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Effect of engine load and biogas flow rate to the performance of a compression ignition engine run in dual-fuel (diesel-biogas) mode

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Abstract. The Government of Indonesia (GoI) has released a target on reduction Green Houses Gases emissions (GHG) by 26% from level business-as-usual by 2020, and the target can be up to 41% by international supports. In the energy sector, this target can be reached effectively by promoting fossil fuel replacement or blending with biofuel. One of the potential solutions is operating compression ignition (CI) engine in dual-fuel (diesel-biogas) mode. In this study effects of engine load and biogas flow rate on the performance and exhaust gas emissions of a compression ignition engine run in dual-fuel mode are investigated. In the present study, the used biogas is refined with methane content 70% of volume. The objectives are to explore the optimum operating condition of the CI engine run in dual-fuel mode. The experiments are performed on a four-strokes CI engine with rated output power of 4.41 kW. The engine is tested at constant speed 1500 rpm. The engine load varied from 600W to 1500W and biogas flow rate varied from 0 L/min to 6 L/min. The results show brake thermal efficiency of the engine run in dual-fuel mode is better than pure diesel mode if the biogas flow rates are 2 L/min and 4 L/min. It is recommended to operate the present engine in a dual-fuel mode with biogas flow rate of 4 L/min. The consumption of diesel fuel can be replaced up to 50%.

1. Introduction

Greenhouse Gases (GHGs) emissions will be a significant problem for the world in supporting life on it. To avoid the world from the catastrophe, many countries have committed to reducing their emissions. The Government of Indonesia (GoI) has released its target on reducing GHG emissions by 26% from level business as usual (BAU) by 2020, and it can be increased up to 41% by international aid [1]. The source of GHG emissions can be divided into four sectors; they are agriculture, energy, land use, land-use change and forestry (LULUCF), and waste sectors. In the energy sector, the emission sources are all activities that burn fossil fuel. In Indonesia, energy sector contributes significant GHG emissions [2]. In specific, the activities that burn fossil fuel using internal combustion (IC) engines to produce power are important in emission reduction actions. Thus, reducing fuel consumption in the IC engines will reduce GHG emissions significantly. Also, in Indonesia, fossil fuel (gasoline, diesel, kerosene) is subsidized, and it is a burden for the GoI budget. These facts suggest that reducing fuel consumption of IC engines will give significant impacts on mitigation GHG emissions and it will help the GoI in reducing fossil fuel subsidy.

Due to the thermodynamic principle of IC engines and the Carnot cycle limit, the emission target can only be achieved with fuel change or blending with biofuel such as biogas. The biogas is produced from anaerobic biodegradation of organic material. Such materials are easily found in the remote area. It consists of methane typically ranges from 40 - 70% and its low heating value are between 15 and 30 MJ/m^3. The IC engines, mostly, can be divided into spark ignition (SI) engines and compression ignition (CI) engines. The CI engines are mainly used in heavy machineries such as a truck, agricultural engines, marine, and power plants. In other word, CI engines are usually used in the remote areas. Considering that biogas is mostly present in the remote areas, thus, fueling CI engines with biogas is a perfect solution for reducing GHG emission. Two methods that can be used to run CI engine with biogas. The first one is by converting the CI engine into SI engine and run on pure biogas. The second one is dual-fuel mode. In this mode, after compression of the charge comprised of biogas and air, a small amount of diesel, called the pilot is injected. This injected pilot fuel gets self-ignited and then becomes the ignition source for the inducted biogas. The main advantage of dual-fuel CI engines is that they can work with a wide variety of gaseous fuels without engine modifications [3].

Study on CI engine run in dual-fuel mode has come under scrutiny in recent year. Ambarita et al. [4] reported a study on the performance and emissions of small CI engine run in dual-fuel mode by using raw biogas with a methane content of 60%. The effect of biogas flow rate is investigated. It was shown that the CI engine without any significant modification can be operated in a dual-fuel mode with raw biogas and diesel oil consumption can be replaced up to 87.5%. In addition, Ambarita et al. [5] reported a study on combustion simulation of a CI engine run in a dual-fuel mode using CFD code. The numerical results and experimental ones show a good agreement. Feroskhan et al. [6] investigate the effects of biogas flow rate and cerium oxide addition on the performance of a dual fuel CI engine. The biogas flow rate and cerium oxide as a diesel additive were investigated. It was found that operating a conventional CI engine on dual fuel mode with biogas flow rate up to 8 L/min improve brake thermal efficiency at high load. The biogas can replace the diesel fuel consumption up to 80%. Cerium oxide affects the brake thermal efficiency, the combination of biogas flow rate 4 L/min and 25 mg/L Cerium oxide give the highest brake thermal efficiency. Rahman and Ramesh [7] studied the effect of reducing methane concentration on the combustion and performance of biogas diesel predominantly premixed charge CI engine. Three biogas compositions with methane proportions of 53 – 58% (raw biogas), 67% (refined), and 22 - 25% (less methane) were tested at constant engine speed of 1800 rpm. Result indicate that extremely low levels of NO and smoke can be reached in the engine at the best efficiency operating condition if the biogas composition is altered based on the output. Verma et al [8] investigated the effect of varying composition of biogas on performance and emission characteristics of compression ignition engine using exergy analysis. Three different composition of biogas are tested, they are 93%, 84%, and 75% of methane by volume. The results show that biogas can substitute 80 – 90% diesel fuel at lower engine loads.

The above literatures show that study on the effect of operational conditions such as biogas flow rate, methane concentration in biogas, and additive in the diesel fuel to the performance of the CI engine have been carried out by several researchers. Those parameters show the strong effect to the performance of the CI engine run in dual-fuel mode. Recently, Ambarita [9] investigated the optimum operational condition of the CI engine run in dual-fuel mode. The results show that brake thermal efficiency of the CI engine run on dual-fuel mode strongly affected by biogas flow rate and methane concentration. And there exist an optimum biogas flow rate for a maximum brake thermal efficiency. It was suggested to operate a CI engine at the optimum flow rate. In this study effect of the engine load and biogas flow rate of the biogas to the performance will be investigate. The main objectives are to explore the optimum operational condition of a CI engine run on dual-fuel mode. The results are expected to supply the necessary information on development of alternative solutions for reducing diesel oil consumption in CI engines.

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2. Method

In order to carry out the study, a CI engine which typically used in a small tractor for agricultural work is used in the experiment. The specifications of the CI engine are presented in Table 1. It is an air cooled, single-cylinder four stroke CI engine fueled by diesel fuel. The maximum output power of the engine is 4.86 W. It is categorized as a small engine with and typically found in small Indonesian farmer.

Table 1. Specification of the CI engine

No	Parameter	Value
1	Commercial name/model	Tiger Diesel Engine R175 AN
2	Number of cylinder/stroke	Single-cylinder/4 strokes and Horizontal
3	Cooling system	Naturally air cooled
4	Bore × Stroke	75 mm × 80 mm
5	Maximum output	4.86 kW
6	Rated output	4.41 kW
7	Rated speed	2600 rpm
8	Engine weight	60 kg

In order to simulate the load, the engine is coupled with a single phase synchronous generator using pulley. The experimental apparatus is shown in Figure 1. To perform experiment, several additional equipments are installed to the experimental apparatus such as a series of lamps, biogas tank, gas mixer, and measurements apparatus. In single fuel mode (pure diesel oil only) the CI engine will be tested without modification. In dual-fuel mode, a gas mixer has been designed and developed in order to mix the fresh air with biogas. The mixture of the fresh air and biogas will be injected into the CI engine.

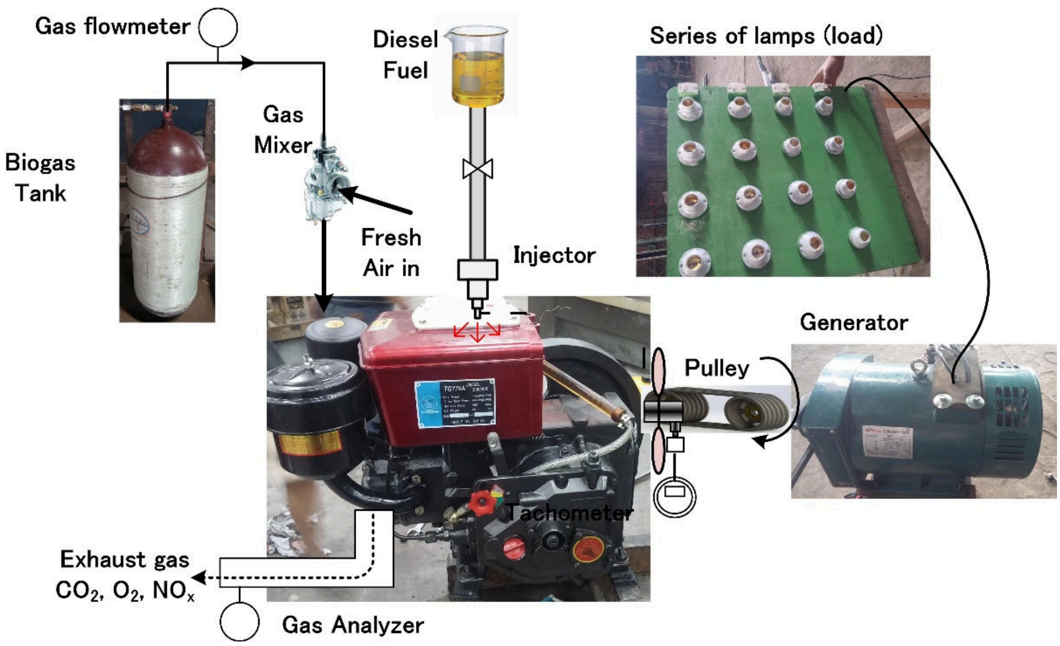

Figure 1. Experimental apparatus

The used generator has the following specification. The maximum power, rating frequency, and rating voltage of the generator are 3 kVA, 50/60 Hz, and 115-230 V, respectively. A series of lamps are used as a load for generator. The load can be operated at load 600W, 900W, 1200W, and 1500W. The biogas is stored in a tank. It is designed and fabricated to store the raw biogas until pressure 20 bar. As a note, Indonesia is known as a biggest produce of Palm Oil in the world [10]. The present biogas is produced from anaerobic biodegradation of Palm oil mill effluent. The effluent is taken from a mill located in Rambutan about 80 km from Medan city and it is operated by PTPN III (state owned plantation III). In this study, the biogas is refined to a higher composition of methane content. The composition of the present biogas consists of CH_4 70% and CO_2 30% of volume. This composition according to Gas Chromatography test. The low heating value (LHV) of the biogas is 20.56 MJ/kg. The diesel oil is purchased from PERTAMINA the government oil retailer in Indonesia. Before used, the LHV of the diesel oil is tested. The LHV is 42.64 MJ/kg.

The characteristics of the exhaust gas are investigated using parameter opacity, HC, and CO number. These parameters are measured using Gas Analyser and engine smoke meter. The model of the engine smoke meter is HD-410. Measuring range, absorption coefficient, oil temperature, and operation temperature of the smoke meter are 0.00-100%, 0.00 - 21.42 m^{-1}, 0 - 800 rpm, 0 - 100ºC, and of -10ºC - 40ºC, respectively. The model of Gas Analyzer is HG-510. The specifications of the Gas Analyser are as follows. Measuring range of CO and HC are 0-9.99% and 0-9999 ppm, respectively. The operating temperature, power, and serial number are -10ºC - 40ºC, 220V, and 2G9C0101, respectively. Thermometer type of KW 06-278 Krishbow is used to measure the temperature. It's accuracy range is $\pm$ 0.5% $\pm$ 1ºC. The load, electricity resulted by generator, is measured using a Multitaster Meter CD800A. The engine speed is measured using Tachometer.

The experiments are performed in two modes. In the first mode, the CI engine is operated with diesel fuel and named as pure diesel. In this mode, the load is varied from 600 W to 1500 W and engine speed is fixed at 1500 rpm. When the CI engine is stable, the measurement is carried out for 5 minutes for every load. The second mode, the CI engine is operated in the dual-fuel mode, when the CI engine is operated, the biogas from the tank is mixed with the fresh air in the mixer. The pressure of the biogas from the tank is decreased to 1.8 bar by using gas regulator. The flow rate of the biogas is varied from 2 to 6 Litre /minute (L/min). For every biogas flow rate, the load is varied and the speed is adjusted to get constant speed. The same measurements with the pure diesel are performed. Every test is replied for three times and the measurement is averaged.

2.1. Problem formulation

The measured data will be analyzed using several parameters. The performance of the engine will be analyzed using output power, brake thermal efficiency, and specific fuel consumption. The output power P_E (Watt) of the CI engine is calculated by using the following equation

$$P_E = V \times I \tag{1}$$

where V [Volt] and I [Ampere] are voltage and current electricity resulted by the generator, respectively. In the experiment, these parameters are measured using the Multitester Meter. Brake thermal efficiency is defined as electric power resulted by the generator divided by total energy input to the CI engine. For pure diesel mode, brake thermal efficiency is calculated by

$$\eta = \frac{P_E}{\dot{m}_{diesel} \times H_{diesel}} \tag{2}$$

where H_{diesel} is the diesel heating value in kJ/kg. While for dual-fuel mode, the brake thermal efficiency is given by

$$\eta = \frac{P_E}{\dot{m}_{dual} \times H_{diesel} + \dot{m}_{biogas} \times H_{biogas}} \tag{3}$$

Specific fuel consumption sfc [kg/kWh] is a comparison of fuel consumption to the useful energy resulted by the CI engine. Since the useful energy here is the electricity, the specific fuel consumption can be viewed as how many kilograms of fuel is needed to result 1 kWh of electrical energy. When the CI engine run in pure diesel mode, it is given by:

$$sfc = \frac{\dot{m}_{diesel} \times 10^3}{P_E} \tag{4}$$

In the case of dual-fuel mode, the fuel is defined as the total sum of diesel and biogas. The *sfc* will be given by:

$$sfc = \frac{\left(\dot{m}_{dual} + \dot{m}_{biogas}\right) \times 10^3}{P_E} \tag{5}$$

The objective of introducing biogas into the engine is to reduce the diesel fuel consumption. The biogas is used to replace diesel fuel. The percentage of diesel fuel replaced by the biogas is calculated, the replacement ratio [r] is calculated by

$$r = \frac{\dot{m}_{diesel} - \dot{m}_{dual}}{\dot{m}_{diesel}} \times 100\% \tag{6}$$

where $\dot{m}_{diesel}$ (kg/s) is the diesel mass flow rate when the engine is operated in pure diesel mode and $\dot{m}_{dual}$ (kg/s) is the diesel mass flow rate when the engine is operate in dual-fuel mode. Using the above formulated parameters, the performance of the CI engine will be analyzed.

3. Results and Discussions

3.1. Output power

Figure 2 shows the output power of the CI engine as a function of engine load. As a note, the load is varied from 600 W, 900W, 1200W, and 1500W, respectively. For every load, the engine speed is kept constant at 1500 rpm. It can be seen that the output power of the CI engine run in dual-fuel mode is higher than the CI engine run in pure diesel mode. This occurs for all biogas flow rate. There is no significant different of the biogas flow rate to the output power. In other words, the output power shown by the CI engine run in dual-fuel mode with biogas flow rate of 2 L/min is similar with the engine with biogas flow rate 4 L/min and 6 L/min. This is because the input energy to combustion chamber of the CI engine in dual-fuel mode is relatively higher than pure diesel mode. This fact suggest that in term of output power, the CI engine run in dual-fuel mode is better than pure diesel mode.

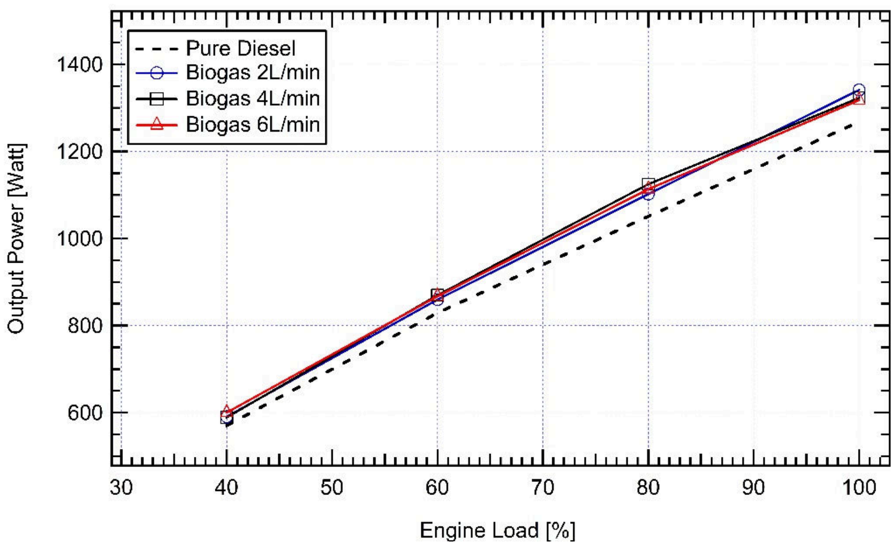

Figure 2. Output power of the CI engine at load engine speed 1500 rpm

3.2. Specific fuel consumption

The specific fuel consumption (*sfc*) as a function of output power is shown in Fig 3. In this case the engine speed is fixed at 1500 rpm. The specific fuel consumption can be viewed as a parameter to show how effective a power generation system to convert an amount of fuel into electrical energy. The lower *sfc* is the better. It can be seen that for all cases, *sfc* decreases as output power increases. This fact suggests that combustion process is better when the CI engine is loaded with high engine load. The effect of biogas flow rate to the *sfc* is clearly shown in the figure. The *sfc* is higher when the CI engine run in dual-fuel mode, in comparison with pure diesel mode. This is because all of the biogas is counted as a fuel. In fact, only 70% of the biogas is methane which content heat energy. This makes the *sfc* of the CI engine run in dual-fuel mode is higher than pure diesel mode. Furthermore, increasing biogas flow rate will increase the *sfc*. Again, this is because CO_2 without energy content is counted as fuel.

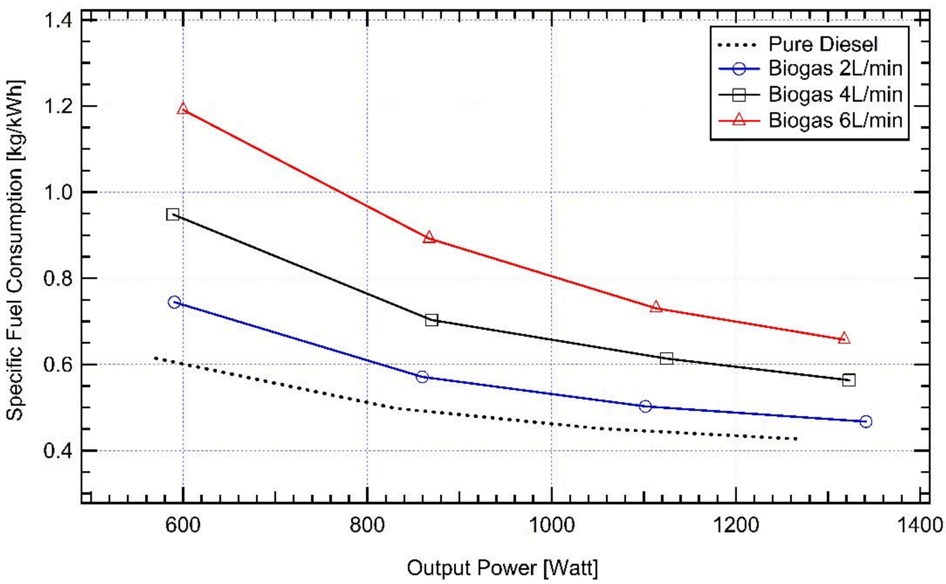

Figure 3. Power vs specific fuel consumption at constant engine speed 1500 rpm

3.3. Brake thermal efficiency

Figure 4 shows brake thermal efficiency of the present CI engine as a function of output power at constant speed of 1500 rpm. It can be seen from the figure that the brake thermal efficiency increases with output power. However, at higher loads the increasing rate of the brake thermal efficiency is decreased. This is because the present CI engine is operated below its maximum rated power. The effect of biogas flow rate to brake thermal efficiency is shown clearly in the figure. Increasing biogas from 2 L/min to 4 L/min will increase the brake thermal efficiency in comparison with CI engine run in pure diesel mode. However, increasing the biogas flow rate to 6 L/min will make the brake thermal efficiency lower than pure diesel mode. It is suggested to operate the present CI engine in dual-fuel mode with flow rate of biogas 2 – 4 L/min.

3.4. Exhaust gas emission

Table 2 shows emissions characteristics of the CI engine run in dual-fuel mode in comparison with pure diesel mode. The opacity numbers show that the CI engine run in dual fuel mode decrease the smoke content in the exhaust gas. The effect of biogas flow rate to the opacity of the exhaust gas can be examined using the table. Increasing biogas flow rate will decrease the opacity number. In the exhaust gas, higher CO related to less effective combustion process in the combustion chamber. In the CI engine run in pure diesel mode, CO number is very low. This is because the engine originally designed for pure diesel mode. Injecting biogas to the engine will decrease fresh air in the combustion chamber. This results in higher CO in the exhaust gas. Increasing biogas flow rate, slightly increases the CO number. The HC number in the exhaust gas related to unburnt fuel that is injected to the combustion chamber. As expected, HC number of the exhaust gas in the CI engine run in dual fuel mode is higher than pure diesel mode. This is because injecting biogas to the CI engine makes more fuel or HC in the combustion chamber. Since not all of the fuel burnt in the combustion chamber, HC number of the exhaust gas will increase. The HC number increases as biogas flow rate increases.

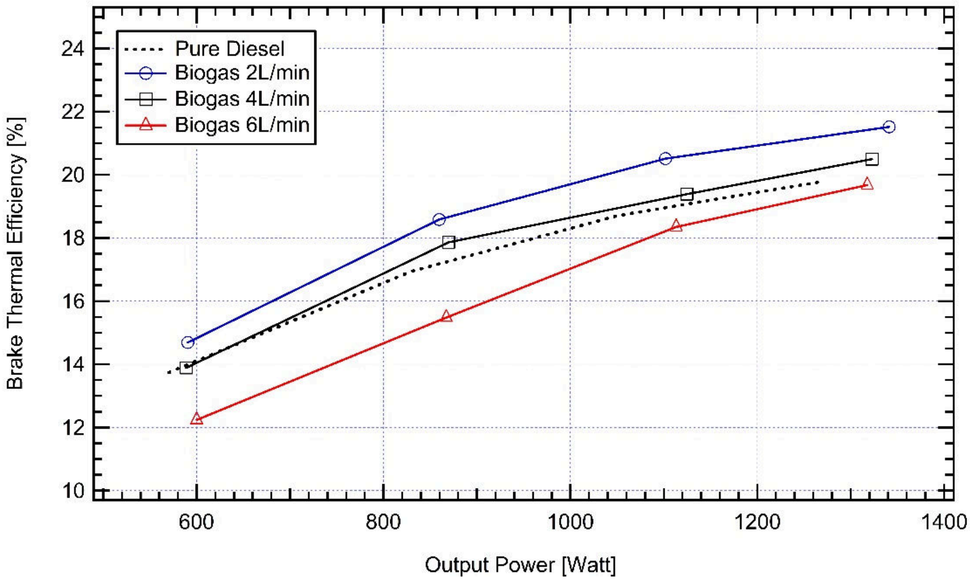

Figure 4. Brake thermal efficiency at constant engine speed 1500 rpm

Table 2. Emissions characteristics of the CI engine

Engine Load [W]	Pure diesel	Biogas 2L/min	Biogas 4L/min	Biogas 6L/min
		OPC Number		
600	13.5	9.0	3.2	1.3
900	26.1	13.9	7.0	6.6
1200	48.8	37.2	10.3	8.9
1500	60.9	64.5	30.2	12.8
		CO number [%]		
600	0.02	0.11	0.16	0.17
900	0.02	0.10	0.13	0.16
1200	0.03	0.08	0.12	0.15
1500	0.03	0.10	0.12	0.17
		HC number [ppm]		
600	6	190	273	325
900	6	176	220	295
1200	6	132	206	251
1500	8	126	173	215

3.5. Diesel replacement ratio

Figure 5 shows Diesel Replacement Ration (DRR) of the CI engine run in dual-fuel mode. When the engine run in single fuel mode, DRR is zero. When the CI engine run in dual-fuel mode the DRR varies from 30% to 20% and it decreases as output power increases. The same trend also shown by the cases with biogas flow rate 4 L/min and flow rate 6 L/min. As expected, increasing biogas flow rate increases DRR. However, the rate of growth is decreased. This suggested that it will be less effective increase the biogas flow rate more than 6 L/min.

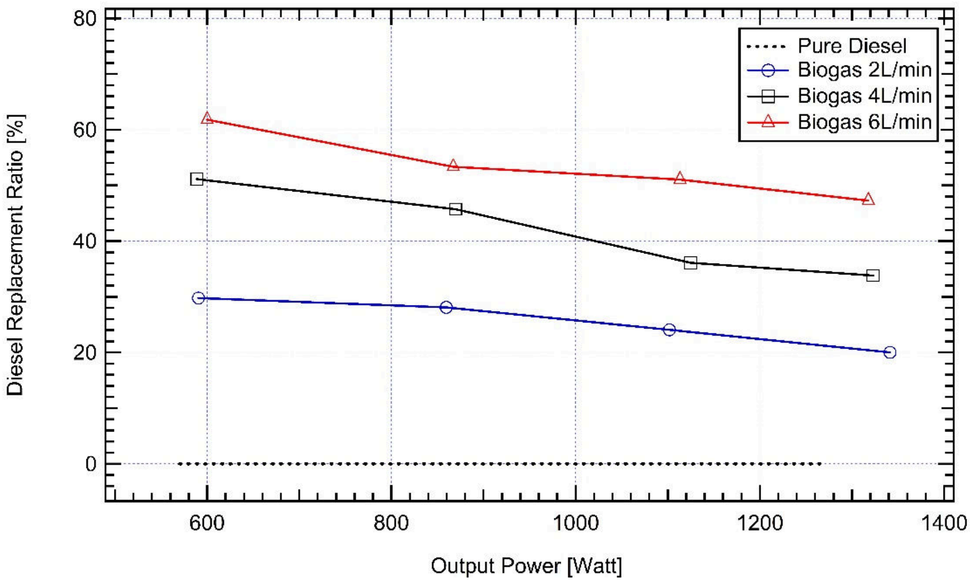

Figure 5. Diesel replacement ratio at 1500 rpm

4. Conclusions

A CI engine with rated power of 4.4 kW has been tested on pure diesel and dual-fuel mode with refined biogas. The methane content of the biogas is 70%. The engine was tested at constant speed 1500 rpm while the load varies from 600 to 1500W. The conclusions are as follows. The output power of the CI engine run in dual-fuel mode is higher than pure diesel mode. Brake thermal efficiency of the CI engine run in dual-fuel mode is better than pure diesel mode if the biogas flow rates are 2 L/min and 4 L/min. The exhaust gas analysis shows biogas reducing opacity of the exhaust gas. On the other hand, the HC number of the engine run in dual-fuel mode is very high in comparison with pure diesel mode. It is recommended to operate the present engine in dual-fuel mode with biogas flow rate of 4 L/min. The consumption of diesel fuel can be replaced up to 50%.

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