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Effect of Methane Concentration in Biogas on the Performance and Emission characteristics of an Otto Cycle Engine

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Abstract- *In recent year, increased environmental awareness and energy shortages have encouraged researchers to investigate the possibility of using alternate fuels. The purpose of finding the alternate sources is to minimize the consumption of conventional fossil fuels and in turn to reduce the degradation of environmental quality to a great extent. The use of bio-based fuels like biogas produced from biomass or bio-wastes is a valuable energy source which is sustainable and can be manufactured from locally available waste streams thereby solving the problem of waste disposal. Local wastes (organic wastes) contain enough energy to contribute significantly to energy supply system especially in the rural regions of developing countries. Biogas is a clean and environment friendly fuel produced from anaerobic digestion of agro, animal or human wastes. The biogas has about 60% methane and 40% carbon dioxide with small traces of H_2S. The large quantity of CO_2 present in raw biogas however, lowers its calorific value, flame velocity and flammability limit. The presence of H_2S leads to formation of SO_2 which combines with the water vapour to form acids and hence corrode the metals. Thus, raw biogas as such cannot be recommended for powering vehicular I.C engine. In the present research work, an attempt has been made to upgrade the quality of raw biogas by lowering its CO_2 and H_2S content, thus enriching its methane content and to study the performance and emission characteristics of upgraded biogas fuelled four stroke Otto cycle engine as fuel. The influence of reduction in the concentration of CO_2 in the biogas on the performance, emissions and combustion characteristics in a constant volume Otto cycle (SI) engine was studied experimentally. A low cost water scrubber was developed and used to lower CO_2 levels from 40% in biogas to 20%. The tests covered the range of equivalence ratios (0.9 to 1.1) from rich mixture to lean operating limit operating in the range of 800-2400 rpm at compression ratio of 9.2:1. With reduction in the CO_2 level, there was a significant improvement in the brake power, brake thermal efficiency and brake specific fuel consumption and also substantial reduction in exhaust emissions of hydrocarbons (HC), carbon monoxide (CO) and carbon dioxide (CO_2). The lean limit of combustion also gets extended with the use of upgraded biogas in the engine. Faster heat release rates indicated enhanced combustion rates, which were mainly responsible for the improvement in thermal efficiency of the engine. However, there was increase in the NOx emission by 3% compared to raw biogas engine operation. To mitigate increase in NOx emission the spark timings were retarded by about 5^0 when CO_2 concentration was decreased by 20%.*

Keywords- upgraded biogas; water scrubber; S.I engine; biogas mixer; engine exhaust emissions.

INTRODUCTION

Gaseous fuels have wide flammability limits and can easily form a homogeneous mixture with air for good combustion. Thus they will lead to very low levels of pollutants and can be effectively utilized in spark ignition (SI) engines [1]. Moreover, gaseous fuels have high hydrogen to carbon ratios. Thus very low CO_2 emissions are possible when they are used in SI engines.

Biogas can be obtained from renewable sources. Renewable fuels will not affect the net CO_2 in the environment. Biogas is an attractive source of energy for rural areas. It can be produced from animal dung and other animal wastes and also from plant matter such as leaves and water hyacinth- all of which are renewable and available in the countryside. Biogas is produced by bacteria which break down organic material under airless (anaerobic) conditions. This process is called ''anaerobic digestion''. Biogas mainly consists of approximately two-thirds (by volume) methane (CH_4) and the rest is mostly carbon dioxide (CO_2) with traces of hydrogen sulphide (H_2S). Biogas can be produced close to the consumption points in rural areas such as engines driving generators and pump sets. It can also be produced on a large scale from urban waste materials and effectively used to generate electricity for local communities.

As a fuel, raw biogas has an extremely low energy density (17 MJ/m^3) on volume basis on account of its high CO_2 content. The flame speed is just 0.25 m/s [2-3]. The large quantity of CO_2 present in biogas lowers its calorific value, flame velocity and flammability range compared with natural gas. The self-ignition temperature of biogas is high (650^0C) and owing to large quantity of CO_2 present in the raw biogas it resists knocking which is highly desirable in SI engines. It also contains a small percentage of H_2S, which can cause corrosion of metal parts. A high compression ratio spark ignition engine may be employed for raw biogas fuelled operation as CO_2 present in the raw biogas suppresses knock [4-5]. As in all SI engines, it is necessary to maintain a proper ratio between the biogas and air in order to attain good combustion characteristics. Removal of CO_2 will lead to an increase in the flame velocity and calorific value of biogas.

PRESENT WORK

This study is an attempt to evaluate the effects of enriching the methane content in the raw biogas on the performance, exhaust emissions and combustion characteristics of an Otto cycle engine. This study also incorporates the development of less expensive purification unit for enrichment of raw biogas obtained from anaerobic digester to upgrade its quality up to 70-75% methane content. Pressurised water scrubber (purification unit) was developed and used to reduce CO_2 content to different levels namely 19% and 17% by volume from the normal level of approximately 41%. The upgraded biogas so obtained from purification unit was tested in a stationary, single cylinder four stroke 4.5 kW S.I engine operating in the range of 1000-3500 rpm. A gas carburettor was also designed and developed for testing of this engine. The tests prove stable operation during starting, idling and no load operation and establish the success of conversion of conventional gasoline engine to operate on enriched biogas obtained from the purification unit. The results obtained from the experiments show substantial reduction in the emission of CO, HC and CO_2 with improved engine brake power and brake thermal efficient compared to raw biogas **[**3 - 5**]**. However 3% increase in NOx emission was noticed when engine was made to run on upgraded biogas. Experiments were conducted at different equivalence ratios (0.9-1.1) and at different concentrations of carbon dioxide (CO_2), namely 41%, 19% and 17%. The best spark timing was maintained for the range of speed based for engine brake power characteristics. Performance parameters such as brake power, brake thermal efficiency, brake specific fuel consumption, exhaust gas temperature, emissions of HC, CO and NOx and combustion parameters such as spark advance and heat release rate were studied.

PROPERTIES OF RAW BIOGAS

Composition of raw biogas as obtained from anaerobic digester was ascertained using gas chromatography and is found to be

CH_4: 53 %
CO2: 41 %
H_2S: 3.6 %
Moisture: 2.4 %
Calorific value: 17 MJ/m^3
Stoichiometric air-biogas ratio (by mass): 5.7 kg of air/kg of biogas
Flammability limits (vol. % in air): 7.5-14
Ignition temperature: 650^0C
Octane rating: 130

PURIFICATION OF RAW BIOGAS

Biogas is suitable as a fuel for heating and cooking purposes without processing. But if it is to be used in internal combustion S.I engine for powering vehicles, the presence of CO_2 and H_2S is not desirable for a number of reasons. First it lowers calorific value of raw biogas and secondly, the presence of H_2S in raw biogas initiates formation of SO_2 and acidic vapour that corrode metallic parts of the engine components. Besides, presence of large quantity of CO_2 in raw biogas occupies more volume in the storage cylinder. Thus, CO_2 and H_2S must be removed from raw biogas to upgrade it to be more suitable and useful in S.I engine. The simplest and cheapest method of lowering CO_2 and H_2S content in raw biogas is by washing the raw biogas with water under pressure. Water has strong affinity to absorb CO_2 and H_2S. Affinity of water to absorb CO_2 and H_2S increases with the increase in water pressure. Thus water under pressure can be used effectively to reduce CO_2 and H_2S gas from raw biogas. This can be achieved by the use of a water scrubber which absorbs CO_2 and H_2S to yield enriched biogas with methane content close to 70-75%. Enriched biogas can be effectively used in automotive vehicles with increased brake power output and reduced exhaust emissions. The scrubber also removes effectively corrosive sulphides. Thus scrubbing of raw biogas is an essential step to obtain upgraded quality biogas.

A low cost water scrubber shown in Fig. 1 was designed and developed from locally available resources like plastics barrel of 1 m high and 0.75 m in diameter. The water at a pressure 1.5 bar and 3 bar respectively were used as an absorbent to absorb CO_2 and H_2S from raw biogas. The pressurized water line was connected at top of the plastic barrel with fine water sprayer that spray continuously pressurized water from the top in the form of spray. The raw biogas is fed directly at a pressure of 1.15 bar into the plastic barrel from the bottom. The absorption process is thus counter flow type. The dissolved CO_2 and H_2S in water were collected at the bottom of the barrel tower while the enriched biogas was collected from the top of the barrel. To remove the moisture from purified biogas, it was passed through a column of silica gel bed and the dry and enriched biogas was collected and compressed in cylinder for use in I.C engine.

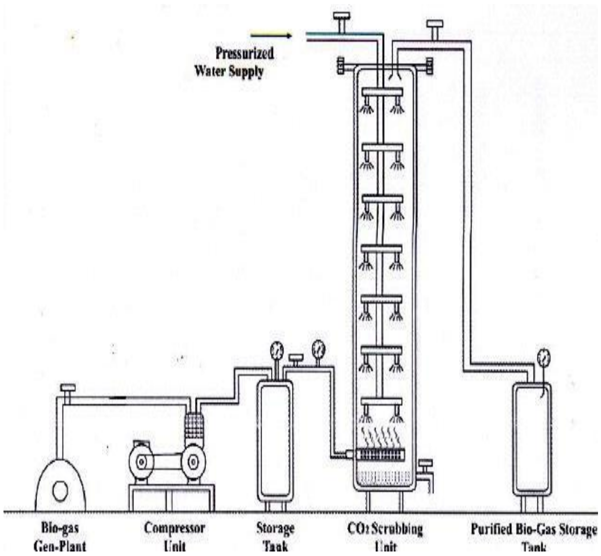

Fig. 1- Biogas purification unit

Purification results shown in Table 1 below depict an increasing trend of methane content in upgraded biogas after purification with respect to feeding water pressure.

Table 1- Methane enrichment in upgraded biogas

Biogas Contents	Raw Biogas (%)	Upgraded Biogas (%)	
		P = 1.5 bar	P = 3.0 bar
CH_4	53.0	71.8	73.0
CO_2	41.0	19.8	17.81
H_2S	3.96	1.04	0.88
Moisture	2.40	7.30	7.76

UPGRADED BIOGAS PROPERTIES

CH_4: 73 %
CO2: 17.81 %
H_2S: 0.88 %
Moisture: 2.4 %
Calorific value: 19.8 MJ/m^3
Flammability limits (vol. % in air): 7.0-18
Ignition temperature: 650^{0}C
Octane rating: 110

DEVELOPMENT OF BIOGAS ENGINE

For admission of biogas as fuel in the given engine, the induction system of the engine was modified. Petrol carburettor was replaced with biogas carburettor (air-biogas mixer) which was designed, developed and installed in the induction system for feeding the raw or upgraded biogas in to the engine cylinder. The pressure of purified biogas was regulated with the help of pressure regulator and maintained at 1.05 bar.
The performance study was performed on Hero Honda motor cycle engine with the following specifications:

Power: 4.5 kW
Total volume: 100 cc
No. of cylinder: 1
Type: S.I engine
Stroke: 4 strokes
Rated Speed: 3500 rpm
Type of cooling: Air cooled
Compression ratio: 9.2:1
Control: Throttle valve controlled

DESIGN OF GAS CARBURETTOR

A venturi type biogas mixer was designed and fabricated as shown in Fig. 2 for a 100 cc four stroke S.I engine application. During suction stroke, the engine inhales the charge (air-biogas mixture) through mixer. The throttle valve controls the amount of charge entering the engine cylinder. The reduction in the cross-sectional area at venturi throat increases the air velocity which creates the vacuum. The biogas is introduced at the throat of the venturi where air and biogas are mixed and the mixture enters engine cylinder where it is ignited by the spark plug provided in the cylinder head.

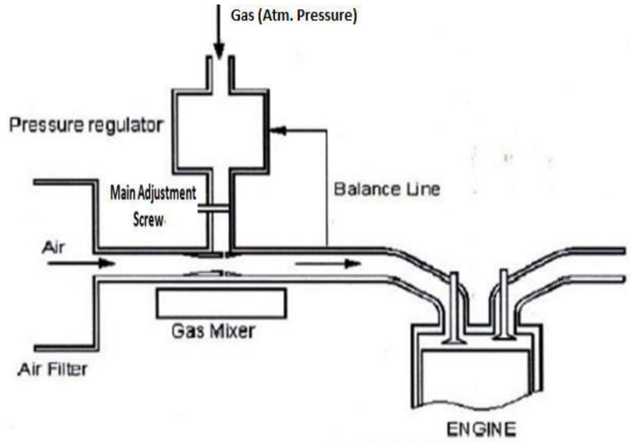

Fig 2- Schematic diagram of air, gas and mixture Flow

EXPERIMENTAL SETUP

The experimental facilities used for S.I engine test are shown in Fig. 3. A single cylinder, four stroke spark-ignition Honda two wheeler research engine along with dynamometer fitted with computer-based display unit and processing system was employed. Supply of biogas was metered with metering device. The system has the facility to measure brake power, gas consumption, exhaust emissions and exhaust temperature. Tests were performed at an engine speed ranging from 1000- 3500 rpm.

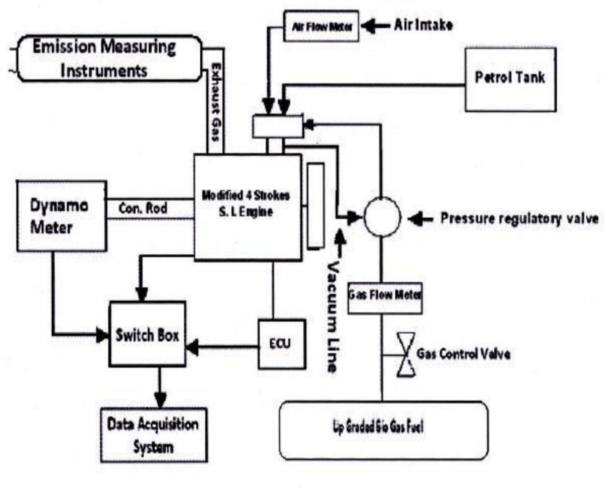

Fig. 3- Experimental set-up of modified 4 stroke S. I. engine

RESULTS AND DISCUSSION

The results obtained from the experiments performed on S.I engine running on raw and upgraded biogas are plotted in the form of graph. Engine performance parameters such as engine torque, brake power, brake specific energy consumption and exhaust gas temperatures were measured and plotted against different engine speeds varying from 1000 rpm to 3500 rpm. On the other hand, the graphs of engine exhaust emissions such as carbon monoxide (CO), hydrocarbons (HC), oxides of nitrogen (NOx) and carbon dioxide (CO2) were also plotted against the same range of engine speed.

Optimum Spark Advance- In order to run the conventional S.I engine on biogas, it was necessary optimise the spark timing for better cold start, smooth accelerations and better engine performance without any undue vibrations or noise. For this to accomplish, the engine was operated on petrol, raw biogas and upgraded biogas and the engine brake power were measured with three different spark advance timings i.e. 25^0, 30^0 and 35^0 of crank angle before top dead centre (btdc) at different air-fuel ratio for maximum power output as shown in Table 2. As evident, the spark advance of 30^0 yielded the highest brake power when the engine was run on raw and upgraded biogas respectively. Thus, further performance tests on the engine inhaling raw and upgraded biogas were carried out at an optimised spark advance of 30^0.

Table 2- Biogas fuelled engine performance for optimum spark advance timing

	Raw Biogas			Upgraded Biogas		
	25^0	30^0	35^0	25^0	30^0	35^0
B.P (KW)	1.08	2.86	2.1	1.9	3.7	2.89
RPM	1582	2190	2050	1860	2330	2100
A:F	14.2:1	11.2:1	13.3:1	14.2:1	11.8:1	12.8:1
η (%)	16.3	19.4	17.9	17.5	21.0	19.8

Engine Torque- Engine torque was measured for upgraded and raw biogas respectively with varying engine speeds as shown in Fig. 4. The graph shows that the torque developed by the engine for raw biogas is lower compared to the torque produced by the upgraded biogas operation at any speed. This is because of the fact that energy input to the engine with raw biogas is lesser than compared to upgraded biogas operation as heating value of raw biogas is lesser than upgraded biogas owing to lesser methane content in raw biogas in comparison to upgraded biogas. Thus the rate of energy release during combustion of raw biogas was lesser compared to upgraded biogas operation. From the results of engine torque it is evident that the performance characteristics of the engine was superior when the spark advance was maintained around 30^0 when the engine was operated on raw biogas or upgraded biogas as fuel.

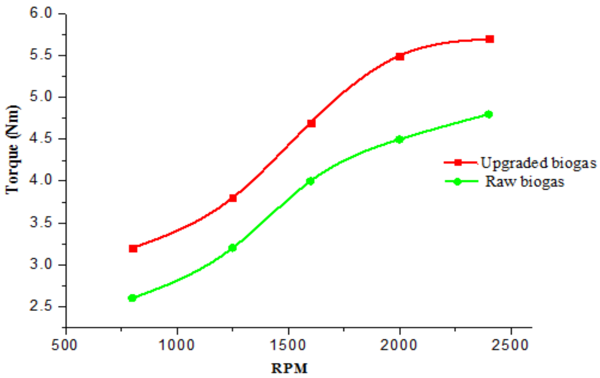

Fig. 4- Engine torque v/s rpm for upgraded and raw biogas fuelled operation

Engine Brake Power- The variation of brake power output with engine speed when the concentration of carbon dioxide in biogas was lowered to different levels (from 41% to 17%) is shown in Fig. 5. There is an increase in the brake power output as expected with reduction in the CO_2 concentration. At any given speed lowering the CO_2 level will mean an increase in the amount of methane admitted. The increase in methane content in the intake charge means increase in the input energy to the engine.

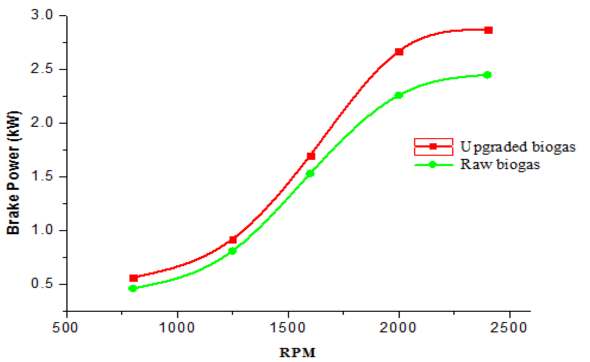

Fig. 5- Engine brake power v/s rpm for upgraded and raw biogas fuelled operation

Thus an increase in the brake power was observed for upgraded biogas compared to raw biogas due to higher calorific value of upgraded biogas (19.2 MJ/kg) at every speed of the engine operation. A maximum of 18% increase in the brake power was obtained with upgraded biogas near 2370 rpm.

Brake Specific Fuel Consumption- The variation of brake specific fuel consumption with engine speed is shown in Fig. 6. When the concentration of carbon dioxide in biogas is lowered to different levels (from 41% to 17%), decrease in brake specific fuel consumption was observed with the increase in speed. This may be attributed to the increase in the heat release rate owing to increase in the calorific value of the upgraded biogas and increase in the flame speed. Reduction in CO_2 content increases the calorific value and the flame speed. As evident, the brake specific fuel consumption decreases with the increase in the engine rpm. The brake specific fuel consumption of raw biogas was found higher at every speed compared to upgraded biogas due to lower power developed by the engine because of lesser calorific value of the raw biogas.

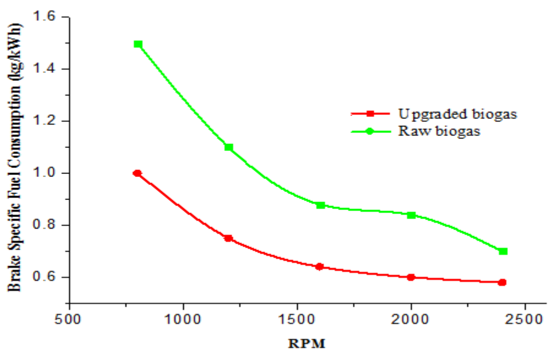

Fig. 6- Engine brake specific fuel consumption v/s rpm for raw and upgraded biogas

Brake Thermal Efficiency- Brake thermal efficiency of the engine has been plotted with respect to engine rpm in Fig.7. At any given speed, the brake thermal efficiency of the engine was higher when fuelled with upgraded biogas compared to raw biogas operation. This may be attributed to the increased power output of the engine with the use of upgraded biogas compared to raw biogas. Lowering the CO_2 level in the biogas produced an increase in the brake thermal efficiency by about 8%. At any given speed lowering the CO_2 level mean an increase in the amount methane admitted. This is because more air can also be admitted and hence the engine can be operated at leaner air-biogas mixture. Lesser concentration of CO_2 in the upgraded biogas actually extended the lean limit of combustion in the engine with the use of upgraded biogas.

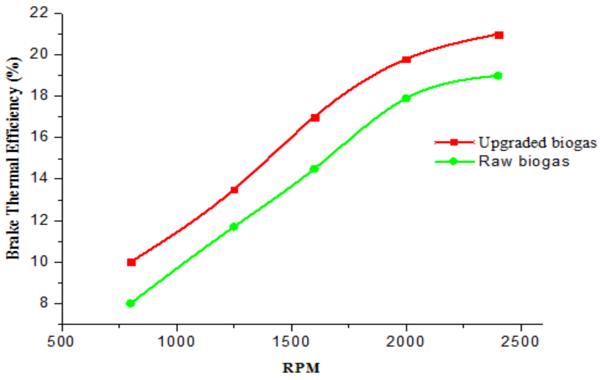

Fig. 7- Engine brake thermal efficiency v/s rpm for upgraded and raw biogas

Exhaust gas Temperature- The temperature of exhaust gas was found higher at all speeds of the engine when it was operated on upgraded biogas fuel compared to raw biogas as shown in Fig. 8. This is because of better combustion characteristics of upgraded biogas owing to lesser concentration of CO_2, faster heat release rate due to increased flame speed and having higher calorific value compared to raw biogas. All these factors resulted in increased temperature of the exhaust gas.

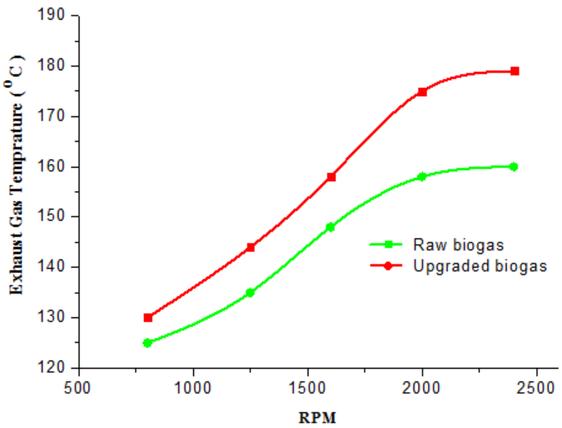

Fig. 8- Exhaust gas temperature v/s rpm for upgraded and raw biogas

Emission of oxides of nitrogen (NOx)- Oxides of Nitrogen is formed when the natural constituents nitrogen and oxygen of air combines during combustion inside the engine cylinder. The formation of NOx is a temperature dependent phenomenon and its concentration increases with increase in the combustion temperature. As evident from Fig. 9, the NOx concetration in the exhaust rises with the increase in exhaust gas temperature and with increasing engine speed. However the rise in NOx concentration was found to be higher at all speeds when the engine was running on upgraded biogas compared to raw biogas. This is because of the fact that exhaust gas temperature increases with reduction in the CO_2 concentration of biogas. Since CO_2 concentration in the raw biogas was much higher compared to upgraded biogas, therefore the exhaust gas temperature was high with upgraded biogas and so is the emission of NOx. A decrease in CO_2 concentration in the fuel leads to increased methane and oxygen contents, and thus faster combustion and higher temperatures. An average of 3% to 5% increase in NOx emission was noted when the engine was operated on upgraded biogas compared to the engine operation aspirating raw biogas as fuel. NOx emissions were reduced by about 47% when the engine was operated on upgraded biogas in comparison to the engine operating on gasoline as a fuel.

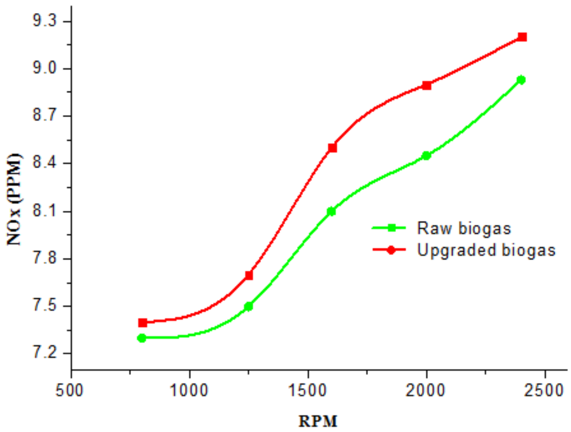

Fig. 9- Emission of NOx v/s engine rpm for upgraded and raw biogas

Emission of hydrcarbons (HC)- Hydrocarbon emission in the exhaust is least when the lean mixture is used in the engine owing to complete combustion of biogas and it increases with increase in the richness of the mixture with the speed as dipicted in Fig. 10. As the speed of the engine is increased, the complete combustion of fuel does not take due to lack of time and increase in the emission of hydrocarbon is being observed.

HC emission was found higher with the engine operating on raw biogas compared to engine operating on upgraded biogas. Due to reduced CO_2 concentration in the upgraded biogas, the combustion efficiency is higher compared to raw biogas therefore HC emission with upgraded biogas fuel is found to be lesser compared to raw biogas.

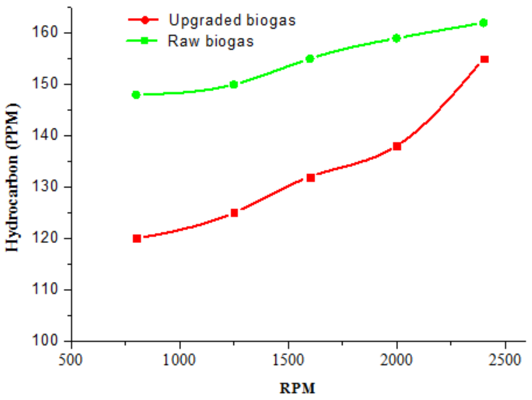

Fig. 10- Emission of hydrocarbons v/s engine rpm for upgraded and raw biogas

Emission of carbon monoxide (CO)- As shown in Fig. 11, the CO level increases with increase in the engine speed due to incomplete combustion of the fuel due to lack of sufficient time for complete combustion to take place. It is also being noticed from the graph that with decrease in the amount of CO_2 in the biogas inducted in to the engine, the CO level in the exhaust increases. Thus, the emission of CO in the exhaust is less with upgraded biogas fuel compared to raw biogas. This may be due to dissociation of CO_2 present in raw biogas in to CO causing increased emission of CO when the engine is running on raw biogas.

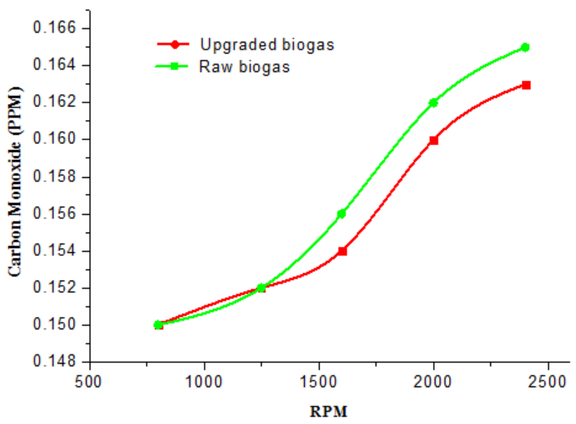

Fig. 11- Emission of carbon monoxide v/s engine rpm for upgraded and raw biogas

CONCLUSION

Biogas is a clean, environment friendly, renewable and sustainable energy source that can be domestically produced from bio-wastes which is not only capable of solving the problem of local waste disposal but also has the potential to save carbon by using it as a fuel for cooking or using it in S.I engines. Raw biogas produced anaerobically contains high concentration of CO_2 and traces of H_2S gas. Raw biogas can be upgraded to natural gas quality by removing its CO_2 and H_2S content using low cost water scrubbing technology. The upgraded biogas so obtained can be compressed and bottled to be used as CNG. Removal of CO_2 and H_2S from raw biogas results in higher methane and oxygen concentrations in the charge and thus leads to faster combustion and significant improvements in the engine performance and reduction in the exhaust emissions. With reduction in the CO_2 cocentration in the biogas not only increases the power output of the engine but also increases the thermal efficiency and lowers exhaust emissions. There is a significant increase in the heat release rate with reduced CO_2 content in the biogas however there is 3% increase in NOx emission from engine exhaust. An average 23% increase in the power output was observed when the engine was run on upgraded biogas (73% methane content) compared to raw biogas (53% methane content) with reduced consumption of air-biogas charge. The brake thermal efficicieny was also found to be higher for upgraded biogas at every speed compared to raw biogas. However the increase in thermal efficiency was significantly high at lower speeds compared to its increasea at higher speeds. The average reduction in CO and HC emissions were found to be of the order of 16% and 24% respectively when the engine was operated on upgraded biogas in comparision to raw biogas. Thus performance characteristics and exhaust emission quality of the engine were found much superior when the engine was made to operate with upgraded biogas fuel. However increase in NOx emission was noticed when the engine was made to operate with upgraded biogas due higher exhaust temperature owing to faster rate of combustion. This increase in NOx emission can be mitigated br retarding the spark advance by 5^0 but at the cost of reduced power output and reduction in thermal efficiency of the engine. The price of domestically produced raw biogas from bio-wastes and its up-gradation to upgraded quality biogas is much cheaper than conventional fossil fuel. Savings in conventional fossil fuel cost will help not only to lower the payback period for the purification unit and the pressure regulator kit but will also help to improve the GDP of the nation. The development of related infrastructure for biogas based economy will also generate employment especially in rural India.

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