Energy 89 (2015) 990–1000

Contents lists available at ScienceDirect

Energy

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

Comparison of the predominantly premixed charge compression ignition and the dual fuel modes of operation with biogas and diesel as fuels

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ARTICLE INFO

Article history:
Received 16 September 2014
Received in revised form
20 April 2015
Accepted 11 June 2015
Available online 16 July 2015

Keywords:
HCCI engine
Biogas diesel HCCI engine
Dual fuel engine
Biogas diesel dual fuel engine
Alternative engine fuels

ABSTRACT

The biogas diesel PPCCI (predominantly premixed charge compression ignition) mode where in biogas was inducted with air and diesel was injected into the cylinder using a common rail system was investigated. The injection timing of diesel which was in the range 55–70 °BTDC was found to be very influential as it affected combustion rate and phasing significantly. Though the best intake charge temperatures needed were in the range of 50–90 °C for best performance, operation even without charge heating was possible. For best performance about 80% of the total energy had to be supplied by biogas. At the best condition the thermal efficiency of the biogas diesel PPCCI mode was better than the biogas diesel DF (dual fuel) mode. HC (hydrocarbon) and NOx (nitric oxides) levels were in general significantly lower than the DF mode. The limited range of BMEPs (brake mean effective pressures) (2–4 bar) can be extended by combining the PPCCI mode with the normal diesel mode at low BMEPs and with the DF mode at high BMEPs. Thus PPCCI mode is an option for operating a diesel engine using biogas as the main fuel with low exhaust emissions.

1. Introduction

Biogas is a renewable fuel which can be produced by anaerobic digestion of organic matter like cow dung, kitchen food wastes, municipal wastes and agricultural wastes. Biogas mainly contains CH_4 (methane) about 60% and CO_2 (carbon dioxide) about 40%. The typical properties of biogas are listed in Table 1. It is an attractive fuel for decentralized power generation. Large community waste treatment plants are often used to produce biogas in sufficient quantities to run engine based electrical generator sets. Generally these plants use two kinds of prime movers for such applications namely, SI (spark ignition) engines and dual fuel engines.

In the case of SI engines, biogas can be used as the sole fuel. However, its low flame speed and poor flammability limits lead to inferior performance as compared to conventional fuels. The high level of CO_2 is the reason for these problems. Another method to use biogas is the dual fuel mode. Here biogas is inducted and compressed along with air in a conventional diesel engine. However, since it has a high self ignition temperature a small amount of diesel called the pilot is injected like in a diesel engine. This self ignites and also leads to ignition of the biogas that has been inducted. The main advantage of dual fuel engines is that they can revert to the diesel mode when biogas is not available. The performance of a dual fuel engine is significantly influenced by the type of primary fuel and the quantity of the pilot fuel used [1–6]. A study of the performance of biogas based SI and dual fuel engines of similar capacities indicate that the thermal efficiencies are comparable. Biogas has a relatively high amount of CO_2 which lowers the flame speed. Thus in the case of spark ignition engines and biogas diesel dual fuel engines the thermal efficiency is generally lower than gasoline/neat diesel operation [2]. Though the NOx (nitric oxides) levels are lower in the dual fuel mode the HC (hydrocarbon) levels are higher particularly when significant amounts of biogas are used [3,5].

Another mode of engine operation which has not been extensively explored in the case of biogas is HCCI (homogeneous charge compression ignition). It has been reported that HCCI engines have potential for high efficiency and low emissions. In these engines a nearly homogeneous lean mixture of fuel and air is ignited by compression. Though the mixture is lean, simultaneous

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http://dx.doi.org/10.1016/j.energy.2015.06.033
0360-5442/

Table 1
Typical properties and composition of biogas [2–4].

Composition (%)	Methane (CH_4) = 50–70 Carbon dioxide (CO_2) = 25–50 Hydrogen (H_2) = 1–5 Nitrogen (N_2) = 0.3–3
Auto ignition temperature (°C)	650
Calorific value (MJ/kg)	17
Density at 1 atm and 15 °C (kg/m^3)	1.2
Flame speed at atmospheric pressure and temperature for $\phi = 1$ (m/s)	0.25
Flammability limits (vol% in air)	7.5–14
Stoichiometeric air–fuel ratio (kg of air/kg of fuel)	5.7
Research octane number	130

combustion that occurs at several locations leads to high heat release rates with the potential to offer superior thermal efficiency. The lean mixture and resulting low temperatures also lead to ultra low NOx levels [7]. However, combustion control (achieving proper combustion phasing and combustion rate without misfire) is difficult in these engines. Several variables affect combustion in HCCI engines and often complex control strategies are required. The range of operating BMEP (brake mean effective pressures) is also limited in these engines due to high combustion rates on one side and misfiring on the other [7,8]. Biogas diesel HCCI operation allows higher loads to be attained than the diesel HCCI mode. Normally diesel fuelled HCCI operation results in advanced combustion that leads to low thermal efficiency. However, in the case of biogas diesel HCCI the CO_2 in biogas retards the combustion process and leads to better combustion phasing. Hence, biogas diesel HCCI operation results in higher thermal efficiency. However, the limited work that has been reported has only focused on injecting diesel into the intake manifold using a mechanical injection system along with biogas and air for HCCI operation. Though performance superior to the normal dual fuel mode has been demonstrated, this mode of operation needs high intake charge temperatures, results in high levels of HC emissions and lubricating oil dilution [9].

Resorting to early direct in-cylinder injection of diesel with a common rail injection system while biogas is inducted along with air could solve some of the problems related to manifold injection of diesel along with biogas. In this case the injection parameters can be adjusted based on the operating condition for proper combustion phasing. Using in-cylinder injection of diesel will also allow change over to biogas-diesel dual fuel or neat diesel operation when required. Such change over to other modes of operation is essential because the HCCI mode does not have sufficient load range but offers significant advantages otherwise. However, literature indicates that biogas HCCI operation with in-cylinder injection of diesel has not been explored in detail. Thus this experimental work aims assessing the potential of this method and comparing it with dual fuel operation under similar conditions.

2. Background

Early studies on HCCI engines have been with manifold injection of diesel. High intake charge temperatures are needed in this case to vaporize the diesel in order to mix it with air effectively. The low self ignition temperature of diesel leads to early combustion and thus thermal efficiency is generally lower than conventional diesel engines. Extremely low levels of NO_X (nitric oxides) and PM (particulate matter) emissions are obtained [10]. Further, the concentrations of HC and CO (carbon monoxide) emissions are high because of low in-cylinder and exhaust temperatures which prevent oxidization of these pollutants [9,11]. This method also leads to dilution of the lubricating oil by diesel because of wall wetting and poor vapourization of diesel [11,14]. More recent studies have only used in-cylinder injection of diesel with common rail systems. Multiple pulse injection strategies have been often employed to create a near homogeneous mixture with one of the injection pulses occurring very early in the compression stroke [12–15]. In a turbocharged engine with multi-pulse injection an IMEP of about 9 bar has been reached with diesel at normal intake temperatures [14]. Under naturally aspirated conditions the maximum IMEP reached is of the order of 4 bar [15]. The levels of NO_X emissions are extremely low but high levels of HC, CO and PM emissions are common. Early injection also leads to impingement of the diesel on the cylinder walls particularly at high BMEPs [11,14,15]. Too advanced combustion and inability to attain high BMEPs are problems which still need attention. Adding fuels that have a high self ignition temperature like hydrogen and biogas to the charge have been effective in delaying the combustion process and improving thermal efficiency [16–18].

Natural gas which is a widely used alternative fuel has also been investigated in the HCCI mode. Pure natural gas HCCI engines require high ICT (intake charge temperatures) in the range of 110–180 °C based on the operating compression ratios and turbocharging [19–21]. This is because of the high auto-ignition temperature of methane which is the main constituent of natural gas [19,21]. The operating range of BMEPs in the range of 1–5.5 bar in the naturally aspirated mode and 6–9.5 bar in the turbocharged mode have been reported with natural gas HCCI operation [20]. EGR (exhaust gas recirculation) has been found to reduce knocking and peak pressures in natural gas HCCI engines [22]. Addition of small amounts of hydrogen to natural gas improved ignition and lowered the ICT that was required. Hydrogen contributes H atoms that are expected to improve the auto-ignition of methane [23]. In-cylinder injection of small amounts of diesel, very early in the compression stroke (about 120 °BTDC) was effective in lowering the ICT with natural gas [24]. Experiments with small amounts of diesel (2–3% on the energy basis) being injected at about 60 °BTDC in a turbocharged diesel engine revealed that HC emissions can be significantly reduced by using hot EGR [25].

Biogas which typically contains about 60% CH_4 and 40% CO_2 has been used in HCCI engines with intake charge heating. Intake charge temperatures in the range 200–250 °C is needed to sustain combustion of biogas [26]. In a turbocharged engine while using a compression ratio of 17:1 an ICT of about 200 °C was needed and the maximum IMEP that could be reached was 7.4 bar [27]. DEE (diethyl ether) has been used as an ignition enhancer with biogas for operation in the HCCI mode. In this case combustion was attainable without intake heating [28]. When diesel was introduced into the intake manifold along with biogas for HCCI operation the ICT needed was in the range 80–135 °C. The maximum amount of energy that could be derived from biogas was about 70% and the maximum BMEP was 4 bar. This method of operation was better than the dual fuel mode in terms of thermal efficiency and emissions [5]. The HC level in the HCCI mode was lower than the dual fuel mode only at low BMEPs. Wall wetting of diesel when injected into the intake manifold that leads to high lubricating oil dilution and the need for high intake charge temperatures were the problems that needed attention [9,18]. Thus strategies to further extend the load range, reduce intake charge temperatures, lower the HC levels and wall wetting of the injected diesel are needed. In this respect the flexibility that common rail diesel injection systems offer can be exploited to improve biogas-diesel HCCI operation.