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# Effects of varying composition of biogas on performance and emission characteristics of compression ignition engine using exergy analysis

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ABSTRACT

Growing energy demands and environmental degradation with uncontrolled exploitation of fossil fuels have compelled the world to look for the alternatives. In this context, biogas is a promising candidate, which can easily be utilized in IC engines for vehicular as well as decentralized power generation applications. Primary constituents of raw biogas are methane ($CH_4$) that defines its heating value, and carbon dioxide ($CO_2$) that acts like a diluent. This dilution effect reduces the flame speed and heating value of biogas, eventually deteriorating the engine performances. Present article focuses on experimental evaluation and quantification of these variations of the engine performance. Three compositions of biogas: BG93, BG84 and BG75 (containing 93%, 84% and 75% of $CH_4$ by volume respectively) were studied on a small CI engine in dual fuel mode. Moreover, to evaluate individual process inefficiencies, exergy analysis based on second-law of thermodynamics is implemented. Exergy balances for different compositions of biogas are presented. Biogas dual fuel operation showed 80–90% diesel substitution at lower engine loads. At higher loads, total irreversibility of the engine was increased from 59.56% for diesel operation to 61.44%, 64.18% and 64.64% for BG93, BG84 and BG75 biogas compositions respectively. Furthermore, combustion irreversibility was found to be decreasing with higher $CO_2$ concentrations in biogas. BG93 showed comparable results to that of diesel operation with 26.9% and 27.4% second-law efficiencies respectively.



## 1. Introduction

Development and dissemination of renewable energy technologies have gained international recognition. In this endeavor, replacement of fossil fuels for transportation by alternative renewable fuels could be a significant contributor to the sustainable development. In this context, biogas has been identified as a potential alternative fuel for vehicular as well as for decentralized power generation applications [1–3]. Biogas has very high auto ignition temperature, therefore, it cannot completely substitute diesel fuel in compression ignition (CI) engines; nevertheless, it can provide major energy share for engine operation [4,5]. Tippayawong et al. [6] studied performance and long-term durability of biogas-diesel dual fuel engine for electricity generation. They found that 90% substitution of diesel by mass is possible with biogas and durability test of 2000 h did not show any major sign of engine deterioration. Successful operation of biogas dual fuel engine for the entire range of engine loads and speeds has also been reported by Duc and Wattanavichien [5]. However, dual fuel operation with biogas as main fuel and diesel as pilot fuel showed significantly lower conversion efficiency, particularly at lower loads. It was also reported that conversion efficiency was improved with increase in engine loads. Another comprehensive study focused on production and utilization of biogas in a small direct injection (DI) diesel engine was performed by Barik and Murugan [7]. Biogas produced with pongamia pinnata de-oiled cakes and cow dung as feed stocks showed 73% methane concentration by volume (17.37% carbon dioxide). Furthermore, utilizing this biogas is dual fuel mode resulted in 39% and 49% decrease in nitric oxides ($NO_x$) and smoke emissions respectively compared to base diesel operation of the engine. It's necessary to mention that above benefits were associated with some penalties in energy efficiency and emissions. 6.2% drop in thermal efficiency with 17% and 30% increase in carbon monoxide (CO) and hydrocarbon (HC) emissions were observed in dual fuel mode at full load condition. In the recent years, various studies have been conducted to improve the performance and emission characteristics of biogas dual fuel engines. Barik and Murugan [8] have investigated the advanced pilot fuel injecting timing technique and found encouraging results. Advanced

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**Nomenclature**

*Abbreviations*

| | |
|---|---|
| AFR | air to fuel ratio |
| BDC | bottom dead center |
| BMEP | brake mean effective pressure |
| BP | brake power |
| BSFC | brake specific fuel consumption |
| CI | compression ignition |
| CO | carbon monoxide |
| $CO_2$ | carbon dioxide |
| CNG | compressed natural gas |
| CR | compression ratio |
| DS | diesel substitution |
| EGR | exhaust gas recirculation |
| EGT | exhaust gas temperature |
| EPC | exergetic performance coefficient |
| HC | hydrocarbon |
| HCCI | homogeneous charge compression ignition |
| LHV | lower heating value |
| $NO_x$ | oxides of nitrogen |
| TDC | top dead center |

*Symbols*

| | |
|---|---|
| Cp | specific heat at constant pressure (J/kg K) |
| e | specific exergy (J/kg) |
| I | irreversibility (J) |
| $\dot{m}$ | mass flow rate (kg/s) |
| N | speed (rpm) |
| P | absolute pressure (Pa) |
| Q | heat (J) |
| R | specific gas constant (J/kg K) |
| $\bar{R}$ | universal gas constant (J/mole K) |
| S | entropy (J/K) |
| s | specific entropy (J/kg K) |
| T | absolute temperature (K) |
| $T_e$ | engine torque (N-m) |
| X | exergy or Availability (J) |
| x | mole fraction |

*Subscripts*

| | |
|---|---|
| 1 | initial state |
| 2 | final state |
| I | first-law |
| II | second-law |
| BG | biogas |
| ch | chemical |
| comb | combustion |
| D | diesel fuel/diesel mode |
| DF | duel fuel mode |
| des | destruction |
| gen | generation |
| in | incoming |
| i, j | arbitrary number/species |
| k | instantaneous in-cylinder condition |
| loss | heat loss from engine |
| mix | mixture |
| prod | products |
| Q | heat |
| reac | reactants |
| W | work |
| w | wall |
| un | unaccounted |

*Superscripts*

| | |
|---|---|
| 0 | reference state |

*Greek symbols*

| | |
|---|---|
| $\theta$ | crank angle |
| $\eta$ | efficiency |
| $\pi$ | Pi |

injection timing of 26 degree before top dead center (°BTDC) showed optimum results in terms of both performance and emission against the standard injection timing of 23 °BTDC. At this injection timing and full load condition, brake thermal efficiency was increased by 4.7%, and CO and HC emissions were reduced by 19% and 23% respectively. In another study, Ibrahim et al. [9] have suggested predominantly premixed charge compression ignition (PPCCI) mode of combustion to improve the performance of biogas dual fuel engines. This technique is achieved by very early injection of diesel (55–70 °BTDC), which allow for more homogeneous mixture formation and therefore better combustion efficiency. However, this technique showed limited range of operation (2–4 bar of BMEP) due to onset of knocking. Studies have also been conducted to explore the feasibility of using biodiesel-biogas dual fuel CI engines as a rural energy option. An experimental investigation utilizing pure Jatropha oil and biogas in dual fuel mode was performed by Luijten and Kerkhof [10]. It was found that in dual fuel mode, thermal efficiency at higher loads are comparable (slightly low) to diesel only mode, however, at low load, 10% decrease in thermal efficiency was observed. Similarly, Bora et al. [11] conducted experimental investigations on rice bran biodiesel-biogas dual fuel operation on 3.5 kW VCR engine with varying compression ratios (CR) of 17 to 18. It was found that at higher CRs, both performance and emission characteristics of dual fuel operation were improved.

Although biogas has many advantages, its utilization presents many technical challenges as well, such as, slow production rate, corrosive substances, low calorific value and cleaning requirements. Biogas from an anaerobic digester is typically composed of methane ($CH_4$), carbon dioxide ($CO_2$), nitrogen ($N_2$) and small traces of hydrogen sulfide ($H_2S$), hydrogen ($H_2$) and oxygen ($O_2$). Although very small in fraction, $H_2S$ and water vapors have shown corrosive effects, and many technologies have been proposed for their removal [12,13]. Apart from these constituents, high concentration of $CO_2$ in raw biogas reduces its calorific value and flame speed, causing the decrease in thermal efficiency of the engines [4,5,7,11]. Moreover, removal of $CO_2$ from biogas is both time and cost consuming process and requires substantial amount of energy. Bearing this in mind, Henham et al. [14] studied performance of diesel engine with changes in $CH_4$:$CO_2$ ratios. It was found that increase in $CO_2$ concentration in biogas renders decrease in overall efficiency along with the significant increase in CO emissions. It was also found that effects on exhaust gas temperature and CO emissions are more sensitive to gas quantity than its quality ($CO_2$ fraction in biogas). In another study, using simulated biogas (varying the % of $CO_2$ in $CH_4$), Bari [4] tried to examine this effect on performance of dual fuel engine. It was found that up to 20–30% $CO_2$ in biogas improved engine performance, which was reflected as decreased brake specific fuel consumption (BSFC); however, when $CO_2$ % was increased beyond