Energy 63 (2013) 76–85

Contents lists available at ScienceDirect

Energy

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

Ethanol dual-fuel combustion concept on heavy duty engine

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A R T I C L E I N F O

Article history:
Received 17 January 2013
Received in revised form
22 May 2013
Accepted 16 October 2013
Available online 11 November 2013

Keywords:
Dual-fuel combustion
Ethanol
Fumigation

A B S T R A C T

Limited crude oil resources and growing environmental awareness have raised a huge led to a huge motivation to seek new fuel alternatives for combustion engines. In this study the goal was to research the potential of ethanol as a compression ignition engine fuel utilizing dual-fuel combustion technology.

In the studied DF (dual-fuel) concept, the primary fuel is injected into the intake manifold and it is ignited by injecting diesel fuel into the cylinder near the TDC (top-dead centre). A similar concept has been widely used in natural gas dual-fuel engines. By using ethanol as a primary fuel instead of gaseous fuel, the dual-fuel concept could be a true alternative for on-road and off-road heavy-duty vehicles without the obstacles of energy density and fuel distribution challenges of the gaseous fuels.

The research engine in this study was a high speed heavy duty diesel engine modified for dual fuel combustion. The engine was equipped with a common-rail diesel injection system, which gave flexibility to modify the diesel injection to control the combustion. Especially the relationship between pilot and main diesel injection was investigated. The gathered results were promising. A maximum ethanol/diesel mass ratio of around 90% was achieved at high load conditions.

1. Introduction

The world energy markets are facing radical changes because of limited crude oil reserves. The IEA (International Energy Agency) World Energy Outlook 2010 report shows that oil production from existing oil fields had started to decline at the end of the last decade [1]. There are different scenarios of world oil production for the next decades, which show that the depletion of current fields can be more or less compensated by new fields, technology development, natural gas liquids, etc [1,2]. On the other hand, world energy demand is growing, which leads to increasing oil prices [1,3]. Together with the raised concern over carbon-dioxide emissions [1,4,5], high oil prices have motivated the search for alternatives to traditional crude oil based gasoline and diesel fuel.

CI (compression ignition) engines using diesel fuel are the main power source of both on-road and off-road heavy duty vehicles. Their conditions of use set high demands for engine efficiency, fuel price and fuel energy density and storage properties. CI engines using traditional crude oil based diesel fuel are facing the challenge of meeting strict emission legislation on particulates and nitrogen oxides. Since transportation consumes a significant portion of total world energy consumption [4], it would be both environmentally and economically important to find alternatives for crude oil based diesel fuel in this market area.

Ethanol contains high oxygen content (34.8 wt. %), which significantly lowers engine particulate emissions. Ethanol has a very low cetane number, so it cannot substitute diesel fuel directly in diesel engines without ignition-improving additives, which are required by as much as 16% by volume to ensure compression ignition [6]. In some studies, the advantages of ethanol have been utilized in CI engines by blending ethanol with diesel fuel [6–9]. Abu-Qudais et al. reports that up to 25% ethanol displacement can be achieved by using emulsifiers, although 15% is reported to be the optimum blend in their study [7]. Lei et al. reports even 30% displacement in their study [8]. Lee et al. studied fuel blends, where water-containing ethanol (wet ethanol) was mixed with biodiesel–diesel blends. The wet ethanol share in their study was 4% and they used also 1% *n*-butanol in their blend to stabilize the blend. Even with rather low ethanol rates, they found up to 10% decrease in nitrogen-oxides (NO_x) emission and 13–24% decrease in PM (particulate matter) emissions in low load conditions [9]. Diesel/ethanol blend always requires additives because of poor solubility, water pick-up and the likelihood of phase separation. With higher than 10% ethanol content, ignition improvers are also needed to reach the same thermal efficiency as with 100% diesel fuel [6].

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0360-5442/$ – see front matter
http://dx.doi.org/10.1016/j.energy.2013.10.053

Nomenclature

BTDC	before top-dead-centre
CA	crank angle (degrees)
CI	compression ignition
CNG	compressed natural gas
CO	carbon-monoxide
CRI	common-rail fuel injection
DF	dual-fuel
HC	hydro-carbon
HCCI	homogenous charge compression ignition
HRR	heat release rate
LNG	liquefied natural gas
NO_x	nitrogen-oxide
p	cylinder pressure (Pa)
PCCI	pre-mixed charge compression ignition
PFI	port fuel injection
PPCI	partly pre-mixed compression ignition
PRR	maximum pressure rise rate (bar/CA)
Q_n	net heat-release J
RCCI	reactivity-controlled compression ignition
rpm	revolutions per minute
SOI	start of injection
t	time (s)
TDC	top-dead-centre
V	volume
wt.	weight
γ	specific heat capacities ratio

The challenges of using ethanol as a direct substitute for diesel fuel or using an ethanol/diesel blend have made intake air fumigation an interesting option to utilize the advantages of ethanol. In the fumigation method, ethanol is introduced in the intake airstream, upstream from the cylinder head, most commonly with low pressure injectors or carburettors [6,7,10–15]. The studied maximum substitutions by fumigation have been in range of 10–50% of the total energy output of the engine, though the most commonly studied ethanol ratios have been 10% and 20% [7,11–13]. In reported studies, thermal efficiencies have increased slightly with the increase of ethanol substitution, while unburned HC (hydro-carbon) and CO (carbon-monoxide) emissions have notably increased, especially at low-load conditions. Soot and (NO_x) emissions have been reported to decrease with increasing ethanol substitution [7,11,12].

In dual-fuel (DF) combustion technology, the primary fuel is injected into the intake manifold with low pressure and it is ignited by injecting diesel fuel into the cylinder near the top-dead centre (TDC). The technology has been mainly developed for natural gas and it has quite a long history [16]. Natural gas DF technology has been utilized mainly on power plants near natural gas sources or pipelines and pipeline compressor stations. From the early 1990s, LNG (liquefied natural gas) has had a small market share in maritime energy markets because of the development of LNG tankers. Lately the upcoming IMO (International Maritime Organization) Tier III regulations have been a driving force for DF ship application development. The lean-burn DF gas engines have very low NO_x and soot emissions, and they can fulfil emission demands without additional exhaust gas after-treatment systems.

Because of the challenges in distribution and energy density, natural gas has not become very popular for on-road or non-road applications. Though the DF concept has been traditionally perceived as natural gas combustion, there are several fuels that can be used in dual fuel combustion. There have been a number of studies reported on dual-fuel or fumigation with the following fuels:

- Ethanol [7,9,11,13,17–19]
- Methanol [20–22]
- LPG (Liquefied Petroleum Gas)/propane [22–24]
- Methane [13,24–27]
- Hydrogen [24]
- Methyl ethyl ketone [22]
- Gasoline [28]
- *n*-butanol [29]
- Diesel [30].

All of the fuels mentioned above, except diesel, are suitable for spark ignition engines and have similar combustion characteristics, e.g. a high octane number (Table 1). When selecting the most suitable fuel for on-road or non-road dual-fuel applications, the distribution network and storability play an important role, which makes ethanol very promising – at least in certain local markets. For these reasons, this study focuses on the ethanol dual-fuel concept.

During the last few years, there has been significant activity in the research area most commonly called RCCI (reactivity-controlled compression ignition) combustion, which is close to the scope of this study. RCCI is further developed from HCCI (homogenous charge compression ignition) combustion and PCCI (pre-mixed charge compression ignition) combustion. The difference between these two combustion (RCCI and DF) technologies is that in RCCI,

Table 1
Typical properties of hydrocarbon fuels studied in dual-fuel or fumigation combustion.

	Octane number [RON]	Density [kg/m3]	Lower heating value [MJ/kg]	Boiling point [°C]	Oxygen content [wt-%]	Reference
Ethanol	109	792	26.8	78	34.8	[6]
Methanol	109	794	19.9	65	50	[6]
Propane	109	2.01/501[a]	46.4	−89	0	[6]
Methane	>127	0.717/466[a]	50	−164	0	[6]
Hydrogen	–	0.084	119.9	−253	0	[24]
Methyl ethyl ketone	–	952	40,952	80	–	[22]
Gasoline	90–100	720–785	43	35–210	0	[6]
n-Butanol	96	810	33.1	118	21.6	[31,32]
Diesel	–	800–860	43	160–370	0	[6]

[a] Liquid density.