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The Study on the Effect of Biogas Addition on the Diesel Tractor Engine for the Development of a Biogas Controller

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Abstract: Using biogas to partially replace diesel fuel in agriculture tractors seems a good solution to reduce greenhouse gases and other pollutants. For this reason, a research project to convert a tractor to dual-fuel operation was initiated; this paper's specific aim was to develop a control algorithm feeding biogas to the engine's intake manifold. The effect of biogas addition on engine performance, focusing on brake specific heat consumption and fuel replacement rates, was first studied. Then several load estimation methods were assessed and the Manifold Absolute Pressure (MAP) sensor was chosen as a main load detector. Finally, a prototype algorithm was built upon an engine control unit and was tested. The algorithm was able to change biogas flow with engine speed and load, without knock and misfire.

1. INTRODUCTION

World wide awareness of environmental pollution and global warming caused by burning fossil fuels has driven researchers as well as industrialists and governments to look for other energy sources. Hamakawa (2002) observed the change in various forms of energy consumption with change in population from year 1750 to 2000; and he predicted the possible future energy forms till year 2100. According to him, nuclear and renewable energy forms will prevail in the near future. Decrease in fossil fuel usage is caused not only by its depletion but also by its harmful environmental effects, namely global warming. In fact the current world seems to face a 3E trilemma: "Economy, Energy, and Environment" where the question is how to provide sufficient energy for economic growth without harming the environment (Trilemma Council, 2000). It is believed that finding clean energy sources will play the most important role in solving the 3E trilemma. In this scope, biofuels are highly regarded for their carbon dioxide emissions are recycled back into the biomass in a short period of time (20 years) and consequently don't contribute to the greenhouse gases.

Specifically, biogas has an important advantage over other biofuel forms because it originates from digestion of wastes, while others (bio-ethanol or biodiesel) often require fresh products. Biogas energy has proved useful in direct heating application as well as electric generation; but its usage in vehicle engines is still limited to some prototypes such as the biogas train in Sweden. Japanese livestock farmers have seen in biogas plants a solution to their farms waste problems as well as an important source of energy; however, this energy can only be used as heat for temperature control of the biogas digester as well as to generate the already inexpensive electric power. Converting the diesel engine of agriculture tractor to dual-fuel operation by feeding biogas into its intake manifold appears to be an appealing solution; on one hand the fuel cost paid by the farmers is reduced, and on the other hand, the carbon dioxide emissions to the environment are minimized. It should be noted that CO2 emissions due to burning of biogas are considered carbon neutral and therefore do not contribute to the global warming effect. Nevertheless, the dual-fuel engine is prone to knocking and misfire if the amounts of biogas injection into its manifold exceeded certain limits; and its efficiency as well as emissions might be altered.

Considering therefore the social and environmental importance of using biogas in agriculture machinery, a tractor was equipped with a biogas unit compromising storage cylinders as well as pressure control devices (Fig. 1).

Fig. 1 The tractor equipped with a biogas unit

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One of the remaining problems was to control the flow of biogas into the intake manifold of its engine. Particularly, this paper's objectives were to accumulate basic engine data at first, based on which the effect of certain biogas flow on engine are understood; namely in terms of specific fuel consumption and fuel replacement rates. Secondly, and since load is a major parameter affecting the amount of biogas to be fed into the engine, a load estimation method was assessed based on the engine's sensor adequacy in predicting power and torque, with the manifold absolute pressure sensor taken as a main load detector. Finally, a prototype algorithm was attempted and tested on both the standalone engine and the tractor itself.

2. MATERIALS AND METHODS

An agriculture tractor (Kubota New Grandom M105D) was modified for dual fuel application; and as mentioned earlier, it was fitted with a front gas unit which could contain 4 cylinders of biogas. The power plant of the tractor was a 4 cylinder 4-stroke cycle diesel engine named V3800-Ti which was equipped with a turbocharger and an intercooler; it had 4 valves per piston. The tractor power was 77.2 kW at the rated speed of 2600 rpm. The engine was first mounted on a dynamometer (SuperFlow company, model SF901) to allow bench testing. The gas chromatography analysis of the biogas used throughout this experiment showed that the only hydrocarbon present was methane which amounted for 99.53% of the volume of biogas. The biogas was stored in FRP (Fibre Reinforced Plastic) cylinders at a pressure of 19.6MPa. Check valves, directional valves, pressure relief valves and pressure gages were used to make sure that the biogas delivery process is as safe as possible. A regulator insured a constant pressure gradient of 255kPa across the injectors; and a plastic hose conveyed the intake manifold pressure to the regulators respective port.

Nonetheless, this research was mainly concerned with biogas injectors, for they were the key control of flow of biogas into the engine. The injectors used in this research are commonly used in cars running on compressed natural gas (CNG). They were placed at a distance of 10cm above the intake manifold of the engine where 6mm holes were perforated. Biogas flow was decided by both frequency of a cycle of opening and closing as well as the time the injector is kept open in each cycle. A switch circuit was developed to control the opening and closing of gas injectors (Asahara, 1995). The base of a transistor (2SD633) was connected to the counter output of a data acquisition card (National Instruments, NI-USB 6211). The high voltage of the counter output stimulates the base of the transistor, thus closing the circuit between the emitter to the ground. A current of almost 6 A flows then through the injectors causing them to open. A program based on LabView was also built to generate the counter output of the board.

To get the basic engine data, the experiment proceeded as follows: an engine speed at no load was set (the throttle lever position was fixed), and a certain load was then applied on the engine. Injector duty was thereafter set to reach the desired biogas flow and engine data was collected. Biogas flow was then set at the next level; when the maximum flow was reached, the biogas flow was reset to 0 L/min and another torque-speed combination was applied to the engine. The experimental setting in terms of engine speeds, loads and biogas flows is shown in Table 1.

Table 1 Summary of experimental setting

Engine speed	3 steps	2600, 2200, 1800 (rpm)
Engine load	5 steps	Minimum, 90, 200, 300, Maximum (N·m)
Biogas flow	6 steps	0, 30, 60, 90, 120, 150 (L/min) (limited by knock or misfire)

To decide on engine load estimation method, several sensors were mounted on the engine to monitor its condition while running on biogas and diesel; manifold absolute pressure, exhaust gas temperature, and mass air flow sensor. Data from these sensors as well as dynamometer data (torque and power) were logged by three means: the dynamometer's software, an engine control unit with internal memory (MoTec, M800) and a data logger (GraphTech, GL500). Table 2 summarizes the data collected and logging scheme. As for the preliminary algorithm, it was built having the MoTec M800 Engine control unit as its platform and it was tested on the engine first. The algorithm was then applied to the tractor itself and it was tested on a PTO dynamometer.

Table 2 Collected data and logging means

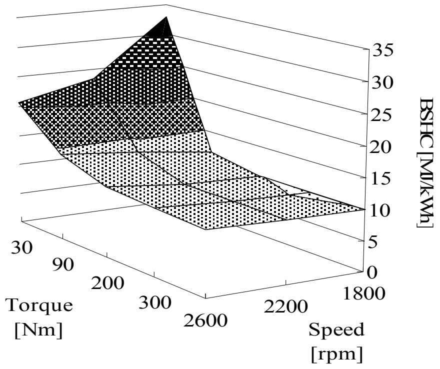
Dynamometer	**MoTec M800**	**Data Logger**
Engine speed (rpm)	Excess oxygen ratio (λ)	Exhaust gas temperature (°C)
Engine torque (N.m)	Manifold air pressure (kPa)	Oxygen sensor voltage (V)
Engine power (kW)	Throttle lever position (%)	Biogas flow (L/min)
Mass air flow (g/s)	Intake air temperature (°C)	

3. RESULTS AND DISCUSSION

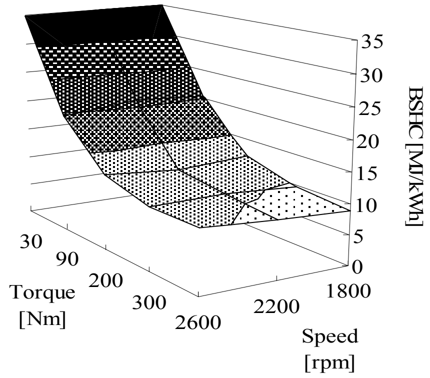
3.1 Basic engine data

3.1.1 Brake specific heat consumption

At first, the engine's Brake specific heat consumption (BSHC) in MJ/kWh was calculated for the engine running solely on diesel. It is shown in Fig. 2-a). The BSHC was then calculated while the highest biogas flows were injected into the engine's manifold (mostly 150 L/min, except when knock or misfire occurred); it is also shown in Fig. 2-b).



a) BSHC at diesel only



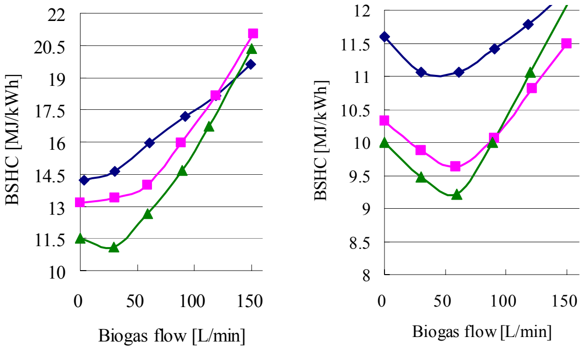
b) BSHC at maximum biogas injection rates

Fig. 2 Brake specific heat consumption of engine at diesel only (a) and at highest biogas flow rates (b)

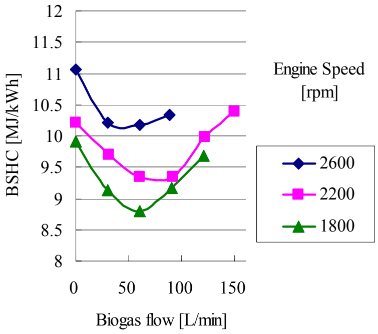
A comparison between these two figures shows that biogas flows decreased the engine's Brake thermal efficiency (increased BSHC) at lower load, while it did not affect it at higher loads. It would therefore be advisable to restrict biogas flow at lower loads; but a close up view was necessary for further understanding of the changes in engine parameters (Karim, 2003).

3.1.2 Change in BSHC with biogas flow

For this reason, the change in BSHC with respect to biogas flow was plotted in Fig. 3 for each load/speed condition of the engine; Fig. 3-a) showing low load conditions (100 N.m engine torque), Fig. 3-b) showing medium loads (200 N.m) and Fig. 3-c) showing high load condition (300 N · m). It is apparent that any inclusion of biogas flow in low load conditions causes an increase in BSHC. For instance, the BSHC of the engine running at 2600 rpm increased from 14.9 MJ/kWh to 15.9 MJ/kWh when 60 L/min of biogas flow was open into the intake manifold. A lot of the injected biogas therefore goes unburned through the exhaust pipe. At medium and high loads however, the BSHC was reduced at first (up to biogas flow of almost 60L/min) and then it increased again. The ratio of decrease in BSHC due to addition of 60L/min biogas flow was 7.8, 6.7 and 4.6% respectively for engine running at 1800, 2200 and 2600 rpm at medium load. It was respectively 11.2, 8.5 and 7.9% for 1800, 2200 and 2600 rpm engine speeds at high load.



a) low load b) medium load



c) high load

Fig. 3 The change in BSHC with increasing biogas flow for the low load (a) medium load (b) and high load (c)

To assimilate this phenomenon, the ignition process of the diesel after its injection and how it is affected by biogas presence should be understood. The biogas, with its very low cetane number, buffers the effect of higher load by delaying the ignition. Nevertheless, higher biogas flows (especially at lower engine loads) would delay the ignition to a point where the exhaust valve opens before combustion is complete, causing a lot of wasted fuel, therefore decreasing efficiency (Jaber and Noguchi, 2007) It is necessary to note that along with delaying the combustion, the biogas itself participates in this combustion. As mentioned in the introduction, by burning, it partially replaces the diesel fuel, reducing the dependency of the engine (and accordingly the vehicle, the agriculture tractor in this research's case) on fossil fuels. A study about fuel replacement rate and reduction in diesel consumption is therefore needed to completely understand the effect of biogas on engine's performance.

3.1.3 Fuel replacement rate and effective diesel consumption reduction

The fuel replacement rate represents the ratio of heat intake into the engine provided by the biogas; it is calculated as the amount of energy provided by biogas divided by the total amount of energy input from both biogas and diesel (Noguchi et al., 1996). A three dimensional graph, showing replacement rates achieved at highest biogas flows, is presented in Fig. 4. It is clear that the highest replacement rates could only be achieved at lower loading condition, but not at the minimum load where occurrence of misfire restricted biogas flow. It is also noticed that replacement rates decreased with engine speed. In fact, the same 150 L/min biogas flow participated with a constant amount of energy to the combustion; nevertheless, the engine requires more input energy when it produces higher power (Goering and Hansen, 2004). This extra energy will therefore come from the diesel, whose system has been kept unchanged; and energy ratio from biogas is reduced.

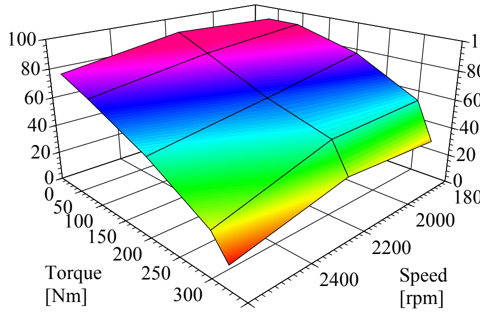


Fig. 4: a three dimensional presentation of the highest replacement rates achieved on the Z axis.

The biogas flow entering the engine burns inside the combustion chamber, therefore replacing some of the diesel energy and reducing engine diesel consumption (Henham and Makkar, 1998). The addition of biogas also caused an increase in the speed of the engine, which translates in higher power output. This reason pushed the authors to calculate the effective diesel consumption reduction based on unit power. In other words, the Brake Specific Fuel Consumption (BSFC) of diesel was first calculated for engine operating solely on diesel; then it was calculated for dual-fuel operation. The difference between the two, divided by the former value was taken as the effective diesel consumption reduction. Fig. 5 shows the diesel consumption reduction change with increase in biogas flow at low loading condition of the engine. In the beginning, the highest reductions are seen; then additional increases in flow displace less and less diesel until a plateau is reached, or misfire or knocking occur. To take a numerical example, the engine running at 1800 rpm in Fig. 5; the first addition of 30 L/min of biogas reduced diesel consumption by 37%, when 60 L/min were added; the diesel reduction was 53%. In other words, the reduction in diesel consumption does not respond linearly to a linear increase in biogas flow.

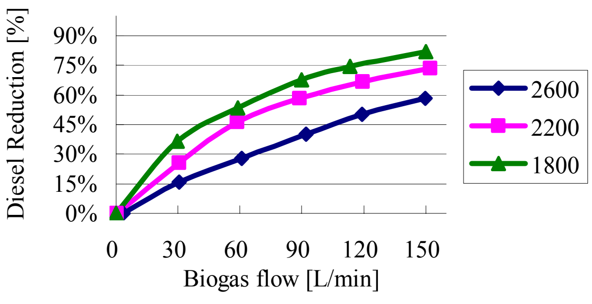


Fig.5 The change in diesel reduction with increasing biogas flow at low engine load

Misfire eventually occurs due to extreme delays in ignition impairing the start ability of the engine and it was distinctively heard when engine was running at almost no load (30 Nm). Knock occurs at higher load where the premature combustion becomes very important causing a very quick surge in pressure inside the combustion chamber; this phenomenon is the reason why the flow of biogas was limited to 90 L/min at 2600 rpm and to 120 L/min at 1800 rpm at the high load condition (Jaber and Noguchi, 2007).

3.1.4 Suitable biogas flow rates

The purpose of the data collected and processed in the above section was to answer the following question: what is the best amount of biogas to be injected at each load-speed combination? There was no clear cut answer. Given that biogas itself is almost free, the highest replacement rates may be desirable; but on the other hand, the biogas flow may be set to achieve optimum engine heat efficiency by targeting the lowest BSHC values. The biogas flow should be limited so that the engine stability is not disturbed, i.e. to avoid knock and misfire. For this reason, the authors have attempted to construct a look-up-table where the highest possible biogas flow injection could be reached; the table is shown as a 3D map in Fig. 6. It should be noted that these values are estimated from engine basic data and the engine was not tested for each combination.

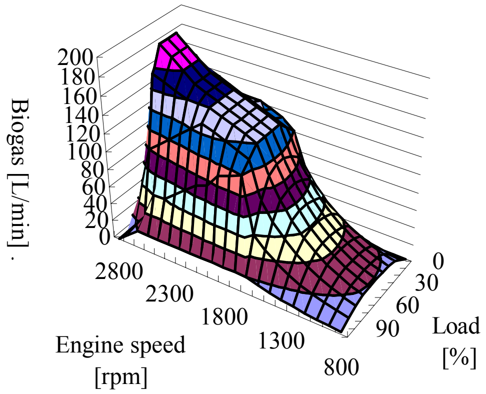


Fig. 6 The 3D map which acts as a look up table for the biogas feeding algorithm

It is obvious that with the above mentioned table the highest fuel replacement rates are attained, however at the expense of reduction in engine efficiency. Another look-up-table can therefore be made to supply enough biogas to run the engine in the most efficient way.

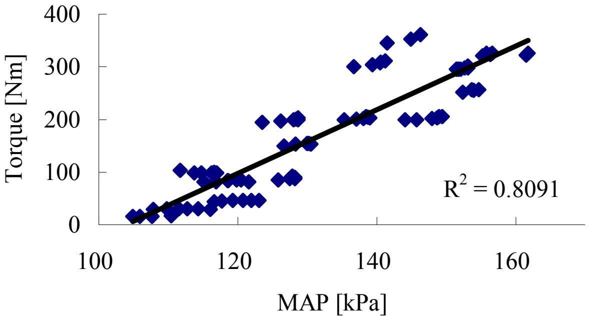
3.2 Load estimation

As mentioned in the above section, the quantity of biogas heavily depended on the operation condition of engine load and speed. Since speed can be easily and directly measured, the only still missing parameter is therefore the load. The load of the engine plays an important role in deciding the flow of biogas. For this reason, many sensors were used and their output was logged and plotted against the engine's torque and power to assess their ability in load estimation.

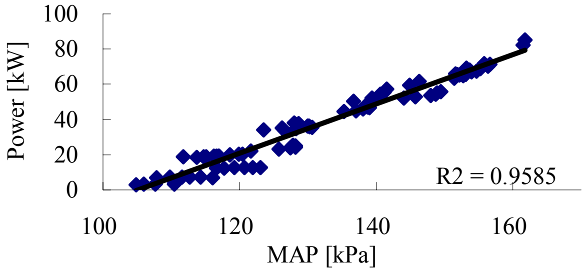
3.2.1 Manifold absolute pressure

The manifold absolute pressure (MAP) sensor is commonly used in gasoline engines, especially turbo charged ones, to estimate engine load. It was therefore tested to see if it could also determine the power or torque of a dual-fuel engine. In this research, the engine was equipped with a turbocharger; therefore the pressure inside the intake manifold should increase with load as well as speed of engine. Engine speed simply increases the gas flow through the cylinders and therefore out of exhaust. Load on the other hand, increases the temperature of the exhaust gases, thus increasing their volume and accordingly the rotation speed of the turbine wheel of the turbocharger. The compressor wheel's speed also increases pushing more air into the intake manifold and therefore increasing the pressure.

Fig. 7-a) and fig. 7-b) show the output of MAP in kPa on the x axis plotted against engine torque and power, respectively. It is clear that the MAP was more sensitive in estimating power ($R^2 = 0.959$) rather than torque ($R^2 = 0.809$) because of the speed factor. This high regression coefficient supported the choice of using the MAP output as the main load detector in the prototype algorithm.



a) MAP with Torque



b) MAP with Power

Fig. 7 Manifold absolute pressure plotted against the torque and power of engine. Its regression was more accurate with power

3.2.2 Exhaust gas temperature

Exhaust gas temperature (EGT) is an important parameter indicating the state of combustion in the diesel engine. In fact, many truck owners are currently installing this sensor to reduce engine load whenever EGT is higher than a certain limit thus minimizing risks of engine failure.

In this research, the EGT sensor's output was also plotted against power and torque while the engine was on a bench dynamometer. It was slightly even more sensitive than MAP in predicting the power with regression coefficient $R^2 = 0.962$; nevertheless the drawback against the usage of this sensor is the large time-delay needed to respond to change in load. On another hand, the sensor itself was very prone to variation in ambient temperature, and its output changed depending on its position in the exhaust system. For instance, the EGT at idling in the bench test was 150°C while it was only 115°C when the engine was mounted on the tractor. These changes require frequent calibrations, which are impractical. Nevertheless it is important to monitor this sensor to prevent excessive loading conditions, especially with higher biogas injections.

3.2.3 Mass air flow sensor

The mass air flow sensor measures the quantity of air coming into the engine in terms of g/s. While it serves as an important factor in deciding the amount of fuel required for gasoline engines, it was found that it generates very low correlation with either power or torque, and therefore it can not be used for load estimation.

3.3 Prototype algorithm

The load estimation technique based on MAP sensor was incorporated into a prototype algorithm. The latter was built using an Engine Control Unit (ECU) (MoTeC M800). Its backbone was a three-dimensional map where speed formed the x axis, MAP the y axis and injector opening time the z axis. The injectors in this case where controlled by the ECU itself, and their opening frequency changed with engine speed. The algorithm was tested on the standalone engine on the bench dynamometer. The three-dimensional map shown in Fig. 8 was at first constructed and fed into the ECU. The engine was then run at different speeds and loads and the biogas flow as well as various other parameters were measured.

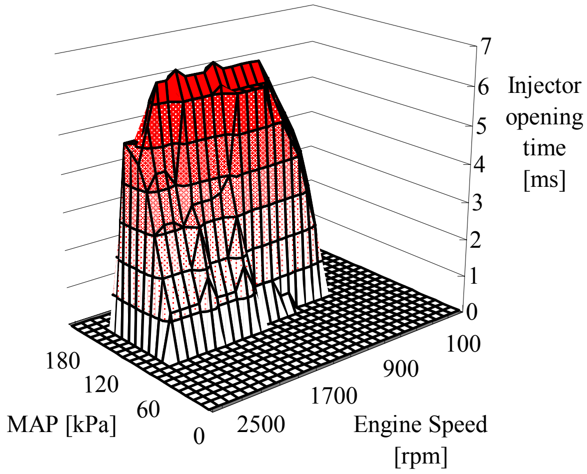


Fig. 8 The prototype three dimensional map that was built for the standalone engine

The biogas flow and the fuel replacement rate achieved are shown in Fig. 9. Most importantly, the algorithm was effectively able to change the biogas flow along the change in engine load: the flow was limited for lower engine loads to prevent misfire, it was stopped at very high loading conditions to prevent knock and engine damage. Nevertheless, a problem arose: the biogas flow did not always correspond to injector opening time. Such an occurrence is clear at the BMEP of 600 kPa; the injector's opening time was increased and the flow was supposed to increase too, however, it was relatively decreased. It should be noted that this trouble was not caused by the algorithm, which correctly decided the injector opening time, but by certain hardware problem, probably related to the MoTec ECU.

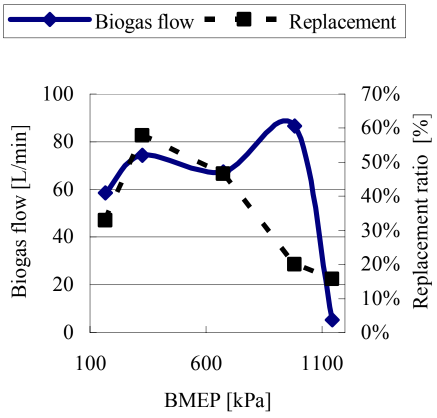


Fig. 9 Biogas flow and replacement rates achieved with the prototype algorithm

On the other side, it was found that the biogas flow does not correspond neither to the maximum flow, nor to the best efficiency point. Amelioration to the 3D map could therefore increase biogas flow level displacing maximum amount of diesel, or inject the suitable amount of biogas to keep the engine at its best heat efficiency point.

4. CONCLUSION

To contribute to the development of an agricultural tractor running on biogas, this study aimed at producing a prototype algorithm controlling the flow of biogas into the intake manifold of the diesel engine. The effects of biogas addition on engine's performance were first observed and it was found that biogas energy partially replaced that of diesel. The biogas maximum participation to intake energy reached 90% at low speed and low (1800 rpm and 90 Nm respectively) causing a reduction in diesel consumption of 82%. Furthermore, the stepwise increase in biogas injections decreased the engine's Brake Specific Heat Consumption (BSHC) by 5 to 10% at medium and higher loads at biogas flows of 60 L/min. further increase in flow worsened (increased) the BSHC.

Secondly, the accuracy of various sensors in determining engine load was tested and accordingly, the load estimation method was decided to be based on Manifold Absolute Pressure (MAP) which gave high regressions with power ($R^2 = 0.959$). A prototype algorithm, setting injector opening time based on engine speed and manifold absolute pressure, was finally built and tested. It was able to adjust biogas flow according to load requirements; avoiding misfire and knock. Nevertheless, further ameliorations are still required to reach best efficiency or highest diesel replacement rates; which will be the objective of a future research by the authors.

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