Energy Conversion and Management 89 (2015) 396–408

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Experimental investigation of CI engine combustion, performance and emissions in DEE–kerosene–diesel blends of high DEE concentration

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ARTICLE INFO

Article history:
Received 20 June 2014
Accepted 8 October 2014

Keywords:
Diethyl ether–kerosene–diesel blend
CI engine
Combustion characteristics
Performance
Emissions

ABSTRACT

An experimental investigation had been carried out to evaluate the effects of oxygenated cetane improver diethyl ether (DEE) blends with kerosene and diesel on the combustion, performance and emission characteristics of a direct injection diesel engine. Initially, 2%, 5%, 8%, 10%, 15%, 20% and 25% DEE (by volume) were blended into diesel. The DEE–diesel blends have reduced the trade-off between PM and NOx of diesel engine and the optimum performance blend has been found as DE15D. Similarly, 5%, 10% and 15% kerosene (by volume) were blended into diesel to investigate the adulteration effect. In addition, a study was carried out to evaluate the effects of kerosene adulteration on DE15D by blending with 5%, 10% and 15% kerosene (by volume). The engine tests were carried out at 10%, 25%, 50%, 75% and 100% of full load for all test fuels. Laboratory fuel tests showed that the DEE is completely miscible with diesel and kerosene in any proportion. It was observed that the density, kinematic viscosity and calorific value of the blends decreases, while the oxygen content and cetane number of the blends increases with the concentration of DEE addition. The experimental test results showed that the DEE–kerosene–diesel blends have low brake thermal efficiency, high brake specific fuel consumption, high smoke at full load, low smoke at part load, overall low NO, almost similar CO, high HC at full load and low HC at part load as compared to DE15D blend.

1. Introduction

Diesel engines have several advantages like high thermal efficiency, torque capacity, reliability, adaptability, low HC and CO emissions and cost effectiveness, but they suffer from high concentration of NOx and particulate emissions. The primary contributing factors for the particulate matters are rich mixture and heterogeneous combustion, sulphur content, lubricating oil, unburned HC and dominant diffusion combustion phase. The NOx formation in diesel engines is a function of higher temperature, oxygen concentration and residence time. Simultaneous reduction in NOx and particulate matter is quite difficult in diesel engines due to the trade-off between PM and NOx, which is often accompanied by fuel consumption penalty [1–3]. Hence, it is more difficult for diesel engines to meet stringent emission norms by the use of conventional neat diesel fuel through engine design or control parameters alone. The diesel engine technology is being upgraded in order to meet stringent emission norms as well as fuel economy requirements. The various methods like EGR, dual fuel mode, catalytic converters, retarding the injection timing, use of high injection pressure, split injection and modifying the combustion chamber geometry to enhance the swirl and squish are being tried to reduce emissions but problems are still prevailing in the operation of these techniques [2,4]. In parallel to this interest, there has also been increased interest in HCCI and PCCI combustion technology [2,5,6].

An alternative fuel is a fuel that would partially or completely substitute a conventional petroleum based fuel. Alternative fuels such as CNG, HCNG, LPG, LNG, Biodiesel, Biogas, Hydrogen, Ethanol, Methanol, DME, DEE, Producer gas, P-series have been tried worldwide [7–10]. The introductions of oxygenated compounds into diesel fuel especially those that are originally bio-resources are the best ways to reduce emissions of diesel engines. Bio-fuels made from agricultural products which are oxygenated by nature, may not only offer benefits in terms of exhaust emissions, but also reduce the world's dependence on oil imports. These oxygenates

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http://dx.doi.org/10.1016/j.enconman.2014.10.022
0196-8904/

Nomenclature

A/F	air /fuel ratio	IBP	initial boiling point
ASTM	American standards for testing materials	KOME	Karanja oil methyl ester
BMEP	brake mean effective pressure	LCV	lower calorific value
BTDC	before top dead centre	LNG	liquefied natural gas
BSFC	brake specific fuel consumption	LPG	liquefied petroleum gas
BTE	brake thermal efficiency	NO	nitric oxide
CA	crank angle	NOx	oxides of nitrogen
CI	compression ignition	NTP	normal temperature and pressure
CO	carbon monoxide	PAH	polycyclic aromatic hydrocarbons
CO_2	carbon dioxide	PCCI	premixed charge compression ignition
CNG	compressed natural gas	PM	particulate matter
DI	direct injection	RTD	resistance temperature detector
DEE	diethyl ether	SI	spark ignition
DME	dimethyl ether	V	cylinder volume
EGR	exhaust gas recirculation	p	cylinder gas pressure
EGT	exhaust gas temperature	γ	ratio of specific heats (Cp/Cv)
FBP	final boiling point	θ	crank angle
FC	fuel consumption	$dQn/d\theta$	net heat release rate
HC	hydrocarbon		
HCCI	homogenous charge compression ignition		
HCNG	hydrogen-CNG blend		

are classified as Alcohols (R–OH), Ethers (R–O–R), Esters (R–C–O–O–R) and Carbonates (R–O–C–O–O–R). Item "R" represents a hydrocarbon chain. Among all oxygenates, a worldwide trend towards the application of bio-fuels and mainly biodiesel and alcohols have been observed for the last two decades [7,8,11]. Alcohol fuels can substitute for gasoline in spark-ignition engines, while biodiesel, green diesel, DEE and DME are suitable for use in compression ignition engines [12,13]. The oxygenate fuels like DEE and DME are attracting notable attention of researchers as a clean alternative fuel for compression ignition engines without large sacrifice in vehicle performance [14].

Biodiesel is considered as a clean fuel which reduces unburned hydrocarbon, CO and particulate matter. It has almost no sulphur, no aromatics and has about 10% inherent oxygen, which helps it to burn fully. Its higher cetane number than diesel fuel improves the ignition quality even when blended with petroleum diesel. However, it suffers from cold starting problems, higher viscosity and increase in NOx emissions as compared to petroleum diesel [15]. DME is one of the promising alternative fuels for diesel engines. DME is the simplest ether expressed by its chemical formula CH_3OCH_3, consisting of two methyl groups bonded to a central oxygen atom. It has a low carbon-to-hydrogen (C:H) ratio. The chemical structure of DME is somewhat similar to methanol; it contains oxygen and no carbon–carbon bonds, thus limiting the possibility of forming carbonaceous particulate emissions during combustion [16]. DME is a synthetic fuel that can be made from a variety of fossil feedstock including natural gas and coal as well as from renewable feedstock and waste. The most cost effective feedstock for both DME and methanol is natural gas at remote locations [9]. The researchers Wang et al. [17] have also studied the feasibility of DME as port premixing fuel in a diesel engine.

Ethanol is another promising alternative fuel because it is a renewable bio-based resource and highly oxygenated (34.7% by weight), thereby providing the potential to reduce particulate emissions in CI engines and shows promise as a future fuel for SI engines due to its high octane quality. However, there are many obstacles in the use of ethanol in CI engines such as very low cetane number (8), poor ignition characteristics and limited solubility in diesel fuel. Phase separation and water tolerance in ethanol–diesel blend fuels are crucial problems. The dynamic viscosity of ethanol is much lower than diesel fuel. Thus, the lubricity is a potential concern of ethanol–diesel blend fuels [11,18].

To overcome these problems, ethanol can be converted easily into DEE through a dehydration process. DEE has several favourable properties for CI engines such as high cetane number (>125), low auto ignition temperature, high oxygen content, reasonable energy density for on-board storage, broad flammability limits, high miscibility with diesel fuel and renewable bio-fuel [19]. DEE is a pungent, volatile, highly flammable liquid and widely used as a common solvent. It is the simplest ether expressed by its chemical formula $CH_3CH_2–O–CH_2CH_3$, consisting of two ethyl groups bonded to a central oxygen atom as shown in Fig. 1. Some important physico-chemical properties of the base fuels and oxygenated fuels are shown in Table 1.

Diethyl ether can be produced both in the laboratory and on an industrial scale by the distillation of ethanol with sulphuric acid (acid ether synthesis). Initially, ethanol (CH_3CH_2OH) is mixed with a strong acid, typically sulphuric acid (H_2SO_4). The acid dissociates in the aqueous environment producing hydronium ions, H_3O^+. A hydrogen ion protonates the electronegative oxygen atom of the ethanol molecule, giving it a positive charge as shown in Eq. (1).

$$CH_3CH_2OH + H_3O^+ \rightarrow CH_3CH_2OH_2^+ + H_2O \tag{1}$$

A nucleophilic oxygen atom of unprotonated ethanol molecule displaces a water molecule from the protonated (electrophilic) ethanol molecule producing water, a hydrogen ion and diethyl ether as in Eq. (2) [7].

$$CH_3CH_2OH_2^+ + CH_3CH_2OH \rightarrow H_2O + H^+ + CH_3CH_2O\ CH_2CH_3 \tag{2}$$

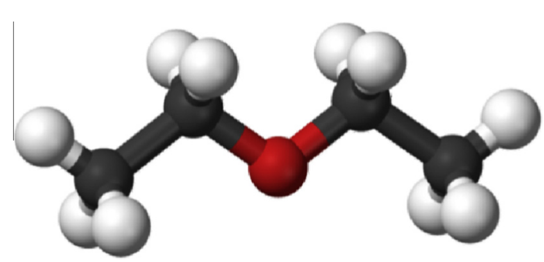

Fig. 1. Chemical structure of DEE molecule.