Bioresource Technology 100 (2009) 6624–6629

Contents lists available at ScienceDirect

Bioresource Technology

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

Effects of mixing system and pilot fuel quality on diesel–biogas dual fuel engine performance

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ARTICLE INFO

Article history:
Received 5 December 2008
Received in revised form 17 July 2009
Accepted 17 July 2009
Available online 14 August 2009

Keywords:
Dual fuel engine
Biogas
Biodiesel
Mixing system
Pilot fuel quality

ABSTRACT

This paper describes results obtained from CI engine performance running on dual fuel mode at fixed engine speed and four loads, varying the mixing system and pilot fuel quality, associated with fuel composition and cetane number. The experiments were carried out on a power generation diesel engine at 1500 m above sea level, with simulated biogas (60% CH_4–40% CO_2) as primary fuel, and diesel and palm oil biodiesel as pilot fuels. Dual fuel engine performance using a naturally aspirated mixing system and diesel as pilot fuel was compared with engine performance attained with a supercharged mixing system and biodiesel as pilot fuel. For all loads evaluated, was possible to achieve full diesel substitution using biogas and biodiesel as power sources. Using the supercharged mixing system combined with biodiesel as pilot fuel, thermal efficiency and substitution of pilot fuel were increased, whereas methane and carbon monoxide emissions were reduced.

1. Introduction

Biogas is a renewable fuel produced by anaerobic fermentation of organic material. It can be produced from animal manure waste, waste water and solid waste. Its composition varies with the source, but usually it has 50–70% CH_4, 25–50% CO_2, 1–5% H_2, 0.3–3% N_2 and traces of H_2S. In countries with poor fossil energy supplies, biogas is of special interest because it is a renewable fuel. A common alternative for biogas utilization are CI engines converted to dual fuel mode for stationary use.

Dual fuel CI engines introduce a premixed air–gaseous fuel mixture, which is ignited at the final stage of the compression stroke by a liquid fuel injection (pilot fuel) with good ignition properties. Induction of gaseous fuel, called primary fuel, reduces the consumption of diesel (substitution level) for power generation, which increases the premixed combustion and decreases NOx and PM emissions related to diesel engine operation. However, when a dual fuel engine operates at part load with high substitution levels, the thermal efficiency is lower than in diesel engines and CO and UHC emissions are increased.

Negative effects of part load and high substitution levels on dual fuel engine performance are a result of the ignition delay increase and poor flame propagation of the air–gaseous fuel mixture, which in these conditions is closer to the lower flammability limit (Badr et al., 1999). Karim (1980) presented several strategies for improving dual fuel operation at part load that have been researched and published by various authors. Among these are the use of low substitution levels (Abd Alla et al., 2000; Papagiannakis and Hountalas, 2003), modification of the pilot fuel injection factors (Abd Alla et al., 2002; Selim, 2004; Nwafor, 2007), preheating of inducted air–fuel mixtures (Poonia et al., 1999; Abd Alla et al., 2001), increase in rich inducted mixture by air throttling (Kubesh and Brehob, 1992; Poonia et al., 1998), modification of temperature and charge composition with controlled exhaust gas recirculation (Wong and Karim, 1996; Selim, 2003; Pirouzpanah et al., 2007), direct injection of gas into the combustion chamber (Hill and Douville, 2000; Carlucci et al., 2008) and using gaseous fuels with high burning rates (Masood and Ishrat, 2008; Saravanan et al., 2008). Quality of injected pilot fuel is another factor that has an effect on dual fuel engine performance, since composition and cetane number of liquid fuels affect ignition delay period and premixed combustion duration (Gunea et al., 1998). Some results suggest that biodiesel and vegetable oils as pilot fuels can improve engine performance (Nwafor, 2000; Kumar et al., 2001; Selim et al., 2008), nevertheless their use in dual technology has not been documented extensively.

The presence of inert gases such as CO_2 and N_2 in the primary fuel increases the negative effects at part load operation due to its influence in burning rate inhibition (Abd Alla et al., 2001; Kobayashi et al., 2007). Some investigations have evaluated the use of biogas in dual fuel engine performance (Henham and Makkar, 1998; Bilcan et al., 2003; Bedoya et al., 2007; Duc and Wattanavichien, 2007; Tippayawong et al., 2007), but the available information about strategies to improve part load operation in these dual systems is still limited. In this study, the results of CI

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doi:10.1016/j.biortech.2009.07.052

Nomenclature

CI	compression ignition	LHV_P	pilot low heating value (kJ/kg)
DI	direct injection	ϕ	total fuel air equivalence ratio
PM	particulate matter	ϕ_b	biogas fuel air equivalence ratio
UHC	unburned hydrocarbon	AFR_B	stoichiometric air fuel ratio of biogas
EGR	exhaust gas recirculation	AFR_P	stoichiometric air fuel ratio of pilot fuel
BTDC	before top dead center	η_v	overall volumetric efficiency
ATDC	after top dead center	ρ_a	air density (kg/m^3)
TDC	top dead center	$\rho_{a,B}$	mixing air–biogas density (kg/m^3)
NDIR	non-dispersive infrared	V_d	engine displacement (m^3)
SM1	dual fuel system with natural aspiration and diesel as pilot fuel	n	engine speed (rpm)
SM2	dual fuel system with supercharged aspiration and biodiesel as pilot fuel	°CA	crank angle (°)
Z	substitution level (%)	θ_R	ignition delay (°CA)
$\dot{m}_P$	pilot mass flow rate (kg/s)	θ_I	crank angle at ignition (°CA BTDC)
$\dot{m}_D$	diesel mass flow rate in diesel mode (kg/s)	θ_{INY}	crank angle at injection (°CA BTDC)
$\dot{m}_B$	biogas mass flow rate (kg/s)	$dP/d\theta$	first in-cylinder derivative pressure related to crank angle (bar/°CA)
$\dot{m}_a$	air mass flow rate (kg/s)	$dQ/d\theta$	total heat release rate related to crank angle (J/°CA)
N_E	electric power output (kW)	T_a	air inlet temperature (°C)
η_E	thermal efficiency (%)	T_g	exhaust gas temperature (°C)
LHV_B	biogas low heating value (kJ/kg)		

engine in dual fuel mode for power generation using biogas and varying mixing system and pilot fuel quality are discussed. Air inlet pressure and temperature, mixer type and mixing length were modified to improve thermal efficiency at part load. Palm oil biodiesel was utilized as pilot fuel to achieve full diesel substitution. Engine performance under these conditions was compared in regards to alternative operation with conventional mixing system and diesel as pilot fuel.

2. Methods

2.1. Test system

A stationary CI engine was coupled with a generator for operating in Medellín city (1500 m above sea level). A generator was selected to run at maximum torque speed (1800 rpm). Table 1 shows technical engine characteristics.

Engine loads were fixed with a variable electrical resistance bank from 3 to 10 kW connected to the generator and power output was dissipated as heat. In the dual fuel mode, Colombian commercial diesel and palm oil biodiesel were used as pilot fuels. Biogas was simulated with a typical composition of 60% CH_4 and 40% CO_2, on a volumetric basis. Table 2 summarizes important properties of fuels utilized in the experimental procedure.

The flow rate of biogas and air were both measured with hot wire sensors (FM 5400, Omega Engineering Inc.) and the flow rate of pilot fuel was measured with coriolis sensor (MASS 2100, Siemens A.G.). Exhaust gas composition in dry basis was measured with NDIR principle (MAIHAK 610, Sick Maihak Inc.) for CH_4, CO_2 and CO, and electro-chemical principle was used for O_2. Cylinder pressure was recorded with a piezoelectric transducer (KISTLER 6121, Kistler Instrument A.G.) and crank angle position was measured using an incremental encoder with resolution of 1024 pulses per revolution (ROD 426, Heidenhain Corporation). Combustion diagnosis was carried out with a cero dimensional one zone model (Heywood, 1988) after obtaining the average pressure signal from 600 engine cycles. The number of cycles recorded was according to results reported about cyclic variability in dual fuel engines (Selim, 2005). The pilot fuel injection pressure was recorded using a piezoelectric transducer (AVL 41DP, AVL Inc.), which was mounted between injection pump and injector.

Table 1
Diesel engine characteristics.

Engine type	Lister Petter TR2, DI, four stroke, two cylinders, naturally aspirated, air cooled
Displacement	1550 cm^3
Bore × stroke	98 × 101 mm
Compression ratio	15.5:1
Rated power	20 kW at 3000 rpm
Maximum torque	76 N m at 1800 rpm
Inlet valve open	36° BTDC
Exhaust valve close	32° ATDC

Table 2
Fuel properties.

Property	Diesel	Palm oil biodiesel	Biogas
API gravity at 60 °F	31.9	31.2	–
Low heating value (MJ/kg)	43	39.55	23.73
Cetane number	44	57	–
Viscosity at 40 °C (cSt)	4.66	4.67	–
Cloud point (°C)	1	18	–
Simplified chemical composition	$C_{10.8}H_{18.7}$	$C_{19.7}H_{36.9}O_2$	60% CH_4 + 40% CO_2 (by volume)
Stoichiometric air fuel ratio (AFR)	14.32	12.55	6.05
Lower Woobe index (kW h/N m^3)	–	–	6.16
Methane number	–	–	160

Signals of flow rate of fuels and air were recorded on a personal computer, as well as signal pressure in the cylinder and the injection system related to crank angle position. The acquisition card could collect data at a rate of 250 kHz, with a resolution of 16 bits. In Fig. 1, the experimental setup is shown.

2.2. Experimental procedure

In the first experimental phase, the maximum substitution level that allowed stable engine operation at part load was determined. Experimentally, at local environmental conditions, electric power