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EMISSIONS AND PERFORMANCE CHARACTERISTICS OF AN SI ENGINE WITH BIOGAS FUEL AT DIFFERENT CO_2 RATIOS

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ABSTRACT

Nowadays increasing emission regulations and environmental concerns have led to the use of alternative fuels in internal combustion engines. Biogas is an alternative fuel that can be produced with clean, green and natural resources. In this study, a single cylinder, four stroke SI engine was operated at stoichiometric conditions, 2800 rpm constant engine speed with biogas fuel at different ratios. As biogas fuel, methane (CH_4) and CO_2 were used during engine tests. Test results which were taken by using only gasoline were compared with the results obtained by using biogas fuel at different CO_2 ratios (10%, 20%, 30% and 40% by volume). Although it was determined specific CO emissions decrease and THC emissions slightly increases with the increasing CO_2 ratio, it is foreseen that the increase in THC emissions can be prevented by the use of three way catalytic converter. Although the NO_x emissions increase with the use of biogas compared to gasoline, it was significantly reduced by the increased CO_2 rate in the biogas fuel, the CO_2's heat carrying capacity and reducing the O_2 availability of the fuel. On the other hand, because of the high cost of purification process of biogas and after-treatment equipment, it is foreseen that use of biogas at high ratio of CO_2 in SI engines will be advantageous in terms of NO_x emissions.

Keywords: *Biogas, CO_2, Methane, SI Engine, Emissions, Combustion*

INTRODUCTION

Nowadays, as the number of vehicles increases, the percentage of diesel vehicles in the vehicle market increases [1]. In 2016, the market of diesel vehicles have 49% share among all vehicles in European countries [2]. In this case, the emission of NO_x and PM emissions increases, affecting the environment and human health negatively [3]. Due to this reason, several steps have been taken in recent years to reduce the number of diesel vehicles. As an alternative to diesel vehicles, electric and Fuel Cell vehicles are targeted to be presented to the market [4]. However, because of the high cost and short life spans of PEM fuel cells and high cost of purification of hydrogen and hydrogen storage problems avoids the use of fuel cells in vehicles [5]. On the other hand, because of the need of improvement at current battery technology and the inadequacy of charge stations prevents the widespread use of these systems in the near future [6]. Due to this reason, it is foreseen that fuel cells will be used to supply very small units' batteries and increase their range which can be used as range extender in small powers and operated as both serial hybrids and parallel hybrids when necessary. In the near future, the use of environmentally friendly, low-cost and alternative gas fuels in SI engines will gain great importance. Because of this reasons, biogas emerges as a clean and environmentally friendly alternative fuel containing methane, CO_2 and other gases that can be produced from natural sources [7]. Due to the methane in its content, biogas is a environmentally friendly fuel, which has low C/H ratio [8]. Because of the methane in its content, the use of biogas in in SI engines provides great benefit in terms of emissions [9].

Related studies in the literature on the use of biogas in SI engines are given below:
Karagoz et al. [10] used an ANN model for a spark ignition engine with use of different methane (CH_4) ratios to estimate engine performance data. The study shows that with the increase in methane concentration, positive effect is seen in volumetric efficiency but a dramatic decrease occurs in thermal efficiency. Despite that there isn't any observable change in brake specific fuel consumption.

Wang et al. [11] studied the effect of methane content to NO_x emissions and indicated thermal efficiency in a biogas fuelled spark ignition engine. It is included that increase in methane content in biogas have positive effect in both indicated thermal efficiency and NO_x emissions.

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Shin et al. [12] studied the effect of using biogas in a small spark ignition engine at different compression ratio and various CO_2 dilution (0%-50%) on engine performance. The results show that, engine performance increases by using biogas with decreasing CO_2 dilution.

Nadaleti et al. [13] made experiments tos see the effect of biogas-syngas dual fuel in a SI engine on engine emission characteristics. The results show that the use of biogas fuel decreases NO_x emissions with a increase HC emissions.

Porpatham et al. [14] investigated the effect of increased oxygen concentration of intake air on engine performance, emissions and combustion in a biogas fuelled spark ignition engine. At higher oxygen levels, an observable improvement was seen in brake thermal efficiency and brake power. With higher oxygen concentration, NO_x emissions increases, but HC and CO_2 emissions decreases. There is also an improvement in thermal efficiency as a result of enchancement in combustion.

Yadav et al. [15] studied exhaust emissions characteristics of a biogas operated automotive SI engine experimentally. Experiments were performed with %100 biogas fuel via petrol. With the comparison of petrol, the results shows that the use of biogas makes reduction in NO_x and CO emissions and causes negligible CO emissions.

Considering the work done so far in the literature, it has been found that there is not enough work on the performance and emissions effects of using biogas with different CO_2 contents directly on SI engines. In addition, the emission and performance impact of using biogas at different CO_2 ratios in SI engines has not been investigated because the naturally purifiable biogas fuel refinement is costly and CO_2 in the content of biogas has a high heat transfer capacity and low O_2 availability. It is known that biogas usage in SI engines may have some negative impact on thermal efficiency and mean effective pressure. However, decreasing the toxic emissions, such as $NO_{x,}$ to the limits determined by the stringent emission regulations requires high cost after-treatment equipments. Because of being a good alternative to reduce the emissions, the research of biogas usage which has different CO_2 ratios on SI engines is performed in this study.

TEST METHODOLOGY

Schematic diagram of test system is shown in Figure 1. A single cylinder SI engine is used in the experiments. Engine is loaded with an 8 kW AC dynamometer. Fuel system consists of a methane gas tank which is connected to intake and exhaust system of the test engine. Details of the test system is given in the next subsection.

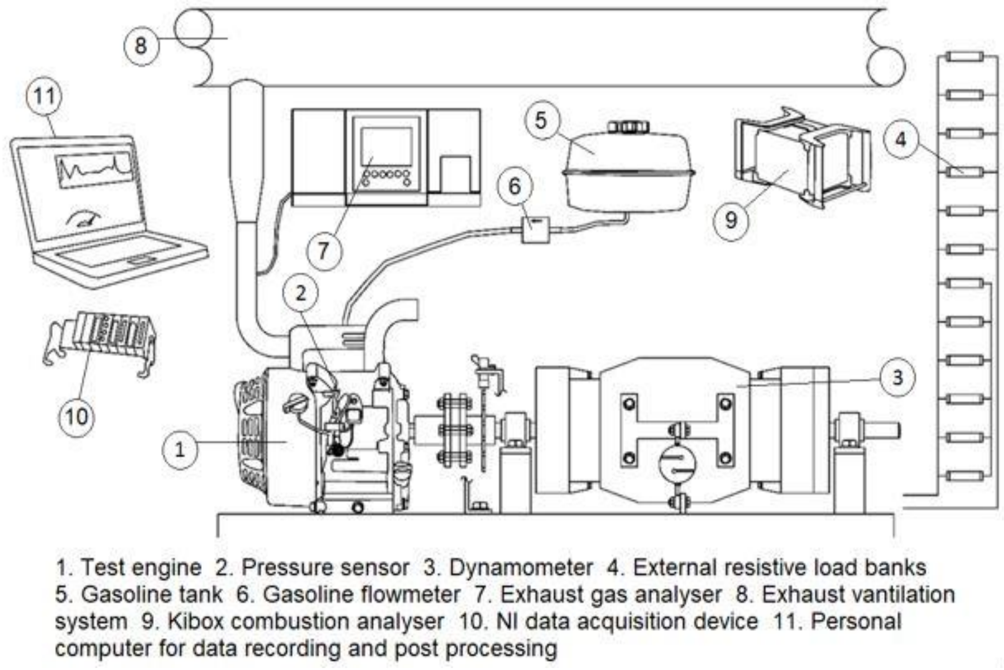

Figure 1. Schematic diagram of engine test system

Test Setup

Experiments were performed on a single cylinder, 270 cc, four stroke, naturally aspirated, SI engine. Engine was operated first with only gasoline then with methane at different CO_2 contents (10%, 20%, 30%, 40%). All the tests were carried out at constant speed (2800 rpm) and repeated three times.

A miniature oval gear type fuel meter was used to measure gasoline consumption. New-flow, TLF series hotwire type mass flow meter was preferred to measure methane and CO_2 gas consumption. Mass flow rate of intake air was measured by a mass flow meter. AVL Digas 4000 was used to carry out the emission measurements. Calculation method which is announced by VDMA exhaust emission legislation for diesel and gas engines was used for the calculation of specific emissions by using gasoline, CO_2 + CH_4 and intake air mass flow rates [16].

Crank angle position and engine speed was obtained with use of a proximity sensor and an incremental type encoder. In order to measure in-cylinder pressure, Kistler 6118B in-cylinder pressure transducer, which can also be used as spark plug was fixed to the engine head instead of original spark plug of the SI engine. Then obtained in-cylinder pressure data were processed by Kistler Kibox combustion analyzer device.

Engine and Dynamometer

A 270 cc, single cylinder, four stroke, naturally aspirated, SI engine was used during the tests. Methane and CO_2 gas tanks were installed to the intake port of the test engine. Test engine was loaded by a 8 kW AC dynamometer. Detailed information of test system can be seen in Table 1. Tests were performed in Yıldız Technical University, Internal Combustion Engines Laboratory. All of the measurement devices and test equipments in Internal Combustion Engines Laboratory of Yıldız Technical University are calibrated and certificated by the authorized companies in Istanbul.

Table 1. Engine specs and dynamometer features

Engine Specs	
Engine manufacturer	Honda
Number of cylinders	1
Bore × stroke [mm]	77 × 58
Cylinder volume [cm^3]	270
Aspiration	Natural
Compression ratio	8.5 : 1
Net power [kW]	6.3 @3600 rpm
Recommended speed range [rpm]	2000-3500
Cooling	Air
Dynamometer Features	
Power [kVA] [kW]	8

Test Procedure

Two independent tests were performed in this study sequentially,

- Firstly, CO_2 and CH_4 gas tanks were equipped to the intake system of the test engine. Engine tests were performed with methane. CO_2 was fed into intake manifold as supplementary fuel at 4 different ratios (10%, 20%, 30%, 40%). All tests were conducted at constant speed (2800 rpm). Then,
- The SI engine were operated using only gasoline as fuel running at constant engine speed (2800 rpm).

DATA PROCESSING

In order to obtain engine performance and combustion analysis, data which were collected form sensors were used. For the calculation, following equations were used:

$$\dot{m}_B = \left[\dot{v}_B \frac{2}{3} x \frac{1}{1000x60} x \rho_B\right] \tag{1}$$

where, $\dot{m}_B$ is mass flow rate of biogas (kg/m^3), $\dot{v}_B$ is measured volume flow rate of biogas, ρ_B is density of biogas (kg/m^3).

The equations [17] used to calculate the indicated engine power and indicated engine work are given as:

$$W_i = P_{mi}\, x\, V_H = \int_0^{720} P\, dV \quad (2)$$

$$N_i = \frac{W_i\, x\, n}{60\, x\, 2} \quad (3)$$

where W_i is indicated work done per cycle (J), P_{mi} is mean indicated pressure (Pa), V_H is cylinder displacement (m^3), P is pressure which was measured from the cylinder (Pa), V is calculated instant cylinder volume (m^3), N_i is indicated engine power (kW).

Indıcated engine torque can be calculated as given in equation (8) by the use of indicated power value [17].

$$M_i = \frac{60}{2\pi n} N_i \quad (4)$$

where n is the engine speed (rpm) and M_i is indicated engine torque (Nm).

In order to obtain engine performance characteristics, the calculated engine power value, measured pressure and flow rates of gasoline, methane and CO_2 can be used.

Equation (5) is used for the calculation of indicated thermal efficiency [17].

$$\eta_{Ti} = \frac{N_i}{\dot{m}_g \times LHV_g + \dot{m}_H \times LHV_B} \quad (5)$$

where, η_{Ti} is indicated thermal efficiency, $\dot{m}_g$ and $\dot{m}_{CO2}$ are mass flow rates of gasoline and CO_2 respectively (kg/s) and LHV_g and LHV_{CO2} are lower heating values of gasoline and CO_2 respectively (kJ/kg).

For the calculation of emission values, which were also measured by volume and mass flow rate of exhaust gases during tests, measured flow rates of intake air, methane, CO_2 and gasoline can be used as seen equation (6) [15]. Thereby, by using these values and indicated engine power, specific emissions can be calculated as given in equation (7) [15].

$$\dot{m}_{ex} = \dot{m}_{ia} + \dot{m}_H + \dot{m}_g \quad (6)$$

$$EP_i = EV_i\, x\, \frac{M_i}{M_{ex}}\, x\, \frac{\dot{m}_{ex}}{N_i} \quad (7)$$

where $\dot{m}_{ex}$ and $\dot{m}_{ia}$ is mass flow rates of exhaust gases and intake air, respectively (g/h), EP_i is specific emission value of relevant gases (g/kWh), EV_i is relevant gases and total exhaust gases ratio by volume for CO and by ppm for THC and NO_x emissions, M_i and M_{ex} are molar mass of relevant gases and exhaust gases respectively (kg/kmol) and N_i is indicated engine power (kW).

The total propagated uncertainty of the Precision and Systematic (Bias) errors measurement determined by Kline and McClintock analysis [18] is:

$$(W_R)_{P,B} = \left[\left(\frac{\partial R}{\partial x_1} w_1\right)^2 + \left(\frac{\partial R}{\partial x_2} w_2\right)^2 + \cdots + \left(\frac{\partial R}{\partial x_n} w_n\right)^2\right]^{1/2} \quad (8)$$

And the computation of the total uncertainty W_R is done with:

$$W_R = \sqrt{(W_R)_P{}^2 + (W_R)_B{}^2} \quad (9)$$

where $(W_R)_{P,B}$ denotes the propagated uncertainty for either precision error $(W_R)_P$, or systematic (Bias) error $(W_R)_B$ functions. x_1, x_2,…,x_n are the measured variables and w_1, w_2,…w_n are the corresponding uncertainties of the variables. The measurement uncertainty values of test setup were given in Table 2.

Table 2. Accuracy values of test devices and obtained total uncertainty values

Parameter	Device	Accuracy
Engine speed	Incremental encoder	±5 rpm
Gasoline flow rate	Biotech VZS-005	±1 % (of reading)
CO	AVL Digas 4000	0.01 % Vol.
THC	AVL Digas 4000	1 ppm
NO_x	AVL Digas 4000	1 ppm
Calculated results		Uncertainty value
Indicated thermal efficiency		±1.18 ÷ 1.32 %

RESULTS AND DISCUSSION

ITE

The efficiency of useful energy conversion from the fuel consumed by the engine is defined by indicated thermal efficiency. In other words, the engine specific fuel consumption is directly affected by ITE [17]. The variation in indicated thermal efficiency due to biogas usage at different CO_2 ratios is given in Figure 2.

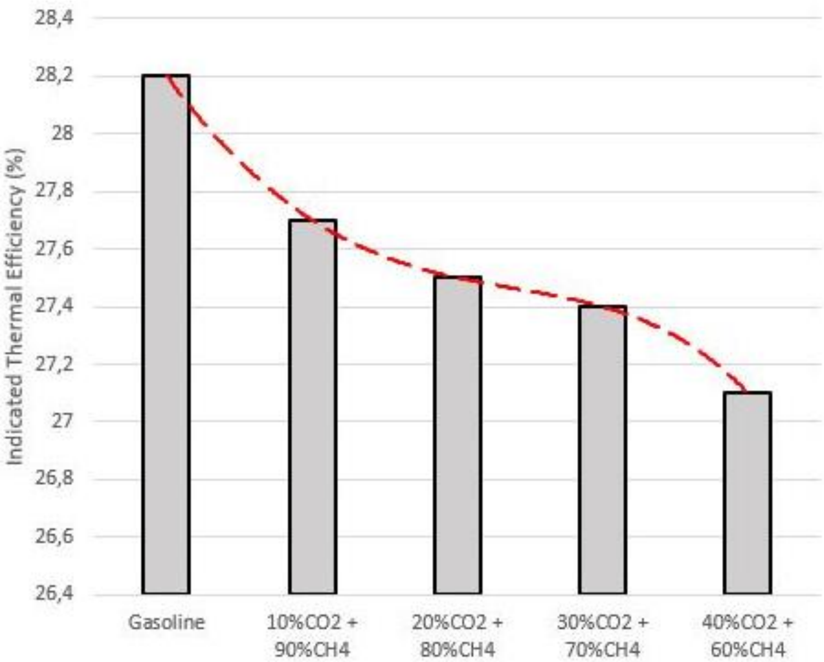

Figure 2. Effect of different level of CO2 and CH4 addition on indicated thermal efficiency

As comparison with the results when the engine is operated with only gasoline, ITE value is reduced at all CO_2 ratios with biogas usage as fuel. ITE value decreased 1.8% at 10% CO_2 ratio, 2.4% at 20 CO_2 ratio, 2.8% at 30% CO_2 ratio and decreased 3.9% at 40% CO_2 ratio.

The heat carrying capacity of CO_2 in the biogas causes reduction of in-cylinder combustion pressure values [20]. This situation explains the reduction of ITE values with biogas usage which contains CO_2.

IMEP

Through the cycle, in-cylinder pressure of an engine changes continuously. In order to estimate an average value of in-cylinder pressure variation, mean effective pressure parameter is defined [19]. Because of independency of engine speed and size, using mean effective pressure is a good way to compare engines in terms of design and output [19]. Indicated mean effective pressure (IMEP) is obtained by using indicated work to define mean effective pressure value of the engine [17]. In this study, indicated mean effective pressure (IMEP) parameter is used to compare engine performance of gasoline and biogas blends.

Figure 3 gives the test results about the variation of IMEP with the usage of only gasoline as fuel and with only biogas at four different CO_2 ratios (%10, %20, %30 and %40) at constant engine speed (2800 rpm). In comparison with the results when the engine is operated with only gasoline, IMEP value is reduced at all CO_2 ratios with biogas usage as fuel. IMEP value decreased %8.9 at % 10 CO_2 ratio, %9.4 at 20 CO_2 ratio, %10.5 at %30 CO_2 ratio and decreased %12.2 at %40 CO_2 ratio.

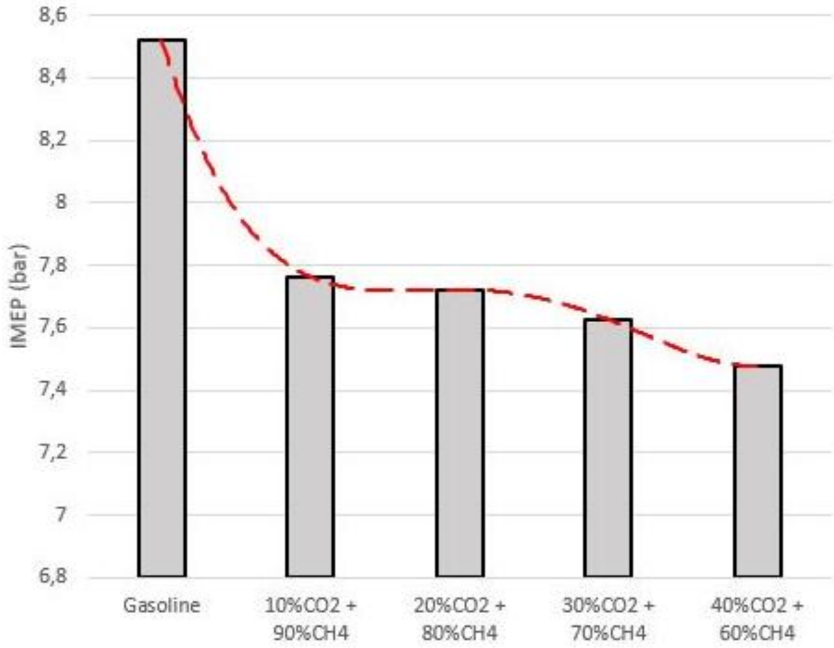

Figure 3. Effect of using CH_4 at different CO_2 levels on indicated mean effective pressure

As seen in Figure 3, with use of biogas and increasing CO_2 content, IMEP values decreases. The main reason of this result is the decrease in maximum in-cylinder pressure because of operating the engine at near stoichiometric conditons. Also, because of using gaseous fuel, low density of methane, methane's rendering high cylinder volume and dilution of combustion chamber by CO_2 (EGR effect) are the other reasons of the decrease in IMEP values.

CO

Carbon monoxide is a colorless, odorless, poisonous gas, which is mostly generated when engine is operated with rich fuel ratio [19]. When there is not enough O_2 to convert all carbon to CO_2, some fuel does not get burned and some carbon ends up as CO [19].

Figure 4 gives the test results about the variation of CO emission with the usage of only gasoline as fuel and with only biogas at four different CO_2 ratios (10%, 20%, 30% and 40%) at constant engine speed (2800 rpm).

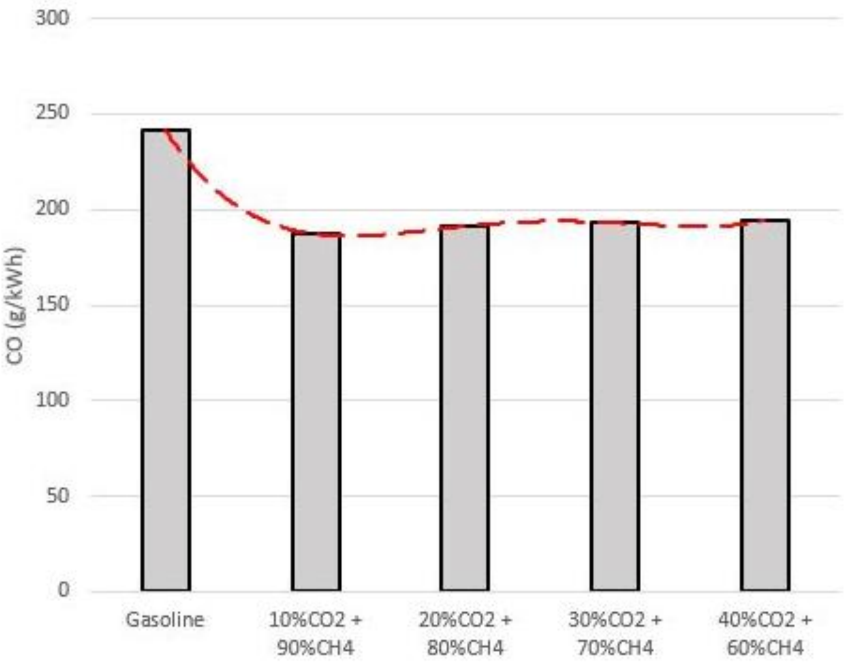

Figure 4. Effect of different level of CO2 and CH4 addition on specific CO emissions

As the comparison with only gasoline usage as fuel, CO emissions are low with only biogas usage at all CO_2 ratios. CO emission reduces about 22,5% at 10% CO_2 ratio, reduces about 20,8% at 20% CO_2 ratio, reduces about 20% at 30% CO_2 ratio and reduces about 19,5% at 40% CO_2 ratio from CO emission released by engine operated with only gasoline.

Methane composes the main structure of biogas. Methane has low C/H ratio and low carbon concentration in its composition. Because of its low C structure, methane increases the oxygenation of the fuel [21]. So, this situation explains the reduction in CO emission with use of biogas as fuel.

Methane has low C content, so it provides low CO emissions. As CO_2 content of mixture increases, CO emissions slightly increases. However, methane is a reactive gaseous fuel, and with the use of methane, a nearly homogenous mixture occurs in combustion chamber. So, the changes in CO emissions at all CO contents are nearly negligible.

THC

As one of the reasons of lung and blood diseases, hydrocarbons are another harmful emission [22]. So, for human health, it is essential decrease in THC emission. THC is the definition of the hydrocarbon emissions which are emitted from tailpipe. It contains both partially burned and unburned hyrocarbons. So, CH_4 emissions are counted in total hyrocarbons and more accurate results are obtained. The measured THC emission values with only gasoline fuel and with biogas at four different ratios (10%, 20%, 30% and 40%) at constant engine speed (2800 rpm) are given in Figure 5.

As compared with only gasoline usage as fuel, hydrocarbon emissions were increased considerably with the use of biogas at all CO_2 ratios. THC emissions increased at about 2.4% at 10% CO_2 ratio, increased about 6.6% at 20% CO_2 ratio, increased about 8.7% at 30% CO_2 ratio and increased about 11.2% at 40% CO_2 ratio in comparison with gasoline.

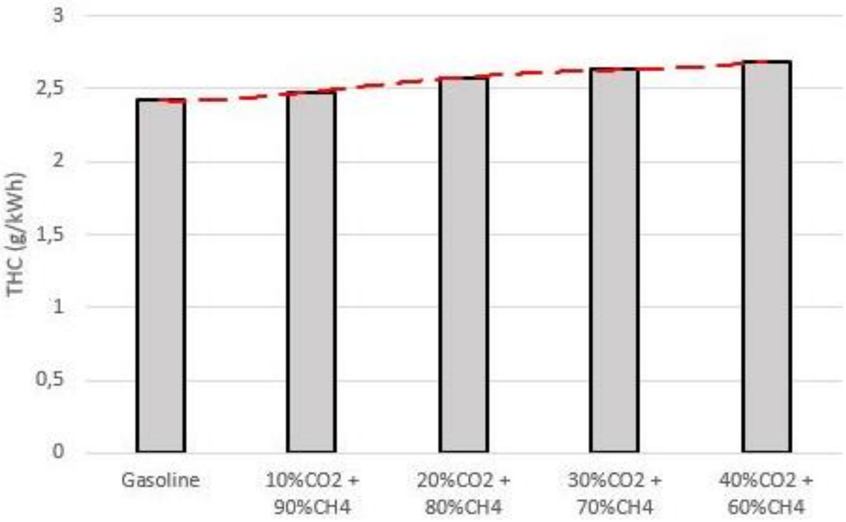

Figure 5. Effect of different level of CO_2 and CH_4 addition on specific THC emissions

Biogas contains high concentration of methane. Because of the high quenching distances and zones of methane and its volatile HC structure, THC emissions increase with biogas usage as fuel [23]. For optimal usage of biogas, crevice zones, electrode gaps, valve seats, piston ring gaps and sealing gaps in the engine should be minimized. The unsuitable design of the SI engine for biogas fuel is another reason of the increase in THC emissions.

NO_x

Oxides of nitrogen, which is emitted by an engine, can reach to 2000 ppm value. Nitrogen in the air is the main source of NO_x. Released NO_x is one of the major reasons of photochemical smog [19]. Nowadays, emission regulations become more stringent, especially for NO_x emissions. Because of stringent emission regulations, SI engines are being named as positive ignition engine as they are compared with diesel engines in terms of released amount of NO_x emissions. Methane has additive effect on NOx emissions. In this study, because of high methane percentage of fuel, NOx emissions are higher than that of pure gasoline at 10% and 20% contents.

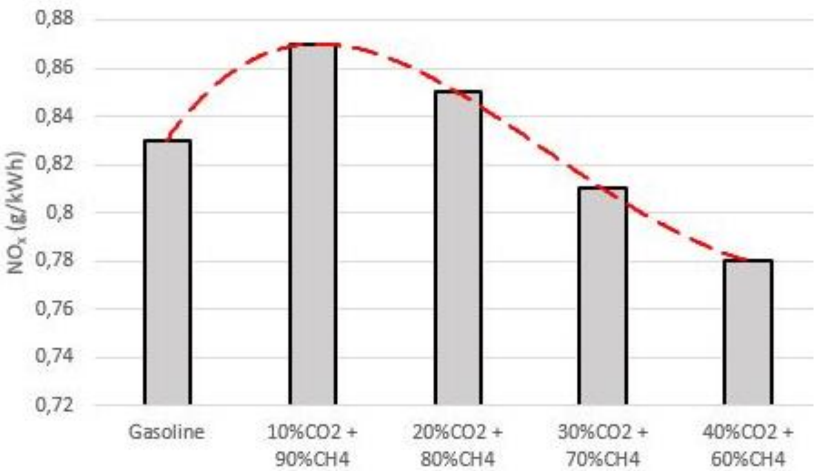

Figure 6. Effect of different level of CO_2 and CH_4 addition on specific NO_x emissions

NO_x emissions are shown in Figure 6 with biogas at different CO_2 ratios (10%, 20%, 30% and 40%) and with only gasoline at constant engine speed (2800 rpm).

When compared to only gasoline usage, NO_x emissions raise about %4.8 with biogas at %10 CO_2 ratio, and raises about 2.4% at 20% CO_2 ratio. Then, NO_x emissions decreases at about 2.4% with biogas at 30% CO_2 ratio and decreases at about 6% at 40% CO_2 ratio.

As seen in the results, with the usage of biogas, NO_x emissions increase because of the increased local peak in-cylinder pressure, but when CO_2 ratio in the biogas reaches to 30% and upper values, there can be seen a decrease in NO_x emissions, The main reason of this decrease is the heating capacity of CO_2 and its decreasing O_2 availability in combustion process [24].

CONCLUSIONS

In this study, in a single cylinder, 270 cc, naturally aspirated, four stroke SI engine, at stoichiometric condition and constant engine speed (2800 rpm), effect of biogas fuel at different CO_2 ratios (10%, 20%, 30% and 40%) on engine performance and emissions was investigated with comparison of only gasoline usage.
The main conclusions were summarized below:

- With the increasing CO_2 ratio, there has been a decrease in indicated mean effective pressure. The main reason of this situation is stoichiometric working conditions and the low heating value (by volume) of biogas. ITE value decrease with use of biogas and increasing ratio of CO_2.
- With use of biogas and increasing CO_2 content, IMEP values decreases. The main reason of this result is the decrease in maximum in-cylinder pressure because of operating the engine at near stoichiometric condition. Also, because of using gaseous fuel, low density of methane, methane's rendering high cylinder volume and dilution of combustion chamber by CO_2 (EGR effect) are the other reason's of the decrease in IMEP values.
- CO emissions decrease with biogas usage. The low C/H ratio of methane, which is main component of biogas, is the main cause of the decrease in CO. THC emissions increases as the CO content in biogas increases. The unsuitable design of the engine for methane fuel, the crevice zones in combustion chamber and the structure of methane which is already an unburned HC are the other reasons of increase in THC emission.
- Because of the increase in local peak in-cylinder pressure values with biogas usage, NO_x emissions increase also. However, when CO_2 ratio in biogas reach 30% and upper values, because of CO_2's heating capacity and decreasing O_2 availability, NO_x emission values are under the values which are taken with only gasoline usage. Although it has some negative impact on engine performance, biogas usage in SI engines can simulate EGR effect, so it can be possible to control the NO_x emissions.

NOMENCLATURE

CA	Crank angle
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
EGR	Exhaust gas recirculation
HC	Hydrocarbons
IMEP	Indicated Mean Effective Pressure
ITE	Indicated Thermal Efficiency
NO_x	Oxides of nitrogen
PM	Particulate matter
SI	Spark ignition
THC	Total unburned hydrocarbons

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