Performance and Emissions of a Small Compression Ignition Engine Run on Dual-fuel Mode (Diesel-Raw biogas)

H Ambarita	extsuperscript{1*}, E P Sinulingga	extsuperscript{2}, M KM Nasution	extsuperscript{3}, H Kawai	extsuperscript{4}

	extsuperscript{1}Sustainable Energy Research Centre, Faculty of Engineering University of Sumatera Utara, Jl. Almamater Kampus USU Medan 20155, Indonesia

	extsuperscript{2}Electrical Engineering, Faculty of Engineering University of Sumatera Utara, Jl. Almamater Kampus USU Medan 20155, Indonesia

	extsuperscript{3}Information Technology Department, Fasilkom-TI University of Sumatera Utara, Jl. Universitas Padang Bulan 20155, Indonesia

	extsuperscript{4}Mechanical Engineering, Mуроран Institute of Technology, 27-1 Mizumotocho, Mуроран Hokkaido 050-0071, Japan

*himsar@usu.ac.id

Abstract. In this work, a compression ignition (CI) engine is tested in dual-fuel mode (Diesel-Raw biogas). The objective is to examine the performance and emission characteristics of the engine when some of the diesel oil is replaced by biogas. The specifications of the CI engine are air cooled single horizontal cylinder, four strokes, and maximum output power of 4.86 kW. It is coupled with a synchronous three phase generator. The load, engine revolution, and biogas flow rate are varied from 600 W to 1500 W, 1000 rpm to 1500 rpm, 0 to 6 L/minute, respectively. The electric power, specific fuel consumption, thermal efficiency, gas emission, and diesel replacement ratio are analyzed. The results show that there is no significant difference of the power resulted by CI run on dual-fuel mode in comparison with pure diesel mode. However, the specific fuel consumption and efficiency decrease significantly as biogas flow rate increases. On the other hand, emission of the engine on dual-fuel mode is better. The main conclusion can be drawn is that CI engine without significant modification can be operated perfectly in dual-fuel mode and diesel oil consumption can be decreased up to 87.5%.

1. Introduction
In order to avoid the world from the Global Warming, many countries have committed on reducing their Green Houses Gases (GHGs) 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]. Energy is one of the biggest sectors that contribute to GHGs emissions of Indonesia [2]. This includes activities that burn fossil fuel using engines in order to produce power. In Indonesia, the main consumption of fossil fuel is diesel oil which is used in Compression Ignition (CI) engines [3]. The CI engines are mainly used in heavy machineries such as truck, agricultural engines, marine, and power plants. Thus, reducing diesel oil consumption will
reduce GHGs emissions significantly. On the other hand, in Indonesia fossil fuel (gasoline, diesel, kerosene) is still subsidized and it becomes a load for the GoI budget. These facts suggest that reducing diesel oil consumption in CI engines will give a significant impact on mitigation GHG emissions and it will help the GoI in reducing fossil fuel subsidy.

Due to thermodynamic principle of combustion engines and the Carnot cycle limit, the emission target can only be achieved with fuel change or blending with biofuel such as biogas. Biogas is produced from anaerobic biodegradation of organic material. It consists of methane typically ranges from 40 - 70% and its low heating value is between 15 and 30 MJ/Nm³. There are two methodologies that can be used to run CI engines with biogas. The first methodology is converting the CI engine into pure biogas engine and the second one is dual-fuel mode (diesel-biogas). In the CI engine with dual-fuel 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 [4]. Here, CI engine run on dual-fuel mode is investigated.

Several studies on CI engine run on dual-fuel mode have been found in literature. Bedoya et al [5] reported a study on the effect of mixing system and pilot fuel quality on diesel-biogas dual-fuel engine performance. The simulated biogas (60% CH₄-40%CO₂) as primary fuel, and diesel and palm oil biodiesel as pilot fuel. Cacua et al [6] studied experimentally the effects of oxygen enriched air on the operation and performance of a diesel-biogas dual-fuel engine. The biogas composition was 60% CH₄ - 40% CO₂ and the oxygen concentration in the intake air engine was varied from 21 to 27% O₂. Tippayong et al [7] carried out a study on electricity production for on-farm using a small CI dual-fuel diesel-biogas. The main objective was to evaluate the effect of long-term operation on performance and wear of the dual-fuel engine. The composition of the biogas was 65.6% CH₄ and 26.4% CO₂. The CI engine was tested for 2000 hours of operation. The dual-fuel engine appeared to perform well and have great potential for use on-farm energy utilization. Makareviciene et al [8] explored the impacts of CH₄ compositions in a big CI four stoke and four-cylinders engine when operated under dual-fuel biogas-diesel mode. The composition of CH₄ in biogas varied from 65%, 85%, and 95%. The impact of exhaust gas recirculation (EGR) was also explored. Tonkunya and Wongwuttanasatian [9] reported a study on the utilization of biogas-diesel mixture as fuel in a fertilizer pelletizing machine for reduction of GHG emission in small farms. In the experiment the rated power of the CI engine and the composition of the biogas were not reported. The results showed that by using biogas as dual-fuel mode in the CI engine, a reduction in diesel fuel of 63% was achieved. This result was equivalent to 13 ton CO₂e/year/farm in Thailand case. Nathan et al [10] performed an experimental study on the biogas-biodiesel HCCI mode of engine operation. The objective was to investigate the potential of the HCCI concept to utilize biogas effectively.

The above literatures show that study on CI engine run on dual-fuel mode in order to decrease the fossil fuel has come under scrutiny. Several modifications have been proposed such as the effects of mixing system, oxygen enrichment of the inlet air, compression ratio, long-term operation, etc. In particular, in the remote areas technical support is minimum and only raw biogas is present. In these such areas, the CI engine should be operated with raw biogas without significant modification. To the best knowledge of the author, study on CI engine without modification run on raw biogas has not found in literature. In this study the performance and emission characteristics of a small CI engine run on dual-fuel mode (Diesel-Raw Biogas) will be investigated experimentally. The main objective here is to explore the performance characteristics of the CI engine if it is fueled by dual-fuel (Diesel-Raw Biogas). The results are expected to supply the necessary information on development of alternative solutions for reducing diesel oil consumption in CI engines.

2. Method
In this study a CI engine which is originally used in a small tractor for agricultural will be tested in the experimental apparatus. The specifications of the CI engine are presented in Table 1. It is a single-
cylinder four stroke CI engine fueled by diesel oil. This engine has a maximum output power of 4.86 W. It is a small engine with a weight of 60 kg and typically found in Indonesian small 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                 | 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                                                                |
| 9  | Commercial name/model          | Tiger Diesel Engine R175 AN                                           |

2.1. Experimental apparatus

In order to perform the study, an experimental apparatus has been designed and developed as shown in Figure 1. It consists of a unit of CI engine, generator, 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. To simulate the load, the CI engine will be coupled with a single phase synchronous generator using pulley.

![Figure 1. Experimental apparatus](image)

The specifications of the generator are as follows. The rating frequency is 50/60 Hz, Rating Voltage is 115-230, and Maximum power of 3 kVA. The electricity from the generator will be used to light a series of lamps which can be operated at load 600W, 900W, 1200W, and 1500W. A tank is designed and fabricated to store the raw biogas. 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). The composition of the resulted biogas is tested by using Gas Chromatography, it consists of CH₄ 60% and CO₂ 40% of
volume. The low heating value (LHV) of the biogas is 17.69 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 measured using engine smoke meter for opacity and gas analyzer for HC and CO. The model of the engine smoke meter is HD-410 with main specifications are as follows. The measuring range, absorption coefficient, oil temperature, and operation temperature are 0.00-100%, 0.00 - 21.42 m$^{-1}$, 0 - 800 rpm, 0 - 100°C, and of -10°C - 40°C, respectively. The model of Gas Analyzer is HG-510 with specifications measuring range of CO and HC are 0-9.99% and 0-9999 ppm, respectively. The operating temperature, power, and serial number are -10°C - 40°C, 220V, and 2G9C0101, respectively. The temperature is measured using thermometer type of KW 06-278 Krishbow with an accuracy range of ±0.5% ± 1°C. The load of electricity is measured using a Multitester Meter CD800A. The revolution speed of the CI engine is measured using Tachometer.

The experiments are performed in two modes. In the first mode the CI engine is run on pure diesel. Here the load is varied from 600 W to 1500 W and engine speed varied from 1000 rpm to 1500 rpm. For every load and speed, when the CI engine is stable, the measurement is carried out for 5 minutes. In the dual-fuel mode (named as DF), 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 flowrate the load and the engine speed are varied. The same measurements with the pure diesel are performed. Thus, a total of 96 experiments have been carried out. Every test is replied for three times and the measurement is averaged.

2.2. Problem formulation
In order to perform the analysis, several parameters are used and formulated here. The objective of introducing biogas into the engine is to reduce the diesel mass flow rate in comparison with single diesel mode. In order to present the percentage of diesel fuel replaced by the biogas, the replacement ratio \( r \) is calculated by

\[
r = \frac{m_{\text{diesel}} - m_{\text{dual}}}{m_{\text{diesel}}} \times 100\%\]  

(1)

where \( m_{\text{diesel}} \) (kg/s) is the diesel mass flow rate in diesel mode and \( m_{\text{dual}} \) (kg/s) is the diesel mass flow rate in dual-fuel mode.

The performance of the engine will be analyzed using the electric power output, efficiency and specific fuel consumption. These parameters are explained as follows. The output power \( P_E \) (Watt) of the CI engine is calculated by using the following equation

\[
P_E = V \times I\]  

(2)

where \( V \) [Volt] and \( I \) [Ampere] are voltage and current resulted by the generator, respectively. These parameters are measured using the Multitester Meter. Here the efficiency is defined as electric power resulted divided by total energy input to the CI engine. For diesel operation mode, it is calculated by

\[
\eta = \frac{P_E}{m_{\text{diesel}} \times H_{\text{diesel}}}\]  

(3)

where \( H_{\text{diesel}} \) is the diesel heating value in kJ/kg. While for dual fuel operation, the efficiency is calculated by

\[
\eta = \frac{P_E}{m_{\text{dual}} \times H_{\text{diesel}} + m_{\text{biogas}} \times H_{\text{biogas}}}\]  

(4)
The specific fuel consumption $sfc$ [g/kWh] is a comparison of fuel consumption to the useful energy. Here, it can be viewed as how many gram of fuel is needed to result 1 kWh of electrical energy. For diesel operation mode, it can be calculated as:

$$sfc = \frac{m_{\text{diesel}} \times 10^3}{P_E}$$

While for dual-fuel mode it is defined as:

$$sfc = \frac{(m_{\text{dual}} + m_{\text{biogas}}) \times 10^3}{P_E}$$

Using the above formulated parameters, the performance of the CI engine will be analyzed.

3. Results and Discussions
The results will be discussed in 5 subsections, they are output power, total efficiency, specific fuel consumption, exhaust gas emission, and diesel replacement ratio

3.1. Output power
Here, the output power is defined as the electric power resulted by the generator. The voltage and the current are measured and the electric power is calculated using equation (1). The electric power as a function of engine rotation speed is shown in Figure 2. The load is fixed at 1500 W. The figure shows that for all cases the output power increases as the engine speed increases. The output power of the CI engine run on dual-fuel is slightly higher than pure diesel at the same speed. The results from other loads show the same trend. It can be said that CI engine can be run on dual-fuel mode perfectly and shows a better output power in comparison with pure diesel.

![Figure 2. Output power of the CI engine at load 1500 W](image)

3.2. Specific fuel consumption
The specific fuel consumptions for pure diesel and dual-fuel mode are calculated using equation (5) and equation (6), respectively. 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. Figure 3 shows that, for all cases, $sfc$ decreases as power increases. The engine run on pure diesel shows the lowest $sfc$ in comparison with dual-fuel engine. By injecting biogas to the CI means adding the fuel consumption. As a note, raw biogas is used in the present study, concentration of methane gas, which contain energy, is only 60%. This is the reason why the specific fuel consumption of the CI engine run on dual-fuel significantly higher than CI run on pure diesel. In addition, a higher biogas flow rate shows a higher specific fuel consumption.

![Figure 3. Power vs specific fuel consumption at constant engine speed 1500 rpm](image)

3.3. Efficiency
As a note, the calculated efficiency in this study is different from thermal efficiency. In the thermal efficiency, the output will be measured as brake power. Here, the efficiency is calculated using the electric output power from the generator and shown in Figure 4. In general, the figure shows that efficiency increases as engine speed increases. However, at higher speed the increasing rate of efficiency decreases. This suggests that there will be a maximum efficiency. It can be seen that efficiency for pure diesel always higher than for that engine run on biogas. This is because biogas in the combustion chamber is not burn perfectly.
There are two main reasons on the lower efficiency of CI engine run on dual-fuel in comparison with it run on diesel only. The first reason is that poorer combustion process and the second one is more energy input within the biogas. In the present biogas there is 40% of CO$_2$. This will decrease the concentration of oxygen which leads to poorer combustion process. Cacua et al [7] suggested that oxygen enriched air will increase efficiency in the CI engine run on dual-fuel.

3.4. Exhaust gas emission
The decreasing efficiency can be explained by examining characteristics of the exhaust gas emission as shown in Table 2. In the table, emissions characteristics for pure diesel and for dual-fuel cases are shown at load 600W and at load 1500W, respectively. As a note opacity number shows opaqueness of the exhaust gas. The highest opacity is shown by IC engine run on pure diesel. The opacity decreases as biogas flow rate increase. The lowest opacity number shown by dual-fuel at biogas flow rate 6L/minute. This is because the biogas has no particulate that can make exhaust gas opaque. In other word, more biogas makes the exhaust gas more clear. The CO number shows the content of CO in the exhaust gas. A high CO number means that combustion of fuel in combustion chamber is not perfect. The lowest CO number is shown by pure diesel fuel. CO number increases as flow rate of biogas increases. The content of CO$_2$ in the biogas makes the percentage of O$_2$, which is needed for combustion, decrease. Thus, CI engine run on dual-fuel mode shows a high CO number in the exhaust gas due to the poorer combustion process. Characteristics of combustion process in the combustion chamber can be shown by HC number. A high HC number shows that combustion is not perfect. The lowest HC number is shown by CI engine run on pure diesel. HC number increases as flow rate of the biogas increases. This is because the combustion process in the combustion chamber is not perfect as the biogas contains CO$_2$. These facts reveal that the present of CO$_2$ leads to poorer combustion. This also make the CH$_4$ in combustion chamber becoming less effective. This supports the reason of decreasing efficiency as discussed in the previous subsection.
Table 2. Emissions characteristics of the CI engine

| Fuel                  | Emission Parameters | OPC [%] | CO [%] | HC [ppm] |
|-----------------------|---------------------|---------|--------|----------|
|                       | At Load 600 W       |         |        |          |
| Pure Diesel           | 13.5                | 0.02    | 6      |
| DF Biogas 2 L/min     | 5.1                 | 0.11    | 200    |
| DF Biogas 4 L/min     | 8.9                 | 0.15    | 264    |
| DF Biogas 6 L/min     | 7.6                 | 0.16    | 290    |
|                       | At Load 1500 W      |         |        |          |
| Pure Diesel           | 60.9                | 0.03    | 8      |
| DF Biogas 2 L/min     | 34.5                | 0.09    | 117    |
| DF Biogas 4 L/min     | 32.2                | 0.12    | 172    |
| DF Biogas 6 L/min     | 22.4                | 0.12    | 182    |

3.5. Diesel replacement ratio

The main objective of using biogas in the CI engine is to decrease the diesel consumption by replacing it with biogas. Diesel oil replacement ratio for the CI engine run on dual-fuel at 1500 rpm is shown in Figure 5. The figure shows that the ratio decreases as power increases. This is because at higher output power the injector of the CI engine still supplies more fuel into the combustion chamber. As a note, in this study the injector is not modified to accommodate the energy input from the biogas flow into the combustion chamber. As expected, the higher biogas flow rate results in the higher diesel replacement ratio. In the cases with speed of 1500 rpm, the highest replacement ratio is 69.2% shown by CI engine run on dual-fuel with flow rate 6 L/min. The lowest replacement ratio is 15.2%, shown by biogas flow rate of 2 L/min.

![Figure 5. Diesel replacement ratio at 1500 rpm](image)

In order to examine the effect of the engine speed to the replacement ratio, the diesel replacement ratio at engine speed of 1000 rpm is shown in Figure 6. The figure shows the same trend as at engine speed 1500 rpm. However, the diesel replacement ratio at low engine speed is higher than high engine speed. The maximum diesel replacement ratio is 87.5% shown by CI engine on dual-fuel with flow rate of 6 L/min. The lowest replacement ratio is 36 %, shown by biogas flow rate of 2 L/min. The
present results show the same trend as results reported by Tippayawong et al [7]. In that study, they used a CI engine with almost similar output rate and the concentration of biogas of 65% CH4 which is slightly higher than this study. It is reported that CI engine operate successfully with biogas substitution rate at above 90% by mass.

Figure 6. 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 (diesel-raw biogas) modes. The load was varied from 600 W to 1500 W and the engine speed was from 1000 to 1500 rpm. The conclusions are as follows. The CI engine operates successfully on dual-fuel mode without any significant modification and results in output power similar to original diesel engine. However, the efficiency and specific fuel consumption are lower in comparison with dual-fuel mode. By using dual-fuel mode with raw biogas, the diesel oil can be replaced up to 87.5%. Further study in order to increase the efficiency and to decrease specific fuel consumption is extremely needed.

Acknowledgments
The authors gratefully acknowledge that the present research is supported by Ministry of Research and Technology and Higher Education Republic of Indonesia. The support is under the research grant BP-PTN USU of Year 2016.

References
[1] Government of Indonesia Presidential Decree No No 61 Year 2011, National Action Plan For Reducing Greenhouse Gas Emissions.
[2] Minister of Energy and Mineral Resources, 2011, Handbook of Energy and Economic Statistics of Indonesia, 2011.
[3] Hutapea M, 2012 Reviewing opportunities for bio-energy and waste to energy development in Indonesia, Ministry of Energy and Mineral Resources of Indonesia.
[4] Henham A, Makkar MK, 1998 Energy Conversion Management 39, 2001-2009.
[5] Bedoya ID, Saxena S, Cadavid FJ, Dibble RW, Wissink M 2012 Applied Energy 618-629.
[6] Cacua K, Amell A, Cadavid F 2012 Biomass and Bioenergy 45 (2) 159-167.
[7] Tippayawong N, Promwungkwa P, Rerkkriangkrai 2007 Biosystem Engineering 98 26-32.
[8] Makareviciene V, Sendzikiene E., Pukalskas S, Rimkus A, Vegneris R 2013 Energy Conversion and Management 75 224 – 233.
[9] Tonkunya N, Wongwuttanasatian T 2013 Energy for Sustainable Development 17 240 – 244.
[10] Nathan SS, Mallikarjuna JM, Ramesh A 2010 Energy Conversion and Management 51 1347 – 1353.