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Performance and emission characteristics of a small diesel engine run in dual-fuel (diesel-biogas) mode

Himsar Ambarita

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

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ABSTRACT

A small compression ignition (CI) engine with a rated power of 4.41 kW has been tested in dual-fuel (diesel-biogas) mode without any significant modification. The objectives are to explore the effects of biogas flow rate and methane concentration on the performance and emissions of the CI engine run in dual-fuel mode. The experiments have been carried out at engine load and speed vary from 1000 rpm to 1500 rpm and 600 W to 1500 W, respectively. The results show that the output power and specific fuel consumption of the CI engine run in dual-fuel mode are higher than the CI engine run in pure diesel mode. Brake thermal efficiency of the CI engine run in dual-fuel mode strongly affected by biogas flow rate and methane concentration. There exists an optimum biogas flow rate for a maximum brake thermal efficiency. The biogas can reduce the diesel fuel consumption significantly. In the present CI engine, diesel replacement ratio varies from 15.3% to 87.5%. At engine load and speed of 1500 W and 1500 rpm, to get maximum efficiency, the present CI engine should be operated at biogas energy ratios of 15% and 18% using biogas with 60% and 70% methane concentrations, respectively.

1. Introduction

Green House Gases (GHG) emissions which result in global warming is a serious problem for the human being. Total anthropogenic GHG emissions were the highest in the history from year 2000 to 2010 and reached 49 (± 4.5) Giga ton CO_2eq/year in 2010 [1]. Many governments addressed their commitment in reducing GHG emission. The Government of Indonesia (GoI) has released a target in reducing its GHG emissions by 26% from level business as usual by 2020, and this target can be increased up to 41% by international aids [2]. One of the significant sector of emission sources is energy sector which includes burning fossil fuel in transportation and machinery [3,4]. In the transportation and machinery, the largest fuel consumption is diesel fuel [5]. Thus, reducing consumption of diesel fuel in CI engines will give a significant impact on mitigation of GHG emissions. Due to the thermodynamic principle of combustion engines and the Carnot cycle limit, the emission target from the transportation and machinery can only be achieved with fuel change or blending with biofuel such as biogas. The biogas is an important source of biofuel produced from anaerobic biodegradation of organic material. It consists of methane typically range from 40 to 70% and its low heating value is between 15 and 30 MJ/Nm^3. Indonesia, as an agricultural country, has an enormous potency of biogas [6]. However, only a very small portion of this potency has been explored. In the present time, the technology of producing small scale biogas in the rural area has matured. Trainings have been performed many times [7–9]. However, the contribution of biogas for Indonesian energy share is very low. An alternative and more promising solution for this situation is extremely needed. Applying biogas as fuel for CI engines which are mainly used in transportation and agricultural machinery [10,11] is proposed.

Two methodologies can be used to operate a CI engine with biogas. The first method is converting the CI engine into spark engine

E-mail address: himsar@usu.ac.id.

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and fueled with biogas only [12–14] and the second one is dual-fuel mode (diesel-biogas). In the first method, the CI engine needs extreme modification, because it must be converted into spark ignition engine. Chandra et al. [12] reported a study on the performance evaluation of a 5.9 kW CI stationary engine which is converted to spark ignition. The engine run on compressed natural gas (CNG), methane enriched biogas (Bio-CNG) and biogas produced from bio-methanation of Jatropha and Pongamia oil seed cakes. The composition of the methane (CH_4)-enriched biogas is 95% CH_4 − 3% CO_2 (Carbon dioxide) and the biogas is 65% CH_4 − 32% CO_2. The results revealed that the methane-enriched biogas showed almost similar engine performance as compressed natural gas in term of brake power output, specific gas consumption and thermal efficiency. Lee et al. [13] studied experimentally a 30 kW biogas power generation enhanced by using waste heat to preheat inlet gasses. The effect of preheating the inlet gas to different temperature was investigated by applying a waste-heat recovery system. The results showed that power generation increases with increasing biogas methane concentration, except when excess air ratio less than 0.85. However, thermal efficiency increased with increasing methane concentration only when excess air bigger than 0.95, although, on the relatively rich side, there was no benefit. The improved generator performance obtained by preheating the inlet gas was apparent when the excess air ratio is relatively high, such as bigger than 1.3. An agricultural CI engine, single cylinder, four strokes, indirect injection engine, 598 cc, and compression ratio of 22 was converted into spark ignition engine and operated 100% on producer gas [14]. The results showed that maximum brake thermal efficiency of 23.9% was obtained. The smoke density of the engine was lower than the diesel engine; however, carbon monoxide (CO) emission was higher with similar hydrocarbon (HC) emission. The same strategy was also used to convert an original CI engine into spark ignition engine and fueled with biogas [15,16].

The second method of using biogas in a CI engine is dual-fuel mode. In the CI engine run in dual-fuel mode, after compression of the charge comprised of biogas and air an 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 a CI engine run in dual-fuel mode is it can work with a wide variety of gaseous fuels without significant engine modifications [17]. Several studies on the CI engine run in dual-fuel mode have been found in the literature. Bedoya et al. [18] studied the effect of mixing system and pilot fuel quality on the performance CI engine run in dual-fuel mode. The tested CI engine was four stroke, two cylinders, air cooled with rated power of 20 kW at 3000 rpm and biogas methane concentration is 60%. The results showed that it was possible to achieve full diesel substitution using biogas and biodiesel as a power source. Thermal efficiency and substitution of pilot fuel were increased in the supercharger mixing system, on the other hand, methane and carbon monoxide emissions were decreased. Cacua et al. [19] reported an experimental study on the effects of oxygen enriched air on the operation and performance of a dual-fuel engine. The biogas composition was 60% CH_4 - 40% CO_2 and the oxygen concentration in the intake air engine was varied from 21% to 27% O_2. The experiments were carried out with a stationary four strokes and two cylinders CI engine with a rated power of 20 kW at 3000 rpm coupled with a generator. The results showed that enriched air with oxygen would decrease ignition delay time and methane emissions and thermal efficiency was increased.

Tippayawong et al. [20] carried out a study on electricity production for on-farm using a small CI engine run in dual-fuel mode using biogas with methane concentration 65.6%. The main objective was to evaluate the effect of long-term operation on performance and wear of the dual-fuel engine. The CI engine was tested for 2000 h of operation. The results showed that biogas could replace 90% of diesel consumption and minor surface wear was evident but not significant enough to cause deterioration in engine performance. Overall, the dual-fuel engine appeared to perform well and have great potential for use on-farm energy utilization. Makareviciene et al. [21] explored the impacts of methane concentration in a big CI engine four stokes and four cylinders when operated under dual-fuel (diesel-biogas) mode. The power of the tested engine was 66 kW at 4000 rpm with biogas composition was 65%, 85%, and 95% of methane. The impact of exhaust gas recirculation (EGR) was also explored. Tonkunya and Wongwuttanasatian [22] reported a study on the utilization of biogas-diesel mixture as a fuel in a fertilizer pelletizing machine for reduction of GHG emission in small farms. The results showed that by using biogas in a CI engine run in dual-fuel mode, a reduction in diesel fuel of 63% was achieved. Nathan et al. [23] performed an experimental study on the biogas-biodiesel homogenous charge compression ignition (HCCI) mode of engine operation to investigate the potential of the HCCI concept to utilize biogas effectively. The conclusion of the study was thermal efficiencies close to diesel engine values can be obtained in the HCCI mode. Ibrahim et al. [24] studied the effects of injection timing, biogas energy ratio, and intake charge temperature on performance, emissions, and combustions characteristics by using HCCI mode diesel engine. The effects of compression ratio on performance, combustion and emissions characteristics using raw biogas on small CI engine 3.5 kW is reported by Bora et al. [25]. The effects of combustion strategies [26,27] and optimizing the injection timing [28] for several type and size of CI engine run on dual-fuel have been explored.

In order to replace the dependency on fossil fuel, the CI engine can also be operated with dual-fuel using biodiesel-biogas mode. Here, the biogas is the main fuel and biodiesel resulted from vegetable oil is used as pilot fuel. Several researchers have reported their works related on biodiesel-biogas [29–33]. Yon and Lee [29] published a study on the comparison dual-fuel CI engine with diesel-biogas and biodiesel-biogas engine. The parameters investigated are combustion characteristics of single fuel and dual-fuel diesel and biodiesel also dual-fuel with biogas. Luijten and Kerkhof [30] used Jatropha oil and biogas in a dual-fuel CI engine for rural electrification. Several operational parameters of the CI engine run in dual-fuel mode by using biodiesel have been explored. Those are the effects of compression ratio using rice brand biodiesel [31], the effects of injection pressure and injection timing using waste cooking biodiesel [32], the effect of indirect injection using blends biodiesel [33], the effect of preheating on the engine using Jatropha biodiesel and using neat Jatropha and Karanj biodiesels.

The above literatures show that research on CI engine run in dual-fuel mode has come under scrutiny in order to decrease diesel fuel consumption and to mitigate GHGs emissions. The focus of those studies varies from effects of mixing system, oxygen enrichment of the inlet air, long-term operation, the source of biodiesel, etc. Those strategies mainly applied significant modifications to the original CI engine such as compression ratio modification, pilot fuel injection systems, etc. In case the biogas is absence, the CI engine