# Anaerobic Digestion of Kitchen Wastes: "Biogas Production, Purification and Application in I.C Engines"

N.H.S.Ray
*Dept.of Mech.Engg.CEB, BBSR, Odisha, India*

M.K.Mohanty
*Dept.of FMP, CAET, OUAT, BBSR, Odisha, India*

R.C.Mohanty
*Dept.of Mech.Engg.CUTM, BBSR, Odisha, India*

**Abstract- Currently, much of our biodegradable wastes such as kitchen wastes, agricultural wastes & animal wastes are used to produce Biogas, a powerful greenhouse gas. Anaerobic digestion (AD) is a treatment that composts these wastes in the absence of oxygen, producing a biogas that can be used to generate Heat & Power. Producing renewable energy from our biodegradable wastes helps to tackle the energy crisis. AD produces biogas of around 60 per cent methane, 30 percent carbon dioxide ($CO_2$), 2 percent hydrogen sulphide ($H_2S$) and other constituents. As well as biogas, AD produces a solid and liquid residue called digestate which can be used as a soil conditioner to fertilise land. The amount of biogas and the quality of digestates obtained will vary according to the feedstock used. More gas will be produced if the feedstock is more liable to decompose. For application as a fuel in I.C Engines it is required to remove carbon dioxide ($CO_2$) and hydrogen sulphide ($H_2S$), because $H_2S$ corrodes vital mechanical components of engine and $CO_2$ reduces heating effect if it is not removed. Therefore Biogas is required to be upgraded through purification by removing $H_2S$ and $CO_2$.**

**Keywords: Anaerobic digestion, kitchen wastes, volatile fatty acid, I.C Engines**

## I.INTRODUCTION

The continuous generation of municipal wastes and kitchen wastes has become an environmental and social concern due to the large impacts of its improper treatment and management. Rapid biodegradation of the organic wastes is of key importance to identify environment in more responsible way to process it rather than land filling or composting it. Anaerobic digestion has the advantage of biogas production and can lead to efficient resource recovery and contribution to the conservation of non-renewable energy sources. Even though proven to be effective for treating organics, anaerobic digestion plants are facing difficulties in obtaining fairly clean feedstock that results in technical difficulties with the equipment and poor compost quality. Biogas is developed from the biodegradation of organic materials in absence of oxygen and consists of mainly methane, hydrogen sulphide and carbon dioxide. There have been continuous efforts in research work for alternative fuel source, development and demonstration to utilize biogas to provide heat and power for the past several decades. Biogas can be upgraded through purification and can be used as an alternative to the partial or total substitution of petrol and diesel fuels in I.C engines without requiring extensive engine adjustments or modifications. In this study we have reviewed the anaerobic digestion reactions of kitchen wastes, biogas production, purification and application in I.C engines along with the exhaust emission.

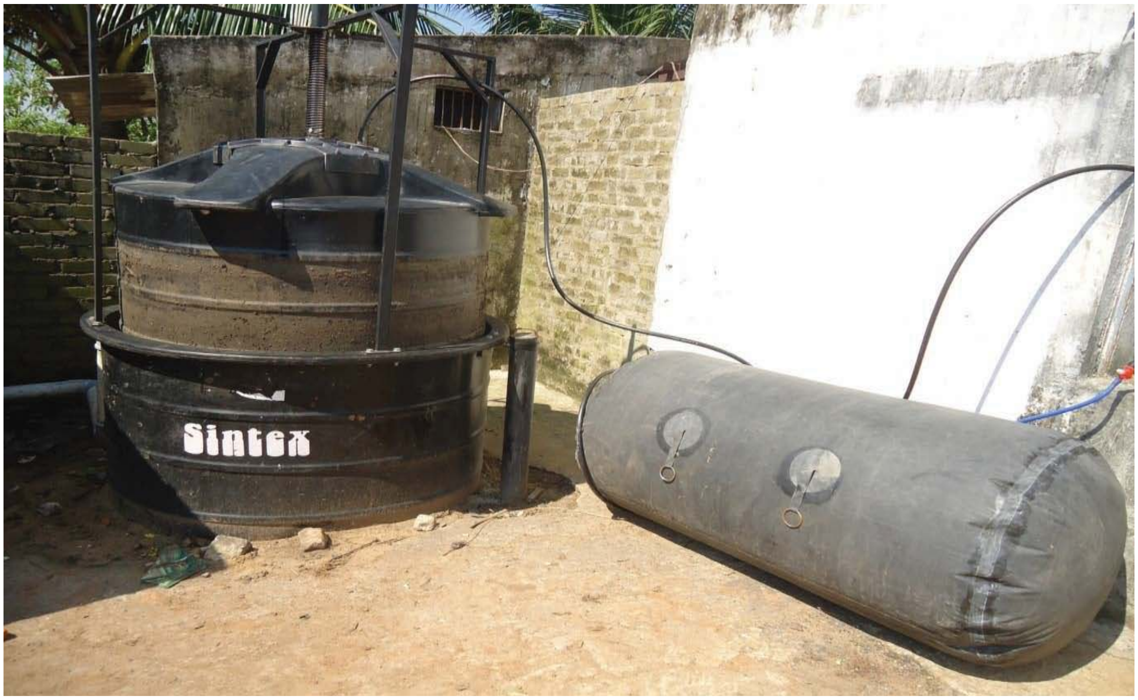


Fig.1 Anaerobic digestion of kitchen wastes

## II. ANAEROBIC DIGESTION

Anaerobic digestion (AD) is a microbial decomposition of organic matter into methane, carbon dioxide, inorganic nutrients and compost in absence of oxygen. This process is also known as bio-Methanogenesis. In the generalized scheme of the anaerobic digestion, the feedstock is collected, coarsely shredded and placed into a reactor with active inoculums of methanogenic microorganisms. Generally three main reactions occur during the entire process of the anaerobic digestion to methane: hydrolysis, acid forming and methanogenesis. Although AD can be considered to take place in three stages all reactions occur simultaneously and are interdependent.

*2.1 Hydrolysis-*

Hydrolysis is a reaction that breaks down the complex organic molecules into soluble constituents. This reaction is catalyzed by enzymes excreted from the hydrolytic and fermentative bacteria. End products of this reaction are soluble sugars, amino acids; fatty acids.

The approximate chemical formula for organic waste is $C_6H_{10}O_4$ (Shefali & Themelis 2002)

Hydrolysis reaction of organic fraction is represented by following reaction:

$C_6H_{10}O_4 + 2H_2O \rightarrow C_6H_{12}O_6 + 2H_2$ (Ostrem & Themelis 2004).

*2.2 Acid-forming stage-*

This stage is facilitated by microorganisms known as acid formers that transform the products of the hydrolysis into simple organic acids and alcohol, carbon dioxide and hydrogen.

Acid forming stage comprises two reactions, fermentation and the acetogenesis reactions. During the fermentation the soluble organic products of the hydrolysis are transformed into simple organic compounds, mostly volatile (short chain) fatty acids.

Typical reactions occurring at this stage are the following

- Conversion of the glucose to ethanol:
- Conversion of the glucose to propionate: (Ostrem & Themelis 2004)

The acetogenesis is completed through carbohydrate fermentation and results in acetate, $CO_2$ and $H_2$, compounds that can be utilized by the methanogens. The presence of hydrogen is critical importance in acetogenesis of compounds such as propionic & butyric acid. These reactions can only proceed if the concentration of $H_2$ is very low (Ralph & Dong 2010). Thus the presence of hydrogen scavenging bacteria is essential to ensure the thermodynamic feasibility of this reaction (Ostrem & Themelis 2004).

*2.3 Methanogenesis-*

Methanogenesis is a reaction facilitated by the methanogenic microorganisms that convert soluble mater into methane. Two thirds of the total methane produced is derived converting the acetic acid or by fermentation of alcohol formed in the second stage such as methanol. The other one third of the produced methane is a result of the reduction of the carbon dioxide by hydrogen. Considering that the methane has high climate change potential the goal is to find an alternative in order to lower the environmental foot print of the organic waste treatment. Therefore this stage is avoided and instead of methane the production of volatile fatty acids is targeted.

The reactions that occur during this stage are as follows (Ostrem & Themelis 2004).

- Acetate conversion:

$$2CH_3CH_2OH + CO_2 \leftrightarrow 2CH_3COOH + CH_4$$

Followed by: $CH_3COOH \leftrightarrow CH_4 + CO_2$

- Methanol conversion:

$$CH_3OH + H_2 \leftrightarrow CH_4 + H_2O$$

- Carbon dioxide reduction by hydrogen

$$CO_2 + 4H_2 \leftrightarrow CH_4 + H_2O$$

## III. COMPOSITION OF BIOGAS

The composition of biogas depends on a number of factors such as the process design and the nature of the substrate that is digested. The main components are methane and carbon dioxide, but several other components also exist in the biogas. The table-1 below lists the composition of Biogas in Anaerobic digestion.

Table-1Approximate Biogas Composition in Anaerobic Digestion

| Gas | Concentration % |
|---|---|
| $CH_4$ | 50-70 |
| $CO_2$ | 25-30 |
| $N_2$ | 0-10 |
| $H_2O$ | 0-5 |
| $H_2S$ | 0-3 |
| $O_2$ | 0-3 |
| $C_xH_y$ | 0-1 |
| $NH_3$ | 0-0.5 |
| $R_2SiO$ | 0-50 mg/m3 |

## IV. PURIFICATION OF BIOGAS FOR I.C ENGINES

*4.1 Removal of $CO_2$ -*

$CO_2$ is high corrosive when wet and it has no combustion value so its removal is must to improve the biogas quality. The processes to remove $CO_2$ are as follows

a) Caustic solution, NAOH- 40% $NAOH + CO_2 = NAHCO_3$

b) Refined process, $K_2CO_3$ - 30 % $K_2CO_3 + CO_2 = 2KCO_3$

$CO_2$ 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. Biogas bubbled through 10% aqueous solution of MEA can reduce the $CO_2$ content from 40 to 0.5-1.0% by volume. 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.

*4.2 Removal of $H_2S$ -*

In physical separation pressurized water is used as absorbent, as both $CO_2$ and $H_2S$ are water soluble agents. The water scrubbing method is used 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% $CH_4$ can be obtained by a pressurized water scrubbing tower with counter current. 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 0.465$m^3$/h in a continuous counter current type scrubber. Compressed biogas at 5.88 bar pressure while passed through a 6 m high scrubbing tower at a flow rate of 2$m^3$/h gives 87.6% removal of $CO_2$. 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. 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℃ and 5.50 bar respectively. Naturally occurred solid Zeolite-Neopoliton Yellow Tuff (NYT) can absorb 0.4 kg of $CO_2$ per kg of chabazite at 1.50 bar and 22°C. During this adsorption process $H_2S$ content is removed out.

## V. BIOGAS IN I.C ENGINE APPLICATIONS

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. Petrol engines can use biogas directly and Diesel engines require combination of biogas and diesel oil for combustion. 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 I.C engines as it contains some other gases like $CO_2$, $H_2S$ and water vapour. For use of biogas as a fuel, it is first upgraded by removing impurities like $CO_2$, $H_2S$ and water vapour. 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 refuelling 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.

### *5.1 Properties of Biogas for Engine Performance-*

The actual calorific value of biogas is function of the $CH_4$ percentage, the temperature and the absolute pressure, all of which differ from case to case. The actual calorific value of biogas is a vital parameter for the performance of an engine. The consumption of biogas in actual volume will differ from these data according to the actual conditions of biogas fed to the engine in terms of temperature, pressure and $CH_4$ content. Determining of actual biogas consumption is vital for dimensioning the engine.

### *5.2 Technical Parameters of Biogas for Engine Performance-*

Technical parameters of biogas are very important because of their effect on the combustion process in an engine. Those properties are:-

→ Ignitability of $CH_4$ in mixture with air: $CH_4$: 5...15 Vol. %, Air: 95...85 Vol. %

→Combustion velocity in a mixture with air at p = 1 bar: cc = 0.20 m/s at 7% $CH_4$, cc = 0.38 m/s at 10% $CH_4$

→The combustion velocity is a function of the volume percentage of the burnable component, here $CH_4$. The highest value of cc is near stoichiometric air/fuel ratio, mostly at an excess air ratio of 0. 8 to 0.9. It increases drastically at higher temperatures and pressures.

→ Temperature at which $CH_4$ ignites in a mixture with air Ti = 918K ... 1023 K

→Compression ratio of an engine, 'e' at which temperatures reach values high enough for self-ignition in mixture with air($CO_2$ content increases possible compression ratio) e = 15...20

→Methane number, which is a standard value to specify fuel's tendency to knocking (uneven combustion and pressure development between TDC and BDC). Methane and biogas are very stable against knocking and therefore can be used in engines of higher compression ratios than petrol engines.

→Stoichiometric air/fuel ratio on a mass basis at which the combustion of $CH_4$ with air is complete but without unutilized excess air.

### *5.3Problems to use Biogas in I.C Engines-*

→High $CO_2$ content reduces the power output, making it uneconomical as a transport fuel. It is possible to remove the $CO_2$ by washing the gas with water. The solution produced from washing out the $CO_2$ is acidic and needs careful disposal.

→$H_2S$ is acidic and if not removed can cause corrosion of engine parts within a matter of hours. It is easy to remove $H_2S$, by passing the gas through iron oxide ($Fe_20_3$ -rusty nails are a good source) or zinc oxide (ZnO). These materials can be re-generated on exposure to the air, although the smell of $H_2S$ is unpleasant.

→There is high residual moisture which can cause starting problems.

→The gas can vary in quality and pressure.

*5.4 Biogas in petrol engine-*

In the case of operation of spark ignition engine compression ratio can even be raised to 13:1 because of the high self-ignition temperature of biogas. 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. Biogas with 40% $CO_2$ 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. 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. 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. Thus by removing $CO_2$ level moderately the engine performance can be improved significantly.

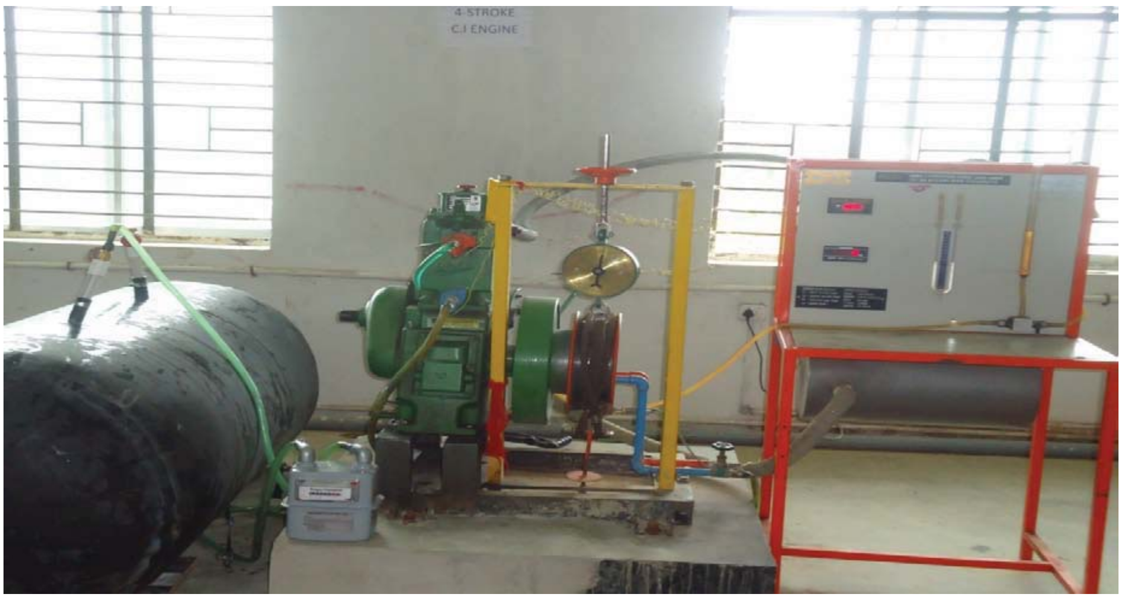


Fig.2 Biogas in Diesel Engine Application

*5.5 Biogas in Diesel Engine Application-*

Biogas generally has a high self-ignition temperature hence; it cannot be directly used in a diesel 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. 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. 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 diluents 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.

*5.6 Biogas in Dual Fuel Engine Application-*

In this case, the normal diesel fuel injection system still supplies a certain amount of diesel fuel. The engine however sucks and compresses a mixture of air and biogas fuel which has been prepared in external mixing device. The mixture is then ignited by and together with the diesel fuel sprayed in. The amount of diesel fuel needed for sufficient ignition is between 10% and 20% of the amount needed for operation on diesel fuel alone. Operation of the engine at partial load requires reduction of the biogas supply by means of a gas control valve. A simultaneous reduction of airflow would reduce power and efficiency because of reduction of compression pressure and main effective pressure. So, the air/fuel ratio is changed by different amounts of injected biogas. All other parameters and elements of diesel engine remain unchanged.

*5.6.1 Modification of Diesel Engine into Dual Fuel Engine-*

Advantages

→Operation on diesel fuel alone is possible when biogas is not available.

→ Any contribution of biogas from 0% to 85% can substitute a corresponding part of diesel fuel while performance remains as in 100% diesel fuel operation.

→Because of existence of a governor at most diesel engines automatic control of speed/power can be done by changing the amount of diesel fuel injection while the biogas flow remains uncontrolled. Diesel fuel substitutions by biogas are less substantial in this case.

Limitations

→The dual fuel engine cannot operate without the supply of diesel fuel for ignition.

→The fuel injection jets may overheat when the diesel fuel flow is reduced to 10% or 15% of its' normal flow. Larger dual fuel engines circulate extra diesel fuel through the injector for cooling.

→To what extent the fuel injection nozzle can be affected is however a question of its' specific design, material and the thermal load of the engine, and hence differs from case to case.

→A check of the injector nozzle after 500 hours of operation in dual fuel is recommended.

*5.6.2 Performance and Operation Parameters-*

The performance of diesel gas engines in dual fuel mode has been found o be almost equal to the performance using diesel fuel alone as long as the calorific value of biogas is not too low. The inlet channel and manifold of diesel engine are dimensioned in such a way that at the maximum speed and power output of the engine sufficient air can be sucked in to obtain an air/diesel fuel ratio, which is optimal for operation at this point. When the diesel fuel is reduced and an air/biogas mixture is sucked instead of air alone, part of the air is replaced by biogas. With less air fed to the engine ad an excess air ratio necessarily maintained at $\lambda$ = 1,2...1,3 the total fuel input will be less than the fuel input in diesel operation. As a result in this reduction in both air and fuel, the maximum power output at high speed in dual fuel mode may be less than in diesel fuel operation. This decrease is less significant than in modified petrol engines. For operation in medium and low speeds the air inlet is larger than necessary and allows a relatively larger amount of air/fuel mixture to be sucked in. Hence the power output will not be significantly lower than in diesel operation.

*5.7 Biogas in HCCI Engine Application-*

The Homogeneous Charge Compression Ignition (HCCI) concept is a potential for achieving a high thermal efficiency and low Nitrogen Oxide (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 Hydro Carbon (HC) level were also low when the biogas is used as a primary fuel for BDHCCI mode. For HCCI operation the inducted charge temperature is required to be maintained at 80-135°C, which can be obtained from the exhaust heat. Thus biogas with HCCI engine gives high efficiency and low emission.

## VI. EXHAUST EMISSION

The exhaust emission contains three specific substances which contribute the air pollution, hydrocarbon, carbon monoxide & oxides of nitrogen. Hydrocarbons are the unburned fuel vapour coming out with the exhaust due to incomplete combustion. Hydrocarbon also occurring in crankcase by fuel evaporation. The emission of hydrocarbon is closely related to many design &operating factors like induction system, combustion chamber design, air fuel ratio, speed, load. Lean mixture lower hydrocarbon emission. Carbon monoxide occurs only in engine exhaust. It is the product of incomplete combustion due to insufficient amount of air in air- fuel mixture. Some amount of CO is always present in the exhaust even at lean mixture. When the throttle is closed to reduce air supply at the time of starting the vehicle, maximum amount of CO is produced. Oxides of nitrogen are the combination of nitric oxide & nitrogen oxide &availability of oxygen are the two main reasons for the formation of oxides of nitrogen. With biogas, co emission levels are low than that of gasoline.

## VII. CONCLUSION

The study concludes the biogas production from organic wastes, its' composition and properties for use in C.I Engines. Different techniques for $CO_2$, $H_2S$ scrubbing are discussed, among which water scrubbing is a simple continuous and cost effective method for purification. The study carried out in this review has shown that the anaerobic digestion of kitchen waste is a feasible alternative to biogas generation. This finding is of special importance because this lowers the operating costs, decreases the capital and operating costs of the anaerobic digestion of source-separated kitchen waste, and reduces the greenhouse gas emissions of both processes. Attention is also focused for making biogas as alternate fuel in I.C Engines and dual fuelling is recommended to be the best one for biogas engine operation. Drop of $CO_2$ in biogas for dual fuelling increases the thermal efficiency. 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. Therefore it is recommended to use biogas as alternate fuel in I.C engines.

## REFERENCES

[1] Parkin, G.F. & Owen, W.F., 1986. "Fundamentals of Anaerobic Digestion of Wastewater Sludge" Journal of Environmental Engineering", 112(5), pp.867-920.

[2] Jiang C, Liu T, Zhong J. A study on compressed biogas and its application to the compression ignition dual-fuel engine. Biomass, vol. 20, pp. 53–59, 1989.

[3] Leif G, Pal B, Bengt J, Per S. Reducing CO2 emission by substituting biomass for fossil fuels. Energy, vol. 20, pp. 1097–1103, 1995.

[4] Henham A, Makkar MK. Combustion of simulated biogas in a dual fuel diesel engine. Energy Conversion and Management, vol. 39, pp. 2001–2009, 1998.

[5] Kim, H.S., Kim, Y.J., Chung, J.S., Xie, Q., 2002. Long-term operation of a biofilter for simultaneous removal of H2S and NH3. Journal of the Air & Waste Management Association, 52, 1389-1398.

[6] Crookes R.J. Comparative biofuel performance in internal combustion engines, International Journal of Biomass and Bioenergy, vol. 30, pp. 461-468, 2006.

[7] Lee, E.Y., Lee, N.Y., Cho, K.S., Ryu, H.W., 2006. Removal of hydrogen sulfide by sulfate-resistant Acidithio bacillu thiooxidans AZ11. Journal of Bioscience and Bioengineering, 101, 309-314.

[8] Phan Minh Duc, Kanit Wattanavichien, Study on biogas premixed charge diesel dual fuelled engine. Energy Conversion and Management, vol. 48, pp. 2286–2308, 2007.

[9] E. Porpatham, A. Ramesh and B. Nagalingam-Investigation on the effect of concentration of methane in biogas when used as fuel for spark ignition engine, Fuel. International Journal, UK, 2007.

[10] Ferrer I, Ponsa S, Vazquez F, Font X. - Increasing biogas production by thermal (700 C) sludge pre-treatment prior to thermophilic anaerobic digestion‖. Biochemical Engineering Journal, vol. 42, pp. 186–192, 2008.

[11] Palmeri, N., Cavallaro, S., Bart, J.C.J., 2008. Carbon dioxide absorption by MEA - A preliminary evaluation of a bubbling column reactor. Journal of Thermal Analysis and Calorimetry, 91, 87-91. .

[12] Barik, D. & Murugan, S. Dept. of ME, NIT, Rourkela, Odisha, India-Production and Application of Biogas as a Gaseous Fuel for Internal Combustion Engines. International Journal of Engineering Research & Technology (IJERT) Vol. 1 Issue 7, September –2012 ISSN: 2278-01

[13] Nand, K , Sumithra Devi, S. & Viswanath, P., 1991. "Anaerobic Digestion of Fruit and Vegetable Processing Wastes for Biogas Production. Bioresource Technology, 40, pp.43- 48.

[14] Bjorkqvist S. et al. (1998), Hydrocarbons in biogas from household solid waste, Environmental Technology 19 (6), 639-642

[15] Llabres, P. et al., 1999. "The Use of Organic Fraction of Municipal Solid Waste Hydrolysis Products for Biological Butrient Removal in Wastewater Treatment Plants". Water Resources, 33(1), pp.214-222.

[16] Mata-Alvarez J., Mace S., Llabres P., (2000), Anaerobic digestion of organic solid wastes. An overview of research achievementsand perspectives, Bioresource Technology, 74 (2000) 3-16

[17] Rao, A. B. and E. S. Rubin (2002). "A technical, economic, and environmental assessment of amine-based CO2 capture technologyfor power plant greenhouse gas control." Environmental Science & Technology 36(20): 4467-4475.

[18] Kim, S., H. T. Kim, et al. (2004). "Optimization of CO2 absorption process with MEA solution." Carbon Dioxide Utilization forGlobal Sustainability 153: 429-434.

[19] Duan, H.Q., Koe, L.C.C., Yan, R., Chen, X.G., 2006. Biological treatment of H2S using pellet activated carbon as a carrier of microorganisms in a biofilter. Water Research, 40, 2629-2636.

[20] Van der Zee, F.P., Villaverde, S., Garcia, P.A., Fdz-Polanco, F., 2007. Sulfide removal by moderate oxygenation of anaerobic sludge environments. Bioresource Technology, 98, 518-524.

[21] Vannini, C., Munz, G., Mori, G., Lubello, C., Verni, F., Petroni, G., 2008. Sulphide oxidation to elemental sulphur in a membrane bioreactor: Performance and characterization of the selected microbial sulphur-oxidizing community. Systematic and Applied Microbiology, 31, 461-473.

[22] Lim, S.-J. et al., 2008. "Anaerobic organic acid production of food waste in once-a-day feeding and drawing-off bioreactor".Bioresource Technology, 99, pp.7866- 7874.

[23] de Hullu, J., Maassen, J.I.W., van Meel, P.A., Shazad, S., Vaessen, J.M.P. (2008). Comparing different biogas upgrading techniques. Eindhoven University of Technology, The Netherlands.

[24] Godini, H. R. and D. Mowla (2008). "Selectivity study of H2S and CO2 absorption from gaseous mixtures by MEA in packed beds." Chemical Engineering Research & Design 86(4A): 401-409.

[25] Lin, C. C. and K. S. Chien (2008). "Mass-transfer performance of rotating packed beds equipped with blade packings in VOCs absorption into water." Separation and Purification Technology 63(1): 138-144.

[26] Barlaz, Morton A et al., 2008. "An Assessment of the State-of-the-Practice of Food Waste Composting in North America",

[27] Pipatmanomai, S., Kaewluan, S., Vitidsant, T., 2009. Economic assessment of biogas-to electricity generation system with H2S removal by activated carbon in small pig farm. Applied Energy, 86, 669-674.

[28] Levis, J.W. et al., 2010. "Assessment of the state of food waste treatment in the United States and Canada". Waste management (New York, N.Y.), 30(8-9), pp.1486-94.

[29] Shefali, V. & Themelis, Nickolas J., 2002. "ANAEROBIC DIGESTION OF BIODEGRADABLE ORGANICS IN MUNICIPAL SOLID WASTE". Available at: http://www.seas.columbia.edu/earth/vermathesis.pdf.

[30] Ostrem, K. & Themelis, Nickolas J., 2004. "GREENING WASTE: ANAEROBIC DIGESTION FOR TREATING THE ORGANIC FRACTION OF MUNICIPAL SOLID WASTES"Availableat:http://www.seas.columbia.edu/earth/wtert/sofos/Ostrem_Thesis_final.pdf.

[31] Biswas, T. D., A. R. S. Kartha, et al. (1977). Removal of carbon dioxide from biogas. Proceedings of national symposium on biogas technology and uses. New Delhi, India, IARI

[32] Hingerl, K. 2001. Scientific Report ESF / PESC - Exploratory Workshop on “The Need for Research towards Biogas Usage in Fuel Cells - A Strategic Question for the European Energy Autonomy” 1-3 April 2001, Steyr, Austria

[33] Modarres RMR, Karim GA. Examination of the dual-fuel engine performance using low BTU gaseous fuels. In: Proceedings of the13th international conference on thermal engineering and thermogrammetry, Budapest, Hungari, 2003.

[34] Soroushian, F., Shang, Y., Whitman, E.J., Garza, G., Zhang, Z., 2006. Development and application of biological H2S scrubbers for treatment of digester gas, WEF's Annual Technical Exhibition and Conference, Texas, USA, pp. 3541-3547.