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BIOGAS PRODUCTION AND STORAGE FOR FUELING INTERNAL COMBUSTION ENGINES

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ABSTRACT

Biofuels derived from biomass are considered as good alternative to petroleum fuels. Biogas, a biomass derived fuel can be used in internal combustion (IC) engines, because of its better mixing ability with air and clean burning nature. Biogas is produced by anaerobic digestion of various organic substances such as food waste, agricultural waste, municipal solid waste (MSW), cow dung (CD) etc., which offers low cost and low emissions than any other secondary fuels. It can be a supplemented to liquefied petroleum gas (LPG) and compressed natural gas (CNG), if it is used in compressed form in cylinders. This paper reviews the current status and perspectives of biogas production, including the storage methods and its engine application. Lower hydrocarbon (HC), smoke and particulates emission has been reported in diesel engines operating on biogas diesel dual fuel mode.

Keywords: Anaerobic digestion, biogas, biomass, dual fuel, liquefied biomethane.

1. INTRODUCTION

Production of methane-rich biogas through the AD of organic materials provides a versatile future of renewable energy. Biogas can be used for the replacement of fossil fuels in both heat and power generation thus contributing to reduction of greenhouse gas (GHG) emissions [1]. Anaerobic digestion is a low cost method to convert the organic substances into useful energy. Biogas is generated from the anaerobic decomposition of a wide range of wet organic materials such as FW, AW, MSW, and CD.

1.1 Mechanism of Anaerobic Digestion

AD is a biochemical degradation process, in which biodegradable organic matters are decomposed by bacteria forming gaseous byproduct. The byproduct is consisting of methane (CH_4), carbon dioxide (CO_2), and traces of other gases [2]. AD is a complex process, which can be divided into four stages: hydrolysis, acidogenesis, acetogenesis or dehydrogenation and methanation [3]. In the first stage the hydrolyzing microorganisms converts the polymers and monomers into acetate, hydrogen and some amount of volatile fatty acid (VFA) such as butyrate and propionate [4-6]. Then a complex consortium of hydrolytic microorganisms excretes the elements of organic materials such as cellulose, cellobiase, xylanase, lipase, protease and amylase into amino acids and long chain fatty acids. *Bacteriocides*, *Clostridia*, *Bifidobacteria*, *Streptococci* and *Enterobacteriaceae* are some common bacteria that are found in the digester [7]. The different stages of AD are shown in Fig.1. The higher VFA that are formed by hydrolysing microorganisms are again converted into acetate and hydrogen by obligate hydrogen producing acetogenic bacteria. These bacteria typically characterized as homoacetogenic named as *Acetobacterium woodii* and *Clostridium aceticum* [8]. The metabolism of acetogenic bacteria is inhibited rapidly by the hydrogen accumulation. Therefore, it is essential to maintain an extremely low partial pressure of hydrogen inside the digester for the survival of acetogenic and hydrogen producing bacteria. The daily biogas production can also be increased by adding hydrogen producing bacteria to the digester slurry [7,8]. At the end of biochemical degradation process two groups of bacteria produce CH_4 or hydrogen and CO_2 from acetate. During AD only a few species e.g. *Methanosarcina barkeri*, *Metanonococcus mazei*, and *Methanotrix soehngenii* are able to degrade acetate into CH_4 and CO_2, whereas all other bacteria use the hydrogen to form CH_4 [9,10]. The schematic diagram of biogas plant is shown in Fig.2.

1.2 Parametric Influence on Biogas Production

Several mechanical, thermal, chemical and biological pre-treatment methods have been considered to improve the performance of digester by easy accessible of intermolecular matters to anaerobic micro

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bacteria. The stability of the process and the rate of gas production depend upon the temperature, pH balance, carbon/nitrogen (C/N) ratio, hydraulic retention time (HRT) and organic feed rates [11,12].

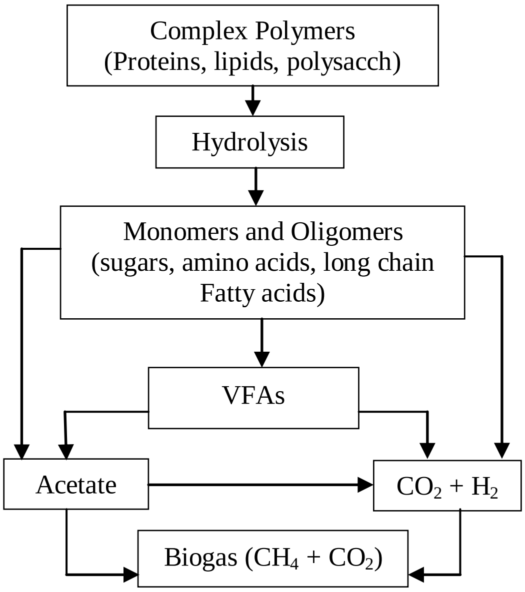

Fig.1. Stages of anaerobic digestion.

CH_4 and CO_2 are the principal gases that are produced during the process of digestion. Small amount of hydrogen sulphide (H_2S) is also produced, which can be characterized by the order of the digester gas [13,14]. Table 1 shows different constituents of biogas. The optimized methane gas production is dependent on the rate of optimized decomposition. Anaerobic bacteria communities can endure temperatures ranging from below freezing to above 57.4 ^oC, but they thrive best at temperatures of about 36.9 ^oC (mesophilic) and 54.6 ^oC (thermophilic). Bacteria activity, and thus biogas production, falls off between about 39.6 ^oC and 51.9 ^oC and gradually from 35.2 ^oC to 5 ^oC [15].

For the optimum growth of the microbes during anaerobic digestion, the suitable pH level of 5.5 to 8.5 has to be maintained by feeding the digester at an optimum loading rate [16]. The amount of CO_2 and VFAs produced during the process of digestion affects the pH of the digester slurry. For normal digestion, the concentration of VFA and acetic acid in the feed stock should be below 2000 mg/lit. The pH level of 5.0-8.5 gives higher CH_4 production of 75% [17].

During AD 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 [18]. HRT is the average time spent by the input feed stock inside the digester before it comes out. Generally the HRT depends upon the tropical climate condition. Shorter HRT is likely to face risk of less active bacterial action while longer HRT requires larger volume of digester and hence requires high capital investment. For mesophilic digestion where temperature varies from 25-40 ^oC the HRT is greater than 20 days [19].

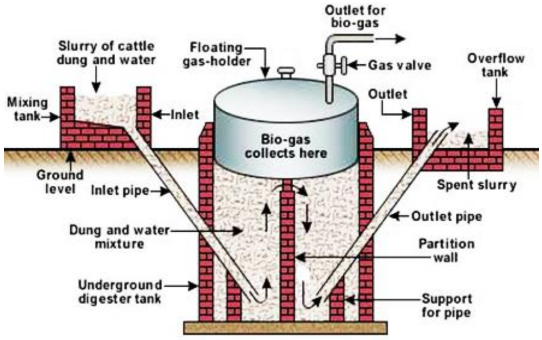

Fig.2. Schematic diagram of biogas plant [20].

Table 1: Different constituents of biogas

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

Biogas can be used as a good alternative fuel for internal IC engine applications. In oil crisis situations, it may act as a promising alternative fuel, especially for diesel engines. This can substitute a considerable amount of fossil fuel. Diesel engines can be easily converted to fumigated dual fuel engines. Fumigation technique is the most practical and efficient method to utilize high ignition temperature alternative fuels, such as biogas [21]. Table 2 shows the detailed properties of biogas. In the fumigated dual fuel method, biogas mixes with air, before the mixture enters into the combustion chamber. At the end of the compression stroke, a certain amount of diesel, called the pilot fuel is injected into the cylinder 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 a critical operation [22]. Because of these benefits, dual fuelling of diesel and biogas has been investigated worldwide in recent decades [23-26].

In the present scenario, it is a great need to use biogas as a transport vehicle fuel. This can be done by compressing biogas in the cylinders after removing its CO_2, H_2S and water vapor components [27]. Pilot level trials to liquefy the biogas were carried out by a number of earlier investigators. This paper reviews the efforts made to improve the quality of biogas by removing CO_2, H_2S and storing it in cylinders, in order to making it viable as a transport vehicle fuel similar to compressed natural gas (CNG). Also attention is focused on storing biogas with moderate pressure in gas bags, for stationary IC engine applications.

Table 2: Properties of biogas [14]

Properties	Parametric values
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 °C
Critical pressure	75-89 bar
Critical temperature	-82.5 °C
Normal density	1.2 kg/m^3
Flame speed	25 cm/s
Odour	Bad eggs (the smell of H_2S)

2. STORAGE MECHANISM

There are two basic reasons for storing biogas, one is for later onsite usage and the other one is before and after transportation to offsite distribution points. Biogas can be stored at low, medium, and high pressures. The density of biogas is approximately 1.2 kg/m^3, which is proximate to air at ambient condition [14]. Hence, it requires a larger volume to store instead in compressed form. The critical pressure and temperature is of 75-98 bar and -82.5 °C. This indicates that it can change its gaseous phase to liquid phase, when compressed up to the critical state. Basically, methane is the main constituent in biogas to make it energy equivalent. Biogas contains CO_2 19% by volume, 37.38% by mass and H_2S 20 ppm by volume basis. Biogas can be transportable via pipeline or by cylinders only after removing CO_2, H_2S and water vapor [28].

Various techniques have been developed for the separation of CO_2 from biogas, such as absorption by chemical solvents, cryogenic separation, physical separation, CO_2 fixation by biological or chemical process and membrane separation [27-29]. There are also techniques to remove H_2S such as physical absorption on solid adsorbents, conversion to base sulphur or low solubility metal sulphides and chemical absorption in aqueous solution [30,31].

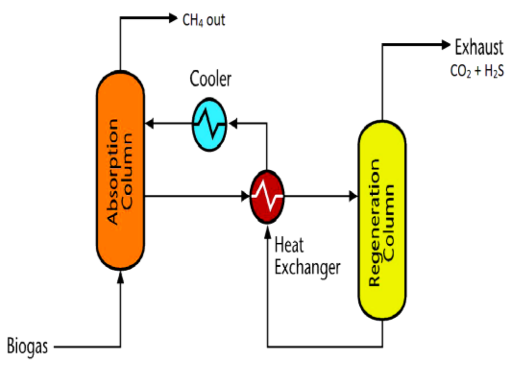

Fig.3. Biomethane scrubbing by chemical solvent [32].

2.1 CO_2 and H_2S Scrubbing

CO_2 removal from biogas can be done by using chemical solvents like mono-ethanolamine (MEA), di-ethanolamine and tri- ethanolamine or aqueous solution of alkaline salts, i.e. sodium, calcium hydroxide and potassium [27]. Biogas bubbled through 10% aqueous solution of MEA can reduce the CO_2 content from 40 to 0.5-1.0% by volume [33]. Chemical agents like NaOH, $Ca(OH)_2$, and KOH can be used for CO_2 scrubbing from biogas. In alkaline solution the CO_2 absorption is assisted by agitation. NaOH solution having a rapid CO_2 absorption of 2.5-3.0% and the rate of absorption is affected by the concentration of solution [34]. Table 3 shows the biogas composition before and after treatment with NaOH, $Ca(OH)_2$, and MEA. Fig.3. shows the biomethane scrubbing by chemical solvent method.

Table 3: Biogas composition after treatment with NaOH, $Ca(OH)_2$, and MEA [35].

Gases in biogas	Initial value	NaOH	$Ca(OH)_2$	MEA
CH_4 (%)	53.1	95.5	95.0	98.0
CO_2 (%)	46.8	3.2	4.0	1.3
H_2S (ppm)	2150	0	0	0

CO_2 removal from biogas by cryogenic separation method involves the separation of gas mixtures by fractional condensation and distillation at low temperature. In this method, the biogas is compressed by a multi stages compressor up to 80 bar and then cooled with chillers maintained at -45 °C. The CO_2 in the chillers condenses and a purity of 97% CH_4 gas is obtained [36]. The biomethane scrubbing using cryogenic separation technique is shown in Fig.4.

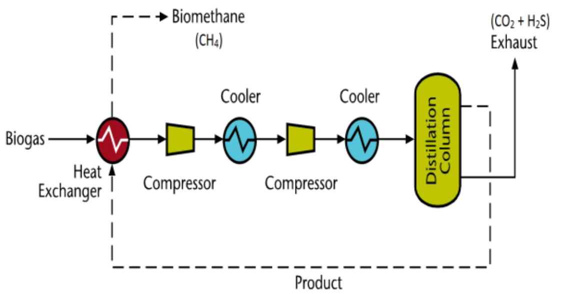

Fig.4. Biomethane upgrading using cryogenic separation technique [37].

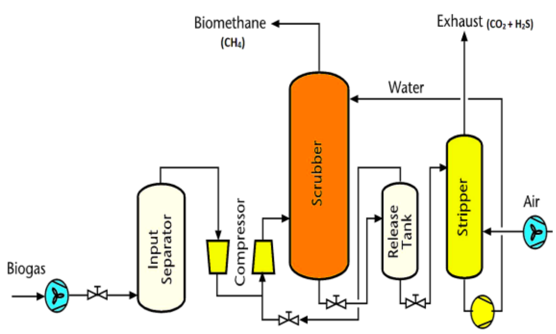

Fig.5. Water scrubbing biogas up gradation technique [37].

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In physical separation pressurized water is used as absorbent, as both CO_2 and H_2S are water soluble agents. Fig.5. shows the water scrubbing method for biogas up gradation. The rate of CO_2 and H_2S absorption depends upon the factors such as, gas flow pressure, composition of biogas, water flow rates, and purity of water and dimension of scrubbing tower. A purity of 100% CH_4 is obtained by a pressurized water scrubbing tower with counter current [38]. A reduction of CO_2 from 30% to 2% in biogas is achieved, when the gas flow rate was $1.8m^3/h$ at 0.48 bar pressure and water flow rate was of $0.465m^3/h$ in a continuous counter current type scrubber [39]. Compressed biogas at 5.88 bar pressure while passed through a 6 m high scrubbing tower at a flow rate of $2m^3/h$ gives 87.6% removal of CO_2 [40].

Solid membrane of acetate-cellulose polymer has permeability for CO_2 and H_2S is 20 to 60 times greater than CH_4, when the biogas flow pressure is maintained at 25-40 bar. Generally the membrane permeability is <1 mm. For higher methane purity the permeability must be high [36]. Monsanto and acetate cellulose membranes give best separation to CO_2, O_2 and H_2S than CH_4 when temperature and pressure was maintained at 25 ^oC and 5.50 bar respectively [41]. Naturally occurred solid Zeolite-Neopoliton Yellow Tuff (NYT) can adsorb 0.4 kg of CO_2 per kg of chabazite at 1.50 bar and 22 ^oC. During this adsorption process H_2S content is also removed out [42]. The addition of $FeCl_3$ to the digested slurry can reduce H_2S up to 10 ppm [27,42]. Fig.6 shows the membrane separation technique for the upgraded biogas production.

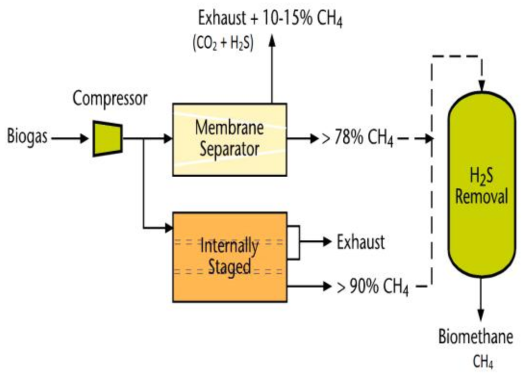

Fig.6. Shows the membrane separation technique for upgraded biogas production [43].

Table 4: Economics comparison of different scrubbing technologies [44].

Biomethane scrubbing technology	Cost economics(Rs./m^3 biogas)
Chemical absorption	12.36
Cryogenic separation	31.99
Water scrubbing	9.45
Membrane	12.36

This study also gives the information on the capital and operating costs of biogas clean up technologies as given in Table 4. The cost comparisons for the scrubbing methodologies will provide a helpful look at the relative costs of the technologies for a better future implementation and modification.

2.2 Biogas Storage

2.2.1 Low Pressure Storage

Floating drum gas holders on the digesters form low pressure storage option. These storage systems typically operate at pressure up to 0.137 bar and maximum temperature of 50 ^oC. These floating gas holders can be made of steel, flexible fabric, fiberglass and poly vinyl chloride (PVC). The least expensive and trouble free gas holder is inflatable fabric top, as it does not react with H_2S. The flexible fabric gas holders are commonly of high density polyethylene (HDPE), low density polyethylene (LDPE), linear low density polyethylene (LLDPE) and chlorosulfonated polyethylene covered polyester. The thickness of these materials varies from 0.5-2.5 millimeter [45].

2.2.2 *Medium Pressure Storage*

Biogas can also be stored at medium pressure between 0.137-13.78 bar. This can be done only by compressing with a two stage compressor having an intercooler. Biogas can be stored in typical propane gas tanks at 17.23 bar pressure. Compressing to 17.23 bar pressure range uses about 5 kWh per 304 m^3 of biogas. As biogas is of 60% methane and heating rate of 14348 kJ/kWh, the energy needed for compression is about 10% of the energy content of the stored biogas [27,45].

2.2.3 *High Pressure Storage*

Biogas can be stored as compressed biomethane (CBM) after purification. At high pressure storage gas scrubbing is important because impurities like H_2S and water vapor are likely to condense and cause corrosion. The cost of compressing biogas to high pressure between 137.89 bar and 344.73 bar is much greater than the cost of compressing gas for medium pressure storage. Because of this high cost biogas is upgraded to biomethane [27]. Compressing biogas to 137.89 bar requires nearly 14 kWh per 304 m^3 of biomethane. If the biogas is upgraded to 97% CH_4 and assumed heat rate is 12660.67 kJ/kWh, the energy needed for compression is 17% of the energy content of the gas [45].

2.3 Biomethane Storage

After removal of CO_2, H_2S and water vapor from the biogas, the product remains is called as biomethane. Biomethane can be liquefied, creating a product known as liquefied biomethane (LBM). The advantage of LBM is that, it can be transported easily and can be dispensed to either liquefied natural gas (LNG) or CNG vehicles. The main disadvantage with LBM is that, the cryogenic liquid will heat up during storage, which results in loss of LBM by evaporation through release valve of tank. Storage of LBM for a longer period results an economically unacceptable level of evaporative loss. So

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LBM should be used fairly quickly after production [45]. Table 5 shows some of the biogas and biomethane storage devices with variety range of pressure and material.

3. BIOGAS ENGINE APPLICATION

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

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. Being a clean fuel biogas causes clean combustion and recesses contamination of engine oil. Biogas cannot be directly used in automobiles as it contains some other gases like CO_2, H_2S and water vapor. For use of biogas as a vehicle fuel, it is first upgraded by removing impurities like CO_2, H_2S and water vapor. After removal of impurities it is compressed in a three or four stage compressor up to a pressure of 20 MPa and stored in a gas cascade, which helps to facilitate quick refueling of cylinders. If the biogas is not compressed than the volume of gas contained in the cylinder will be less hence the engine will run for a short duration of time.

3.1 Biogas SI Engine Applications

Biogas fuel allows the use of high compression ratios in SI engines on account of its high self-ignition temperature. In addition with its wide flammability limit permit operation with lean mixtures. Lean operation can also lead to low NO_X levels. The high flame velocity of scrubbed biogas (CH_4) in comparison to conventional fuels will lead to higher increased combustion rate and thus lead to high thermal efficiency [46]. If biogas is directly used in SI engine, the presence of CO_2 lowers its calorific value. Biogas also contains a small percentage of H_2S, which can cause corrosion to metal parts. The simulated biogas compression ratio engine has a compression ratio in the range of 11:1 to 13:1, which is suitable for normal operation without knock. The performance of biogas fuelled SI engine can be increased by scrubbing CO_2, H_2S. The NO emission is found to be less significant in an engine with a higher compression ratio of 13:1. The use of LBM enhances the flame velocity and widens flammability limit [47]. Biogas with 37.38% CO_2 by mass is the normal gas from the biogas plant. Significant improvements in thermal efficiency can be achieved, if a minimum best timing (MBT) is maintained properly. By removing CO_2 from biogas, spark timing has to be retarded to compensate for the reduced ignition lag and increased flame speed [46]. Peak brake thermal efficiency increases from 26.2 to 30.4% when the CO_2 level is reduced from 41 to 20%. When CO_2 level is reduced to 30% the HC level drops significantly. Generally, the HC emission is found to be more with the biogas SI operation. The drop in the HC emission may be due to the concentration of oxygen in the charge when CO_2 reduced at the same equivalence ratio. Because the volume occupied by CO_2 that has been removed mostly by air. The increase in the O_2 concentration is responsible for the drop in HC and has an adverse effect on the NO emission level. Again, 10% drop in the CO level lowers the HC emission significantly. Thus by removing CO_2 from biogas the engine performance can be increased significantly [47].

3.2 Biogas CI Engine Applications

Biogas generally has a high self-ignition temperature hence; it cannot be directly used in a CI engine. So it is useful in dual fuel engines. The dual fuel engine is a modified diesel engine in which usually a gaseous fuel called the primary fuel is inducted with air into the engine cylinder. This fuel and air mixture does not auto ignite due to high octane number. A small amount of diesel, usually called pilot fuel is injected for promoting combustion. The primary fuel in dual fuelling system is homogeneously mixed with air that leads to very low level of smoke [48]. Dual fuel engine can use a wide variety of primary and pilot fuels. The pilot fuels are generally of high cetane fuel.

Biogas can also be used in dual fuel mode with vegetable oils as pilot fuels 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 significant improvements in the performance of biogas dual fuel engines [49]. The ignition delay of the pilot fuel generally increases with the introduction of biogas and this will lead to advance the injection timing. Injectors opening pressure and rate of injection also are found to play important role in the case of biogas fuelled engine, where vegetables oil is used as a 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 a superior performance as compared to a dual fuel mode of operation.

As explained earlier biogas needs a high cetane fuel for dual fueling mode. The high cetane fuel may be diesel, biodiesel or straight vegetable oil (SVO). Jatropha oil has a high viscosity and low volatility as compared to diesel, hence leads to low thermal efficiency and high HC and smoke emission. In order to improve the combustion of jatropha oil, the injection timing and rate of injection are to be advanced [48]. When the methane concentration in a primary fuel is increased, there is a good improvement in thermal efficiency due to enhanced combustion rate. Hence reduction of CO_2 level of 15% in biogas improves the engine performance and the HC emission reduces significantly. Dual fuel mode with LBM, the HC level is always higher, because of premixed fuel and air. In this case the inducted charge is always lean that leads to partial combustion. The smoke number is found to be reduced, as well as CO_2 by induction of biogas to the engine [50]. Thus biogas can be used in a CI engine effectively in dual fuel mode with a high cetane pilot fuel injection.

3.3 Biogas HCCI Engine Applications

The HCCI concept is a potential for achieving a high thermal efficiency and low NO emission. The HCCI engine with 50 % biogas as a primary fuel and 50% diesel as pilot fuel gives a maximum NO of 20 ppm is a major advantage over biogas diesel dual fuel mode. In biogas diesel dual fuel mode the presence of CO_2 in biogas lowers the thermal efficiency however, in biogas diesel HCCI (BDHCCI) mode CO_2 reduces high heat release rate. The break mean effective pressure (BMEP) in BDHCCI mode is in the range of 2.5 bar to 4 bar. The smoke and HC level were also low when the biogas is used as a primary fuel for BDHCCI mode [51]. For HCCI operation the inducted charge temperature is required to be maintained at 80-135 ^oC, which can be obtained from the exhaust heat. Thus biogas with HCCI engine gives high efficiency and low emission [21].

The comparison of performance and emission characteristics of biogas fuelled engines with diesel/gasoline at full load condition is given in Table 6.

4. CONCLUSIONS

The study concludes the potential explore of biogas production from various organic biomass wastes. Attention is also focused for making biogas as a transport vehicle and stationary engine fuel by storing it in cylinders and reinforced plastic bags. Different techniques for CO_2, H_2S scrubbing are discussed, among which water scrubbing is a simple continuous and cost effective method. This gives 87.6% and 100% pure methane with biogas flow rates of 2 m^3/hr and 1.8 m^3/hr respectively. Study shows that monsanto and acetate cellulose membranes give best separation to CO_2, O_2 and H_2S at pressure and temperature of 5.5 bar and 25 ^oC. Cryogenic separation gives 97% pure methane by condensing CO_2 at -45 ^oC. In biogas SI operation, the thermal efficiency is improved from 26.2% to 30.4%, when there is 21% reduction of CO_2 in biogas. Dual fueling is recommended to be the best one for biogas CI operation. Drop of 15% CO_2 in biogas for dual fueling increases the thermal efficiency of 22%. Also the HC and smoke level are reduced significantly. In biogas HCCI mode, the presence of CO_2 controls the high heat release rate, hence the durability of engine components will not be affected. The NO emission in HCCI engine is of maximum up to 20 ppm is observed.

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Table 5: Biomethane and biogas storage options.

Purpose	Pressure (bar)	Storage device	Material	Size (m^3)
Short and intermediate storage for on farm use	< 0.006	Floating cover	Reinforced and non-reinforced rubbers and plastics.	Variable volume (for one day production)
	< 0.137	Gas bag	Reinforced and non-reinforced rubbers and plastics.	45.72 – 3,352.8
	0.13-0.4	Water sealed gas holder	Steel.	1066.8
		Weighted gas bag	Reinforced and non-reinforced rubbers and plastics.	268.2 – 8,534.4
		Floating roof	Plastic, reinforced plastic.	Variable volume (for one day production)
Later on- or off- farm use	0.68-200	Propane or butane tanks	Steel.	609.6
	> 200	Commercial gas cylinders	Alloy steel.	106.68

Table 6: Comparison of performance and emission characteristics of biogas fuelled engines with diesel/gasoline at full load condition.

Fuel type	Test engine specefication	Mode of fuel used	BTE	SFC/SEC	EGT	HC	CO	NO	Smoke	Reference
Biogas (80% pure CH_4)	4 stroke, air cooled, single cylinder CI engine modified to run in the SI mode, 4.4kW, 1500rpm.	Sole	↑	↓	↑	↓	↓	↑	↓	[47]
Biogas+diesel	single cylinder, watercooled, DI, diesel engine, 3.7 kW at 1500 rpm.	Dual (HCCI)	↓	NA	↓	↑	↓	↓	↓	[21]
Biogas+diethyl ether (DEE)	Single cylinder, water cooled, direct injection CI engine, 3.7 kW, 1500 rpm.	Dual (HCCI)	↑	NA	↑	↓	↓	↓	NA	[54]
Biogas	Four stroke, air cooled, single cylinder, CI engine modified to run in the SI mode, 4.4kW, 1500rpm. (High compression ratio).	Sole	↑	↓	↑	↑	↑	↑	↓	[55]
Biogas+biodiesel	Four cylinder, four stroke, turbocharged, prechamber CI engine, 46 kW, 4000 rpm.	Dual	↓	↑	↓	↑	↑	↓	↓	[56]
Hydrogen	Four stroke,		↑	↓	↑	↓	↓	↑		

	water-cooled, single cylinder, SI Engine, 13 bhp, 2500 rpm.	Sole							NA	[57]
Biogas+hydrogen	Four stroke, Single cylinder, air cooled, CI engine modified to run in the SI mode, 4.4kW, 1500rpm.	Dual	↑	↓	↑	↓	↓	↑	↓	[58]