed for various n-nBDFBs and nBF at different engine speeds and loads. For nBDFBs and nBF tests; nB2, nB4 and nB6 and nBF2, nBF4 and nBF6n-butanol percentages were selected. Here, for example nB2 and nBF2 contains 2% n-butanol and 98% diesel fuel by volume respectively. The test results showed that smoke decreases significantly by applying both of these two methods. However, decrement ratios of smoke for fumigation method are higher than that of blend method. NO_x emission decreases for nB2, but it increases for nB4 and nB6 at selected engine speeds and loads. NO_x emission decreases generally for nBF. For nB2 and nB4, BSFC decreases slightly but it increases for nB6. For nBF, BSFC increases at all of the test conditions. Adding n-butanol to diesel fuel becomes expensive for two methods. For nBDFBs, heat release rate (HRR) diagrams exhibit similar typical characteristic to NDF. However, for nBF, HRR shows slightly different pattern from NDF and a double peak is observed in the HRR diagram. The first peak occurs earlier than NDF and the second peak takes places later. In addition, this diagram shows that the first peak becomes larger and the second peak diminishes as n-butanol ratio is increased. Because of pilot injection of diesel fuel, it can be seen that diesel fuel could be exceed the lower flammability limit and self ignition could be occur. Thus, pre-combustion occurs at the interval of $\sim(-20 \text{ to } -10)\,^\circ$CA.

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1. Introduction

In diesel engine, various alternative fuels and fuel additives such as alcohols [1,2], biodiesel [3,4], dimethyl ether [5,6] and natural gas [7,8] can be easily used. Among them, oxygenated fuels have drawn more attentions as they have capability of dramatically reduction of particulate matter (PM) emissions, without causing serious penalties on unburned hydrocarbon (UHC), nitrogen oxides (NO_x), and engine performance parameters [9–11]. Also, many oxygenated fuels, such as biodiesel, ethanol and n-butanol, can be produced from plants. Since plants absorb CO_2 during growth [12], the combustion of those fuels does not lead to additional carbon dioxide (CO_2) emission, which is one of the key solution of the global warming gas emissions. Moreover, being oxygenated fuels biologically renewable, using them as alternative fuels or fuel additives can reduce the dependence on un-renewable fossil fuels [1], support local agricultural industries and enhance farming incomes [12]. Because of these advantages, much effort has been devoted to investigate the effects of various oxygenated fuels especially alcohols on the performance and emissions of diesel engines by applying different techniques [1,9,12].

Blending and fumigation techniques are the most preferred methods for using different alcohols in diesel engines [12]. The first technique is the simplest method and here any suitable alcohol is mixed with diesel fuel. This mixture is used by typical fuel supply system and the engine mainly operates due to diesel principle. However, it is well known that limited amount of alcohol (up to 10% v/v) can be used in the blends because of the miscibility problems of various alcohols in diesel fuel. For this reason solubility additives are also required [12,13]. The second technique is the

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http://dx.doi.org/10.1016/j.enconman.2015.06.089
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alcohol fumigation method. In this technique alcohol is introduces into intake air by using a simple carburetor or a low-pressure injection system. Here, minor modifications are required for intake system and the engine mainly operates due to diesel principle.

In the relevant literature alcohol, especially ethanol and methanol blends and fumigation applications can be found [2,12,14–17]. All those studies revealed promising results for exhaust emissions and engine performance parameters. Abu-Qudais et al. [14] investigated experimentally ethanol fumigation and ethanol–diesel fuel blends and they compared obtained results. They found that both blends and fumigation methods show similar effects on engine performance and exhaust gases. However, the improving effects of fumigation method were better that blending method. 20% ethanol fumigation, which is stated as optimum percentage, decreases soot mass concentration 51% and increases brake thermal efficiency 7.5%. However 15% ethanol/diesel fuel blend, which is stated as optimum percentage, decreases soot mass concentration 32% and increases brake thermal efficiency 3.6%. HC and CO emissions increase for both methods. Similar results can be found in literature for ethanol and methanol fumigation and blends [2,12,15–17].

From this brief evaluation of literature it can be said that n-butanol is a very competitive biomass-based renewable fuel and it has more advantages as automotive fuel compared to methanol and ethanol. The main advantages of n-butanol as engine fuel can be summarized as follows: n-butanol has larger lower heating value, a higher cetane number, lower volatility, larger viscosity, better lubricity and a higher flashpoint. In addition, butanol can be mixed with diesel fuel without serious phase separation. Owing these advantages, n-butanol–diesel fuel blends studies began to increase in the recent years [1,18–21]. Even so, n-butanol fumigation studies are very limited [9]. For this reason, in the present study both using of n-butanol/diesel fuel blends and applying of n-butanol fumigation have been investigated experimentally and the obtained results for two methods are compared to neat diesel fuel (NDF). Also, flammability analysis of n-butanol has been done.

2. Experimental system and test procedure

2.1. Engine and experimental set up

Experiments for NDF, nBDFBs and nBF were conducted in a 4 cylinder, 4-stoke, water-cooled, turbocharged, common-rail injection, 1.461 L Renault DI automotive diesel engine (model K9K 700). Main technical specifications of the engine are given in Table 1 and schematic diagram of the test system used were presented in Fig. 1a. The test bed was produced by Cussons. Here, loading was done by a water brake and the brake moment (loading force) was measured electronically.

Table 1
Main technical specifications of the test engine.

Engine	Renault K9K 700 turbocharged automotive diesel engine
Displacement	1.461 l
Number of cylinder	4
Bore & stroke	76 & 80.5 mm
Compression ratio	18.25:1
Maximum power	48 kW @ 4000 rpm
Maximum torque	160 N m @ 1750 rpm
Connecting rod length	130 mm
Injection system	Common rail injection system[a]
Number of nozzle holes	5
Nozzle hole diameter	0.12 mm

[a] The high pressures up to 2000 bar.

In-cylinder gas pressure was measured by using of an air cooled quartz pressure sensor (type GH13P, AVL). This sensor has a measuring range of 0–250 bar and linearity of ±0.3% for full scale output and it was mounted on the head of the first cylinder of the engine in place of the hot plug. The signal outputs of the pressure sensor were amplified by an electronic indicating system (type P4411, Cusson). TDC signal of the engine which use for injection timing was also used to determine TDC position. The signals of pressure and crank angle were synchronized and recorded by a data acquisition system (NI PCI-6221 type, National Instruments). The average in-cylinder pressure profile over 100 complete cycles was used to calculate the rate of heat release since low cetane number fuels can give rise to cyclic irregularity [22,23].

NO_x emission was measured by using a NO_x gas analyzer (MEXA-720, Horiba) which employs a zirconia ceramic sensor. The main specifications of this NO_x gas analyzer are given in Table 2. Smoke was determined by a smoke opacimeter (MGA-1500, Sun). The readings values are provided as smoke opacity in % Hartridge units and the accuracy of smoke measurement is within 0.1%. The concentrations of carbon dioxide (CO_2) and unburned hydrocarbon (HC) in the exhaust gases were measured by using an exhaust gas analyzer (DiGas 4000, AVL). The main specifications of the DiGas 4000 gas analyzer are given in Table 3.

2.2. Operating conditions

In this study, the effects of nBDFBs and nBF on engine performance, combustion and exhaust emissions were experimentally studied and compared for two different loads and speeds. Here, experiments were conducted at two different engine speeds of 2000 rpm (i.e. the max-torque condition) and 4000 rpm (i.e. the rated-power condition) for three different low n-butanol ratios (2%, 4%, and 6%, by vol.). Here, engine loads of (145 and 132) N m at 2000 rpm and (110 and 96) N m at 4000 rpm were selected. Tests were firstly carried out for NDF to obtain a database for comparison of the results of three n-butanol ratios. Then, during nBDFB tests, blends of nB2 (e.g. nB2 contains 2% n-butanol and 98% diesel fuel in volume basis), nB4 and nB6 were prepared and used in the tests under the same conditions.

After completed n-butanol blend experiments, n-butanol fumigation tests were performed. In the fumigation method, n-butanol was introduced into intake air by using a simple carburetor. This carburetor was mounted on the inlet manifold and gas and air throttles and the other auxiliary equipments of the carburetor dismantled and orifice diameter is chosen sufficiently large. By this way, it was aimed to eliminate probable effects of carburetor orifice restriction on the intake air flow and volumetric efficiency. As usual, air inlet was connected to the air consumption measuring box by a flexible hose. On the other hand, n-butanol flow rate is controlled by a fine threaded adjustment screw which can change the carburetor main fuel jet section. Technical view and photograph of this adapted carburetor was presented in Figs. 1a and 1b respectively. Here, for fumigation tests, to obtain 3 different n-butanol ratios of ~2 (nBF2)%, 4 (nBF4)% and 6 (nBF6)%, by vol., carburetor main jet opening was adjusted at 3 different position.

At the beginning of the experiments, engine was run for approximately 30 min and at the end by its reaching to the steady state conditions cooling water temperature becomes (70 ± 5) °C. For example, at 2000 rpm for NDF tests, firstly the load of the engine was adjusted as 145 N m (506 N loading force). Then, tests were performed for loading moments 145 and 132 N m. Here, constant 2000 rpm speed is retained by adjusting fuel delivery rate suitably. Thus, tests for NDF at 2000 rpm were carried out at two different engine loads. Similar experiments were repeated at engine speeds

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