An Exposition on the Results of Utilizing Biogas as an Alternative Fuel on the Attributes of Internal Combustion Engines

Huirem Neeranjan Singh*‡, Apurba Layek**

*Department of Mechanical Engineering, National Institute of Technology Durgapur, Durgapur-713209, India

**Department of Mechanical Engineering, National Institute of Technology Durgapur, Durgapur-713209, India

(nrjan.h@gmail.com, apurba_layek@yahoo.co.in)

‡ Corresponding Author; Huirem Neeranjan Singh, Department of Mechanical Engineering, National Institute of Technology Durgapur, Durgapur-713209, India, Tel: +91-9774051084,

nrjan.h@gmail.com

Received: 03.05.2019 Accepted:29.06.2019

Abstract- With the depletion of fossil fuels and the ever-growing environmental concerns, biogas as an alternative fuel is gaining popularity. Biogas has the potential to simultaneously solve the crisis of energy shortage and waste management. As a fuel, biogas is carbon dioxide (CO_2) neutral and can withstand engine knock. Several researchers have reported the application of biogas in internal combustion (IC) engine. Studies reveals that existing IC engine may be effortlessly transformed to run on biogas with minor modifications. The study aims to present a comprehensive analysis of the investigations conducted on the characteristics of emission, combustion and performance; of biogas fuelled IC engines. Various aspects of enhancing the emission and performance of biogas fuelled IC engines, viz. optimization of compression ratio, ignition/ injection timing, fuel flow rate, hydrogen supplementation etc. have also been discussed in detail. Comparative evaluation of the emission and performance of biogas powered engine along with other gaseous fuels using exergy analysis is also presented. Experimental finding suggests the use of biogas in dual fuel compression ignition (CI) mode powered by biodiesel or diesel as pilot fuel; as a superior way to realize the resourceful use of biogas. Increase in combustion characteristics has been observed with increase in CH_4 concentration; and compression ratio. Prediction of engine parameters using various techniques like artificial neural network; and multi-objective response optimization of IC engines fuel with biogas, are limited and may be further investigated in future.

Keywords Biogas, dual fuel, performance, combustion, emission, review.

1. Introduction

With the increase in demand and in turn, the prices of the world's fossil fuel, the development of renewable energy has been given a keen interest. There is also a huge concern for the climatic change brought about by the greenhouse gases and pollutants resulting from the combustion of fossil fuel. Bioenergy is considered to be one of the most favourable renewable energy source as it is produced from readily available biodegradable material or biomass [1]. Biogas, one of the bioenergy source, possesses limitless potential as a sustainable renewable source of energy that is economically feasible and environmentally friendly in nature [2], [3]. It is obtained through anaerobic digestion of biomass as shown in Fig.1 [4]–[6]. The composition of biogas varies with feed material, though in general, it is composed primarily of methane (55–75%) and carbon dioxide (30–40%) by volume, along with small percentages of hydrogen and/ or oxygen, nitrogen, and trace quantities of other unwanted impurities such as hydrogen sulphide (H_2S), in addition to volatile organic compounds, sulphide compounds, aromatics, siloxanes and halogens [7].

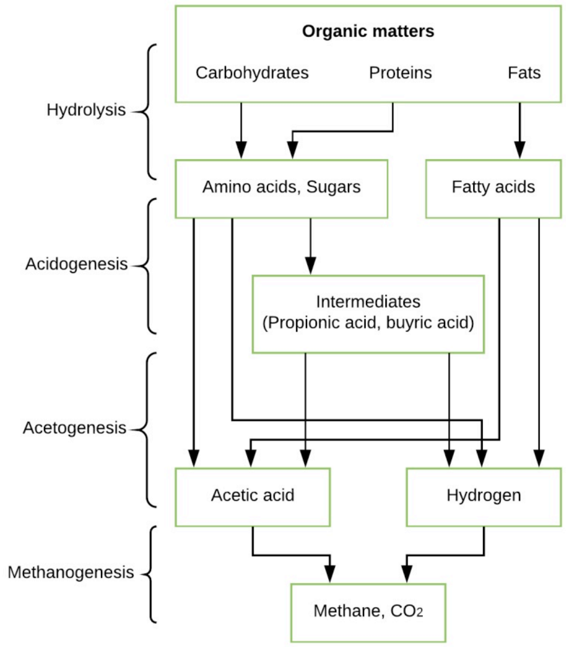

Fig.1. Different stages of anaerobic digestion process [6]

There are certain advantages of using biogas as a fuel, viz. it is a renewable energy source, eco-friendly in nature, comparatively solves waste management problems, the digested are rich manure, and helps in conservation of resources [8]. However, the presence of H_2S may corrode metal parts, and CO_2 presence lowers its flame speed and calorific value. Through purification of gas; prolonged engine life owing to elimination of H_2S, exhaust free of sulphur compounds, enhanced volumetric efficiency and also higher specific output can be obtained. Chemical absorption, cryogenic separation, chemical conversion methods, physical absorption, membrane separation, liquid phase oxidation and dry oxidation processes are some of the methods used for the purification and scrubbing of biogas [9]. The use of biogas as a fuel has been widely studied and reported, specially its application as biofuel in internal combustion (IC) engines, namely spark ignition (SI) engine and compression ignition (CI) engine. Biogas application in IC engines can be effectively achieved with or without minor modification.

Different literatures have reviewed on the combustion characteristics and chemical kinematics of IC engines, gaseous fuel induction in dual fuel mode with diesel or biodiesel in CI engines. This study mainly aims to review the effects of concentration of CO_2 and CH_4, compression ratio, ignition timing in SI engine; and the effects of duel fuelling, biogas flow rate, CH_4 concentration, compression ratio and injection timing in CI engine. It also presented the various experimental investigations reported for the enhancement of combustion characteristics, emission and engine performance of both SI and CI engines, powered by biogas. A comprehensive analysis of the diverse methodologies adopted for the usage of biogas in both the CI and SI engines have been discussed here.

2. Biogas as an Alternate Fuel for IC Engines

Table 1 shows a comparison of the biogas properties and those of other gaseous fuels. Comparatively, the biogas auto ignition temperature is greater than those of natural gas (NG) and liquefied petroleum gas (LPG). When biogas supply is assured, it may be employed in SI engine effectively using a higher compression ratio (CR) engine with magneto ignition and modifying the piston and carburettor system. In CI engine it can be employed efficiently in dual fuel mode with biodiesel or diesel as pilot fuel.

Table 1. Comparison of biogas properties with other gaseous fuel [10].

Property	**LPG**	**Natural gas**	**Hydrogen**	**Biogas**	**Producer gas**
Composition (% volume)	C_3H_8−30% C_4H_{10}−70%	CH_4−85% C_2H_6−7% C_3H_8−2% N_2−1% CO_2−5%	H_2	CH_4−57% CO_2−41% CO−0.18% H_2−0.18%	CO−24.3% H_2−22.6% CH_4−2.2% CO_2−9.3% N_2−41.2%
Lower heating value (MJ/kg)	45.7	50	120	17	5
Density (kg/m^3)	2.26	0.79	0.08	1.2	1.05
Flame speed (cm/s)	44	34	275	25	50
Stoichiometric A/F (kg of air/kg of fuel)	15.5	17.3	34.2	5.8	1.4
Flammability limits (vol.% in air)					
Leaner	2.15	5	4	7.5	7
Richer	9.6	15	75	14	21.6
Octane number					
Research	103−105	120	130	130	100−105
Motor	90−97	120	130	–	–
Auto ignition temperature (°C)	405−450	540	585	650	625

2.1. Biogas as an alternate fuel for SI engines

Being a fuel with a high temperature of self-ignition and high-octane number, biogas can resist knocking and may be effectively employed in SI engines. These engines fuelled by biogas have relatively higher compression ratio than that of petrol counterpart. However, the presence of diluents like carbon dioxide (CO_2), and nitrogen (N_2), affects in-cylinder characteristics of combustion, lowering the flammability limit, calorific value and flame speed [11]. Additionally, increase in diluents percentage aggravate cyclic variation and also lower power output.

Several experimental investigations have been conducted to evaluate the influence of methane and CO_2 concentration in biogas. J. Huang and R. J. Crookes [12], tested the influence of CO_2 present in simulated biogas on SI engine's thermal efficiency, exhaust temperature, power, and emission characteristics. Simulated biogas created through mixing varied compositions of carbon dioxide (0 to 40% by volume) and domestic natural gas were tested for various air to fuel ratios (between the rich and lean operating limit), at varied compression ratios and four different speeds. Test outcomes showed that CO_2 presence decreased the emissions of oxides of Nitrogen (NO_x), but there was a reduction in thermal efficiency and engine power; and also, un-burnt hydrocarbons (HC) level increased with increase in CO_2 percentage as shown in Fig. 2. The study indicated that increasing compression ratio can improve the performance of biogas powered SI engine under CO_2 presence but however in general, it would result in increase in both NO_x and HC emissions. Inversely, E. Porpatham et al. [13], conducted experiment evaluating the influences of enhancing concentration of methane (CH_4) in biogas through CO_2 removal using limewater scrubber, on the emissions, performance and combustion of SI engine. Notable improvement in performance and reduction in hydrocarbons emissions could be achieved with CO_2 level reduction (from 41% in biogas to 30% and 20%) in biogas especially at lean mixtures. The optimal equivalence ratio was found to be between 0.8 and 0.95 when CO_2 was removed from biogas and the operation of the engine with lean air-fuel mixtures. A small reduction in CO_2 level from normal 30 - 40% yielded notable reduction in HC emission without almost negligible rise in NO level.

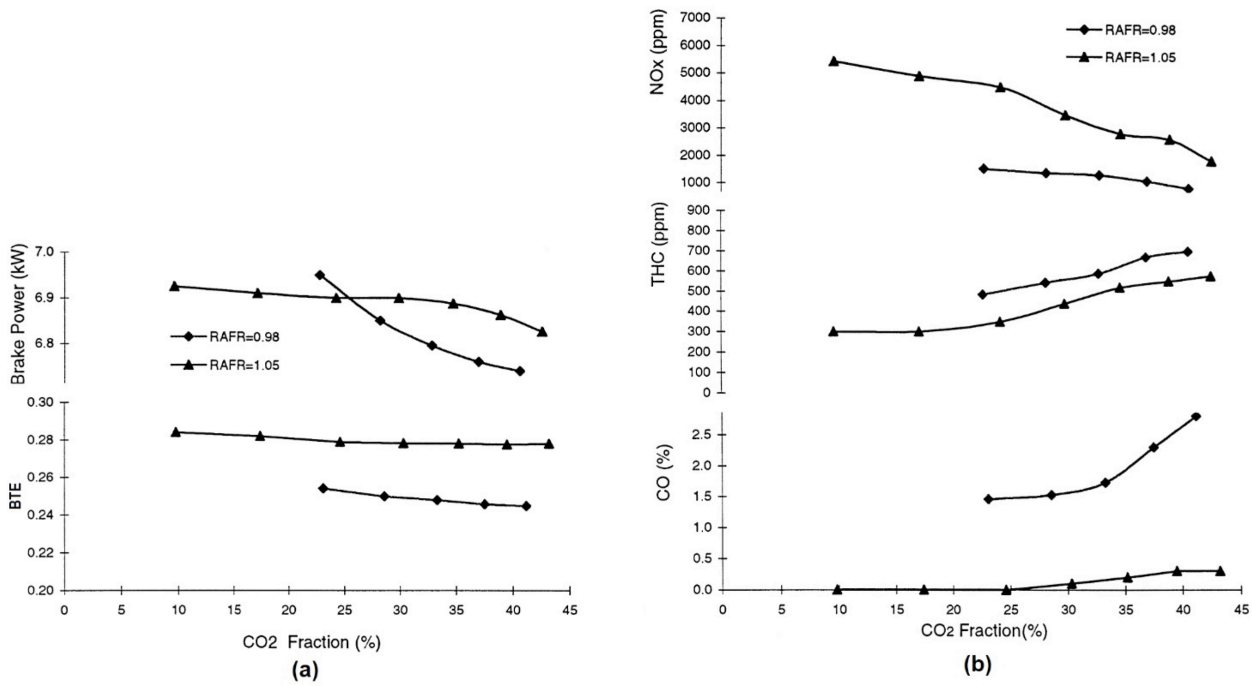

Fig. 2. Variation of **(a)** BTE and brake power; **(b)** exhaust gas emissions with CO_2 fraction in mixture at CR = 13 and speed = 2000 rpm for rich and lean settings [12]

The presence of CO_2 has a substantial influence on the characteristics of combustion of biogas fuelled SI engines and thereby affecting its performance and emissions. As a way of overcoming these drawbacks, addition of hydrogen (H_2) gas; a well-known combustion enhancer, have been considered by many researchers. E. Porpatham et al. [14], investigated the consequence of addition of hydrogen to the combustion and performance of a biogas fuelled SI engines. Test results indicated that hydrogen introduced to biogas in trace quantities (15%, 10% and 5% on the basis of energy) improves brake power, brake thermal efficiency, rate of combustion and increases biogas lean limit of combustion. Hydrocarbon emission levels were reduced. The addition of H_2 and with the delay of ignition timing to avert knocking, the peak pressure and heat released rates were lowered. Overall, addition of 10% hydrogen was optimal. C. Park et al. [15] experimentally investigated an SI engine fuelled by simulated-biogas composed of varied concentrations of methane with respect to its combustion characteristics, thermal efficiency and emissions. Two sets of tests were conducted viz. the addition of hydrogen (H_2) and dilution of nitrogen (N_2) tests. The dilution of N_2 test results show enhancement in thermal efficiency and reduction in NO_x emission with increase in inert gas in biogas but at the same time aggravating total hydrocarbons (THC) emissions and cyclic variations. H_2 added for improving the stability of combustion for the fuel of least energy density (case of dilution of inert gas by 80%), shows improvement in-cylinder characteristics of combustion, tumbling the emissions of THC as well as increasing lean operating limit, on the other hand plummeting NO_x production. Also, test results show mild H_2 blending favourable to engine efficiency. But H_2 fraction above 5% results in cooling energy loss and efficiency drops. As a way to increase the thermal efficiencies under higher fractions of H_2 and to reduce the levels of emitted NO_x, C. Park et al. [16] also extended their study by investigation the effects of exhaust gas recirculation (EGR). Test results shows that at lower H_2 blending ratio i.e. less than 20%, the lean burn technique has superior fuel economy. But as the blending ratio increases, the EGR approach could realise greater engine performance with much lesser emission of NO_x. Test outcomes show improvement in maximum tolerable EGR rate and thermal efficiency due to high electrode temperatures and relatively short flame propagation lengths. J. Arroyo et al. [17] conducted combustion test of synthetic gases powered SI engine to compare with the results when fuelled with methane, gasoline and with biogas. It is observed that hydrogen fraction in the synthetic gas increases maximum in-cylinder pressure. The proportions of H_2 and diluents in the gaseous blend have strong influence in combustions speed and heat released. In comparison with other fuels, the contents of CO_2 and carbon monoxide (CO) in the synthetic gases aggravate exhaust concentration of these contaminants. NO_x emissions increase due to hydrogen increasing flame temperature even though diluents like CO_2 and excess air mitigates its emission. An investigation done to observe the outcome of addition of H_2 to biogas at different spark timings by Porpatham et al. [18], found that at a spark timing of 20^o crank angle (CA) before Top Dead Centre (bTDC), the condition of 5% H_2 share was the optimal. At 10% hydrogen energy share, the thermal efficiency and power output could be realized at a maximum but at the same time the NO level were also high. With increased in hydrogen induction, remarkable delay of the ideal ignition timings was observed [18].

Another approach of overcoming the shortcomings posed by the CO_2 incidence is to increase the compression ratio of a biogas engine. Experiments have been directed towards analysis of the influence of CR changes in biogas fuelled SI engines. E. Porpatham et al. [19] investigated the influence of CR; varying from 9.3:1 to 15:1, for a biogas fuelled SI engine. Results indicated that higher brake power and thermal efficiency could be achieved when compression ratio was increased. As CR was increased from 9.3:1 to 15:1, an increase from 23% to 26.8% was resulted in the peak brake thermal efficiency. Through an increase in CR, there was improvement in combustion as the lean limit was stretched and as such there was increase in HC and NO emission. Beyond the critical compression ratio value of 13:1, no noteworthy increment in thermal efficiency and brake power were observed and also rise in emissions of NO_x, HC, and CO were noted. Increasing compression ratio is positive for improving performance and reducing emission.

Ignition timing is also important parameters for improving biogas fuelled SI engines. R. Chandra et al. [20], reported the evaluation of the performance of engine at CR=12.65 and 30^o, 35^o and 40^o ignition advance of TDC for methane enhanced biogas (95% CH_4), CNG, and raw biogas, and was found to be at ignition advance of 35^o TDC. The engine power degradations were found to be 46.3%, 35.6% and 31.8% for biogas, bio-CNG and CNG respectively when contrasted with diesel in original CI mode. CNG and bio-CNG showed almost identical performance in terms of specific gas consumption, thermal efficiency, and brake power.

K.A. Subramanian et al. [21] studied the methane enriched biogas (93% CH_4) viability in its use for Modified Indian Driving Cycle, in place of CNG. Test results show that though HC, CO and NO_x emissions are slightly greater for enhanced biogas as compared to CNG, they meet BS IV Emissions Norms. Fuel consumption shows almost identical data. Transient emission characteristics for both fuels are greater for low speed in contrast to high speed cycle. The study confirmed that without any hardware modification, automotive SI vehicle powered by methane enhanced biogas, met BS IV Emission Norms.

Various other studies have been reported for enhancing the emission and performance of biogas fuelled SI engines. E. Porpatham et al. [10], [22] tested the effects of swirl and enhancing oxygen (O_2) concentration in biogas. Test results found that enhancing swirl by masked intake valve increased heat release rate thereby increasing brake thermal efficiency and power output. Also, the NO emission level rose with masked valve in comparison to normal conformation. Increase in concentration of O_2 induction in the intake air also resulted in the increase of brake power and thermal efficiency as heat release rate were significantly improved. At higher oxygen level, emissions of CO and HC were decreased but that of NO_x rose. G.S. Jatana et al. [23] similarly examined the characteristics of performance for very low power (450 - 1000 W) small biogas-fuelled engines operated in 'fuel injection' and 'premixed' method, making use of both dual and single configurations of spark plug. Experimental results show the sensitivity of biogas combustion to ignition schemes, influencing both efficiency and power. At low loads, continuous fuel injection display much better performance in comparison with premixed case due to probable stratification of charge in the cylinder. The investigation identified that stable and extremely efficient operation of biogas powered small SI engine, could be achieved by the combination of dual spark plug ignition, lean burn and fuel injection technologies.

J. P. Gomez Montoya et al. [24] investigated an internal combustion diesel engine, converted to spark ignition mode for high compression ratio and thermal efficiency output using various gaseous fuels viz. simulated biogas (60% CH_4, 40% CO_2), 25% methane enriched biogas (equivalent to 70%

CH_4, 30% CO_2) and 50% methane enriched biogas (equivalent to 80% CH_4, 20% CO_2). The optimal experimental condition for the engine without knocking was observed with 50% methane enriched biogas at 12° CA bTDC spark advance. Also decreased in the emissions of NO_x, CO, and unburnt methane were also observed with 50% methane enriched biogas.

K.S. Reddy et al. [25] focussed on a hybrid system constituted of a biogas powered SI generator and solar concentrated photovoltaic. Different loading conditions in combination with varied fuel flow rates were experimented. Owing to its low calorific value, raw biogas witnessed 32% power deterioration in comparison with LPG. Significant reduction of CO and HCs, with relatively no effect on NO concentration levels were also observed from the analysis of exhaust emission. A 19.5% brake thermal efficiency and 812 W maximum power output were resulted. This hybrid energy system fuelled with the eco-friendly fuel; biogas can help in sustaining rural energy supply.

2.2. Biogas as an alternate fuel for CI engine

Numerous researchers considered the usage of gaseous fuels, to supplement the diesel fuel partially as a promising alternative for reducing pollutants emitted from direct injection diesel engines. Biogas having a high temperature of self-ignition (650 °C), prevents its usage in a CI engine directly. Superior engine performance may be attained with an alternative methodology utilising biogas-diesel dual fuel engine [26]. This approach involves an initial supply of a mixture of fresh air and gaseous fuels to a cylinder and injection of diesel/biodiesel fuel in small quantity for the ignition of the combustible mixture. As compared to a sole biogas SI engine, this engine can attain higher efficiency owing to its high compression ratio as it is typically modified from a diesel CI engine. Within the combustion chamber, faster combustion speed and complete combustion takes place as the diesel fuel injected provides multi-point ignition sources, which thus lessens the sensitivity of the in-cylinder combustion activity from the biogas configuration fluctuations, thereby increasing the stability of the onsite engine performance. Nevertheless, expensive maintenance cost than the SI engine poses as demerits of the dual fuel engine, in addition to the risk of recurrent injector failures attributing to decrease in the cooling effect, and also the concerns of engine durability owing to the peak cylinder pressure.

Characterization of the air-excess ratio, volumetric efficiency and thermal efficiency versus output power of a 12 kW diesel motor generator with pure jatropha oil and diesel as the reference fuels, was presented by Luijten and E. Kerkhof [27]. The diesel and pure jatropha oil reference examinations performed showed no critical distinction for thermal efficiency. The dual fuel experiments with addition of diverse qualities of synthetic biogas (CH_4/ CO_2 proportions) to the intake air, demonstrated a reduction of 10% in thermal efficiency irrespective of the biogas quality for lower loads whereas the same remain unaffected for higher loads. They observed the smooth functioning of the engine till a definite fraction of methane heat release, above which irregularities resulted possibly due to light end-gas knock.

As investigation of the combustion pressure and the rate of heat release give better insight for the investigation of characteristics of combustion and their effects on exhaust emissions, several researchers have performed experiments in this direction. H. Yoon and C.S. Lee [28] conducted such an experiment for dual-fuel (biogas-biodiesel and biogas-diesel) and single-fuel (biodiesel and diesel) modes of combustion for a diesel engine. The study resulted in identical patterns of combustion characteristics for both biodiesel and diesel only mode at varied engine loads. However, the dual-fuel combustion approach at low load (20%) lead to a slightly lesser peak pressure and rate of heat release for biogas–biodiesel in comparison to biogas-diesel. When dual-fuelled with biogas-biodiesel, combustion at 60% load resulted in greater indicated peak pressure, mean effective pressure and heat release rate to an extent compared to those exhibited by biogas-diesel as depicted in Fig. 3. Moreover, the biogas-biodiesel exhibited shorter ignition delays than the diesel dual fuel approach, in account of the greater cetane number of biodiesels. Under all the engine load conditions, emissions of NO_x were substantially reduced for both the pilot fuels in dual fuelling modes in comparison with the single fuelling modes. Soot emissions were also greatly reduced by biogas-biodiesel owing to the low contents of oxygen and sulphur and absence of aromatics in biodiesel. N.N. Mustafi et al. [29], also investigated the emissions of exhaust and performance of a diesel engine dual powered with biogas and natural gas through the assessment of the rate of heat release and combustion pressure for single and dual fuel combustion modes. For the dual fuel approach, the peak cylinder pressure was analogous with diesel engine with output rated at 75%. Natural gas and biogas fuel mode showed extended ignition delays but shorter combustion periods and greater maximum net heat release of around 27–30% than the diesel mode. Dual fuel approach exhibited lesser specific NO_x and particulate matter emissions but abruptly increased unburned hydrocarbons emissions as compared to diesel fuelling mode.

Several different researches have testified the influence of biogas flow rate on the emission and performance of biogas dual fuel CI engines. An investigation of anaerobically produced biogas from non-edible de-oiled cakes, by D. Barik and S. Murugan [30] to serve as an alternative fuel in a dual fuel approach was accomplished. Under four distinct biogas flow rates, viz., 1.2 kg/h, 0.9 kg/h, 0.6 kg/h and 0.3 kg/h, biogas had been introduced via the intake along with the air and the pilot fuel, diesel. Experimental analysis and comparison of results with those of diesel operation showed that superior performance and lesser emission could be achieved with 0.9 kg/h flow rate of biogas than with the other flow rates. Dual fuel mode exhibited longer ignition delay for the various load, approximately 11 bar higher cylinder peak pressure and lesser emissions of smoke and NO by around 49% and 39% correspondingly in comparison to those of diesel mode. An investigation by D. Barik and S. Murugan [31], using biogas and Karanja methyl ester (KME) as the main and pilot fuels correspondingly, again found 0.9 kg/h flow rate of biogas offering lesser emissions and superior performance, compared to the rest. At full load, the dual fuel approach exhibited lesser emissions of smoke and NO by approximately 14% and 34% and longer ignition delay by approximately 1-2º CA than those of KME only approach.

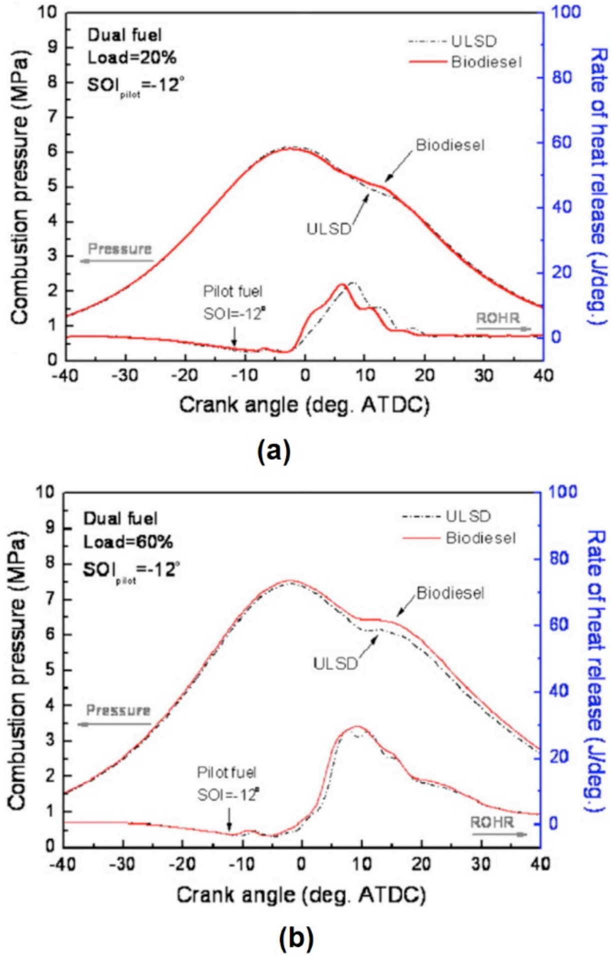

Fig. 3. Variation of combustion characteristics with (a) Engine load = 20%. (b) Engine load = 60%, for the dual fuel approach at constant speed of engine (2000 rev/min) [28].

For improving the efficiency, ignition delay and fuel consumption of biogas-KME dual fuelled engine at par with those of diesel operation, D. Barik and S. Murugan [32] employed diethyl ether (DEE) port injection strategy. In this procedure, an electronic injector injected DEE in small quantities (2%, 4%, and 6%). Under the dual fuel set-up, setting the KME injection timing at 24.5º CA bTDC, biogas was introduced at the optimal 0.9 kg/h flow rate. Test results showed that superior characteristics of emission, performance and combustion were shown by BDFM24.5/DEE4 (24.5º CA bTDC injection timing and 4% DEE injection, biodiesel-biogas dual fuel mode) than the remaining cases of DEE injections. It also enhanced the BTE by 2.3%, decreased the BSFC by about 5.8%, decreased emissions of smoke, CO and by 5.7%, 12.2% and 10.6% compared to BDFM24.5 (without DEE injection), at full load, but however it exhibited 12.7% higher NO emission as shown in Fig. 4.

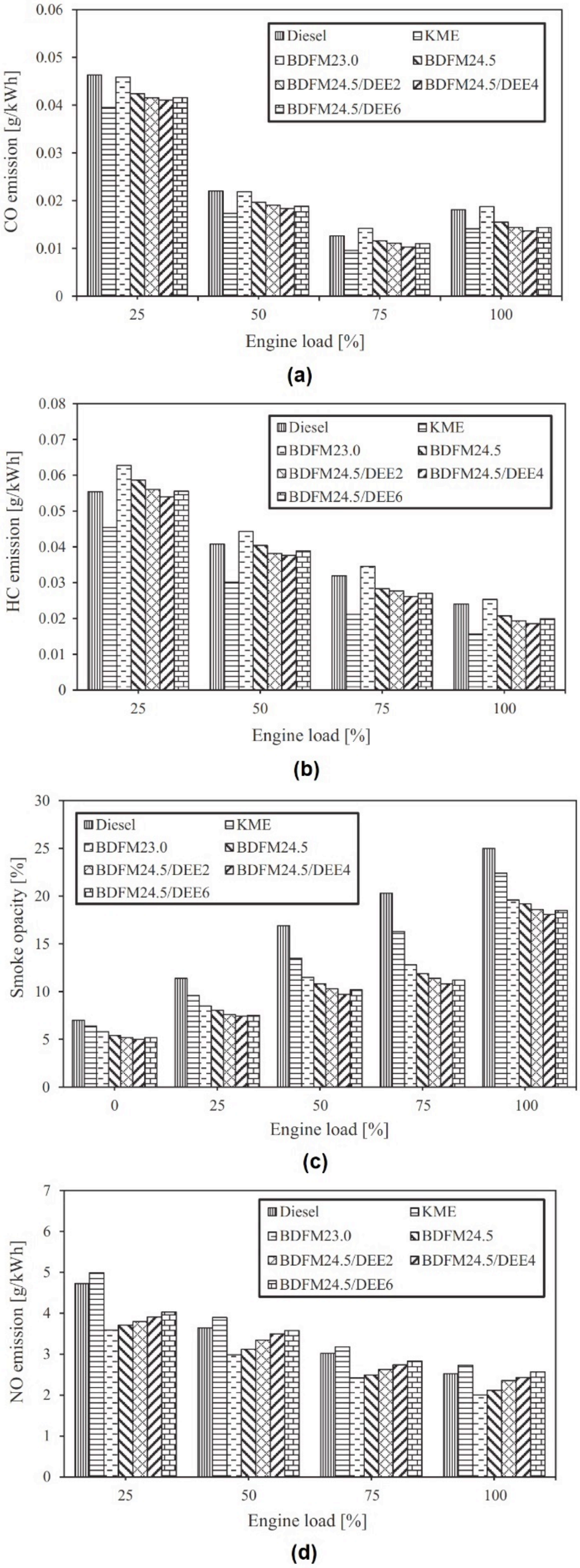

Fig. 4. Parametric variation of emissions of **(a)** CO **(b)** HC **(c)** Smoke **(d)** NO with the engine load [32]

In another study the influence of concentration of methane and flow rate of biogas on the emissions and performance of a dual-fuelled CI engine were investigated by H. Ambarita [33]. The specific fuel consumption and output power for dual diesel biogas mode were higher than when executed in pure diesel approach. Greater brake thermal efficiency was found at low biogas flow rate in comparison with diesel only mode but its value lowered at greater flow rate of biogas. Engine speed, load and methane concentration all affected the optimum biogas flow rate. CO emission increased with increase in biogas flow rate, however, it remained unaffected by methane concentration. Optimum biogas flow rate was established to be between 2 L/min and 4 L/min.

The presence of CO_2 in biogas presents a negative effect reducing the biogas heating value and flame speed, ultimately affecting the performances of engine. V. Makareviciene et al. [34] gauged the CO_2 concentration impact on the emissions of exhaust gas and performance of a biogas-diesel dual fuel engine. Two stages of tests were carried out where first the influence of various configurations of biogas an EGR on the parameters of engine had been studied and during the subsequent stage the highest methane concentrated biogas had been utilized for determining the influence of injection timing on the performance of engine. Except for the NO_x, lower pollution emissions were recorded without the EGR system. To lessen the consumption of fuel, the HC and CO concentrations, and also to increase the thermal efficiency for increasing methane concentration in biogas, gradual advance of the injection timing was required, but this led to upsurge in NO_x emission.

S. Verma et al. [35] also conducted an experimental assessment and quantification of a small CI dual fuel engine performance based on variations of the raw materials of biogas, methane and carbon dioxide. The investigation involved three biogas configurations, namely BG75, BG84 and BG93 (consisting of 75%, 84% and 93% CH_4 by volume). Exergy balances for these configurations were analysed to assess individual process inefficiencies. At low loads, the dual fuel mode resulted in 80–90% diesel substitution, while at higher loads, BG75, BG84 and BG93 biogas configurations led to increase of total engine irreversibility to 64.64%, 64.18% and 61.44% from 59.56% of diesel mode. Moreover, with increase in concentration of CO_2 in biogas, there was reduction in combustion irreversibility. BG93 exhibited equivalent second-law efficiencies results to that diesel mode.

The influence of CRs on the characteristics of emission, combustion and performance of dual fuel diesel engine powered by raw biogas was presented experimentally at numerous compression ratios, viz., 16, 17, 17.5 and 18 and at varied load conditions with the standard injection timing fixed at 23° bTDC by B.J. Bora et al. [36]. Under full load setting, the dual fuel approach with CR=18 showed a maximum 20.04% brake thermal efficiency, while the diesel mode showed 27.76% efficiency at 17.5 compression ratio for the same load, as can be seen from Fig. 5. At the same load, the maximum fossil fuel replacement (79.46%) was also found at the compression ratios of 18, Fig. 5. As the CR was varied from 18 to 16, the dual fuel mode exhibited significant decrease in emissions of HC and CO, while an upsurge in emissions of NO_x and CO_2 were recorded. Higher emissions of HC and CO were witnessed in dual fuel approach than diesel mode in all the test cases owing to lesser volumetric efficiency in the dual fuel approach.

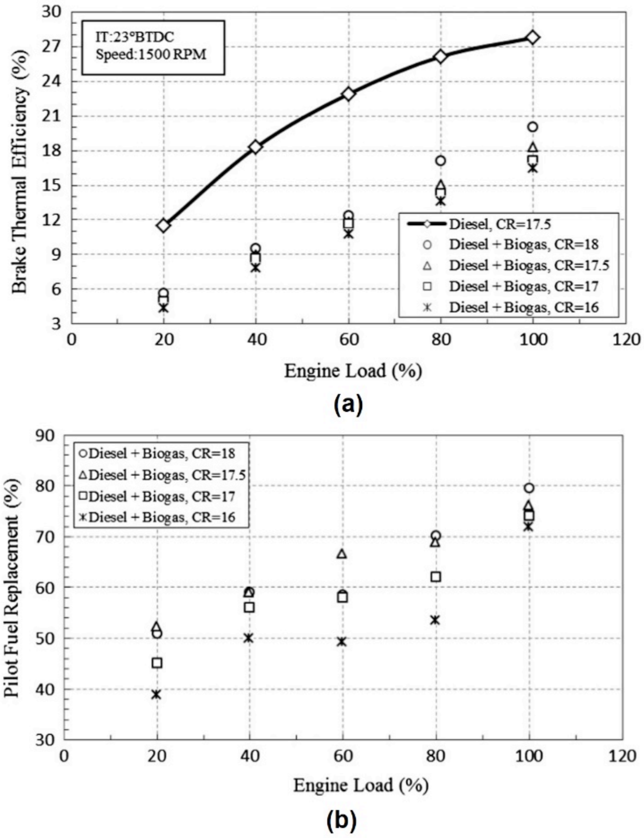

Fig. 5. Variation of **(a)** brake thermal efficiency **(b)** pilot fuel replacement with engine load for different CRs [36].

Improvement of biogas fuelled dual engines efficiency and emissions were investigated through optimisation of injection timing (IT) of pilot fuel. An endeavour to improve emission and efficiency through optimisation of CR and IT of pilot fuel was made by Bora and Saha [37]. The investigation involved a set of arrangement consisting of 26°, 29° and 32° bTDC injection timings and compression ratios of 16, 17, 17.5 and 18 for various load conditions of which the optimum IT of 29° bTDC for the pilot fuel and compression ratio of 18 were established while achieving a maximum 25.44% brake thermal efficiency besides an 82.11% liquid fuel replacement. Additionally, least emissions of CO and HC were achieved at this specific configuration. D. Barik, and S. Murugan [38] also investigated the behaviour of biogas fuelled direct injection dual fuel engine at diverse injection timing ranging between 23º CA bTDC and 27.5º CA bTDC. An overall better performance was observed at the IT of 26º CA bTDC than the rest. For the full load case, the dual fuel approach manifested 2% and 10% greater brake specific CO and HC emissions respectively, 39% lesser smoke emissions and about 14% greater cylinder peak pressure in comparison to those of diesel. Dual fuel mode exhibited enhanced engine performance at part load with the advanced IT and substantial decline in the exhaust emissions. Moreover, advanced pilot injections resulted in higher emissions of brake specific nitric oxide in contrast to original IT, which was however lesser than full load diesel by around 16%.

D. Barik et al., further inspected the influence of injection timing on a biogas fuelled DI engine with pilot fuel, Karanja methyl ester [39]. Under the biodiesel dual fuel mode, the injection timing had been varied between 21.5º CA bTDC and 27.5º CA bTDC, with superior performance and lesser emissions shown by BDFM24.5. The same exhibited 23.9% higher brake specific fuel consumption at full load in comparison to KME. Under high load setting, BDFM24.5 resulted in 6.6% greater brake thermal efficiency and 18.2%, 17.1% and 2.1% decrease in emissions of HC, CO and smoke respectively than BDFM23.0 (with IT of 23º CA bTDC). However, the 5.5% greater emission of NO was observed for BDFM24 than BDFM23.0, at full load.

S. Verma et al. [40], in a similar investigation coupled with exergy analysis, studied the injection timing advance as a method for improving low load characteristics of emission and performance of dual fuel engine powered with diesel as pilot fuel, and hydrogen, CNG and biogas as main fuels. The experiments were conducted under high and low loads, at injection timings of 20, 23, 26, 29 and 32º CA bTDC. Test results showed that the main fuel type and engine load significantly affected maximum diesel substitution while IT advance has considerably less influence. CNG and hydrogen as the main fuel in dual mode achieved the highest and the least maximum diesel substitution, respectively. The optimal IT for performance and emissions also varied with the gaseous main fuel type and load settings of engine. Under both the load settings, hydrogen dual fuel mode at its optimal IT showed superior exergy efficiency than that diesel only mode. The exergy destruction at the optimal IT (low load condition) was also found to be lower for hydrogen in DF mode than that of diesel mode. Advancing ITs reduced the emissions of smoke, CO and HC, but that of emission of NO_x greatly increased.

Verma S, et al. [41], conducted an experimental research coupled with exergy analysis on a diesel, biogas and hydrogen fuelled conventional diesel engine adapted for operation in dual fuel mode with diesel and biogas as the pilot and the main fuels respectively. Slight supplementations of hydrogen, viz., 20%, 15%, 10% and 5% in biogas have introduced to enhance the characteristics of emission and performance of the engine in comparison to the neat biogas-diesel approach and the characterization was carried out through exergy based method along with investigations of key irreversibility sources in the different engine processes and comparisons with the cases mentioned above. Supplementations of hydrogen in biogas resulted in minor influence on the characteristics of combustion under low load, Fig. 6(a), while the same showed significant change with higher peak compression pressures and heat release rates at high load Fig. 6(b). Moreover, 5% hydrogen supplementation had no effect on the characteristics of emission and performance at both the load settings. However, enhancement in performance was observed with additional increase of hydrogen in biogas.

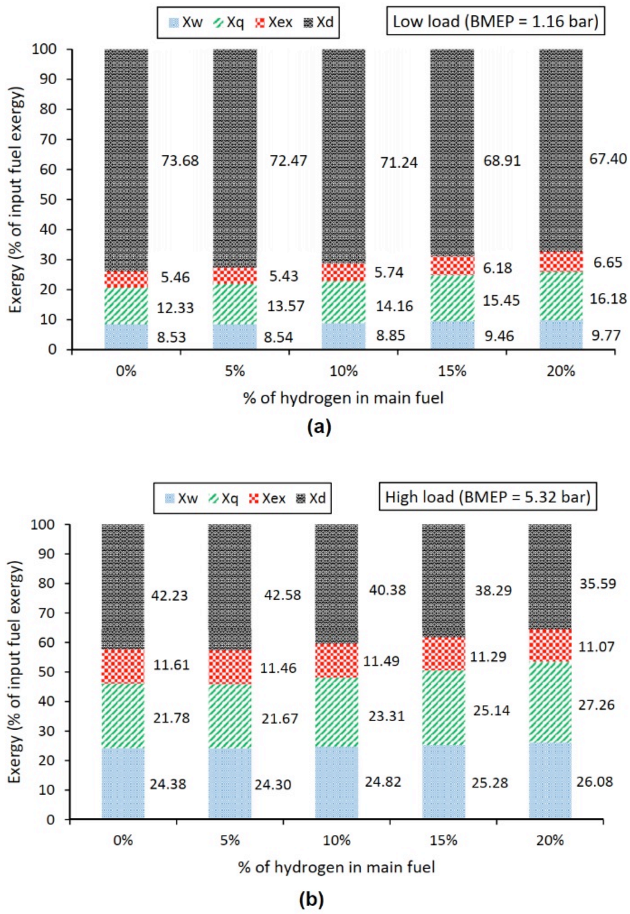

Fig. 6. Balance of exergy for the total fuel input exergy at different loading conditions **(a)** low **(b)** high, for biogas fuelled dual-fuel mode with enriched hydrogen [41]

In an experimental research by F.Z. Aklouche et al. [42], synthetic biogas (60 % CH_4, 40 % CO_2) fuelled dual fuel engine operating under high loading condition and with fixed percentage of rate of energy substitution was investigated, where the primary fuel, synthetic biogas was mixed with air in the intake manifold. While maintaining introduction of constant energy into the engine, air flow rate was varied to vary the equivalence ratio. Comparison of the dual fuel mode performance, ignition delay and combustion characteristics were made with those of conventional mode. Increase in equivalence ratio resulted in longer ignition delays and increase in peak heat release. Additionally, with an increase of equivalence ratio from 0.35 to 0.7, 58 % and 77 % reductions in HC and CO emissions respectively, 24 % reductions in NO_x emissions at 60 % PES (percentage energy substitution) and enhancement of 13% of BTE were observed.

The direct use of raw untreated biogas results in corrosion and sulphidation of engine parts. Removal of sulphur compound or envisaging a method to directly use raw biogas is essential for long term engine protection. In this regard, M. Maizonnasse et al. [43] assessed pre-heating of raw biogas in combination with phase-separation as an alternative to using sulphur compound free biogas. A low-cost engine adjustment comprising of heat-exchanger between biogas and exhaust together with phase-separation and replacement of lubricating oil were performed. The engine was run using pre-heated raw biogas (H_2S-2000 ppm) for 550 hours. Engine parts visual, size and weight investigation, lubricant inspection and cylinder pressure examination were performed for checking the degradation of the engine. Inspection showed almost no degradation. Similar tests were performed using untreated raw biogas and results were compared and found that untreated biogas use deteriorated lubricating oil and produced faster cylinder head gasket wear. The technique assessed posed as a good alternative to treating biogas of sulphur compounds.

3. Conclusions and Future Research Scope

As a renewable energy source, biogas is considered as a potential alternative for fossil fuel replacement. The advantages of using biogas in IC engines have been reported in various literatures. The current paper presents a detail review of the researches conducted for investigating the emission, performance and combustion of biogas fuelled IC engines. From the study of literatures, the following conclusion can be presented:

1. In SI engines application, the presence of CO2 in biogas lowers its flame speed, calorific value and combustion temperature and thus reduced power output and thermal efficiency. Its presence also increases un-burnt HC emission while lowering NOx emissions. A small reduction in CO2 level from normal level yielded notable reduction in HC emission without almost negligible rise in NO level.
2. For both SI and CI engines application, additions of H_2 have also found to enhance the combustion characteristics which are otherwise affected by the CO_2 presence. Boost in in-cylinder combustion characteristics, brake power and thermal efficiency, combustion rate and extension of biogas lean operation limit are observed with the addition of H_2, however with a disadvantage of increase in NO_x emissions. Retardation in optimum ignition timing in case of SI engine application is also manifested by increase in hydrogen addition, which in turn averts knocking and reduce the peak pressure and heat release rates.
3. Similar enhancement of combustion characteristics is also observed for SI engine application with increasing CR, in spite of a rise in HC and NO_x emissions. For dual fuel mode, increasing compression ratio significantly decreases the emissions of HC and CO while increasing the emissions of CO_2 and NO_x. However, emissions of CO and HC are greater for dual fuel approach as compared to the diesel only approach owing to the lesser volume of dual fuel mode. In-cylinder pressure, heat release rate and brake power also increase with increasing CR for dual fuel mode. Literatures suggest operation of dual fuel mode at higher CRs.
4. Optimal setting of ignition/ injection timing is also required for enhancing combustion characteristics of biogas fuelled IC engines.
5. Increasing oxygen concentration in inducted air for SI engine application, increases the brake thermal efficiency and power, however, for higher oxygen concentration level, there is an increase in emission of NO_x and a decline in CO and HC emissions.
6. Biogas application in IC engines is more efficient in dual fuel mode. In comparison with a diesel only mode, biogas fuelled dual CI engine showed better emission of NO_x, particulate matter and soot while that of CO and HC emissions deteriorated.
7. EGR in biogas dual fuel approach results in higher NO_x emissions while lowering HC, CO and CO_2 emissions.
8. Under low loading conditions, the biogas-biodiesel dual fuel approach exhibit slightly lesser peak pressure and heat release rate than biogas-diesel dual fuel approach. However, the opposite holds true under high loading conditions. NO_x emissions reduce in both dual fuel approach of biogas-diesel and biogas-biodiesel, in comparison to the single fuel counterpart.
9. Preheating of biogas with phase separation can be employed as an alternative to biogas purification.
10. Prediction of engine parameters using various techniques like artificial neural network are limited and may be pursued in future.
11. Multi-objective response optimization of IC engines fuel with biogas may be further investigated in future.

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