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Experimental study on the ability of different biogas level dual fuel spark ignition engine: Emission mitigation, performance, and combustion analysis

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Abstract. The major aim of the research is to investigate the ability of biogas as an alternative fuel for gasoline-powered Spark Ignition (SI) engine. In this study, biogas/gasoline fuel mixtures containing different ratios of biogas, gasoline, and biogas were tested in an SI engine with an increased compression ratio at different engine loads and constant engine speed. According to the comparison with gasoline, the utilization of biogas generally decreased the Brake Thermal Efficiency (BTE), while the Brake Specific Fuel Consumption (BSFC) rose. The lowest BTE and the highest BSFC were obtained with 100% biogas. Compared to gasoline, a decrease of 16.04% and an increase of 75.52% were observed, respectively. On the other hand, the use of biogas has improved all emissions. The best emission values were obtained with 100% biogas. Compared to gasoline, Carbon monOxide (CO), HydroCarbon (HC), and Nitrogen Oxide (NO_x) emissions decreased by 56.42%, 63%, and 48.96%, respectively. Finally, according to the results of the combustion analysis, the peak pressures were reduced with the utilization of biogas, and the position of the peak pressure shifted by 2° to 3° Crank Angle (CA). Compared to gasoline, the lowest pressure was obtained with 100% biogas, resulting in a reduction of approximately 24.69%.

Nomenclature

Abbreviations	
BTE	Brake Thermal Efficiency
BSFC	Brake Specific Fuel Consumption
CA	Crank Angle
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
HC	HydroCarbon
LPG	Liquefied Petroleum Gas
MGT	Mean Gas Temperature
NO_x	Nitrogen Oxide
SI	Spark Ignition
100G	100% gasoline
100Bio	100% biogas
75G + 25Bio	75% gasoline + 25% biogas
50G + 50Bio	50% gasoline + 50% biogas
25G + 75Bio	25% gasoline + 75% biogas

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1 Introduction

Energy has always had an important place in human life and energy needs must be met until the end of the world [1, 2]. As a result of the developments in health and technology and the increasing quality of life compared to the past, the average human life span is getting longer, and the world population is increasing [3]. Accordingly, the energy demand also increases at the same rate [4, 5]. Fossil fuels have been used mostly from past to present for the supply of energy need [6–8]. However, with the oil crisis in the 1970s, the fact that fossil fuels are exhaustible and that different energy sources are needed has been understood by the whole world [9, 10]. Moreover, another and most important problem in the use of fossil fuels is air pollution [11, 12]. According to a study, it was stated that more than 8 million deaths occurred due to fossil fuel-related air pollution in 2018, and air pollution from the use of fossil fuels is responsible for 1 out of every 5 deaths worldwide [13]. Accordingly, studies on renewable, clean, and environmentally friendly fuels have gained momentum due to both the gradual decrease in fossil fuel reserves and their negative effects on the environment [14–16].

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As an alternative to fossil fuels, many different materials have been used from past to present. Alcohols, biodiesels obtained from vegetable, animal, and waste products, Liquefied Petroleum Gas (LPG), and biogas are the main ones. Biogas is an odorless, colorless, and environmentally friendly fuel that is produced by the anaerobic fermentation of organic, agricultural, food residues, wastes, etc., into smaller molecules [17, 18]. Biogas has many benefits compared to both fossil fuels and other fuels derived from biomass. Biogas technology performs a significant role in obtaining energy from organic materials and bringing waste materials to the soil, and after it is produced, the wastes do not disappear but turn into a much more valuable organic fertilizer [19, 20]. In addition, it has advantages such as easy transportation in pipelines, safe storage as compressed gas in high-pressure cylinders, not diluting the lubricating oil, and less harmful exhaust gas emission to the environment. Biogas also reduces the possibility of knocking due to its high auto-ignition temperature [21, 22]. Biogas generally contains 50–70% methane (CH_4), 25–50% carbon dioxide (CO_2), and 1–5% of hydrogen. The rates of these gases may vary depending on effects such as bacteriological, raw material stocking rate, water content, temperature, and feeding source [23]. For the most suitable combustion conditions to be realized in the cylinder, at least 50% of CH_4, which is the most basic content of biogas, must be present [24]. Biogas can be used on the internal combustion engine without the need for major structural changes [25, 26]. Also, if a structural change is needed, it is much easier to modify a spark-ignition engine to run on biogas than a diesel engine [27, 28]. The control of the engine is carried out by changing the combination delivered to the engine by running the throttle valve located among the biogas mixer and the engine intake system.

Biogas can be used more efficiently in internal combustion engines by purifying the flammable gases in their content [29, 30]. The usage of biogas in SI engines has become widespread in recent years. Hotta *et al.* [31] performed tests at several engine speeds to investigate the usability of raw biogas in SI engine. Compared to working with gasoline, they found a 66% increase in BSFC, a 12% decrease in BTE, and an 18% decrease in brake power, according to the results obtained with raw biogas. Then again, the authors indicated that while CO and NO_x decreased by 40% and 81.5%, HC and CO_2 rose by 6.8% and 40%. Moreover, they stated that the cylinder pressure obtained with the utilization of biogas is smaller than that of gasoline, the position of the peak cylinder pressure is at a lower level and appears much later. Simsek and Uslu [23] evaluated the effects of LPG and biogas use in terms of emissions, performance, and combustion in a single-cylinder, four-stroke SI engine by various throttle positions and compared with gasoline use. The tests were performed at different engine loads, at full throttle opening and two different throttle positions, at half throttle. The authors indicated that BSFC rose and BTE diminished with the utilization of LPG and biogas at both full gas opening and half gas opening. Then again, the authors indicated that all emissions were reduced in all throttle positions, using LPG and biogas. Finally, they stated that LPG and biogas have a decreasing effect on cylinder gas pressure. Kriaučiūnas *et al.* [32] tested biogas mixtures containing 0%, 20%, 40%, and 50% CO_2 by volume in an SI engine at two separate spark timings. As stated by the results of the study, the authors indicated that increasing the CO_2 concentration and using the fixed spark timing reduced in-cylinder pressure, BTE, and NO_x. On the other hand, they stated that optimum spark timing selection increases BTE as well as HC and CO_2 emissions. Hotta *et al.* [25] investigated the effects of using biogas in a single-cylinder, four-stroke SI engine with a compression ratio of 10–14. The authors stated that by increasing the compression ratio from 10 to 12, engine power and efficiency increased by 12.72% and 5.68%, respectively. Moreover, the authors asserted that overall emissions increased with increasing compression ratio. The authors stated that, after a series of experiments, they concluded that the optimum compression ratio was 12.

As mentioned in the above studies, the use of biogas in SI engines has mostly been limited to using 100% biogas and changing various engine parameters. In the detailed literature review, it was concluded that there is a lack of studies related to the use of biogas in different volumetric ratios. From this point of view, in the present research, the impacts of the utilization of biogas at different rates were evaluated in a single-cylinder, four-stroke SI engine, at various engine load values, in terms of emission, performance and combustion indicators and compared with the use of 100% gasoline.

2 Materials and methods

Tests were performed on an air-cooled, 4-stroke, and single-cylinder Honda GX390 model SI engine. Since the octane number of the biogas is higher than that of gasoline, the compression ratio of the engine, which was originally 8.0:1, has been increased to 9.12:1 to obtain more efficiency. To enhance the compression ratio, the cylinder head cover is ground 0.8 mm.

During the use of biogas in the engine, the flow pressure of the biogas is supplied with the support of the manometer and regulator on the tube. The flow of biogas was monitored through flow meters and digital displays positioned on the biogas line, and its passage through the one-way valve in a controlled manner was ensured. The definition of the engine air mass flow percentage with the manifold absolute pressure sensor and the proportional adjustment of the amount of fuel needed for optimal combustion were offered by a computer-controlled electronic control unit and the biogas coming out of the injector was proportionally mixed with the gasoline. A water-cooling system is positioned among the two flow meters to prevent a fire that may appear as a result of a backfire from the valves or a flame ignition for any reason.

In this study, experiments were carried out using five different test fuels as 100% gasoline (100G), 100% biogas (100Bio), 75% gasoline + 25% biogas (75G + 25Bio), 50% gasoline + 50% biogas (50G + 50Bio), and 25% gasoline + 75% biogas (25G + 75Bio), at six different engine loads

(500, 1000, 1500, 2000, 2500, and 3000 W) and constant engine speed (3000 rpm). The gasoline and biogas utilized in the tests are demonstrated in Table 1, and the engine characteristics are demonstrated in Table 2. The schematic test system is presented in Figure 1.

Table 1. Qualification of gasoline and biogas.

Qualification	Gasoline	Biogas
Chemical formulation	C_8H_{18}–C_7H_{16}	CH_4 – 55.6% CO_2 – 42.3% N_2 – 2.1%
Density at 15 °C (kg/m^3)	720–775	1.11
Lower thermal value (MJ/kg)	43.55	17.0
Research octane number	91	110
Stoichiometric air/fuel ratio	14.7	5.67
Autoignition temperature (°C)	257	650
Flame velocity (cm/s)	45	25
The heat of evaporation (kJ/kg)	330	500
Evaporation temperature (°C)	20–200	−42

Table 2. Qualification of engine.

Engine Qualification	
Honda GX390 – 4-Stroke/single-cylinder	
Original compression ratio	8.0:1
Type of cooling	Air
Displacement (cm^3)	389
Power @ 3600 rpm	8.7 kW
Torque @ 2500 rpm	26.5 N/m

3 Results and discussion

3.1. Performance indicators

BTE and BSFC are among the most important parameters for the evaluation of engine performance. BTE is a measure of how much of the energy produced by the combustion of fuel can be used beneficially. On the other hand, BSFC refers to the amount of fuel that requires to be consumed to obtain unit power per hour. The graphs of change of BTE and BSFC depending on the changing engine load and biogas ratio are shown in Figure 2. Both BTE and BSFC were negatively affected as the biogas content in the fuel increased. As seen in Table 1, while the octane number of gasoline is 91, the octane number of biogas is 110. Although the higher-octane number brought about better BTE, the BTE decreased with the increase in the biogas ratio. The low density of biogas compared to gasoline also reduces its volumetric efficiency [29]. The low volumetric efficiency also causes a decrease in BTE. In addition, the low flame rate of biogas compared to gasoline affects BTE negatively. The highest BTE was obtained with 100G as 28.25% at 500 W load. The lowest BTE was determined as 22.20% with 100Bio and 3000 W load. There was an average of 16% reduction in all loads with 100Bio compared to 100G. In the comparison made in terms of BSFC, it can be seen that BSFC increases with increasing biogas. The lower calorific value of biogas compared to gasoline causes the BSFC to increase. While the highest BSFC was found to be 940 g/kWh with 100Bio at 3000 W load, the lowest BSFC was determined as 440 g/kWh at 2500 W load with 100G. Differences between BSFC improved with increasing engine load from 500 W to 3000 W. While the difference between BSFC values at 500 W load was approximately 29%, at 3000 W this difference was approximately 52%.

3.2. Environmental indicators

It can be seen from all emission figures that emissions are positively affected by increasing biogas ratio. The variation of HC and CO emissions, which are products of incomplete combustion, depending on the biogas ratio and engine load are shown in Figures 3 and 4, respectively. Both HC and CO emissions decreased depending on the biogas ratio. As can be observed in Table 1, the carbon content of biogas is less than that of gasoline. In addition, the fact that biogas has a more homogeneous mixing ability with air compared to gasoline has commanded a decrease in HC and CO emissions. On the other hand, the variation of NO_x emission depending on the biogas percentage and engine load is shown in Figure 5. Biogas, which has a small lower calorific value compared to gasoline, reduces the in-cylinder temperature and pressure, as well as the fuel combustion rate, resulting in a decrease in NO_x emissions [32, 33]. In addition, increasing engine load increased NO_x emissions in all test fuels. Growing engine load improved the in-cylinder temperature and NO_x emissions. Because the formation of NO_x emissions accelerates with growing in-cylinder temperature. Currently, HC emission has decreased in all fuels with increasing load. With biogas-containing fuels, the decreasing trend of HC with increasing load indicates improved combustion compared to gasoline. Biogas can easily mix by air and form a homogeneous air-fuel combination. Also, by the boost of engine load, the volumetric efficiency of the biogas-fueled engine was smaller compared to gasoline. The weak mixture concentration given to the engine causes better combustion of the air-fuel mixture and a smaller amount of HC is produced by growing engine load. In addition, while the CO concentration with growing engine load in the fuel containing 50% biogas remained almost balanced, the increased engine load in the biogas ratios exceeding 50% caused a decrease as in the HC emission.

3.3. Combustion indicators

Cylinder gas pressure changes according to the crank angle obtained by using fuel mixtures containing both gasoline and different proportions of biogas in the SI engine are shown in Figure 6. It can be seen that the peak pressure obtained with biogas-containing fuels is lower than that of gasoline and is changed from 2° to 3° CA. Although the

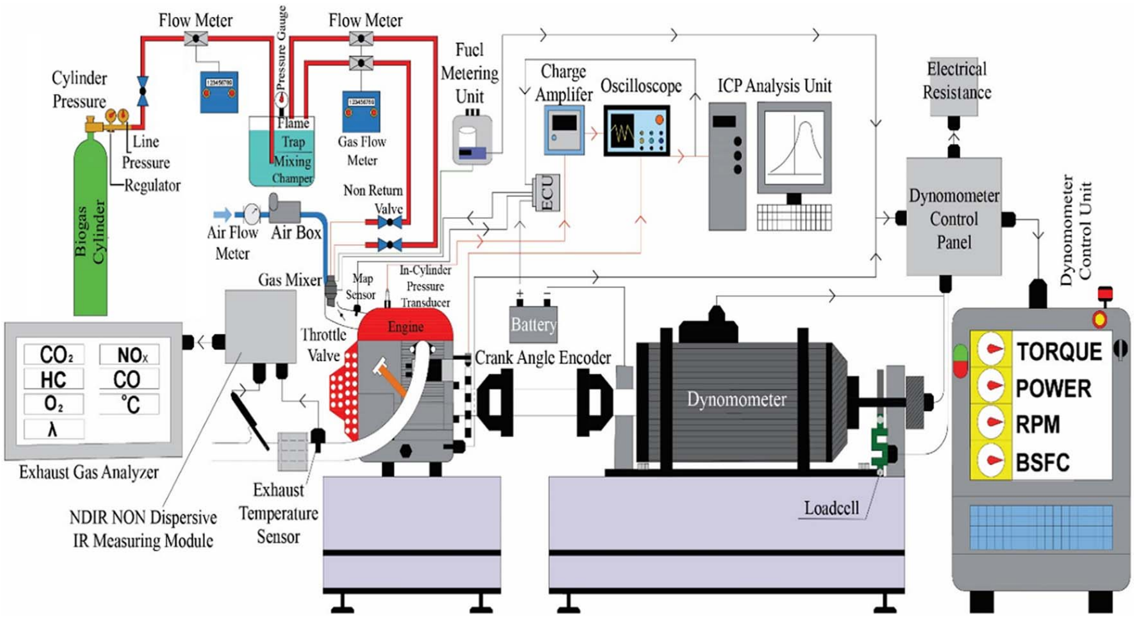

Fig. 1. Schematic test setup.

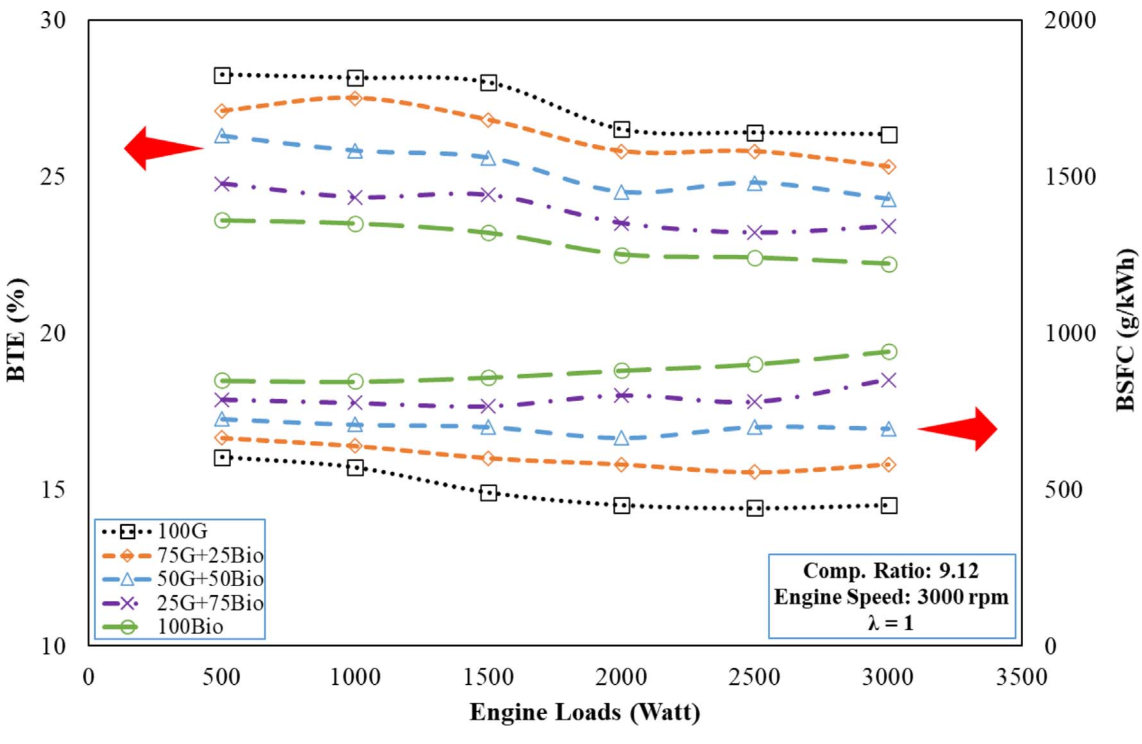

Fig. 2. Variation of BTE and BSFC according to biogas ratio and engine load.

gas pressure peak remained almost the same due to the increasing biogas ratio, the gas pressure values decreased. This was due to the variation in spark timing and the much slower combustion rate of biogas compared to gasoline. The maximum pressure was obtained with 100G as 32 bar at 372° CA, while the minimum pressure was determined with 100Bio as 24.1 bar at 375° CA. The cylinder gas pressure obtained with 100Bio was approximately

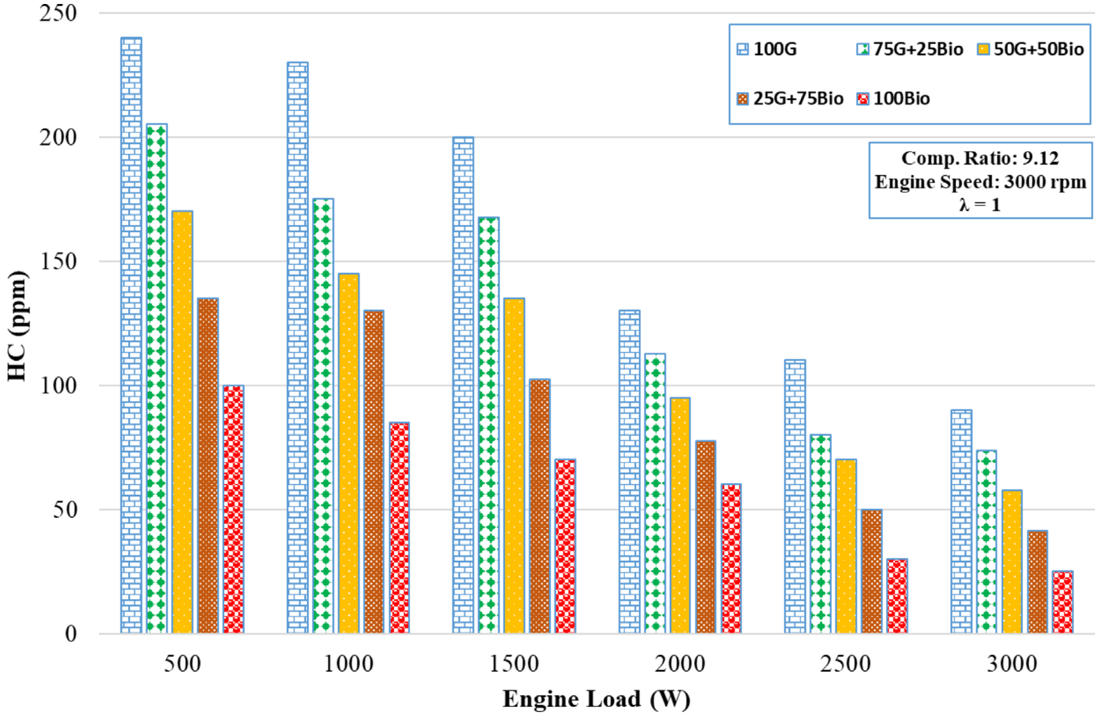

Fig. 3. Variation of HC emission according to biogas ratio and engine load.

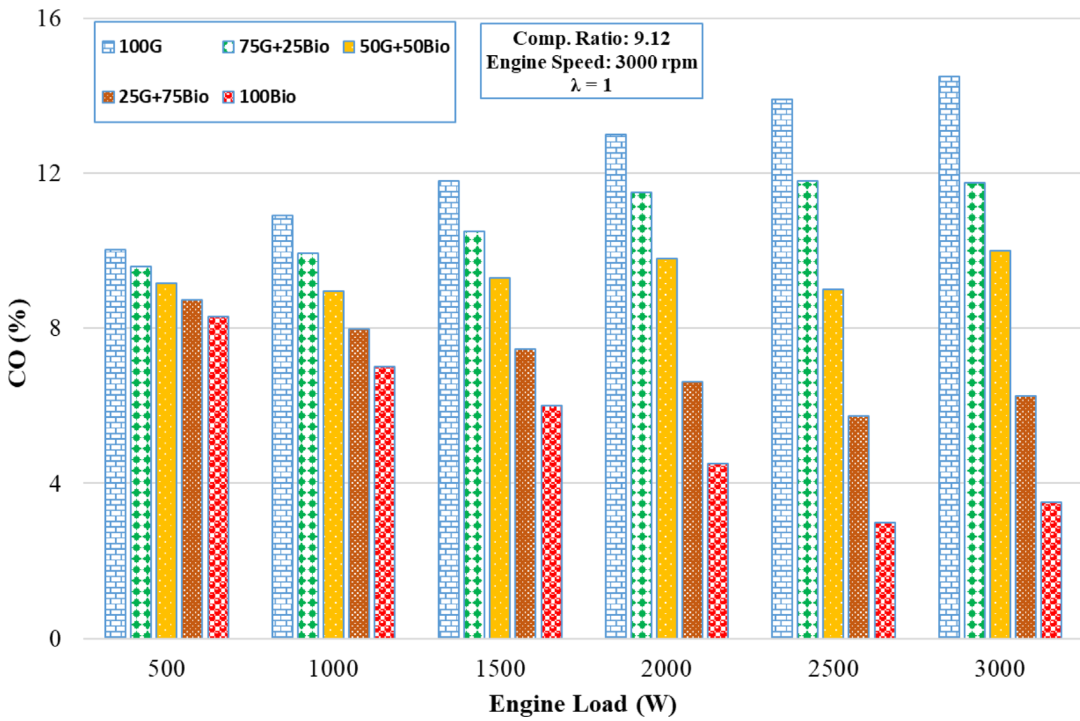

Fig. 4. Variation of CO emission according to biogas ratio and engine load.

24.69% lower than that of 100G. On the other hand, the pressures obtained with 75G + 25Bio, 50G + 50Bio, and 25G + 75Bio fuels were determined as 29.90, 28.20, and 25.80 bar, respectively. Compared to the pressure value obtained with 100G, there was a decrease of 6.56%, 11.88%, and 19.38%, respectively.

The change of the Mean Gas Temperature (MGT) in the use of gasoline and biogas-containing fuel mixtures in the SI

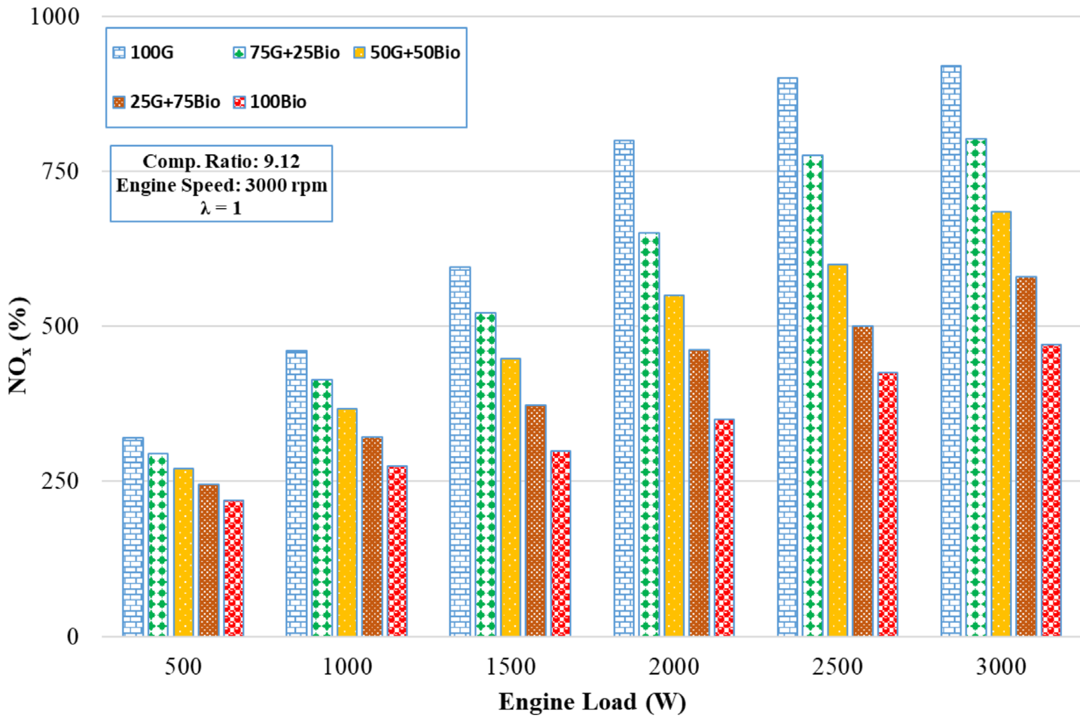

Fig. 5. Variation of NO_x emission according to biogas ratio and engine load.

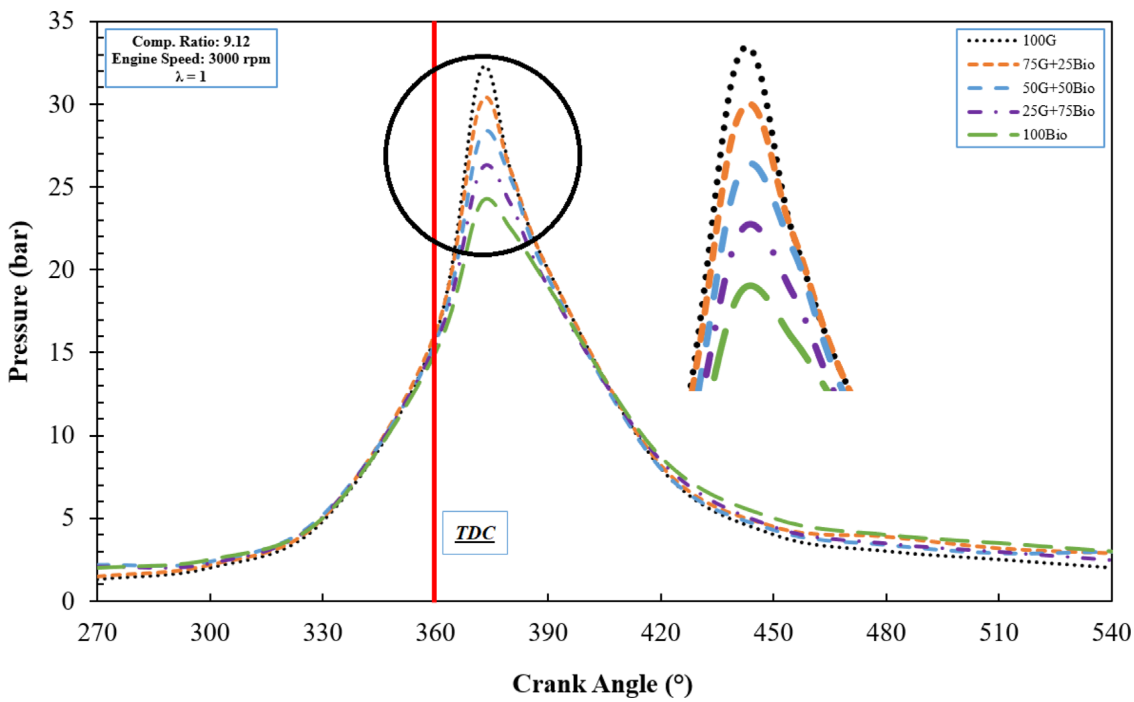

Fig. 6. Variation of cylinder gas pressure according to crank angle.

engine is shown in Figure 7. It is seen that the MGT of the SI engine is always lower in the expansion stroke of the biogas fueled combustion compared to the gasoline-fueled combustion. It can be said that this is owing to the small energy conversion efficiency of biogas due to its lower calorific value compared to gasoline. In addition, it has been detected that the MGT of the engine in the compression stroke of the engine is greater than that of gasoline in the use of fuels

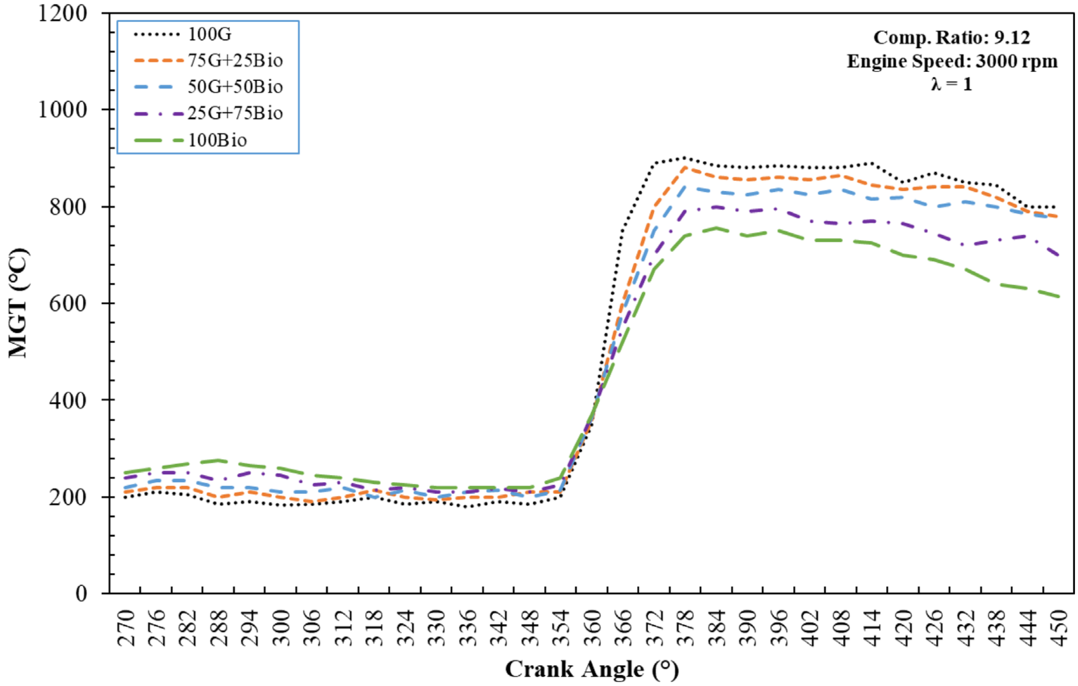

Fig. 7. Variation of MGT according to crank angle.

containing biogas. The reason for this can be explained as the higher heat transfer rate in the use of gasoline.

4 Conclusion

The attributes of a single-cylinder, SI engine operating by biogas and biogas-gasoline fuel mixtures were investigated experimentally, and compared with the gasoline operation, the following inferences were obtained:

- In the use of biogas-containing test fuels 75G + 25Bio, 50G + 50Bio, 25G + 25Bio, and 100Bio, the SI engine produced an average of 3.27%, 7.55%, 12.26%, and 16.04% less BTE than gasoline, respectively.
- At all loads, the BSFC value increased with the use of biogas compared to gasoline, and this increase increased with the increasing biogas ratio. The BSFC values obtained with 75G + 25Bio, 50G + 50Bio, 25G + 25Bio, and 100Bio were on average 20.48%, 39.63%, 58.47%, and 75.52% higher, respectively, compared to gasoline.
- The utilization of biogas has reduced HC, CO, and NO_x emissions, and this decrease has increased from 25% biogas to 100% biogas. With the use of 75G + 25Bio, 50G + 50Bio, 25G + 25Bio, and 100Bio fuels, an average of 12.22%, 24.16%, 42.32%, and 56.42% improvement in CO emissions has been achieved, respectively, compared to 100G. In addition, HC emissions decreased by 18.63%, 32.75%, 46.38%, and 63%, respectively. The improvement in NO_x emissions was realized as 13.46%, 26.92%, 37.88%, and 48.96% on average, respectively.
- The peak pressure obtained with biogas-containing fuels is lower than that of gasoline and is changed from 2° to 3° CA. Compared to the pressure value obtained with 100G, there was a decrease of 6.56%, 11.88%, 19.38%, and 24.69% with 75G + 25Bio, 50G + 50Bio, 25G + 25Bio, and 100Bio, respectively.

In general, it can be said that the innovative approach of combining promising biogas with gasoline in different proportions is a very effective methodology. On the other hand, a more comprehensive study is planned by opting for optimization applications to determine the optimum biogas ratio and engine operating conditions with high accuracy.

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