Performance of 4 Stroke Petrol Engine with Methane with H_2 Gas as Fuel

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Abstract: A heat engine is a device which transforms the chemical energy of a fuel into thermal energy and uses this energy to produce mechanical work. Engine is the power house of an automobile. It is the heart of an automobile, which is alive due to major two elements i.e. fuel and oxygen. The major fuels used today are Petrol, Diesel, etc. These fuels emit various green house gases like CO_2, CO, NO_X etc which leads to Global Warming. Hence the need for **Alternate Fuel** has raised. The main objective is to use **Methane+H_2** gas as fuel which is considered as one of the cleanest & safest fuel. Moreover the use of these gases can increase the life span of engine by 50% and can reduce the Global Warming up to 4% of the total.

Keywords: Alternative fuel; Vegetable oil; Bio-diesel; Renewable energy, exhaust gas recirculation (EGR) and ***S***elective catalytic reduction (SCR)

I. INTRODUCTION

Alternative fuels, known as non-conventional or advanced fuels, are any materials or substances that can be used as fuels, other than conventional fuels. Conventional fuels include: fossil fuels (petroleum oil), coal, propane and natural gas), as well as artificial radioisotope fuels that are made in nuclear reactors, and store their energy.

Alternative fuels include biodiesel, bio alcohol (methanol, ethanol, and butanol), and chemically stored electricity (batteries and fuel cells), hydrogen, non-fossil methane, non-fossil natural gas, vegetable oil, and other biomass sources.

Some of the alternate fuels are listed below:

Bio fuel, Biomass, Algae based fuels, Biodiesel, Alcohol fuels, Ammonia, Hydrogen, Liquid Nitrogen, Compressed air, Alternative fossile fuels (LPG, CNG, etc),Vegetable oil, Nuclear power, Radio thermal generators, Methane+Hydrogen.

Methane (CH_4) is a very simple molecule (one carbon surrounded by four hydrogen atoms) and is created predominantly by bacteria that feed on organic material. In dry conditions, there is plenty of atmospheric oxygen, and so aerobic bacteria which produce carbon dioxide (CO_2) are preferred. But in wet areas such as swamps, wetlands and in the ocean,

There is not enough oxygen, and so complex hydrocarbons get broken down to methane by anaerobic bacteria. Some of this methane can get trapped (as a gas, as a solid, dissolved or eaten) and some makes its way to the atmosphere where it is gradually broken down to CO_2 and water (H_2O) vapour in a series of chemical reactions.

Due to low evaporation losses it safer for transportation and storage. Many researchers have been conclude that with the use of bio-fuels as a fuel in engines a reduction in harmful emissions as well as a comparable engine performance with petroleum fuels can be possible. Performance parameter such as specific fuel consumption, thermal efficiency, break power, ignition qualities, viscosity, torque, etc. can be comparable.

II. PROPERTIES OF METHANE

Methane is the simplest member of the paraffin series of hydrocarbons. Its chemical formula is CH_4. It is lighter than air, having a specific gravity of 0.554. It is only slightly soluble in water. It burns readily in air, forming carbon dioxide and water vapour; the flame is pale, slightly luminous, and very hot. The boiling point of methane is −162 °C(−259.6 °F) and the melting point is −182.5 °C (−296.5 °F). Methane in general is very stable, but mixtures of methane and air, with the methane content between 5 and 14 percent by volume, are explosive. Explosions of such mixtures have been frequent in coal mines and collieries and have been the cause of many mine disasters.
The chief source of methane is natural gas, which contains from 50 to 90 percent methane, depending on the source. Methane produced by the destructive distillation of bituminous coal and by coal carbonization is important in locations where natural gas is not plentiful.
Since commercial natural gas is composed largely of methane, their uses may for all practical purposes be considered identical. Because of its abundance, low cost, ease of handling, and cleanliness, such gas is widely used as a fuel in homes, commercial establishments, and factories. Methane is an important source of hydrogen and some organic chemicals. Methane reacts with steam at high temperatures to yield carbon monoxide and hydrogen; the latter is used in the manufacture of ammonia for fertilizers and explosives. Other valuable chemicals derived from methane include methanol, chloroform, carbon tetrachloride, and nitro methane. The incomplete combustion of methane yields carbon black, which is widely used as a reinforcing agent in rubber used for automobile tires.

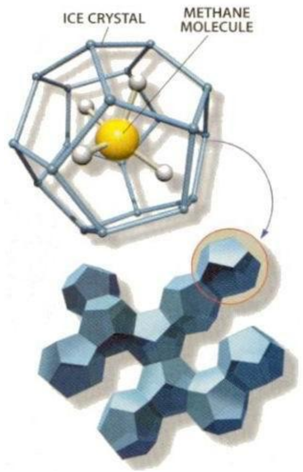

Fig.1 Molecular Structure of Methane

Methane hydrate consists of a cage of water molecules trapping a methane molecule within. This can form large crystals of hydrate in cold and heavily pressurized situations (mainly on the continental slope in the oceans).

III. LITERATURE ON METHANE AND BIOGAS

In 1977 Wong studied various mixtures of methane and carbon dioxide as fuels in an internal combustion (IC) single cylinder, four stroke gasoline engines. The engine was modified for fuelling gaseous fuel. Brake horsepower, brake specific fuel consumption, concentrations of unburned hydrocarbon, nitric oxide and carbon monoxide were measured based on fuel quality. At the same engine speed (RPM), as the fuel quality lowered (the fraction of carbon dioxide increased), brake horsepower decreased while brake specific fuel consumption increased.

When the fuel quality was lowered, unburned hydrocarbon and carbon monoxide emissions were increased. However, lowering the fuel quality tended to reduce nitric oxide emission. In 1987 Caterpillar, Inc tested landfill gas operation in its 3516spark-ignited, turbocharged, separate circuit, after cooled, 16 cylinder engine 4211 in.3 displacement volume at Waste Management's CIDl and fill in Calumet City, IL. In the study, the engine was modified for optimizing engine performance to meet the EPA standards for stationary gas engines. Some engine modifications were undertaken including enlarging and increasing the flow capacity, increasing flow pressure regulation and enlarging the fuel piping between the pressure regulator and the carburettor, and the addition of metering valves sized to operate on low-Btu fuel. This engine was not de-rated in spite of the low heating value of the landfill gas. The durability of the engine was demonstrated through 90 days of continuous operation.

In 1995 another engine made by Caterpillar, Inc was developed for landfill gas application. The Caterpillar G3600 spark-ignition engine was developed to demonstrate engine performance and identify any issues caused by the application. Engine performance, exhaust emissions, and fuelling system were estimated by simulated landfill gas in the lab and tested through field experiments. The engine durability test was conducted for 12,000 hours.
Karim and Wierzba examined the mixtures of methane and carbon b dioxides as a fuel in 1992. A single cylinder CFR engine was used for this study. The mean values of the brake power, the concentration of carbon dioxide and unburned methane in the exhaust, and the exhaust gas temperature were measured according to the variation of equivalence ratio. The brake power increased with the increase in equivalence ratio and decreased with carbon dioxide fraction in a fuel. The concentration of carbon dioxide in the exhaust increased with equivalence ratio and the amount of carbon dioxide in a fuel. Unburned methane increased near lean conditions, but sharply decreased at rich conditions. Higher carbon dioxide fraction in a fuel leaded higher concentration of un burned methane. The average exhaust gas temperature had the maximum value at the stoichiometric region, and decreased with the volumetric percentage of carbon dioxide.

The evaluation of simulated biogas as a fuel for the spark ignition engine was studied by Huang and Crookes in 1997. A single-cylinders park-ignition engine was operated on a simulated mixture fuel consisting of different fractions of natural gas and carbon dioxide with a variable compression ratio. The study covered a wide range of relative air-fuel ratios from lean to rich. The main effect of higher fractions of carbon dioxide was to lower nitrogen oxides while carbon monoxide and total hydrocarbon emissions were increased. At constant speed of 2000rpmand relative air-fuel ratio of 0.98 (fuel rich condition) with changes ofCO2 fraction in the fuel mixture from 23.1% to 41.2%, CO emissions increased from 1.5% to 2.5% and THC emissions also increased from500ppm to 680ppm, whereas NO_X emissions decreased from 1200ppm to1000ppm. Brake power also decreased with the presence of carbon dioxide in the fuel mixture from 6.95kW to 6.75kW.

IV. COMPONENTS OF BIOGAS PRODUCTION PLANT

There are two major models - fixed dome type and floating drum type both the above types have the following components:

(i) Digester: This is the fermentation tank. It is built partially or fully underground. It is generally cylindrical in shape and made up of bricks and cement mortars.
(ii) Gas holder: This component is meant for holding the gas after it leaves the digester. It may be a floating drum or a fixed dome on the basis of which the plants are broadly classified. The gas connection is taken from the top of this holder to the gas burners or for any other purposes by suitable pipelines.
(iii) Slurry mixing tank: This is a tank in which the dung is mixed with water and fed to the digester through an inlet pipe.
(iv) Outlet tank and slurry pit: An outlet tank is usually provided in a fixed dome type of plant from where slurry in directly taken to the field or to a slurry pit. In case of a floating drum plant, the slurry is taken to a pit where it can be dried or taken to the field for direct applications.

Table 1.1 ***Average maximum biogas production from different feed stock***

Sr. No.	Feed Stock	Litre /kg of dry matter	% of Methane content
1.	Dung	350*	60
2.	Night-soil	400	65
3.	Poultry manure	440	65
4.	Dry leaf	450	44
5.	Sugar cane Trash	750	45
6.	Maize straw	800	46
7.	Straw Powder	930	46

* Average gas production from dung may be taken as 40 lit/kg of fresh dung when no temperature control is provided in the plant. One Cu. m gas is equivalent to 1000 litres.

Table 1.2 ***Carbon to Nitrogen ratio of various materials***

Sr. No.	Material	Nitrogen Content (%)	Ratio of Carbon to Nitrogen
1.	Urine	15.18	8:1
2.	Cow dung	1.7	25:1
3.	Poultry manure	6.3	N.A.*
4.	Night soil	5.5-6.5	8:1
5.	Grass	4.0	12:1
6.	Sheep waste	3.75	N.A. *
7.	Mustard straw	1.5	20:1
8.	Potato tops	1.5	25:1

9.	Wheat straw	0.3	128:1

Table 1.3 ***Calorific values of commonly used fuels***

Commonly used fuels	Calorific values in Kilo calories	Thermal efficiency
Bio-gas	4713/m^3	60%
Dung cake	2093/Kg	11%
Firewood	4978/Kg	17.3%
Diesel (HSD)	10550/Kg	66%
Kerosene	10850/Kg	50%
Petrol	11100/Kg	---

V. BIO GAS CLEANING

Biogas is composed primarily of methane (CH_4), carbon dioxide (CO_2) and various other gases. Typically, the compositions of raw biogas from anaerobic digestion are as under:

Table 1.4 Compositions of raw bio gas from anarobic digestion

Methane	CH_4	50%-80%
Carbon dioxide	CO_2	20%-50%
Water Vapour	H_2O	Saturated 2-5% (mass)
Nitrogen	N_2*	1%-4%
Oxygen	O_2*	<1%
Hydrogen Sulphide	H_2S	50-5000ppm
Ammonia	NH_3	0-300ppm
Trace gasses	Siloxanes and halogenated hydrocarbons in very low concentrations	
Non-gaseous	Particulate and oil in low concentrations	

*Only present if air is injected into the digester for H_2S reduction

Biogas from on-farm anaerobic digestion should not contain relevant amounts of anything that is not present in the list above. In fact, even the potential trace gasses should be absent from farm biogas due to the feed stocks utilized, and the hydrogen sulphide and ammonia should be at the lower end of the spectrums presented above.

Since, the primary objective of an on-farm anaerobic digestion system is to produce methane, it is desirable to remove other biogas components because they represent an environmental hazard, a processing problem, or dilute the energy density of the biogas. The following section presents various ways of managing the non-methane components of biogas. The removal of these other components is broken down into two steps, biogas cleaning and biogas upgrading. Biogas cleaning refers to the removal of H_2S, water vapour, NH_3, particles, etc, whereas biogas upgrading generally refers to the removal of CO_2. All biogas applications have some level of biogas cleaning, however, co-generation requires significantly less.

VI. REMOVAL OF HYDROGEN SULPHIDE (H_2S)

(1) H_2S is present in biogas resulting from the anaerobic digestion of organic material containing sulphur.
(2) The concentration of this toxic and corrosive gas in raw biogas may vary greatly depending on the nature of the feedstock. Concentrations are reported between 50 – 5000 ppm for H_2S in raw biogas.
(3) H_2S in biogas has to be reduced to levels where it does not harm the process downstream.
(4) Downstream concerns revolve around public health and safety issues such as human toxicity and corrosive effect on mechanical parts and gaskets.
(5) In terms of equipment tolerances, H_2S concentrations have to typically be reduced to between 200 ‐ 500 ppm for combustion of biogas in an internal combustion engine (co ‐ generation) while injection into the grid as upgraded bio-methane (natural gas equivalent), would require reduction down to below 4 ppm.

➢ **Water Scrubbing**

Technical description: Create a solution of H_2S in water by feeding the biogas through a Counter flow of water. Normally only used in combination with water scrubbing biogas upgrading technologies

Contaminants Introduced to Biogas or Digestate: No contaminants introduced.

Waste Discharges: Scrubbing water is discharged. The process can be designed as a regenerative process, in which case scrubbing water discharge would be significantly reduced.

If the process is regenerative the desorbed gas will be vented out through an absorption filter of active carbon, iron hydroxide or iron oxide

VII. REMOVAL OF WATER VAPOUR

Biogas from anaerobic digestion is commonly saturated with water. Most biogas utilization processes require relatively dry gas, so drying is often necessary. Some cleaning and upgrading techniques (e.g., water scrubbing), add water vapour to a non ‐ saturated biogas. Nevertheless, biogas has to be dry prior to grid injection and fairly dry before combustion. Water vapour is a problem, as it may condense into water or ice when passing from high pressure to lower pressure. This may result in corrosion issues and the pressure regulator clogging in the gas conveyance system.
Several methods for reducing the presence of water vapour can be applied in an on ‐ farm anaerobic digestion context.

➢ **Passive Gas Cooling**

Technical Description: Gas is lead underground for a short period of time to be cooled. Cooling condenses water from the gas which is collected.

Contaminants Introduced to Biogas or Digestate: No contaminants introduced.

Waste Discharges: Could result in discharge of condensate water to the sewer but normally the condensate is recycled back into the digester.

- **Refrigeration**

Technical Description: Heat exchangers are used to cool the biogas to desired dew point where water vapour condenses. Biogas can be pressurized to achieve further dryness.

Contaminants Introduced to Biogas or Digestate: No contaminants introduced.

Waste Discharges: Could result in discharge of condensate water to the sewer but normally the condensate is recycled back into the digester.

Spent refrigerant contaminated with another substance may constitute a hazardous waste and must be disposed of accordingly.

VIII. SPECIFICATIONS OF MACHINERY EQUIPMENTS AND TOOLS

1. Screw Drivers: Handle and blade are main parts. These are specified according to length of the blade and width of the tip.

2. Spanners: These are specified according to the size of the nut or the bolt head over which the spanner fits.

3.Hammers: Main parts are the head and handle. Striking part of the head is called 'face' while the uppermost part is called the 'peen'. Hammers are classified according to peen shape, viz, ball peen, cross peen & straight peen types. Other bases of classification are weight and material of the head.

4.Chisels: Various types are, the flat type, diamond point type & the round nose type.
5.Hacksaws: A hacksaw consists of an adjustable frame with a handle and a replaceable blade. Blades are generally available in lengths of 250-300mm and number of teeth varies from 14 to 32 per 25mm of blade length. Blades are classified according to their lengths, pitch and type.

6.Taps &Dies: Taps are the tools used for cutting inside threads, while dies are for cutting outside threads. T-type or long handles are used for holding taps for threading. Taps are of 3 types: Taper tap, Plug tap, Bottom tap.

7. Drilling Machines and Twist Drills: Drilling machines may be hand-operated or electrically operated. The tool used for drilling is called a twist drill having three main parts, viz, the shank (straight or tapered), the body and the point.

8. Reamers: After drilling a hole, the same can be finished by a reamer. A reamer may be straight-fluted type or the spiral-fluted type.

9. Measuring tools: Various measuring tools used in an auto shop are Vernier caliper, Outside micrometer, Inside micrometer, Dial gauge, Bevel protractor, Combination set.

10. Tire tools: Tire levers, tire changer vulcanizing machine, air compressor and the tire pressure gauge.

11. Electric equipment: Auto shop electrical equipment consists of testing bulb or testing pen, soldering iron, stroboscopic light, beam setter & complete rigs for testing of alternator & starting motor.

12. Other equipments: Lifting jacks, Lubricating equipment,Lift & high pressure washing equipment,Creeper,Battery testing & charging equipment, Brake testing equipment,Engine analyzer, Hydraulic press & arbor press,Chassis dynamometer, Equipment for repainting

IX. EXPERIMENTAL DETAILS & ENGINE SPECIFICATIONS

The following experimental work was conducted to evaluate and examine the direct use of biogas in a small internal combustion engine in terms of the engine performance and exhaust emissions.
A Bajaj Platina & Hero-Honda Splendor, gasoline (spark ignition) type engine was fuelled on biogas. The engine was modified to allow gaseous fuelling. The major gases fed into the engine cylinder were CH_4 and air. Exhaust emissions such as carbon monoxide (CO) and unburned hydrocarbon (HC) were measured.

- **Engine Specification:**

In this study, the experiments were performed on a Bajaj Platina & Hero-Honda Splendor, single cylinder, four-stroke, spark-ignition gasoline engine. The engine picture is shown in given table:

Table 1.5 Engine Specification of Bajaj Platina

Engine	4-Stroke, Single Cylinder, Air Cooled
Displacement	99.27 cc
Bore and Stroke	53 X 45
Compression Ratio	9.5:1
Max. Power	8.2 PS (6.03 KW) @ 7500rpm
Max. Torque	8.05 Nm @ 4500rpm
Transmission	4 Speed, constant mesh
Clutch	Multiplate- Wet
Ignition	Digital CDI
Fuel Supply	Carburettor

Table 1.6 Engine Specification of Hero Honda Splendor

Engine	4 Stroke, Single Cylinder, Air Cooled
Displacement	97.2 cc
Bore and Stroke	50 X 49.5
Compression Ratio	9:1
Max. Power	7.5 PS (5.5 KW) @ 8000rpm
Max. Torque	7.95 Nm @ 8000rpm
Transmission	4 Speed, constant mesh, 4 up
Clutch	Multiplate Wet
Ignition	CDI
Fuel Supply	Carburettor Side draft, variable venturi- type

X. METHODOLOGY USED & PROBLEMS ENCOUNTERED

The engine performance and emissions from fuelling with CH_4 were evaluated in comparison with gasoline as fuel. A series of experiments were carried out using CH_4. The engine was started using CH_4 and it was operated until it reached the steady state condition. After this emission parameters such as CO, CO_2,O_2 and HC measured by the gas analyzer were recorded.

➢ **Detailed Procedure**

1. The air flow was turned on to engine.
2. The CH_4 flow was turned on.
3. The engine ignition switch was positioned to the 'ON' setting.
4. The engine was started.
5. 10 minutes were allowed to pass so that steady state was reached.
6. A probe connected to the gas analyzer was put into the center of exhaust pipe.
7. 5 minutes were allowed to pass until data from the gas analyzer stabilized.
8. Gas analyzer data recording was started on the computer during these 5 minutes.
9. The probe was removed from the exhaust pipe.
10. Each experiment was repeated three times to calculate the mean values of the experiments.
11. The CH_4 flow was turned off.
12. Air flow was turned off.
13. The engine ignition switch was positioned to the 'OFF' setting.

14. The engine was allowed to draw in ambient air until all emission values approached 0 ppm or 0 %.
15. It was checked to make sure that gas storage tank was completely closed and gas remaining in pipeline was vented.

Emission Comparison of Petrol & Biogas as Fuel in Both Engines

The following PUC Report explains about the emission report of petrol and biogas as a fuel in Bajaj Platina Engine and Hero-Honda Splendor Engine.

Table 1.7 Readings for Bajaj Platina Engine

Sr. No	Fuel	CO(Toxic Gas)		HC(Un Bernd Oil)	
		CO Reading		HC Reading	
		Regulation	Actual	Regulation	Actual
1.	Petrol& Biogas	3.5	0.800	4500	267
2.	Petrol& Biogas	3.5	0.060	4500	1064

Table 1.8 Readings for Hero Honda Engine

Sr. No	Fuel	CO(Toxic Gas)		HC(Un Bernd Oil)	
		CO Reading		HC Reading	
		Regulation	Actual	Regulation	Actual
1.	Petrol & Biogas	3.5	0.08	4500	863
2.	Petrol & Biogas	3.5	1.94	4500	207

Problems Encountered During CH_4 as Fuel

1.Difficult to start engine in cold condition (Flooded Engine).
2.Complete combustion does not take place
3.During high speed the combustion of CH_4 is Unstable (stratified charge).
4.Emission of HC.

XI. CONCLUSIONS

The main objective is to use Methane+H_2 gas as fuel which is considered as one of the cleanest & safest fuel. Moreover the use of these gases can increase the life span of engine by 50% and can reduce the Global Warming up to 4% of the total.
It is seen that both engine can be run safely as per PUC results obtained. But some of the above arises problems can be solve by having some modifications in the engines as follows:

1.Controlling equipment can be added to maintain air-fuel ratio.
2.Reducing the emission of HC (in case of Bajaj Engine).
3.Reducing the emission of CO & CO_2 (in case of Hero-Honda Engine).

For controlling emissions characteristics major agents and devices to be used are:

(i) Three way Catalytic converters:- I t converts the three main pollutants in automobile exhaust an oxidizing reaction converts carbon monoxide (CO) and unburned hydrocarbons (HC) to CO_2 and water vapour, and a reduction reaction converts oxides of nitrogen (NO_x) to produce CO_2, nitrogen (N_2), and water (H_2O).

(ii) Cerium (III) oxide:- It is used as a catalytic converter for the minimisation of CO emissions in the exhaust gases from motor vehicles. When there is a shortage of oxygen, cerium (IV) oxide is reduced by carbon monoxide to cerium (III) oxide:

$$2\,CeO_2 + CO \rightarrow Ce_2O_3 + CO_2$$

When there is an oxygen surplus, the process is reversed and cerium (III) oxide is oxidized to cerium (IV) oxide:

$$2\,Ce_2O_3 + O_2 \rightarrow 4\,CeO_2$$

(iii)NO_x adsorber:-It is designed to reduce oxides of nitrogen emitted in the exhaust gas of a lean burn internal combustion engine. The NO_x adsorber was designed to avoid the problems that EGR (exhaust gas recirculation) and SCR (selective catalytic reduction) experienced as NO_x reduction technologies. The theory is that the zeolite will trap the NO and NO_2 molecules in effect acting as a molecular sponge. Once the trap is full (like a sponge full of water) no more NO_x can be absorbed, and it is passed out of the exhaust system. Various schemes have been designed to "purge" or "regenerate" the adsorber. Use of hydrogen has also been tried, with the same results, however hydrogen is difficult to store. Some experimental engines have mounted hydrogen reformers for on board hydrogen generation; however fuel reformers are not mature technology.

XII. REFERENCES

[1]EIA International Energy Outlook 2010, http://www.eia.doe.gov/oiaf/ieo/highlights.html
[2] Westby, K.J.; Castaldi, M.J., A Comparison of Landfill Gas to Energy Technologies, IT3-120, 2008
[3] Themelis, N.J.; Ulloa, P., Methane Generation in Landfills, Renewable Energy, 32 (2007), pp. 1243-1257
[4] Themelis, N.J., The environmental impacts: Assessing waste-to-energy and landfilling in the US, Waste Management World, 2002, pp. 35-41
[5] EPA, Landfill Methane Outreach Program, 2006
[6] Susan A. Thorneloe, Landfill gas utilization – options, benefits and barriers, In: The US conference on MSWM, 1992

[7] Kohn, M.P.; Castaldi, M.J.; Farrauto, R. J., Auto-thermal and dry reforming of landfill gas over a Rh/Al2O3 monolith catalyst, Appl. Catal. B: Environmental, 94 (2010), pp. 125-133
[8] Kohn, M. P.; Lee, J.; Basinger, M. L.; Castaldi, M. J., Performance of an Internal Combustion Engine Operating on Landfill Gas and the Effect of Syngas Addition, Ind. Eng. Chem. Res., 2011, 50 (6), pp. 3570-3579
[9] Bove, R.; Lunghi, P., Electric Power Generation from Landfill Gas using Traditional and Innovative Technologies, Energy Conversion and Management, 47 (2006), pp. 1391-1401
[10] Wong, J. K. S., Study of mixtures of methane and carbon dioxide as fuels in a single 56 cylinder engine (CLR), SAE reprints, 1977, No. 770796, p. 12
[11] Marcari, N. C.; Richardson, R. D., Operation of a caterpillar 3516 spark-ignited engine on low-btu fuel, Trans. ASME J. Engineering for Gas Turbines and Power, 1987, 109(4), pp.443–447
[12] Mueller, G. P., Landfill gas application development of the caterpillar G3600 spark ignited gas engine, Trans. ASME J. Engineering for Gas Turbines and Power, 1995, 117(4),pp. 820–825
[13] Karim, G. A.; Wierzba, I., Methane–carbon dioxide mixtures as a fuel, SAE Special Publications, 1992, No.927, No 921557, pp. 81–91
[14] Huang, J.; Crookes, R.J., Assessment of simulated biogas as a fuel for the spark ignition engine, Fuel, 1998, Vol.77, No.15, pp. 1793-1801
[15] Shrestha, S.O.; Narayanan, G., Landfill gas with hydrogen addition – A fuel for SI engines, Fuel, 87 (2008) 3616-3626
[16] Heyhood, J.B., Internal combustion engine fundamentals, New York: McGraw-Hill; 1988
[17] Turns, S.R., An introduction to combustion: concepts and applications, 2nd edition, McGraw-Hill; 2000

