INVESTIGATIONS ON THE PERFORMANCES AND EMISSIONS OF A SPARK IGNITION ENGINE FUELLED BY BIOGAS

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Abstract

Biogas is a combustible gas obtained from anaerobic digestion of various organic waste resources. It can be considered as a renewable fuel and can be used in automotive engines as well as for cooking and lighting. In this study, an experimental study on the performances and exhaust emissions of a spark ignition engine of fuelled by mixtures of 65% CH_4 and 35% CO_2 (a typical biogas composition) has been performed at different engine speeds and different air excess ratios. The work has been carried out on a Ford engine. This is a four-stroke four-cylinder spark ignition engine with a compression ratio of 10:1 and with water cooling. The engine performances and emissions are compared between the engine running with biogas and with a conventional fuel. The results are discussed and compared to the literature.

Nomenclature

CA Crank angle
CH_4 Methane
CI Compression Ignition
CO Carbon monoxide
CO_2 Carbon dioxide
EAR Excess air ratio
HC Hydrocarbon
NO_x Oxides of nitrogen
O_2 Oxygen
SI Spark Ignition
TDC Top dead center

1. Introduction

The majority of the energy used today is obtained from fossil fuels. Due to the continuing proce increases of fossil fuels, demands for alternative energy sources, are also increasing. Some of the potential fuels are biogas, syngas, vegetable oil and its esters alcohols and hydrogen. Biogas is one of the renewable energy sources and is obtained from various biomass sources, animal and human waste, and has been intensively tested in internal combustion engines.

Reduction of engine emissions is also a major research aspect in engine development with the increasing concern on environmental protection and the stringent exhaust gas regulations. The lower running cost and the use of alternative fuel sources with dual fuel engine operation has attracted many investigators to apply this type of engine in different areas. The main aspiration for the use of dual fuel engines is mainly to reduce particulate emissions and nitrogen oxides.

For the gasoline engine, biogas generated from waste disposal, using anaerobic digestion of organic matter, has been shown to exhibit suitable properties. Composed predominantly of methane (like natural gas), carbon dioxide, hydrogen and nitrogen, it is able to give enhanced performance and reduced emissions under appropriate operating conditions [1,2]. The ability to accept the fuel without excessive treatment to remove non-fuel components would enable production costs to be reduced in developing nations.

Bade Shrestha and Narayanan[3] discussed landfill gas as a fuel for a spark ignition engine to produce power in an effective way. Though the performance and combustion characteristics of the landfill gas fueled engine deteriorated in comparison with methane operation, increasing compression ratio and advancing spark timing improved the performance of the landfill gas operation compared with methane operation. The effects due to composition changes in the landfill gas were found more pronounced at lean and rich mixture operation than at stoichiometry. In addition, the effects of hydrogen addition up to 30% in volume in the landfill gas were studied. Addition of even small quantities of hydrogen such as 3ï5% delivered better performance improvement particularly at the lean and rich limit operations and extended the operational limits. Additions of hydrogen also improved the combustion characteristics and reduced cyclic variations of landfill gas operations especially at the lean and rich mixtures

Porpatham and et al.[4] have been experimentally studied the influence of reduction of CO_2 concentration in biogas on the performances, emissions and combustion properties in a constant speed spark ignition (SI) engine. A lime water scrubber was used to lower carbon dioxide (CO_2) levels from 41% in biogas to 30% and 20%. The tests covered the range of equivalence ratios from rich to the lean operating limits at a constant speed of 1500 rpm and at compression ratio of 13:1 with a masked valve to enhance swirl. With the reduction of the CO_2 level, significant improvement in the performances and reductions in emissions of hydrocarbons (HC) particularly with lean mixtures were observed. The lean limit of combustion was also extended. Heat release rates indicated enhanced combustion rates, which are mainly responsible for the improvement in thermal efficiency. A reduction in the CO_2 level by 10% seemed to be sufficient for reducing HC levels and NO levels did not increase significantly. The spark timings were to be retarded by about 5^o when the CO_2 concentration was decreased by 10%.

Henham and Makkar[5] work concerns the use of biogas in dual-fuel diesel engines. They examined engine performances using simulated biogas of varying quality representing a range of methane carbon dioxide ratios which may be encountered in biogas from different sources. Their research program, also includes the effects of biogas quality and of the proportion of energy from pilot fuel injection over a range of speeds and loads. A two-cylinder, indirect-injection diesel engine of stationary type was used as the first experimental test bed in this work and the variation of fuel quality is provided by mixing natural gas and carbon dioxide. A data acquisition system for in-cylinder pressure and crank angle was used successfully and some emissions, measurements were also made, particularly for CO and O_2.

Forsich and et al.[6] investigated fuel-rich to fuel-lean biogasï air mixtures were ignited by a Nd: YAG laser at initial pressures of up to 3 MPa and compared to the ignition of methaneï air mixtures. The investigations were performed in a constant volume vessel heated up to 473 K. An InGaAsSb/AlGaAsSb quantum well ridge diode laser was used to track the generation of water in the vicinity of the laser spark in a semi-quantitative manner. Additionally, the flame emissions during the ignition process were recorded and a gas inhomogeneity index was deduced. Laser-induced ignition and its accompanying effects was characterized. The presence of CO2 in the biogas reduces the flame burning velocity. The flame emissions result in a much higher intensity for methane than it was the case during biogas ignition.

In experiments using simulated biogas by Crookes [7] for compression ratios ranging from 11:1 to 13:1, suitable conditions for operation without knock were found. In the case of a biogas fuelled engine, the compression ratios that can be employed can be considerably higher than normal as the CO_2 present helps to suppress knock [8]. High compression ratios were found to increase HC and NOx levels. Dilution by N_2 and CO_2 was found to be beneficial in lowering NOx. Lowering the CO_2 level produced an increase in the thermal efficiency by about 3% and an increase in the power output by about 2%. These experiments were conducted in the equivalence ratio range of 0.98ï 1.05. Lower HC and higher NOx levels have also been reported with reduced CO_2 concentration. When CO_2 in biogas was replaced by N_2, similar performance characteristics were observed [8].

Rakopoulos and Michos [9], used a simulation code of an SI engine operating on biogasï hydrogen mixtures of variable composition. The main focus was on the demonstration of the spatial distribution of combustion inhomogeneties during the combustion process for the various hydrogen fractions examined. This is revealed by the use of a multi-zone thermodynamic model, in combination with a quasi-dimensional combustion model.

Many studies have confirmed that the engine output and pollutants are affected when hydrogen is added to gaseous fuels, such as natural gas and methane. Most of these studies have focused on automotive applications.

Çeper et al. [10], Akansu et al.[11] and Kahraman et al. [12] examined the burning of methane-hydrogen mixtures in internal combustion engines. They found that methane-hydrogen mixtures helped decreasing exhaust emissions, such as HC, CO, CO2, and the engine efficiency could be increased under certain conditions.

Huang et al. [13] investigated the combustion characteristics of a direct-injection spark-ignition engine fueled with natural gas-hydrogen blends under various ignition timings and lean-mixture conditions. The ignition timing had a significant influence on the engine performance, combustion, and emissions. The emission of hydrocarbon concentration decreased and the NOx concentration increased with advancing ignition timing, while the exhaust CO varied little with ignition timing.

Bauer and Forest [14] studied a single-cylinder research engine operated with mixtures of hydrogen and methane. Fuels with various mixing ratios were tested at speeds of 700 and 900 rpm, at full and partial loads, and equivalence ratios from stoichiometric to the burn limit. Their results showed that the spark advance for the best torque could be reduced by a high hydrogen concentration and decreased power, due to a reduction in the volumetric lower heating value.

Wang et al. [15] investigated the combustion behavior of a direct-injection engine operating on various fractions of methane-hydrogen blends. The heat release rate and exhaust NOx increased with the hydrogen concentration in the blends. The brake effective thermal efficiency was increasing as the hydrogen fraction increased at various engine loads. They recommended an optimum hydrogen volumetric fraction in methane-hydrogen blends of around 20% to reach an optimum between the engine efficiency and emissions.

Karim et al. [16] conducted experiments with various hydrogen proportions. They studied the average power output, maximum cylinder pressure, combustion duration, indicated output efficiency, flame speed, and knocking regions as functions of the H_2 and CH_4 percentages, various equivalence ratios, and the angle before top dead center (BTDC). For 10 and 20 BTDC, the performance characteristics of methane-fuelled spark ignition engines were enhanced significantly by the presence of some hydrogen with the methane. If hydrogen was added, the possibility of knocking was higher than when only methane was used, due to the increased cylinder pressure.

This paper focuses on the effect of biogas (%65 CH_4-%35 CO_2) on engine performances and emissions at different engine speeds and different excess air ratios. Tests were conducted on a four cylinder spark ignition engine at full load.

2. Biogas

Gaseous fuels have wide flammability limits and can easily form a homogeneous mixture with air for a good combustion. They can lead to very low levels of pollutants and can be effectively utilized in both spark ignition (SI) and compression ignition (CI) engines. Moreover, gaseous fuels have high hydrogen to carbon ratios. Thus very low CO_2 emissions are possible when they are used in IC Engines. Natural gas and Liquefied Petroleum Gas (LPG) are the readily available petroleum-based fuels, while hydrogen, biogas and producer gas can be obtained from renewable sources. Renewable fuels will not affect the net CO_2 in the environment[4].

A biogas system is a means of digesting animal manure or biomass residues anaerobically to produce methane gas which is burned to provide heat or light. Biogas is produced when bacteria decompose organic material such as garbage and sewage, especially in the absence of oxygen. Biogas consists of methane (CH_4) 55-65%, carbon dioxide (CO_2) 35-45%, with the balance being made up of nitrogen (N_2), hydrogen (H_2) and hydrogen sulphide (H_2S).

Biogas is about 20 percent lighter than air and has an ignition temperature in the range of 650 to 750 ºC. It is an odourless and colourless gas that burns with a blue flame similar to that of Liquefied Petroleum Gas (LPG). Its calorific value is 21 Mega Joules per m^3 and burns with 60 percent efficiency in a conventional biogas stove [17].

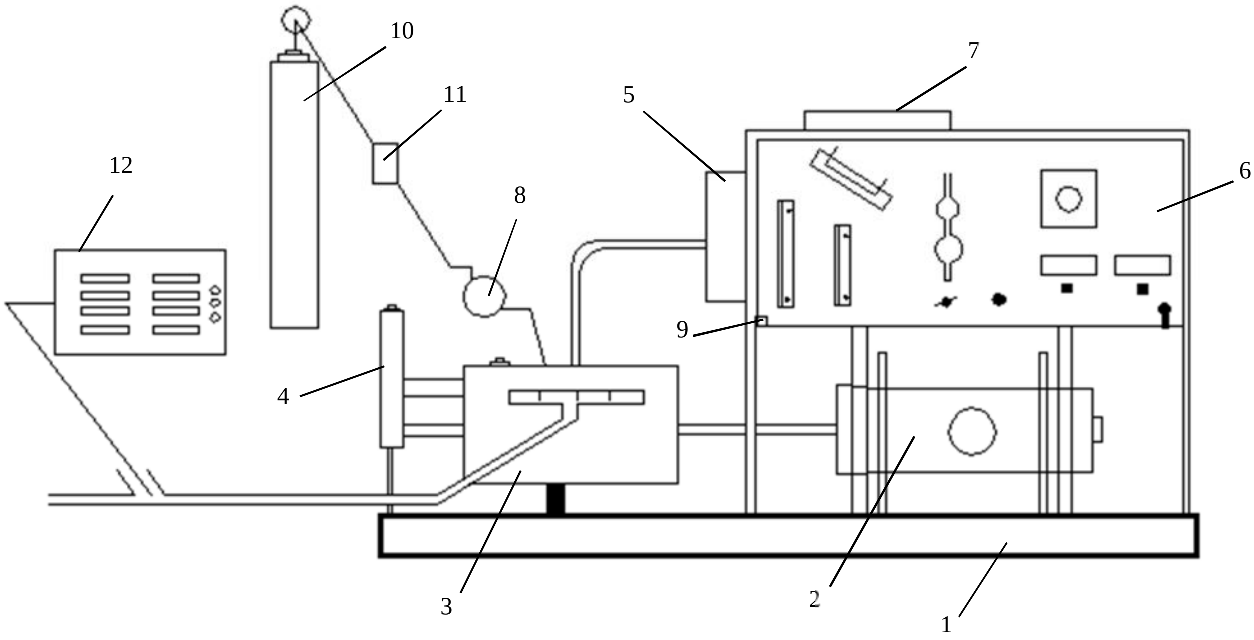
Natural gas and biogas have been found to possess good resistance to knocking. Their octane numbers are higher than that of petrol: for natural gas at 120 [18] and biogas with a composition of 65% CH_4 and 35% CO_2 at 136 [19]. The engines can therefore be operated at a higher compression ratio for better efficiency. The choice of compression ratio for biogas is thus based to some extent on the composition of biogas.

3. Experimental apparatus and test procedure

The present study was conducted on a Ford gasoline engine. This is a four-cylinder, four strokes and spark ignition engine with a swept volume of 1800 cc. The general specifications of the engine are shown in Table 1. A Cussons-P8601 brand hydrokinetic dynamometer was used for the tests. The schematic view of the test equipments is shown in Figure 1.

Table 1. General specifications of the Ford engine

Bore	80.6	mm
Stroke	88	mm
Compression Ratio	10:1	-
Exhaust valve opening	55	BBDC
Exhaust valve closing	50	ATDC
Intake valve opening	13	BTDC
Intake valve closing	47	ABDC



1-Engine Chassis, 2- Hydrokinetic Dynamometer, 3- Engine, 4- Engine Cooling Unit, 5-Air Tank, 6-Control Unit, 7- Main Fuel Tank, 8- Regulator, 9- Fuel Select Key, 10-Fuel Tank, 11-Mass Flow Meter, 12- Exhaust Gas Analyzer

Figure 1. Experimental rig

The work was conducted in the Engine Laboratory in the department of Mechanical Engineering at the University of Erciyes. A Sun MGA 1500 gas analyzer was used to measure CO, NO, CO2, HC and λ values. The in-cylinder pressure was measured with AVL type 8QP500C water cooled piezoelectric pressure transducer. The transducer is connected to a Cussons Model 4441 charge amplifier, which provides a calibrated voltage signal for display on a Signal Processing Rack 4410 oscilloscope. Selected profiles subsequently transferred to a personal computer system for further analysis. Before experiments, pressure transducer is calibrated regularly in a pressurized gas chamber and the amplifier output versus gas chamber pressure is plotted. An example calibration curve of pressure transducer and charge amplifier output is shown in Figure 2.

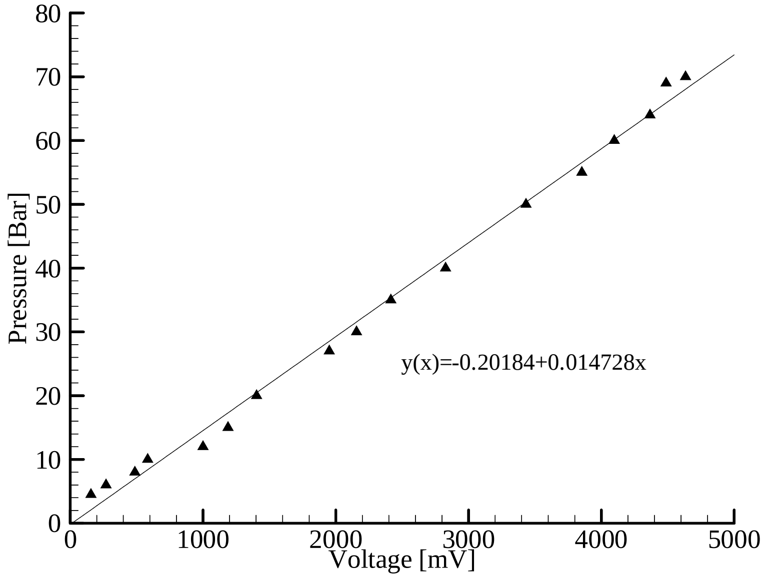


Figure 2. Pressure transducer calibration curve

4. Results and discussions

In internal combustion engines the airï fuel ratio λ has a large influence on NOx-formation in the exhaust gas, leading to reduced NOx emissions with increasing λ-values due to lower combustion temperatures. On the other hand, unburned (hydrocarbon) HC concentrations in the exhaust gas have to be considered as well as the thermal efficiency and the power output of the engine when operating in fuel-lean regimes. Too lean fuelï air mixtures may cause harsh and irregular running of the engine due to incomplete combustion processes and slow burning velocities. When using biogas as fuel one must also pay attention to several harmful ingredients such as H_2S polluting the catalytic converter of the engine. Biogas-air flames are cooler and propagate more slowly than the corresponding methane ï air flames. The reason for these results could be due to the presence of CO_2 in the biogas which reduces the burning velocity due to its larger heat capacity compared to nitrogen.

For CO_2 added CH_4/air flames, the global combustion reaction is:

$$(1-\beta)[(CH_4 + (2 +X)(O_2+3.78N_2)]+ \beta CO_2 \rightarrow CO_2 + 2(1-\beta) H_2O + 7.56(1-\beta)N_2 + x(1-\beta) (O_2+3.78N_2)$$

where x is the excess air parameter. β is the CO_2 mole fraction in the fuel knowing that the (CH_4 + CO_2) mole fraction is equal to 1. So β is defined as $\beta = n(CO_2)/(n(CH_4) + n(CO_2))$. In the present work we prefer to characterize the CO_2 addition or CO_2 dilution rate with its mole fraction in the fuel and not in the oxidant (air) [20].

The experiments were carried out with biogas by varying the excess air ratio for different engine speeds at full load. The effects of most influential operating variables such as excess air ratio on cylinder pressure, brake thermal efficiency, CO, CO_2, HC and NO emissions are tested.

4.1. Performance and emission parameters

The pressure versus crank angle variations during biogas and methanefuelled engine operations at two different excess air ratios (1.1;1.2) are shown in Figure 3, at 1500 rpm and 100% throttle. We see that the peak pressure of methane increases significantly when compared with biogas (%65 CH_4 - %35 CO_2). This is due to faster combustion, which also results in improved thermal efficiency and power output at these conditions. The variations at different EAR do not affect significantly the peak pressure of biogas. The peak pressure values are obtained at 14^o and 18^o after TDC for methane and biogas, respectively. Generally, the engine can reach its highest efficiency when maximum pressure occurs at 10ï 15Ŭ ATDC. While EAR is increasing, peak pressure values are decreasing for either fuels.

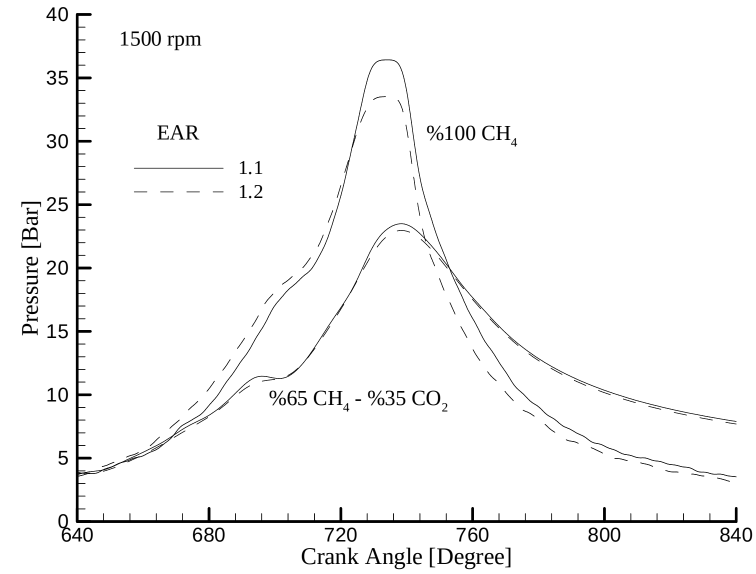


Figure 3 Cylinder pressure values versus the crank angle at 1500 rpm for methane and biogas operations

Figure 4 shows the brake power and thermal efficiency (η_{BT}) for methane and biogas operations. With increasing EAR, brake power and brake thermal efficiency values are decreasing for biogas operations. When compare to methane operations, brake power and brake thermal efficiency values with biogas are lower.

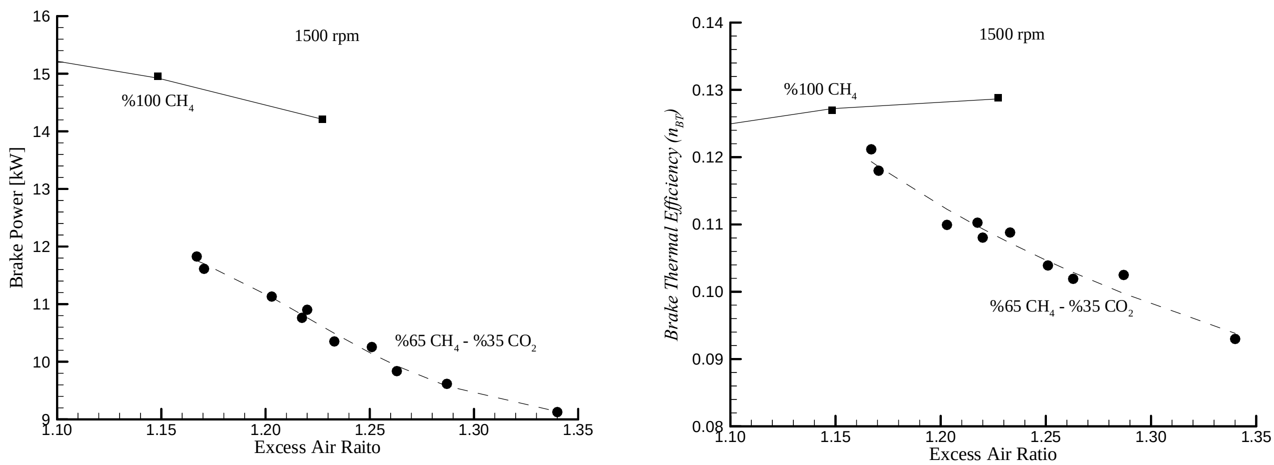


Figure 4 Brake power and brake thermal efficiency values versus EAR at 1500 rpm for methane and biogas operations.

Figure 5 shows the variation of CO_2, CO and HC emissions versus EAR at 1500 rpm for methane and biogas operation. Because of the CO_2 present in biogas the CO_2 emission of biogas operation is higher. With increasing of EAR, CO_2 emissions for each fuel are decreasing. The CO emission values for methane operations is higher than the one with biogas. With increasing EAR, the HC emissions with methane operations are decreasing, while the HC emissions with biogas operations are increasing.

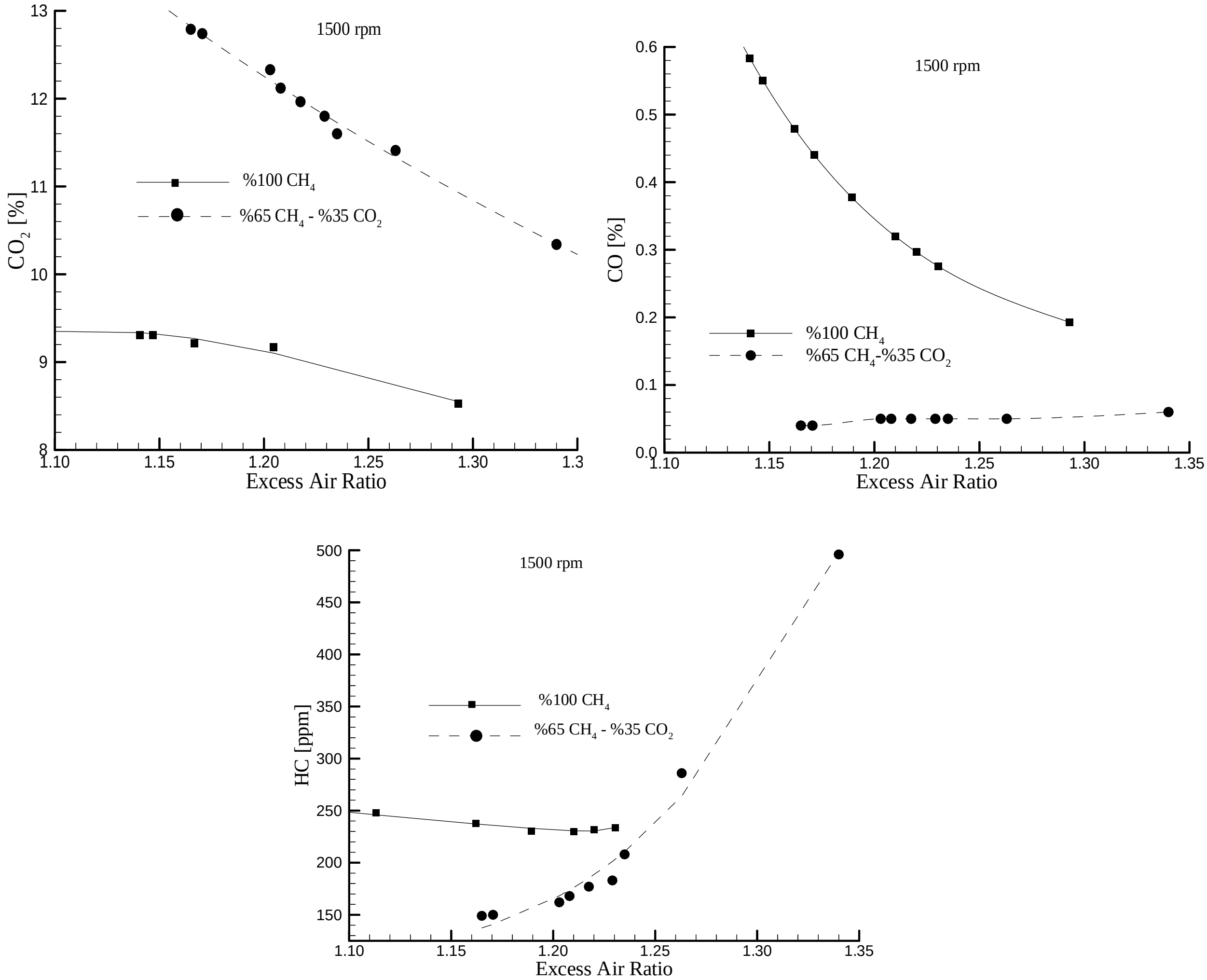


Figure 5 Variation of CO_2, CO and HC emissions versus EAR at 1500 rpm for methane and biogas fuelled engine operations

The variations of CO_2, CO, HC and NO emissions versus EAR at different engine speed for biogas are shown on Figure 6. there is no significant change of CO_2 emission values with increased engine speed. With increasing EAR, CO_2 emissions decreases for each engine speed and there is only a slight increase of CO emissions. HC emissions increase with EAR at different engine speed values due to incomplete combustion. The increases of HC emissions at different engine speeds values are similar. NO emissions decrease with EAR for all engine speeds.

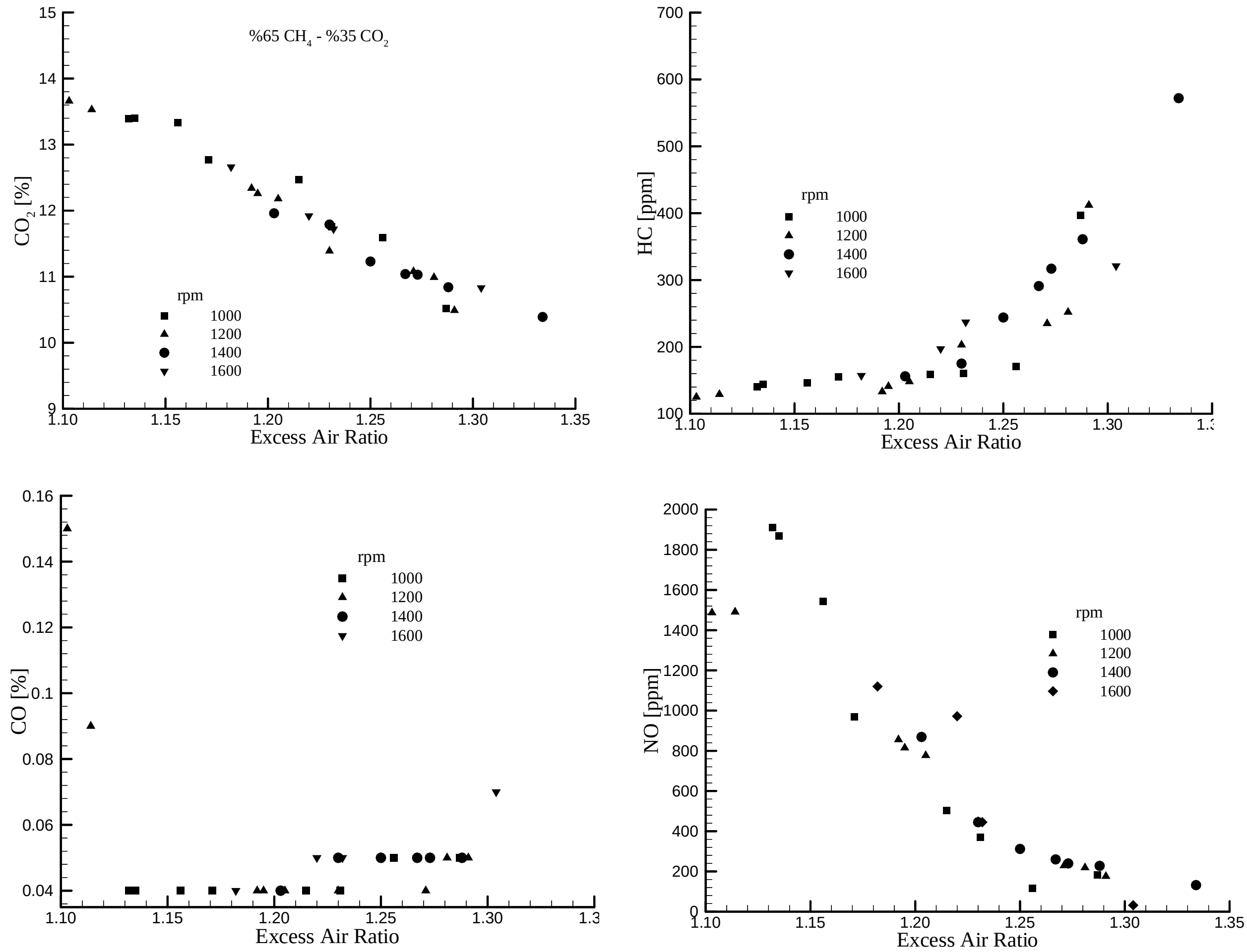


Figure 6 Variation of CO_2, CO, HC and NO emissions versus EAR at different engine speed for biogas operations.

5. Conclusions:

An experimental study on the performances and emissions of a spark ignition engine operated with biogas was conducted. The main results can be summarized as follows.

- The experimental measurements give results coherent with the literature data.
- Increasing the EAR values leads to a decrease in peak pressure values.
- For biogas operations, emission parameters do not change significantly with the engine speed.
- Brake thermal efficiencies of biogas operations are lower than methane operations.
- Biogas is an important form of renewable energy, which can be used where organic waste is produced in appropriate quantities.
- Biogas can make an important contribution to the protection of natural resources and environment.

References

[1] Huang JD, Crookes RJ. Assessment of simulated biogas as a fuel for the spark-ignition engine. Fuel 1998;77(15):1793ï 801.
[2] Huang JD, Crookes RJ. Spark-ignition engine performance with simulated biogas a comparison with gasoline and natural gas. J Inst Energy 1998;71:197ï 203.
[3] Bade Shrestha S.O., Narayanan G., Landfill gas with hydrogen addition ï A fuel for SI engines, Fuel 87 (2008) 3616ï 3626
[4] Porpatham E., Ramesh A., Nagalingam B., Investigation on the effect of concentration of methane in biogas when used as a fuel for a spark ignition engine, Fuel 87 (2008) 1651ï 1659
[5] Henham A., and Makkar M.K., Combustion of Simulated Biogas in a Dual-Fuel Diesel Engine, Energy Convers. Mgmt Vol. 39, No. 16±18, Pp. 2001±2009, 1998.

[6] Forsich C., Lacknera M., Winter F., Kopecek H., Wintner E., Characterization of laser-induced ignition of biogasï air mixtures, Biomass and Bioenergy 27 (2004) 299 ï 312.
[7] Crookes R.J., Comparative bio-fuel performance in internal combustion engines, Biomass and Bioenergy 30 (2006) 461ï 468.
[8] Jingdang Huang, Crookes RJ. Assessment of simulated biogas as a fuel for the spark ignition engine. Fuel 1998;77(15):793ï 1801 [UK].
[9] Rakopoulos C.D., Michos C.N., Generation of combustion irreversibilities in a spark ignition engine under biogasï hydrogen mixtures fueling, Int. Journal of Hydrogen Energy 34 (2009) 4422 ï 4437.
[10] Ceper B, Akansu SO, Kahraman N. Investigation of cylinder pressure for H_2/CH_4 mixtures at different loads. Int. J. Hydrogen Energy 2009;34:4855ï 61.
[11] Akansu SO, Kahraman N, Ceper B. Experimental study on a spark ignition engine fuelled by methaneï hydrogen mixtures. Int. J. Hydrogen Energy 2007;32:4279ï 84
[12] Kahraman N, Ceper B, Akansu SO, Aydēn K. Investigation of combustion characteristics and emissions in a spark-ignition engine fuelled with natural gas hydrogen blends. Int. J. Hydrogen Energy 2009;34:1026ï 34.
[13] Huang Z, Wang J, Liu B, Zeng K, Yu J, Jiang D. Combustion characteristics of a direct injection engine fueled with natural gasï hydrogen blends under different ignition timings. Fuel 2007;86:381ï 7.
[14] Baurer C.G., Forest T.W., Effect of hydrogen addition on the performance of methane-fueled vehicles. Part I: Effect on SI engine performance. Int. J. Hydrogen Energy 2001;26:55ï 70.
[15] Wang J, Huang Z, Fang Y, Liu B, Zeng K, Miao H, et al. Combustion behaviors of a direct injection engine operating on various fractions of natural gas-hydrogen blends. Int. J. Hydrogen Energy 2007;32(15):3555ï 64.
[16] Karim GA, Wiezba I, Al-Lousi Y. Methane-hydrogen mixtures as fuels. Int. J. Hydrogen Energy 1996;20:625ï 31.
[17] http://www.makinemekanik.com/?page_id=15
[18] Zhang, D., Frankel, S.H., A numerical study of natural gas combustion in a lean burn engine, Fuel, Vol. 77, No. 12, pp. 1339-1347, 1998.
[19] Ferguson, C.R., Internal Combustion Engines, 437, Wiley, New York, 1986.
[20] Cohe C, Chauveau C, Gökalp Ķ, Kurtulus D. F., CO_2 addition and pressure effects on laminar and turbulent lean premixed CH_4 air flames, Proceedings of the Combustion Institute 32 (2009) 1803ï 1810.