Modification and Tuning of Multi-valve Diesel Bus Engine to Run On Biogas for Electricity Production

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ABSTRACT

This study is to modify and tune a multi-valve bus diesel engine for electricity production in a farm using biogas as fuel. The engine under study is a Hino Model K-13CTI 6 cylinder 13,000 cc 24 valves turbocharged with intercooler engine. The engine is coupled to an induction motor to work as a 3-phase 4-pole 132 kW generator to produce electricity at 50 Hz. Modifications include replacing the fuel injection system with spark ignition system, reduction of compression ratio from the original 16:1 to 8:1 by using a custom made cylinder head spacer, modification of the turbocharger waste gate so the boost pressure can be adjusted to find the optimal operating point, and an addition of biogas carburetor for proper air-fuel mixing. In this configuration when the generator is synchronized to the power grid, the system running speed is 1,500 rpm. When the system is finely tuned, optimal engine efficiency was achieved at 28.6% by setting the lambda factor at 1.097, ignition timing at 54^o before top dead center, and the turbocharger boost at 56 kPa. With this setting, the generator power output is 134.2 kilowatt with emission of CO and NO_X being 1,154 and 896 ppm respectively.

Keywords: Engine Development, Internal Combustion Biogas Engine, Biogas Engine, Engine for Biogas, Engine for Electricity.

1. INTRODUCTION

Today's cattle industry produces biogas from dung, especially from large-sized pig-farms. Biogas has some special qualities i.e. biogas is formed by digestion of animal waste by anaerobic bacteria and the approximate composition is 60-80% methane (CH_4), 20-40% carbon dioxide and about 1% of hydrogen sulfide (H_2S) and other trace gases. The gas is normally used at the site of production because the gas density is roughly the same as air and it is difficult to liquefy and transport [1, 2, 3]. Biogas has liquefying pressure of 200-300 bar and heating value of about 23,400 kJ/m^3 [4, 5]. The gas density is 1.2 kg/m^3 and has research octane number (RON) of about 130 [6, 7]. Also, about one percent of other trace gases are present, such as corrosive hydrogen sulfide (H_2S) which will have the same qualities of acid when mixed with moist air. The rest is between 35 and 45% CO_2 and 55 to 65% CH_4 [8, 9]. The properties of biogas cause limitations in its usability. The majority of biogas is used for electricity production by using an electric generator set (an assembled biogas engine and electrical generator). When the energy from fuel combustion is converted to electrical current, it can be applied easily [10]. The 4 stroke internal combustion engine is often chosen to produce electricity because it is easy to get, can be repaired by a local technician and it is cheap [11, 12, 13]. Thailand has modified 4 stroke internal combustion engines to use biogas as fuel more cheaply when compared with biogas generator sets from other countries [14]. However, it appears that the existing biogas generator set modified in this country encounters many problems. One problem is low efficiency caused by the abnormal wearing out of the engine's moving parts. There is a lack of knowledge about how to find the way to protect against unusual wearing out caused by using biogas as fuel, can't prevent the engine overheating when it is running continuously, the engine not running smoothly, the power of the engine is irregular, poisonous exhaust gas is unstable and exceeds the maximum internationally accepted pollution control standard of a vehicle engine [15]. All these problems, are due to incorrect engine modifications of the ignition timing, compression ratio, mixed-gas pressure (especially engines with a turbocharger), and inappropriate air-fuel mixing equipment (biogas carburetor) [11].

This study focus to modify a 4 stroke 6 cylinder 13,000 cc diesel internal combustion engine into a biogas engine and couple to a large-sized biogas generator set (100 kW or more). In the adaptation involve an addition of biogas carburetor for air-fuel mixing, replacing the fuel injection system with spark ignition system, reduce the compression ratio to suit biogas fuel using a cylinder head spacer, and modification of the turbocharger waste gate so the boost pressure can be adjusted. The test rig uses Hino K-13CTI 24 valve turbocharged engine coupled to a 3-phase 4-pole induction motor to produce electricity at 50 Hz. The engine is then tuned by fine tune all the settings of the engines such as, ignition timing, air/fuel ratio, compression ratio, and turbocharger boost pressure when running the engines with biogas for minimum pollution and maximum efficiency.

2. MODIFICATION METHODS

2.1 Engine Selection

Larger engines like those found in heavy trucks or large buses are designed to carry a full load for most of its operating cycle and also designed to run at lower engine speeds [16, 17]. The engine will need to run at a speed synchronized with the generator. In this case, the generator requires an engine speed of 1,500 rpm for a 4-pole induction-motor. The bus engine under consideration provides maximum torque at 1,500 rpm and therefore suitable for the 1,500 rpm running speed. The Hino K-13CTI engine being studied is a turbocharged bus diesel engine that came with fuel injection system as well as the high compression ratio of 16.5:1 and fixed waste gate boost control. The engine used is a second hand engine. For the test to be accurate and the results to be trusted, the engine must be fully overhauled to the manufacturer's specifications.

2.2 Compression Ratio Modification

The compression ratio of gas engine is a function of the fuel used. Higher compression ratios result in higher temperatures of the air-fuel mixture. This may cause uncontrolled self-ignition and an uneven combustion process, both disadvantages for engine performance and life span [6]. Another variable to be considered is the feasibility of reducing the compression ratio down to 8:1 for the spark ignition range for lower value to avoid engine knock [18]. An increase in the compression ratio appears to be desirable as it provides an increased efficiency of the process from the thermodynamic point of view. The additional volume to be created can be established by first determining the previous volume, $V_{c,prev}$ of the compression chamber. This can be done by using the previous compression ratio and calculating with equation 1 or by measuring the volumes of the cylinder head and the cavity in the piston (if any) with a liquid and adding the displaced volume created by the distance between the piston at TDC and cylinder head plane (including the original gasket thickness). A displaced volume or swept volume, V_d can be calculated by equation 2. Next, determine the new volume, $V_{c,new}$ of the compression chamber according to the required compression ratio. This can be calculated by using equation 1. Thus establishing the additional volume, ΔV_c to be created by using equation 3. Finally, the additional volume is created by increasing the gap between the cylinder head and gasket's additional thickness, Δh is calculated by equation 4 [6].

$$V_c = \frac{V_d + V_c}{\varepsilon} \quad (1)$$

$$V_d = \frac{\pi \times d^2}{4} \times h \quad (2)$$

$$\Delta V_c = V_{c,new} - V_{c,prev} \quad (3)$$

$$\Delta h = \frac{4 \times \Delta V_c}{\pi \times d^2} \tag{4}$$

where d is the inside diameter of the cylinder bore, h is the engine stroke, and ε is the engine compression ratio.

The adapted engine is shown in Fig. 1. To reduced compression ratio, the piston should not be modified because of reduced strength and upset of engine balances. Thus, the steel spacer should be installed between the cylinder head and cylinder block, and the valve-pushrod length has to be extended.

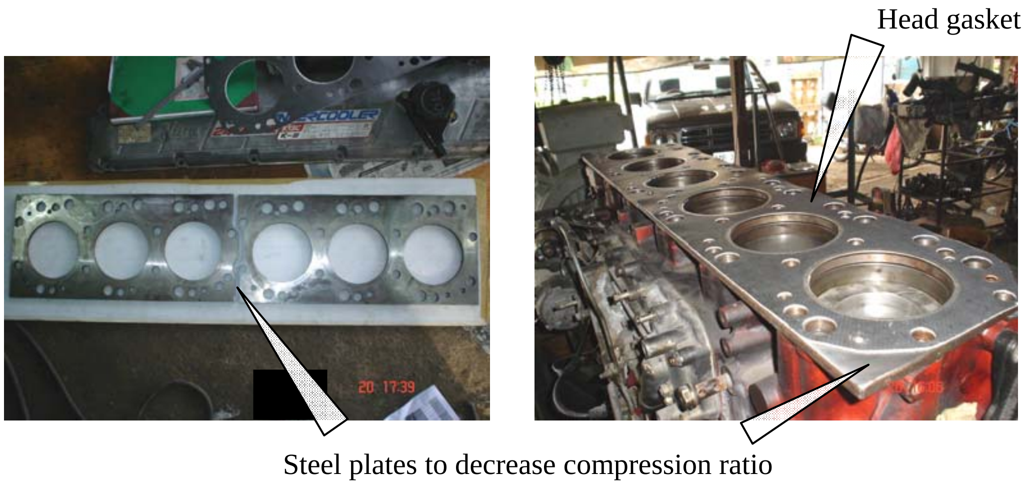


Fig 1. A picture of the steel spacer and two standard gaskets installed on the cylinder block.

2.3 Ignition System Modification

The diesel engine modified to use biogas in this study came from factory with a diesel fuel injection system. The distributor and ignition coil was adapted from the one used in a 6-cylinder Toyota 5-ME engine. The vacuum and centrifugal advance was disabled because the engine would run at a constant speed (1,500 rpm) and at full load when used to drive the generator. The distributor was driven by the original fuel injection distributor mechanism. The fuel injection nozzle in the cylinder head was removed and replaced with a spark plug and an appropriate guide tube. The cylinder head before and after modification is shown in Fig. 2.

2.4 Carburetor Design

The function of a carburetor is to mix air and fuel in appropriate proportion for the engine to run efficiently. In this case, the fuel is biogas and is supplied to the engine under very low pressure (about 2 inches of water) and part of the carburetor function is to suck fuel in to the engine. Since the engine will run at a constant speed and load, a venturi mixer design is chosen for the carburetor along with a metering system to adjust the air/fuel ratio supplied to the engine.

The schematic diagram of the biogas carburetor designed and assembled in this study is shown in Fig. 3. It consists of eleven components as shown in Fig. 3(*a*) and for the time being the isometric drawing is shown in Fig. 3(*b*). A survey shows that a suitable carburetor for a biogas engine should be a venturi with the accelerator cone being tapered as a curve of 40 mm radius and a diffuser cone angle of 10^o. The biogas is fed into the venturi through multiple circular ports around the throat area and the throat air velocity should be between 100 to 150 m/s [6]. With this information, a carburetor designed for the 13,000 cc engine with direct coupling to a 3-phase 4-pole induction-motor and operating at a constant speed of 1,500 rpm should have a throat diameter of 47 mm and no throttle valve at the end of the diffuser cone. The venturi and contained components were machined from aluminum stock, stainless steel, and polymer. The components of the biogas carburetor are durable to erosion from H_2S. The venturi was machined from aluminum stock and the carburetor body was fabricated from PVC pipe parts.

2.5 Waste Gate Modification

Engine performance parameters, such as engine power, torque, and cylinder pressure are proportional to the mass of air (or gas mixture) inducted per cycle. This depends primarily on the density of the inlet gas mixture. Thus the performance of an engine of a given displacement can be increased by compressing the inlet gas mixture prior to entering the cylinder. One method for achieving higher inlet gas mixture density in the gas exchange processes is turbo-charging. This method will cause the spark-ignition engine to have increased power and torque. A naturally aspirated spark-ignition engine may have a sufficient margin of safety relative to engine-knock, allowing modest inlet-air boost. Any attempt to boost the output of a given size spark-ignition engine by using an inlet gas mixture compression device will aggravate the knock problem. This is due to increased cylinder pressure and temperature [18]. However, the potential advantages of power boosting are significant as the output power given for displaced volume will increase.

Increasing the turbocharger pressure will lead to increased inlet gas mixture density and tends lead to increase engine power and torque as well as increasing the compression ratio. In some cases, the compression stroke work transfer increases, peak cylinder pressure increases, gases burn at higher temperatures, there is higher flame speed and engine knock occurs. The basic limitation in using higher turbocharger pressure for spark-ignition engines depends on the properties of the fuel used. Therefore, if the turbocharger pressure is increased past optimum point, it will give higher engine power and torque, but also higher friction loss (from components rubbing against each other, for example, piston and piston-ring with the cylinder wall) including all bearings etc. These problems will shorten the engine’s life through abnormal wear and tear.

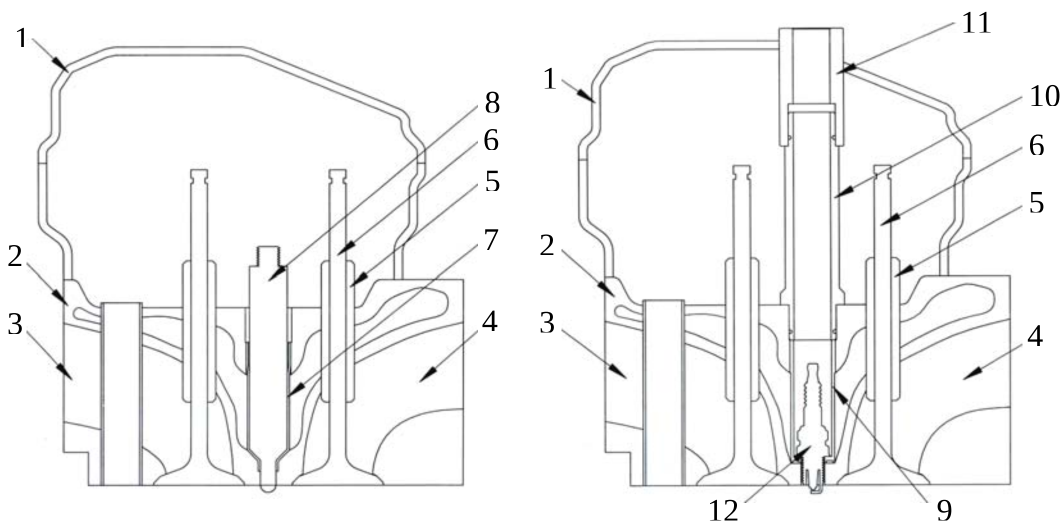
The turbocharger pressure of the standard engine is control at constant pressure by waste gate. Low pressure will cause loss of efficiency while too much will cause knocking, eventually damaging the engine. The boost pressure in the experimental engine was varied by modifying the waste gate spring housing so it could be adjusted to vary the turbocharger pressure. After the modification, the turbocharger boost could be adjusted between 40 kPa and 100 kPa. Details of the modification are in Fig. 4 and there are eight components.

2.6 Modification of Engine Cooling System

The diesel engine, when installed in a bus, runs at variable speed and not always at full load. When the same engine is used for electrical power generation, it is operated at constant speed with full load and generates more heat. The original radiator was modified to cope with the new loading condition by adding another radiator as well as another cooling fan and the modification is shown in Fig. 5.

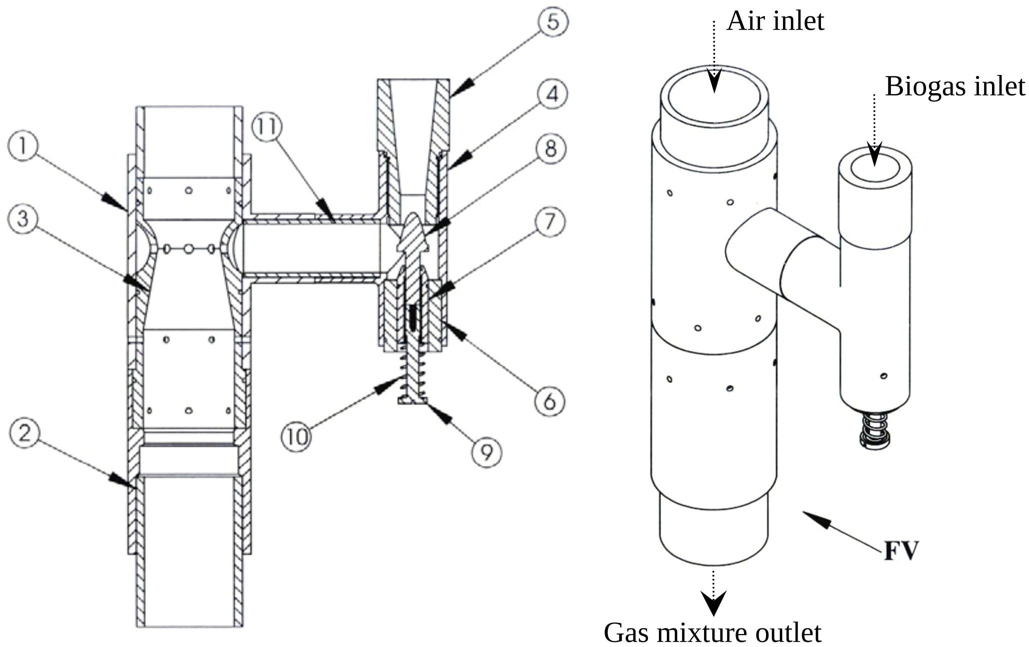
2.7 Biogas Generator Assembly

The biogas generator in this study consists of a 13 liter biogas engine coupled to the 3-phase 4-pole 132 kW induction-motor which acts as the generator. Coupling between the engine and the generator will use direct coupling by clutch plate with the clutch engagement control mechanism. This will make the operation of the coupling much smoother. A control unit is installed in this same set and all components are installed on a base strong enough to withstand the total weight of 3 tons and the additional vibration force. Fig. 6 shows a picture of the assembled biogas generator.



(*a*) (*b*)

Fig 2. Cut-away view of the modified cylinder head: (*a*) before modification, and (*b*) after modification; the twelve part layout: (1) valve cover, (2) cylinder head, (3) intake port, (4) exhaust-port, (5) valve guide, (6) exhaust valve, (7) diesel-injection nozzle guide, (8) diesel injection nozzle, (9) sparkplug guide, (10) middle-sparkplug rod guide, (11) upper sparkplug rod guide, and (12) sparkplug.



(*a*) (*b*)

Fig 3. Schematic diagram of the 13 liter biogas carburetor: (*a*) cut-away view of eleven components are; (1) venturi housing, (2) venturi base, (3) venturi mixer, (4) metering housing, (5) main jet, (6) metering adjusting nut spacer, (7) metering-adjusting nut, (8) metering needle, (9) metering-adjusting screw, (10) return spring, and (11) pipe junction, and (*b*) isometric drawing.

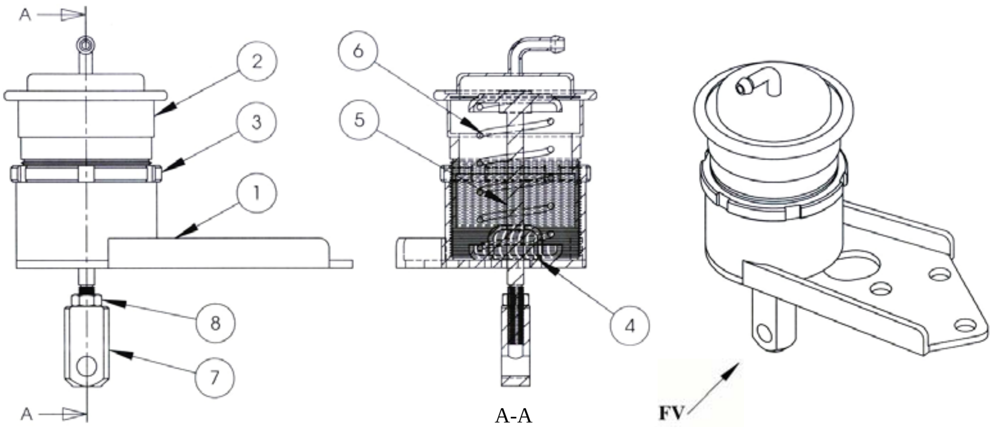


Fig 4. Schematic diagram of the waste gate adjustment: (1) waste gate base, (2) waste gate spring housing, (3) waste gate adjustment lock nut, (4) push rod-bushing, (5) push rod waste gate, (6) return-spring, (7) adjustable push rod junction, and (8) lock nut.

Fig 5. A picture of the two standard radiators of the biogas generator.

Fig 6. A picture of the assembled biogas generator.

3. EXPERIMENTAL SETUP

The overall block diagram of the test rig is shown in Fig. 7. The purpose of this experiment is; to find optimum tuning conditions for when a diesel bus engine is modified to use pure biogas as fuel; and drive an electrical generator to produce electricity. The air intake and biogas are both monitored so air/fuel ratio can be calculated. The exhaust gas is checked for CO, O_2, and NO_X emissions at various engine settings. Each component of the test rig is briefly described as follows.

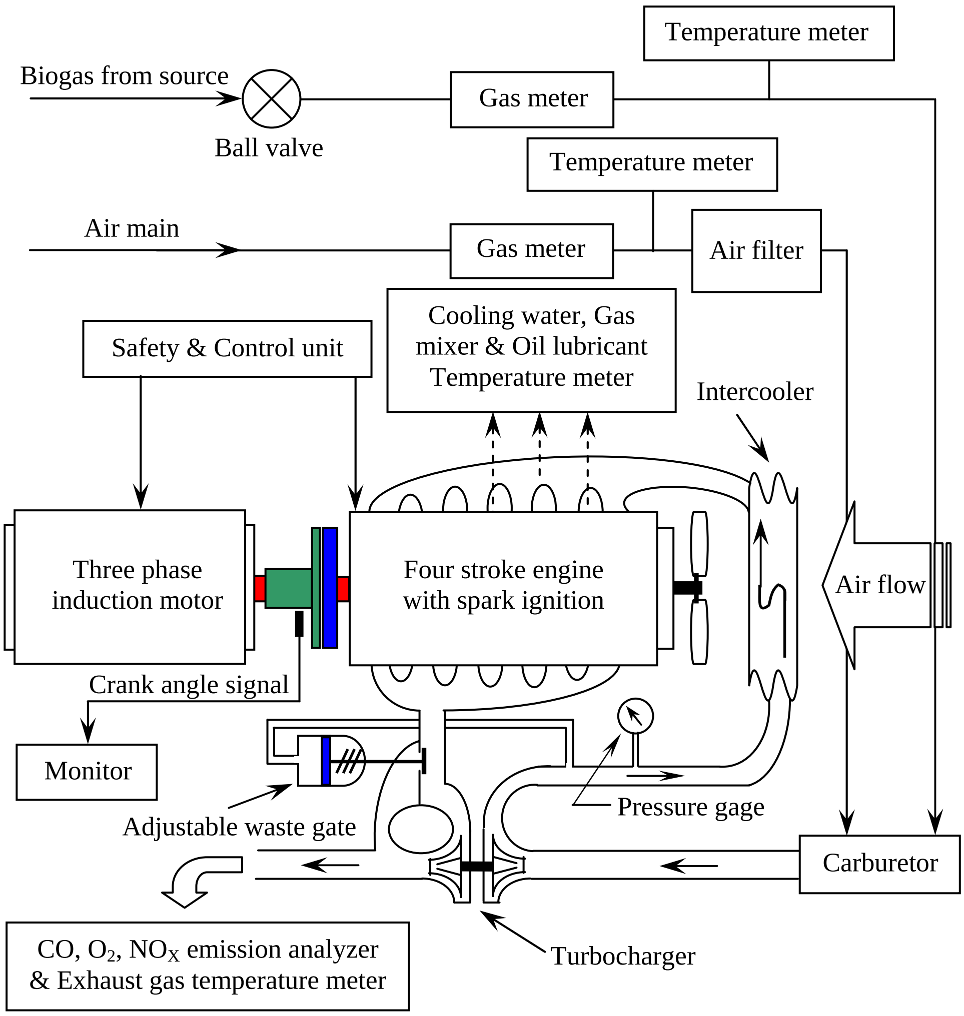


Fig 7. The block diagram of the test rig of the engine.

3.1 Test Engine

The test engine is a Hino diesel engine, with 4 valves per cylinder. The engine has a manufacturer-installed turbocharger and intercooler that are both able to be modified to use biogas fuel. The engine is commonly installed in buses and large trucks in Thailand. This engine was chosen because both used engines and spare parts are easily available. It was overhauled to a new engine specification before testing and is currently undergoing an endurance test at the Establishment of Domesticated Animals (4T farm), Chiang Mai, Thailand. The biogas fuel for testing the engine has a total CH_4 content of 70% by volume.

3.2 Electrical Generator Unit

The generator used is an induction motor, HASCON model 200L2-2 3-phase 4-pole 132 kW generator. The generator is directly coupled by clutch mechanism to the test engine and synchronized to the power grid when in operation. The nominal operating speed is 1,500 rpm.

3.3 Control Unit

The control unit is used to control and run engine with generator set. It consists of electrical and electronic equipment which indicates results with a digital display. The control unit is used to start the test engine, synchronize the generator with the power grid and for safety function monitoring. Those monitored include: gas supply shortages, short circuits, power-grid overload, engine overheating, loss of oil pressure in the engine and power grid failure.

3.4 Temperature Measurement

The air-intake, biogas, engine oil lubricant and engine water coolant are all measured for their temperature using a digital thermometer. The Kane-May model KM330 equipped with K-type thermocouple wire and probe. The K-type wires and probes are attached to the engine.

3.5 Air and Biogas Intake Measurement

The air and biogas intake flow rate are measured for an oscillator meter for gases, Kobold model DOG-1 (GVPA-303-GDR) with a range of 0-110 m^3/hr. Installed oscillator meter for gases between the air pipes before the carburetor to measure the air flow rate and installed one oscillator meter for gases between the biogas supply pipes to measure the biogas flow rate.

3.6 Exhaust Gas Measurement

Flue gas emission is measured using a Testo flue gas analyzer, model 300XL-I, which is equipped with a sampling probe. It was used to monitor the quantity of O_2, CO, and NO_X in the exhaust gas emission. The probe attached can also measure the exhaust gas temperature.

3.7 Pressure Gage Measurement

The turbocharger booster pressure was monitored using an analogue pressure gauge. At intake manifold, installed connecter and flexible high pressure plastic tube connected to the pressure gauge. The mixed air and biogas mixture is transferred to the pressure gauge via the flexible plastic high pressure tube. The pressure gauge is installed on a stand, separate from the engine in order to protect from the engine’s vibration. Vibration can disturb the pressure readings.

3.8 Ignition Timing Measurement

Ignition timing is set and measured using a Technotest engine, model 8020. It is equipped with a timing light and trigger signal, via high tension wire, from the distributor to the number one cylinder spark plug.

3.9 Electrical Power Measurement

Electrical power output from the generator is monitored by an electrical power supply network analyzer; CIRCUTOR model AR5. It has three clamps equipped with electrical trigger indicators attached to the generator via high tension wires.

4. TUNING PROCEDURE

4.1 Turbocharger Pressure Adjustment

The experiment started with a compression ratio of 8:1 and the turbocharger pressure adjusted by the waste gate at 40 kPa and increased by an increment of 4 kPa until the engine efficiency began to decrease.

4.2 Initial air/fuel mixture adjustment

The engine was started with the ignition timing set in the middle range (an estimated 55^o BTDC). The air/fuel mixture screw was adjusted to a position where the engine was running smoothly with a lean mixture.

4.3 Initial ignition timing adjustment

The ignition timing was set at 50^o BTDC before the collection of data.

4.4 Data collection

Recordings of intake air or ambient temperature, intake biogas temperature, mixed-gas temperature before turbocharger, mixed-gas temperature at the turbocharger outlet, and following being cooled by the intercooler, engine's water temperature, engine's lubricating oil temperature, exhaust gas temperature, air and biogas consumption rate, ignition timing, generator power output, level of O_2 following combustion, CO and NO_X emissions in the exhaust gases are made.

4.5 Ignition timing increment

The ignition timing was advanced by 2^o BTDC and *Data collection* repeated each time. The process was repeated until the ignition timing reached 60^o BTDC or excessive pre-ignition was observed.

4.6 Air/fuel mixture increment

After a set of data was collected, the air/fuel mixture screw was turned half a revolution to make a richer mixture. Another set of data was collected and the process repeated until the mixture was too rich for the engine to run smoothly.

4.7 Data processing

Collected data was processed to calculate the air and biogas consumption, specific biogas consumption, air/fuel ratio, excess air ratio, average total electric power output from generator, engine efficiency, and overall or system efficiency. The exhaust gas temperature, average total electric power output, specific biogas consumption, engine efficiency, CO and NO_X emissions, and O_2 quantity in the exhaust gas are plotted against the ignition timing, excess air ratio, and turbocharger pressure.

5. RESULT AND DISCUSSION

The description of the test results and discussion covered and presented by the resulting graph and table. The graph were illustrated with exhaust gas temperature, engine output power in formed electric power production or actual electric power output, specific fuel consumption, engine efficiency, CO and O_2 content in exhaust gas, and NO_X were plotted against the turbocharger pressure as shown in Fig. 8. The engine performance and pollution figure are recorded for a range of engine tuning parameters such as ignition timing, air/fuel ratio and turbocharger boost. The compression ratio was set at 8:1 and the turbocharger boost was varied by adjusting the waste gate. When the system is operating at 1,500 rpm, the range of engine setting is air/fuel ratio between 0.9 to 1.2, ignition timing between 50^o to 60^o BTDC, and turbocharger pressure setting between 40 to 68 kPa. Under these operating conditions, the engine efficiency increases as the boost is increased from 40 to 56 kPa and there is a slight increase of CO and NO_X as the turbocharger boost goes up. As the boost is increased from 56 kPa to 68 kPa, the engine efficiency begins to decrease and the amount of pollution is increased. Increase in engine vibration is also noted in this turbocharger boost range. NO_X and CO emissions as well as high when high pressure and temperature occur in the combustion. The system will produce electrical power of 93.40 to 143.20 kW. Test shows that more power can be generated if the engine is operated with rich air/fuel ratio and high turbocharger boost. Higher engine output will yield shorter payback period for the investment but increasing the boost pressure beyond 56 kPa will cause excessive pollution emission and engine vibration which will probably shorten the engine life. The engine output power and engine efficiency dropped off at higher turbocharger pressure or at any turbocharger pressure that is not 56 kPa. With the presented data, it can be shown that a diesel engine can be economically adapted to a biogas engine for power generation on a farm. The payback period is less than one year and when properly tuned, the engine passes the internationally accepted pollution control standard of carbon monoxide of a vehicle engine [22, 23, 24]. Three categories of tuning optimisation were done. They are lowest CO emission, highest engine efficiency, and highest power output. The tuning parameters and collected data for the three categories are presented in Table 1.

Table 1 Summary of fine tuning a biogas engine for optimum operation when compression ratio is 8:1 and turbocharger boost pressure is 56 kPa.

Item	Lowest CO emission	Highest engine efficiency	Highest power output
Optimum ignition timing (^{o} BTDC)	57	54	52
Excess air ratio, λ	1.215	1.097	0.989
Fuel consumption, f_c (m^3/hr)	71.80	78.60	86.10
Specific fuel consumption, sfc (m^3/kWh)	0.64	0.59	0.61
Actual electric power output, p_{el} (kW)	111.40	134.20	140.70
Engine efficiency, η_{eng} (%)	26.01	28.63	27.40
Overall efficiency, η_{tot} (%)	23.41	25.76	24.66
Oxide of nitrogen emission, NO_X (ppm)	511	896	843
Carbon monoxide emission, CO (ppm)	854	1,154	2,576
Oxygen in exhaust gas, O_2 (%)	10.00	6.20	5.90
Engine coolant temperature, T_{eng} (^{o}C)	88.2	88.7	89.0
Lubricating oil temperature, T_{oil} (^{o}C)	87.8	87.2	87.6
Exhaust gas temperature, T_{fg} (^{o}C)	536.0	521.5	533.8
* Payback period (year)	0.61	0.42	0.39

Note: * The sets are running continuously 12 hours per day and at best efficiency conditions.

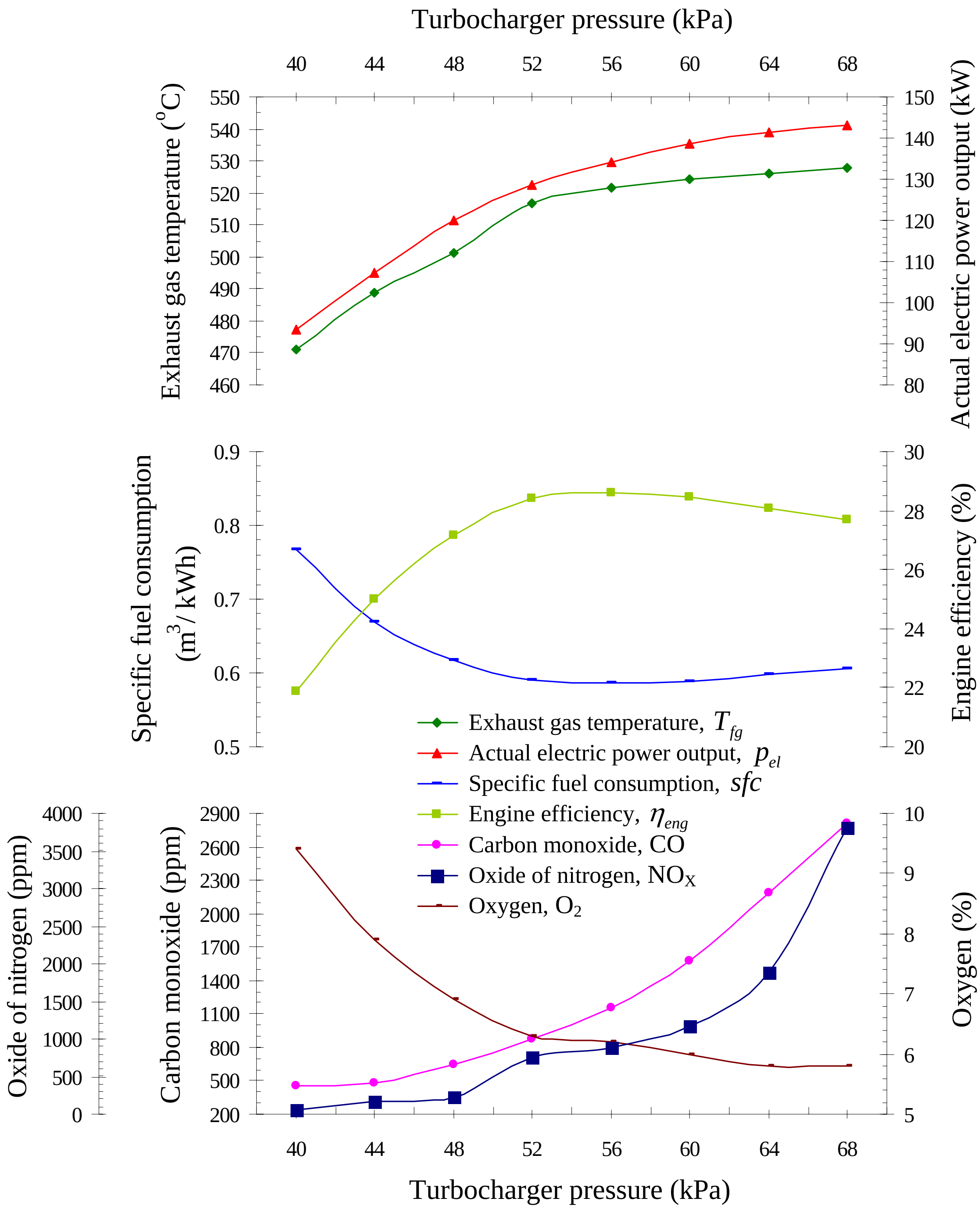


Fig 8. Exhaust gas temperature, actual electric power output, specific biogas consumption, engine efficiency, carbon monoxide, oxide of nitrogen, and oxygen plotted against turbocharger boost pressure to find the highest efficiency for a compression ratio of 8:1.

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