Production and Application of Biogas as a Gaseous Fuel for Internal Combustion Engines

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Abstract

The enormous growth in industries and increase in population are the main reason for heavy depletion of fossil fuel. In recent years, the desire of energy independence, foreseen depletion of non-renewable fuel sources, fluctuating petroleum fuel costs, the necessity of stimulating agriculture based economy, and the reality of climate change have created an interest in the development of biofuels. Though large amount of biomass is available they are not properly utilized for the energy conversion. Keeping this in mind the trapping of energy from various biomass sources is essential. Biogas technology is one which can be adopted for heat and power generation. Biogas produced by the anaerobic digestion from various organic substances offers low cost and low emissions than any other secondary fuels. This paper provides a short review on the potential biogas production and its application, as a gaseous fuel in Internal Combustion (IC) engines.

Key words- Anaerobic digestion, biogas, biowaste, dual fuel, gaseous fuel.

1. Introduction

In view of the depletion of fossil fuel resources, considerable research is being devoted to looking for alternative fuels to comply with transportation needs while reducing the environmental impact of the transport activity sector. In this sector, off road vehicles and agricultural machinery consume a small, but vital amount of energy of around 2 Mtoe [1]. As for transport, the goal is to reduce both fuel consumption and greenhouse gas emissions by 20% in the year 2020 and the target is even to reduce these by a factor of 4 in 2050. Among biofuels, biogas is an interesting candidate, because it can easily be used to partially replace diesel fuel in the compression ignition (CI) engines generally used for tractors. Biogas is also produced from the methanisation of farm waste [2]. Anaerobic digestion is one way to produce energy from biomass.

Anaerobic digestion is a biological process in which biodegradable organic matters are decomposed by bacteria forming gaseous byproducts. The gaseous byproduct consists of methane (CH_4), carbon dioxide (CO_2), and tresses of other gases [3]. The anaerobic digestion process is considered to be a minimum of two stage biological reaction, involving at least two different groups of microorganisms, one is acid forming bacteria (saprophytic) and the other is methane forming bacteria. The acid phase is generally considered to include the conversion of complex organic compounds into simpler organic compounds and finally into the organic acids i.e. acetic acid by acid forming bacteria [4,5,6]. It is a multi-stage process which can be divided in to four phases: hydrolysis, acidogenesis, dehydrogenation/ acetogenesis, and methanation [7,8,9]. The first phase is namely as single stage unmixed, second phase is two stage mixed primary, the third phase is anaerobic contact process with sludge recycle and the fourth phase is anaerobic filter with methane formation. The first two processes are generally used for digestion of solid wastes and waste water sludge and the other two process are for the formation of acetic acid, CO_2, and methane CH_4 [7]. During this process, the organic compounds are hydrolysed into smaller components like sugars, amino acids, alcohols and long chain fatty acids so both solubilisation of particulate matter and biological decomposition of organic polymers to monomers or dimers take place [10].

Anaerobic biological treatment is the process by which anaerobic bacteria decompose organic matter/agricultural solid waste (ASW) in to methane, carbon dioxide, and a nutrient-rich sludge involves a step-wise series of reactions requiring the cooperative action of several organisms. The rate of digestion and biogas production is affected by a variety of factors; the most important is temperature [11]. Anaerobic bacteria communities can endure temperatures ranging from below freezing to above 330.4 K, but they thrive best at temperatures of about 309.9 K (mesophilic) and 327.6 K (thermophilic). Bacteria activity, and thus biogas production, falls off significantly between about 312.6 K and 324.9 K and gradually from 308.2 K to 273.2 K

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[12]. Figure 1 shows the pathway of anaerobic digestion process. The first two processes are generally used for digestion of solid wastes and wastewater sludge and the other two process are for the formation of acetic acid, CO_2, and methane CH_4 [13].

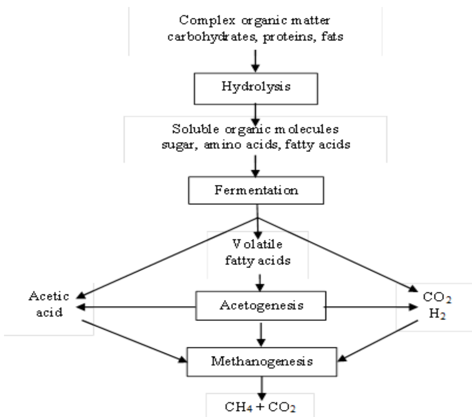

Figure 1. Pathwa of anaerobic digestion process [14]

Biogas is a clean fuel for internal combustion engines. In oil crisis situations, it may act as a promising alternative fuel, especially for diesel engines, by substituting for a considerable amount of fossil fuels. Diesel engines can be easily converted to fumigated dual fuel engines. This is the most practical and efficient method to utilize high spontaneous ignition temperature alternative fuels, such as biogas. In the fumigated dual fuel method, biogas mixes with air before the mixture enters the combustion chamber, and at the end of the compression stroke, an amount of diesel, called the pilot fuel injection, is injected to ignite it. This method has the advantage of the ability to switch back to diesel operation in case of a shortfall in biogas supply during an important operation [15]. Because of these benefits, dual fuelling of diesel and biogas [16–19] has been investigated widely worldwide for some past decades. Table 1 and Table 2 give some typical details of biogas.

Table 1 Different constituent of biogas

Constituent	By volume	By mass
CO_2	19%	37.38%
N_2	6.5%	8.14%
O_2	1.5%	2.15%
CH_4	73%	52.34%
H_2S	20ppm	
Density	0.9145kg/m^3	
LHV	26.17 MJ/kg	
$(A/F)_{Stoichiometric,}CH_4$	17.23	

Table 2 Details of biogas [20]

Composition	55-70% methane, 30-45% carbon dioxide, traces of other gases
Energy content	6.0-6.5 kW/m^3
Fuel equivalent	0.6-0.65 L oil/m^3 biogas
Explosion limits	6-12% biogas in air
Ignition temperature	650-750 ^{o}C
Critical pressure	75-89 bar
Critical temperature	-82.5 ^{o}C
Normal density	1.2 kg/m^3
Flame speed	25 cm/s
Odour	Bad eggs (the smell of hydrogen sulphide)

2. Feed stocks for anaerobic digestion

Total solid contained in a certain amount of materials is usually used as the material unit to indicate the biogas production rate of the materials. Most favourable total solid (TS) value desired is 8%. The total solid content of some common solid and liquid digestible materials in rural areas are given in Table 3.

Table 3 Total solid content of some common solid and liquid digestible materials

Materials	Dry matter content (%)	Water content (%)
Dry rice straw	83	17
Dry wheat straw	82	18
Corn stalks	80	20
Green grass	24	76
Humanexcrement	20	80
Pig excrement	18	82
Cattle excrement	17	83
Human urine	0.4	99.6
Pig urine	0.4	99.6
Cattle urine	0.6	99.4

At mesophilic condition the bacteria have the optimum output at a temperature of 25-40 ^{o}C and in thermophilic bacteria survives best at 50-65^{o}C. Table 4 shows biogas produced from some common digestible materials at different temperatures [21]. The pH value for anaerobic digestion is in the range of 5.5-8.5.

Table 4 Biogas yield from common feed stocks

Materials	Biogas produced at 35 °C (m^3/kg)	Biogas produced at 8°C ~ 25 °C (m^3/kg)
Pig manure	0.45	0.25 ~ 0.30
Cattle dung	0.30	0.20 ~ 0.25
Human wastes	0.43	0.25 ~ 0.30
Rice straw	0.40	0.20 ~ 0.25
Wheat straw	0.45	0.20 ~ 0.25
Green grass	0.44	0.20 ~ 0.25

During anaerobic digestion microorganisms utilize carbon 25-30 times faster than nitrogen. High C/N ratio indicates low biogas production. Similarly low C/N ratio indicates accumulation of ammonia that increases the pH level of the digested slurry more than 8.5. Thus, to meet this requirement, microbes need 20-30:1 ratio of C to N [21]. Table 5 gives the information on the carbon nitrogen ratios of some common digestible materials and Table 6 shows biogas production rate and methane yield of some digestible materials.

Table 5 Carbon- nitrogen ratios of digestible materials (approx.)

Materials	Carbon content (%)	Nitrogen content (%)	C/N ratio
Dry wheat straw	46	0.53	87:1
Dry rice straw	42	0.53	67:1
Corn stalks	40	0.75	53:1
Fallen leaves	41	1.00	41:1
Soybean stalks	41	1.30	32:1
Wild grass	14	0.54	27:1
Peanut stems and leaves	11	0.59	19:1
Fresh sheep droppings	16	0.55	29:1
Fresh cattle dung	7.3	0.29	25:1
Fresh horse droppings	10	0.42	24:1
Fresh pig manure	7.8	0.60	13:1
Fresh human wastes	2.5	0.85	29:1

Two categories of biogas plants were studied by the researchers. The first one was farm based plant and the other was community based, or cooperative plants. The farm based plants were located on farms. Some were solely operated by the farm owner, while others involved partnerships between two or three farm owners. Others were located at the farm site, but were owned and operated by companies separate from the farm. The community and cooperative plants were located in large commercial sites which collect manure from as many as farms, digesting it, and then returning it to the farms to be applied as landfills [23].

Table 6 Rate of biogas production and methane yield for some digestible materials

Feed stocks	Yield of biogas (m^3/kg TS)	Methane content (%)
Animal barnyard manure	0.260 ~ 0.280	50 ~ 60
Pig manure	0.561	45 ~ 68
Horse droppings	0.200 ~ 0.300	55 ~ 65
Green grass	0.630	70
Flax straw	0.359	55
Wheat straw	0.432	59
Leaves	0.210 ~ 0.294	58
Sludge	0.640	50
Brewery liquid waste	0.300 ~ 0.600	58
Carbohydrate	0.750	49
Lipid	1.440	72
Protein	0.980	50

The present paper describes the use of biogas in automotive applications in dual fuel and single fuel mode. Dual fuel mode is generally for CI engines and single fuel mode is for SI engines. In dual fuel mode the biogas was mixed with air before induction into the engine cylinder and the liquid fuel (diesel/ biodiesel) is injected in to the cylinder as a pilot fuel.

3. Engine applications

Biogas can be used in both heavy duty and light duty vehicles. Light duty vehicles can normally run both on natural gas and biogas without any modifications whereas heavy duty vehicles without closed loop control may have to be adjusted if they run alternately on biogas and natural gas.

Biogas provides a clean fuel for both SI (petrol) and CI (diesel) engines. Diesel engines require combination of biogas and diesel while petrol engines run fully on biogas. Use of biogas as an engine fuel offers several advantages. Biogas being a clean fuel causes clean combustion and reduced contamination of engine oil. Biogas cannot be directly used in automobiles as it contains some other gases like CO_2, H_2S and water vapour. For use of biogas as a vehicle fuel, it is first upgraded by removing impurities like carbon dioxide, hydrogen sulphide and water vapour, then compressed in a three or four stage compressor up to a pressure of 20 MPa and stored in a high pressure gas storage cascade which helps to facilitate quick refuelling of storage cylinders. If the biogas is not compressed than the volume of gas contained in the storage cylinder will be less hence the engine will run for a short duration of time.

Biogas contains larger quantity of CO_2 which lowers its calorific value, flame velocity. Flammability range is shown in Table 1 and Table 2. The self-ignition temperature of biogas is high hence it is resists to knocking which is a desirable feature in spark ignition (SI) engine. It also contains small percentage of H_2S, which can cause corrosion to metal parts. A high compression spark ignition engine for biogas can be built by replacing the injectors of a diesel engine by spark plug and modifying the pistons. In experiments, using simulated biogas, compression ratio ranging from 11:1 to 13:1 were found to be suitable for operation without knock [24]. Removal of CO_2 from biogas, using proper compression ratio and addition of fuels with wide flammability limits and high flame velocity will improve the performance of biogas fuelled spark ignition engines.

Biogas can also be used in dual fuel mode with diesel or vegetable oils as pilot fuel in diesel engines. Introduction of biogas normally leads to deterioration in performance and emission characteristics. The performance of engine depends on the amount of biogas and the pilot fuel used. Measures like addition of hydrogen, LPG, removal of CO_2 etc. have shown significance improvements in the performance of biogas dual fuel engines [24]. The ignition delay of the pilot fuel generally increases with the introduction of biogas and this will leads injection timing to be advanced. Injectors opening pressure and rate of injection also are found to play important role in the case of biogas fuelled engine, which used vegetables oil as pilot fuel. The CO_2 percentage in biogas acts as diluent to slow down the combustion process in Homogenous Charged Compression Ignition (HCCI) engines. However, it also affects ignition. Thus a fuel with low self-ignition temperature could be used along with biogas to help its ignition. This kind of engine has shown superior performance as compared to dual fuel mode of operation.

In the case of operation of stationary spark ignition engine compression ratio can even be raised to 13:1 because of the high self-ignition temperature of biogas. Up to this compression ratio the raise in NO emission is also not very significant. This will enable operation at high thermal efficiency. The flame velocity can also be further enhanced by increasing the swirl level using manifold modification. These methods are particularly effective at part load operating condition. As mentioned earlier the presence of CO_2 affects combustion of biogas. Removal of CO_2 from biogas enhances the flame velocity and widens flammability limits. However, this method needs additional devices, which can be used in large stationary applications. Effective removal of CO_2 may be difficult in rural areas with small units are used [25]. Biogas with 41% CO_2 is the normal gas from the biogas plant. The significant improvements in thermal efficiency can be held if best ignition timing is maintained. If the CO_2 is removed from biogas, spark timing has to be retarded to compensate for the reduced ignition lag and leads increased flame speed. In stationary SI engine the peak brake thermal efficiency rises from 26% to 30.4% when the CO_2 level is reduced from 41% to 20%. It is observed that there is significant drop in HC levels when the CO_2 level is reduced to 30%. HC levels are generally high with biogas SI operation [25]. The raise in the concentration of oxygen (O_2) in the charge is more, when CO_2 is reduced, at the same equivalence ratio and this is because the volume occupied by CO_2 that has been removed is mostly taken over by air [24,25]. Of course it is also need to raise the amount of fuel to keep the same equivalence ratio. The increase in O_2 concentration is responsible for the improvement of thermal efficiency; however, it is having an adverse effect on NO emission levels. Since at 10% drop in CO level lowers the HC emission significantly. Thus by removing CO_2 level moderately the engine performance can be improved significantly.

4. Conclusion

From the above study of using biogas in automobiles the observed outlines are given below.

- Biogas is a renewable fuel, derived from the anaerobic digestion of organic wastes or biomass crops, and as such it can contribute to reducing carbon emissions from transport and tackling climate change.
- As a renewable fuel biogas helps to reduce dependence on conventional fossil fuels.
- Biogas is a product of organic waste treatment process, the use of this helps in the management of waste, hence it is both waste treatment and energy production process.
- The exhaust emissions from biogas-fuelled vehicles are relatively low in particulates and nitrogen oxides and hence contribute to improve local air and climate quality.

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