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Development of the Biogas Tractor with Two Biogas Feeding Algorithms

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Abstract: The research on biogas tractor was started as a possible solution to reduce tractor's fuel consumption and increase farmer's benefit out of a biogas plant. The tractor was equipped with a fontal gas unit containing 4 cylinders of purified biogas (more than 95% methane) with a volume of 26.5 L each at 19.6 MPa. A pressure regulating system was used to insure constant pressure potential across the biogas injectors. Based on previous study regarding biogas effects on the diesel engine, two possible algorithms were developed and tested. In the field tests, the first one was successful at replacing the high amounts of fuel (about 80%) while the other was able to run the engine at its best efficiency point.

1. INTRODUCTION

Energy is posing important challenges to the current world. The increase awareness of the scarcity as well as the negative environmental effects of fossil fuels is calling for new energy forms (Nasser, 1997). The biomass is therefore regarded as a potential energy supplier, having the characteristic of being both sustainable and carbon neutral. Biogas, which is mainly extracted from farm manure and other organic wastes, has two benefits, from one side, it helps solving several waste related problems, and from the other hand, it provides the farms with a gaseous fuel: the methane. The methane from biogas has been already used for heat, whether it is a household, a farm or a factory in many places of the world. Electrical production, and combined heat and power production from biogas is also proliferating supported by government incentives. The usage of biogas as a vehicle fuel is however still limited. It is thought that the biogas usage in vehicles in general, and in agriculture tractors in particular, might help the farmers to increase their benefit from the biogas plant and reduce their fuel cost. The goal of this research is therefore to build a biogas tractor, driven by a dual-fuel diesel biogas engine. Many problems had to be taken into consideration: the gas storage unit, the gas pressure regulation, the injection system and the amount of biogas to be fed into the engine. This paper therefore presents the biogas tractor and its components, and discusses in details two biogas feeding algorithms that were tested.

2. HARDWARE DESCRIPTION

2.1 The base tractor

Fig. 1: the biogas tractor with its biogas unit opened to show the 4 cylinders of biogas

An agricultural tractor (Kubota New Grandom M105D) was chosen as the base tractor to be converted into dual-fuel operation. The tractor had a 4 cylinder, 3.8 L displacement engine equipped with a turbocharger and an intercooler; it had 4 valves per cylinder and a direct diesel injection system. The engine produced 77kW at the rated speed of 2600 rpm and reached its maximum torque of 345 Nm at the rotation speed of 1500 rpm. The base tractor was fitted with a frontal gas unit as seen in figure 1.

2.2 The biogas cylinders

The gas unit had 4 biogas cylinders, each of which can

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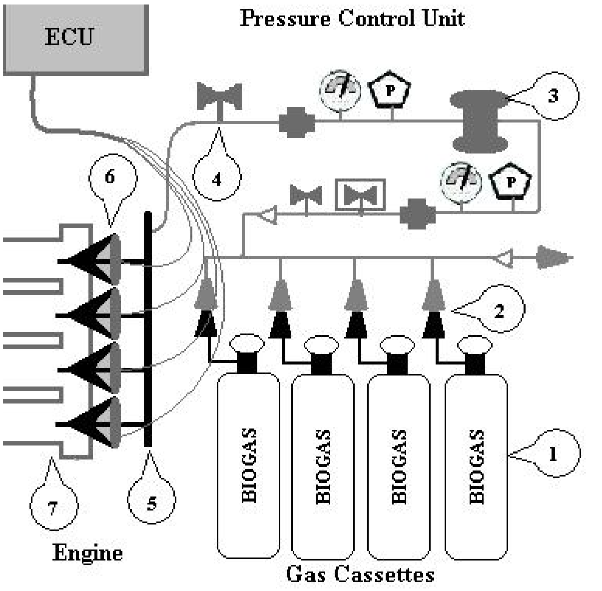
contain a volume of 26.5 L of methane at a pressure of up to 19.6 MPa. The biogas storage was estimated to be enough to run the tractor for at least two hours with the highest biogas supply of 150 L/min. it should be mentioned that the gas cylinders were made of fiber reinforced plastic (FRP) to keep their weight to the minimum and to ease the task of changing the empty cylinders with full ones. Provisions were also taken to allow the direct refilling of biogas from the main compression system. The biogas used in this research was purified into about 95% methane.

2.3 The pressure regulating system

A pressure regulating system was also built in the frontal gas unit to insure a constant pressure gradient along the gas injectors. A hose conveyed the pressure inside the intake manifold to the respective port in the regulator to insure a constant pressure gradient of 255 kPa across the biogas injectors. a series of check valves, pressure relief valves, manual and electrical valves as well as analogue and digital gages composed the rest of the pressure regulation system (see figure 2: the schematic diagram of biogas unit).



Gas Cassettes	1	Biogas cylinders (26.6 L each, 19.6 MPa)
	2	Gas couplers (for quick substitution of cylinders)
Gas Pressure Control Unit	3	Pressure regulator (from 19.6 MPa to 255 kPa)
	4	Manual valve (open the flow towards the engine)
Engine	5	Injector rail (distribute biogas to all injectors)
	6	Injectors (controlled by ECU)
	7	Intake manifold

Fig 2: schematic diagram of biogas unit

2.4 Injectors and their control circuit

Finally gas injectors were mounted on the intake manifold of the engine. This set up allowed the tractor to operate in dual-fuel mode when biogas is abundant; and it also allows smooth and nonstop conversion to diesel fuel operation in case the biogas was not available.

The circuit controlling the biogas injectors was adapted from Asahara 1995. A transistor opened and closed the current flow from the battery to ground through the injectors, controlling therefore their opening and closing. The transistor's base was connected to the counter output of a counter board which in turn was controlled by a computer. The computer was able to control both the frequency of the counter as well as the ratio of opening within one cycle.

2.5 Load estimation

The importance of load in deciding the biogas flow was previously described in many literatures (Jaber and Noguchi, 2007). Its estimation in real-time basis was therefore crucial for the completion of biogas feeding algorithm. Based on the results of a previous research by the authors, it was found that the manifold absolute pressure sensor is the most suitable means to estimate engine load in dual-fuel mode.

The above completes the necessary backbone of the biogas feeding algorithm. The hardware insures that the desired flow actually reaches the engine; and the load estimation accurately describes the engine status. To complete the picture, the amount of biogas to be injected in every load/speed condition should be known. In other words, the algorithm becomes a three-dimensional look-up table, and the biogas flow for each condition remains to be found.

3. DEVELOPMENT OF ALGORITHMS

Although the hardware of biogas feed was already set up for the tractor, the remaining important task was to define the amount of biogas that should be injected into the engine. The fulfillment of this task required extensive testing on a bench dynamometer to understand the effects of biogas addition on the engine. The full details of the results are the subject of a paper by the authors titled "the effect of biogas addition to the diesel engine of a tractor and development of prototype biogas control algorithm" and submitted to IFAC08 (Jaber et al. 2007).

3.1 Effect of biogas on engine

In summary, the engine was tested was several speeds and several loads. It was subjected to increasing biogas flow rates and the fuel consumption as well as other parameters was measured.

It was found that very important biogas injection into the engine's intake manifold caused misfire at low loads and knocking at higher loads. The flow was therefore limited by the occurrence of these two events. The biogas flow participated in the combustion and partially replaced the diesel fuel in the engine. The replacement was more important at lower loads; where the biogas share of total energy input reached more than 90%. The effective diesel reduction was calculated as the ratio of amount of diesel fuel required to operate the engine at a fixed speed and torque in dual fuel mode to that required in diesel only mode and it was found to be up to 80%.

On the other hand, the addition of biogas to the engine altered its break specific heat efficiency (BSHC). At lower loads even small addition of biogas increased the BSHC (reducing the heat efficiency); while at higher loads, partial biogas flow first decreased the BSHC; to see it increasing again as the flow becomes more important. Figure 4 clearly shows this phenomenon.

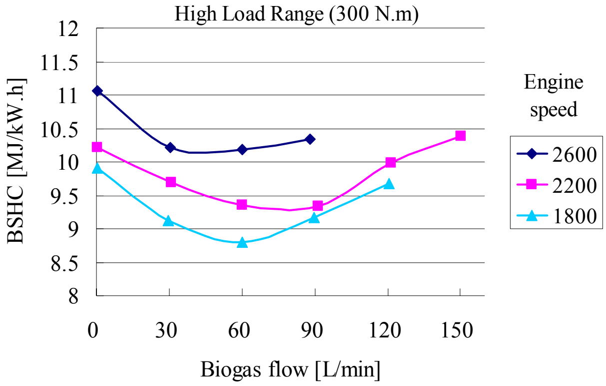


Fig. 4: Effect of biogas addition on engine at higher load.

Smaller biogas flows would be able to increase the engine's efficiency at medium and high loads, while more important ones replace a higher amount of diesel fuels. Nevertheless, the load was an important factor deciding the amount of biogas to be injected into the engine.

3.2 Performance parameters

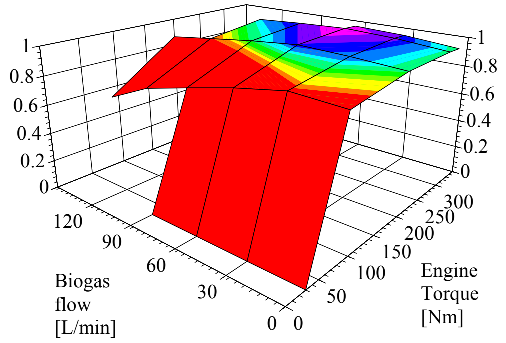
Based on these findings, two performance parameters were selected to control the biogas feeding. The first parameter was engine's break specific heat efficiency, while the other parameter was the fuel replacement rate, calculated as the share of biogas in total energy input to the engine. The two parameters having two different units were first normalized to allow for comparison between them (Noguchi et al. 1996).

3.2 BSHC performance index

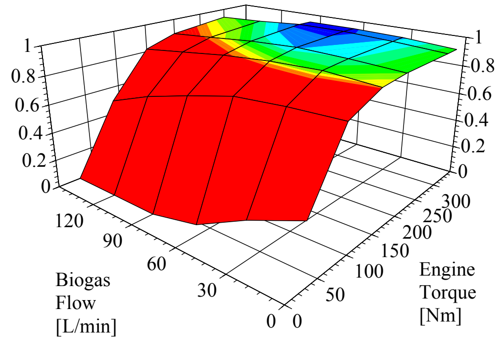
The minimum break specific heat efficiency reached during the dynamometer testing (8.79 MJ/kWh) was given the value 1. As for the maximum, it was chosen as the maximum BSHC value reached with the engine running only on diesel (33.16 MJ/kWh). Any value above that was taken to be 0. It is assumed that any value exceeding this one means that the engine is extremely inefficient. On the other side, the maximum replacement rate of 93% was given the value 1 while the minimum 0% was affected with the value 0.

3.3 Best efficiency algorithm

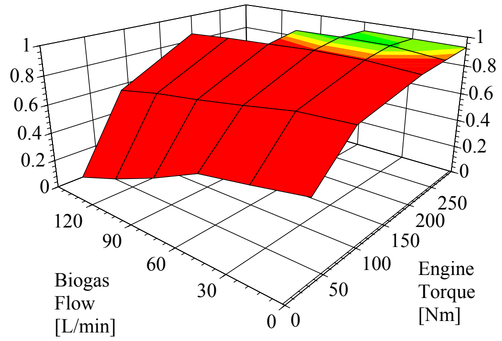
Graphs a, b and c in figure 5 show the three dimensional representation of the normalized plots of BSHC for each engine speed setting.



Graph a) BSHC performance index of engine running at 1800 rpm



Graph b) BSHC performance index of engine running at 2200 rpm



Graph c) BSHC performance index of engine running at 2600 rpm

Figure 5 showing the BSHC performance index of engine running at three different speeds

From the values of performance index shown in figure 5, it is understood that partial biogas injections tend to improve the performance of the engine in terms of heat efficiency. These facts have lead the authors to construct a 3D look-up table that could run the engine at its best efficiency mode, i.e. its minimum BSHC. The so called "best efficiency map" is thereafter shown in figure 6. It should be noted that the values of the Z axis are not the actual biogas flow, but they consist of the injector opening time in ms.

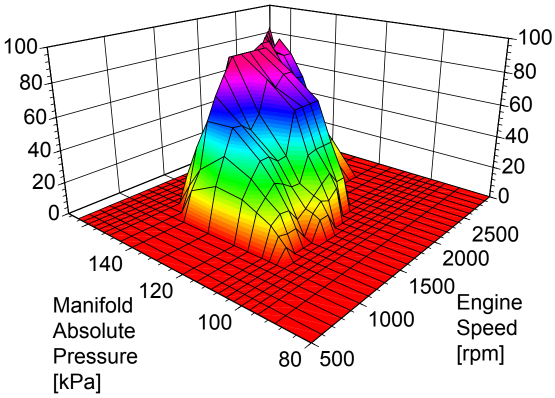


Fig. 6 the "best efficiency map" runs the engine at its best efficiency point

It is clearly seen in figure 6 that the biogas flow is restricted at lower manifold pressures, where the actual engine torque is low.

3.4 Best replacement algorithm

The other performance index chosen in this study, i.e. the replacement rate, was easier to handle. In fact, it was found that the higher the flow of biogas is, the better the fuel replacement will be. The fuel replacement was also inversely proportional to the torque of the engine. Figure 7 shows the normalized graph of replacement rate for the speed setting of 2200 rpm. The graphs of other speed settings show the same trends and therefore they were not represented in this paper.

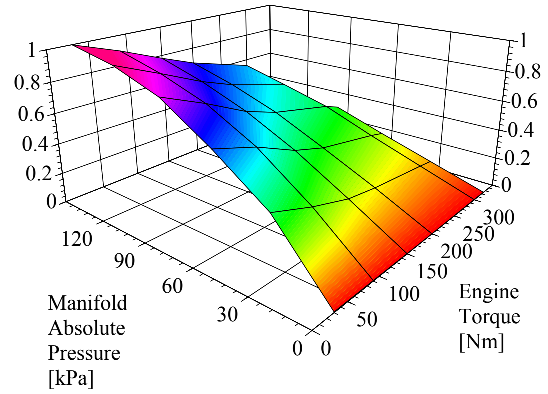


Fig. 7: the normalized graph for replacement rate

To draw the 3D map that would be able to replace the highest amount of diesel fuel, it would be enough to inject the highest possible amount of biogas into the engine. However, the map should avoid reaching the stages where misfire and/or knock might occur. The 3D map named "best replacement map" is shown in figure 8.

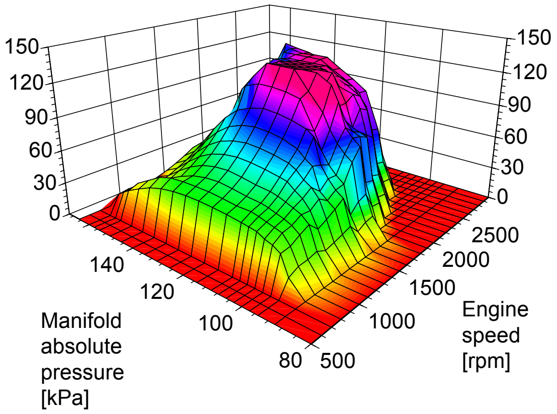


Fig. 8: the best replacement map. The map that will allow the engine to replace the maximum amount of diesel fuel

The map of the figure 8 is believed to be to provide more biogas to the engine at a wider load and speed range, because it does not take into consideration the fact that efficiency is reduced. On the other hand, it is clear that the biogas was limited at the very low and very high manifold pressures. The highest fuel injections happen to be when the engine is running at high speed and at middle to high load.

4. TESTING OF THE ALGORITHMS

4.1 Experiment setup

These two algorithms were tested in the field of the village of Ashoro. The tractor was used to harvest forages for feed for a dairy farm. The implements used with the tractor were consequently: mower conditioner, tedder, rake, roll-baler and finally broadcaster. For each implement, the tractor was run in three modes: best efficiency, best replacement and diesel only modes. Diesel and biogas consumption as well as other data were collected during the experiment. Table 1 states the various implements used in the field test in Ashoro and the load conditions of the tractor.

Table 1: description of implements and the load and engine speed they required from the tractor

Implement	Load	Engine speed [rpm]
Mower conditioner	High	2500
Tedder	Low	2200
Rake	Low	1800
Roll-baler	Variable	2200
Broadcaster	Low	2200

The items that were measured during the experiment are summarized in table 2.

Table 2: summary of data collection of field experiment

Parameter	Measuring means	Unit
Engine speed	Magnetic sensor	rpm
Manifold Pressure	MAP sensor	kPa

Throttle position	Variable resistor	%
Exhaust gas temp.	Thermocouple	℃
Biogas flow	Mass Air flow sensor	L/min
Diesel consumption	Fuel flow meter	L/hour

From the biogas flow and diesel consumptions, the authors calculated the total energy input to the engine as well as the biogas share of total energy input (replacement rate).

4.2 Heat Consumption

The energy consumption was calculated on hourly basis for each implement at each setting (diesel only, best efficiency and best replacement) the results are shown in figure 9.

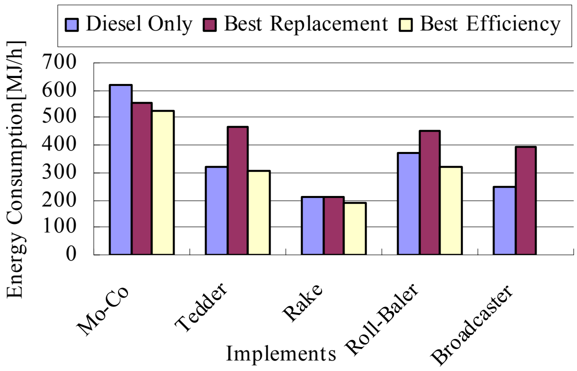


Fig. 9: Energy consumption in MJ/h for each implement at the three modes diesel only, best replacement and best efficiency

As compared to diesel only operation, figure 9 shows that the best replacement algorithm consistently increased the heat consumption of the engine except with the mower. This phenomenon was in fact expected because the amount of biogas injected was beyond the best efficiency points observed in figure 4. In fact the increase in heat consumption reached 31 and 36% for the tedder and broadcaster respectively. Nevertheless, when the mower was used, the load became very important and further injections of biogas were impeded by the occurrence of knock. This is why the heat consumption of the best replacement algorithm was lower than that of diesel.

As for the best efficiency, it is clear that the best results were those of the mower and the baler. The heat consumption of the tractor was reduced by 15 and 14% respectively. As for the tedder and the rake, the very low load requirement of these implement prohibited any biogas injection into the engine. In other words, and as figure 4 shows, any addition of biogas at low load tends to increase the engine's break specific heat consumption. This means that the engine was running solely on diesel even when the best efficiency algorithm was used.

A look at the replacement rates achieved during these experiments would help in better understanding the whole figure.

4.3 Replacement rate

Figure 10 shows the replacement rate achieved with the best replacement and best efficiency algorithms for the implements in consideration.

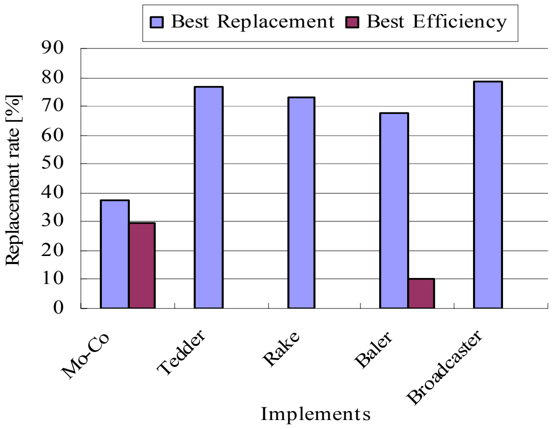


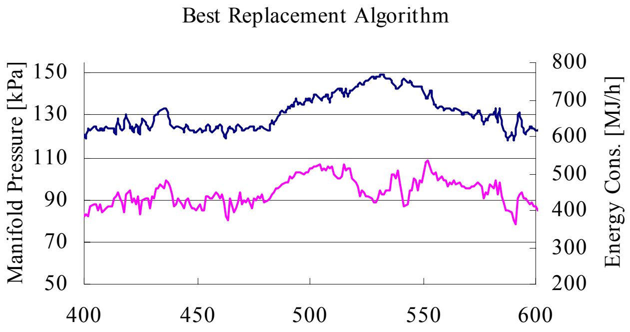
Fig. 10: Replacement rates achieved with the two algorithms and the 5 implements

The figure 10 proves that there was no biogas injection into the engine at the best efficiency algorithm and low load implements. These same implements however saw the highest replacement rates with the best replacement algorithm.

The results of the mower in figure 9 and 10 are interesting to see. In fact, as the load on the engine increases, the injector opening time decided by the best efficiency and best replacement algorithms converge towards one point. This is due to the fact knock occurs and prevents the addition of biogas beyond the best efficiency point.

4.4 Special case: the roll-baler

The load of the roll baler varied as the bale was formed. In fact the gradual pressure increase in the bale chamber gradually increases the load on the engine. This allowed better understanding of how the algorithms respond to the load change when the engine speed is fixed. It is also an important tool to compare between the behaviors of the two algorithms.



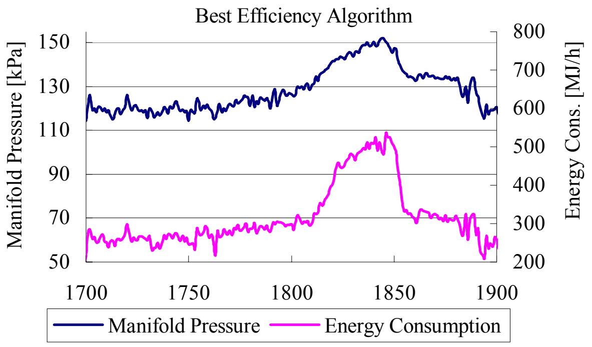


Fig. 11: Energy consumption change with engine load estimated by manifold pressure

Figure 11 shows how the total energy consumption of the engine grows with the engine load in the time series. In the best replacement algorithm, the total energy input is constantly high, and the increase in energy consumption between the high load and low load is only 10%. This energy increase is due to the extra diesel fuel usage caused by governor to keep the engine speed. With the best efficiency algorithm the difference between the high load and low load is more important and it amounts to about 41%. This is because the biogas injections are limited to where the engine's efficiency could be improved. It should be noted that the diesel only operation saw an increase of 46% in energy consumption.

Considering the evolution of biogas share of total energy input to the engine, the differences between the two algorithms are even clearer. Figure 12 compares between the evolution of the manifold pressure as an index of load with that of replacement rate.

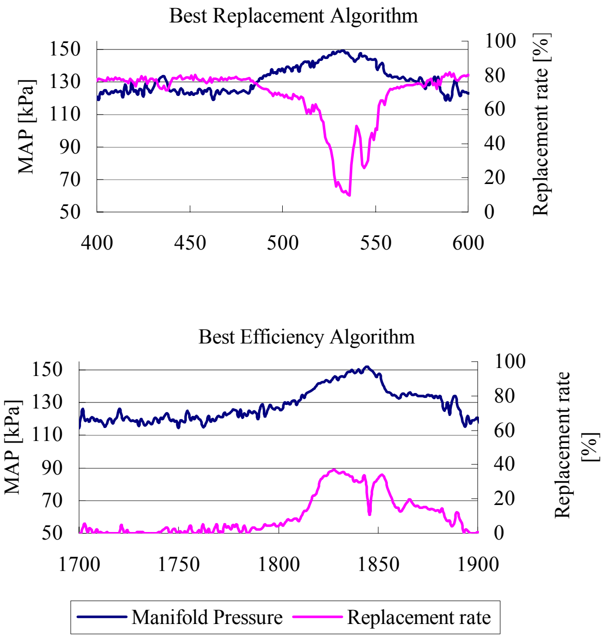


Fig. 12: the change in replacement rate with increase in load

Figure 12 shows that for the best replacement rate algorithm, the biogas flow decreases as the load increase beyond a certain limit. As said before this was a necessary precaution to prevent knock and thereafter engine wear. On the other hand, the best efficiency algorithm only fed biogas while engine was loaded. This is where an increase in engine's heat efficiency can be observed.

5. CONCLUSION

This research aimed at building a biogas tractor. An agricultural tractor was fitted with a biogas unit containing 4 cylinders of pure methane with the necessary pressure regulator and gas handling system. The biogas was injected into the intake manifold via computer controlled injectors. A study was then made to assess the effect of biogas addition to the engine, based on which two possible algorithms were created. The first algorithm aimed at replacing the maximum amount of diesel fuel while the other's goal was to run the engine at its minimum break specific heat efficiency point. The hardware and two algorithms were tested in the field in the village of Ashoro. The results showed that the both algorithms worked satisfactorily. A new algorithm based on the previous two is to be constructed and tested. Other performance parameters such as emissions could also be included in future series of experiments.

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