Fuel 232 (2018) 743–754

Contents lists available at ScienceDirect

Fuel

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

Full Length Article

Role of global fuel-air equivalence ratio and preheating on the behaviour of a biogas driven dual fuel diesel engine

Achinta Sarkar, Ujjwal K. Saha*

Department of Mechanical Engineering, Indian Institute of Technology Guwahati, Guwahati 781039, India

ARTICLE INFO

Keywords:
Diesel engines
Dual fuel engines
Biogas
Preheating
Global fuel-air equivalence ratio
Performance
Combustion
Emissions

ABSTRACT

The practice of the green renewable fuels in diesel engines is increasing concerning the progressive deterioration of the green environment and the scarcity of the fossil fuels. In these aspects, several experiments in dual fuel mode (DFM) at different global fuel–air equivalence ratio (Φ_{global}), intake charge preheating and loads have been carried out considering biogas as the inducted renewable fuel. The Φ_{global} was varied from 0.30 to 0.89 from part to higher loads with biogas flow rate (BFR) of 0.67–3.99 kg/h. The maximum diesel replacements (DR) and biogas energy share (BES) are found to be 92.49% and 97.55%, respectively. However, at higher Φ_{global}, the brake thermal efficiency (BTE) reduces drastically. Although with preheating, there is an increment of BTE by 5.72% and 2.60% at loads of 4.36 N·m and 21.78 N·m, respectively. At lower Φ_{global} in DFM and with preheating, the diesel like trends of BTE is achieved. Overall combustion behaviour deteriorates at higher Φ_{global}. However, it significantly improved with the preheating and at controlled Φ_{global}. Higher cycle-to-cycle variation of cylinder peak pressure (CPP) is noticed at higher Φ_{global}. With preheating, at part and higher loads the reduction of CO of 29.41% and 65.49% are estimated. At higher load (21.78 N·m) and with preheating a reduction of 53.33% of HC is noticed. The drastic reduction of NO_x is observed with the increment of Φ_{global}. The superior performance is achieved at each of the tested loads at the optimum Φ_{global} and with preheating.

1. Introduction

Explosion of population and decoration of modern lifestyle are accelerating use of the high-grade energy. As a consequence, there is a rapid depletion of fossil reserves and detrimental pollutant emissions. This led many countries to impose intrinsic emissions regulations, and therefore, researchers over the globe are searching an alternative way to mitigate these teething troubles. Literature demonstrated that the best alternative way would be the use of clean green renewable fuels. In recent times, power production in the field of internal combustion engines grab the biomass in the form of liquid or gaseous fuels as the alternative source of energy. Among different biofuels, biogas has become the most attractive one as it is found feasible and economical [1–3] to use in diesel engine under dual fuel mode (DFM). Biogas further has high potentiality [4] to produce from different industrial and biological feedstock by anaerobic digestion. It is primarily composed of 40%–60% methane (CH_4) and 40%–60% carbon dioxide (CO_2) by volume [5,6]. The composition of biogas attributes that it has a relatively lower calorific value because of its lower methane fraction in contrast to methane enriched gaseous fuels. As compared to diesel fuel, biogas also has a very high self-ignition temperature (632–813 °C), higher flammability limits, and lower flame speed (Table 1 [5,7–13]). Use of this kind of fuels in diesel engines under DFM means unstable combustion in relation to cycle-to-cycle variations, lower release of heat, lower cylinder peak pressure (CPP) development and higher pollutant emissions. Most of the researches reported that the dual fuel engine performance degraded at part loads. Several ways to improve the dual fuel engine performance at part load has been unveiled by Karim [14] and at a later stage, reported in open literature. The most important techniques that have been employed to improve the dual fuel engine performance are the lower pilot fuel substitution at lower loads [15,16], advancement of injection timing [17–19], preheating of intake charge [20,21], injection of gaseous fuel inside the engine cylinder [22,23], controlled exhaust gas recirculation [24,25] and use of highly flammable gaseous fuels [26–28]. However, these methods in dual fuel engines using raw biogas as the primary fuel are limited.

Duc and Wattanavichien [29] conducted experiments on a biogas run dual fuel diesel engine at different engine speeds and loads. They observed smooth engine operation with biogas in DFM. However, the investigators found lower energy conversion at lower loads in contrast to higher loads, and observed that the higher unburned hydrocarbon emission is the consequence of lower energy conversion of biogas.

---

* Corresponding author.
E-mail address: saha@iitg.ernet.in (U.K. Saha).

https://doi.org/10.1016/j.fuel.2018.06.016
Received 5 March 2018; Received in revised form 19 May 2018; Accepted 6 June 2018

Nomenclature

Notations

$C_{12}H_{26}$	diesel
CO	carbon monoxide (vol.%)
CO_2	carbon dioxide (vol.%)
HC	hydrocarbon (ppm)
N_2	nitrogen molecule
NO_x	oxides of nitrogen (ppm)
x	mole fraction of CH_4 in biogas
y	mole fraction of CO_2 in biogas
Φ_{global}	global fuel–air equivalence ratio

Abbreviations

AFR	air–fuel ratio
BES	biogas energy share (%)
BFR	biogas flow rate (kg/h)
BTE	brake thermal efficiency (%)
CD	combustion duration (°CA)
CMGT	CMean gas temperature (K)
CPP	cylinder peak pressure (bar)
CR	compression ratio
DFM	dual fuel mode
DR	diesel replacements (%)
EOC	end of combustion (°CA)
GC	gas chromatography
ID	ignition delay (°CA)
IT	injection timing (°CA)
LHV	lower heating value (kJ/kg)
LPG	liquefied petroleum gas
NHRR	net heat release rate (J/°CA)
PDM	pure diesel mode
SOC	start of combustion (°CA)
TDC	top dead centre
VCR	variable compression ratio

Subscripts

a	air
d	diesel
pd	pilot diesel
g	global
ref	reference

Mustafi et al. [30] in their review work disclosed the various research gaps with the use of biogas as the promising green fuel in diesel engines. In a numerical work with biogas as the fuel, Bedoya [31] observed ultra-low emission of oxides of nitrogen (NO_x). Various tests have been done on simulated biogas [32–35] in a DFM engine operation. These investigators mainly worked with different percentages of CH_4 and CO_2 (synthetic biogas) as the primary fuel, various liquid fuels (diesel and biodiesels) as the pilot fuels and oxygen as the combustion improver at different engine loads. All these studies show an improved performance and emission characteristics at higher loads in comparison to part loads. Irrespective to the biogas quality, Cacua et al. [35] found 10% reduction in thermal efficiency at lower load of DFM engine operation. Papagiannakis and Hountalas [36] demonstrated the combustion duration to be higher at part loads and vice versa in a natural gas run dual fuel diesel engine. During the last decade, laboratory level experiments with raw biogas (as primary fuel) and various liquid fuels such as diesel, different biodiesels, emulsified diesel and biodiesels (as the pilot fuel) under various engine loads, compression ratios (CRs) and injection timings (ITs) have been carried out at IIT Guwahati [37–41]. These tests are done based on misfire limits of the biogas inducted inside the cylinder at each of the operating loads to get the maximum pilot fuel replacements. However, with very high replacements (misfire) of pilot fuels there would be a substantial deterioration of DFM engine performance in comparison to pure diesel mode (PDM). The investigators mainly had focused their eye on the higher amount of biogas consumption rather than the variation in equivalence ratios. Besides, most of the researchers noticed the deterioration of engine's overall performance at part loads in comparison to higher loads [34,42,43].

Table 1
Fuels properties used in the present study [5,7–13].

Properties	Diesel	Biogas
Chemical structure	$C_{12}H_{26}$	Approximately (vol.) 60% CH_4, 40% CO2
C (wt%)	84.7	–
H (wt%)	15.3	–
O (wt%)	–	–
Density (kg/m^3), at 32.2 °C	824.91[a]	1.096[a]
Lower heating value (MJ/kg)	42.10[a]	19.1[a]
Cetane number	50	–
Kinematic viscosity (mm^2/s, at 40 °C)	2.54[b]	–
Stoichiometric air–fuel ratio	14.94[a]	6.17[a]
Auto Ignition temperature (°C)	200–220	632–813
Flammability limits (% by volume of air)	1.5–7.6	7.5–14
Flame speed (m/s)	0.86	0.25

[a] Calculated.
[b] Measured.

As evident from the above discussion, there is no comprehensive and satisfactory study that reports the effects of Φ_{global} and intake charge preheating on the performance, combustion, and emission characteristics of a biogas run DFM engine. In DFM, the fuels used have different phases and characteristics such as calorific value, cetane number and auto-ignition temperature. Moreover, as biogas as a fuel has very high self-ignition temperature as compared to pure diesel (Table 1), therefore, the Φ_{global} together with intake charge preheating will have a greater impacts on the engine's overall performance. In these aspects, a subterranean study on the optimization of Φ_{global} from part to higher loads on a biogas run DFM engine using diesel as the pilot fuel. The other aim is to explore the behaviour of the biogas DFM engine at the optimized Φ_{global} with intake charge preheating. The available literature in DFM engines demonstrates the improvement in the combustion behaviour with intake charge preheating, however, this preheating of intake charge hitherto have been limited to natural gas and liquefied petroleum gas (LPG) only [20,44–46]. In this investigation, CO, CO_2, HC, and NO_x are considered as the parameters to study the emission characteristics of the DFM engine. The study, as a whole, aims at the state-of-the-art investigation of a biogas run DFM engine with Φ_{global} as the main parameter and intake charge preheating as the combustion augmenter.

2. Experimental setup and procedure

The investigation has been carried out in a four-stroke, single-cylinder, water-cooled, direct injection (DI), naturally aspirated, variable compression ratio (VCR) diesel engine (Kirloskar, TV1). An eddy current water-cooled dynamometer (Saj Test Plant, AG10) is coupled with the engine as the loading unit to measure the engine load in kg. The engine has the facility to vary the CR with the help of the tilting block