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Utilization of Poor Biogas as Fuel for Hybrid Biogas-Diesel Dual Fuel Stationary Engine

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Abstract: An experimental investigation was conducted to examine the effect of combustion of biogas on the performance of hybrid biogas-diesel dual fuel engine converted from a diesel engine. Effects of biogas composition, equivalence ratio, engine speed and pilot injection on engine performance were taken into consideration. The tests were carried out on the AVL engine test bed with APA204 dynamometer. The results show that peak of cylinder pressure and indicated engine cycle work decrease as decreasing CH_4 concentration in biogas or/and as increasing engine speed. To ensure the original rated output power as the hybrid biogas-diesel dual fuel engine fueled with diesel alone, pilot injection must increase up to 30% of rated injection as the engine fueled with raw biogas containing 60% CH_4. With rich biogas, diesel injection is needed only for ignition purpose, about 10% of rated injection. As the dual fuel engine fueled with biogas containing 70% CH_4, maximum output power is higher than diesel rated output power but lower than diesel maximum brake power. With biogas containing 80% CH_4, maximum output power of dual engine is close to diesel maximum brake power. Indicated efficiency of the engine decreases as increasing engine speed. Indicated engine cycle work of hybrid biogas-diesel dual fuel engine fueled with biogas containing from 60% to 80% CH_4 reaches its maximum value at equivalence ratio in range from 1.10 to 1.02. In case of shortfall of biogas supply, the engine can be switched automatically to diesel operation. The new concept of hybrid biogas-diesel dual fuel engine fueled with poor biogas is very useful in rural area. It can operate and save fossil fuel at any biogas supply conditions.

Keywords: energy; renewable energy; green energy; energy saving

Nomenclatures:

D_b: Diameter of biogas supply pipe (mm)

$g_{cycle\ rated\ max}$: Rated diesel injection (g/cycle)

n: Engine speed (rpm)

p_i: Indicated pressure (bar)

P_e: Brake engine power (kW)

S_o: Maximum section of biogas supply pipe as complete open of butterfly valve (mm^2)

S: Flow section of biogas supply pipe as throttling (mm^2)

W_i: Indicated engine cycle work (J/cycle)

ϕ: Biogas-Air equivalence ratio

φ: Crank angle (°)

φ_s: Injection timing advance (°)

TDC: Top Dead Center

1. Introduction

In view of the limitation of conventional fossil fuel reserves intensive search for alternative fuels for use in internal combustion engines is going on. Biogas is an attractive alternative energy source because in view of energy crisis, it can act as an alternative fuel using for internal combustion engine and otherwise, it is renewable in nature, thereby not net contributors to the green house gases emission.

Biogas can serve as a fuel for internal combustion engines of both the spark-ignition and the compression-ignition type to drive various stationary agricultural machines or small alternators in rural area [1]. Much of the effort has been paid to spark-ignition engines [2], [3]. Compression-ignition biogas engine is more limited because the required modifications is quite complex, particularly for small high-speed engines subjected to variable loads [4]. However because of its high octane number, biogas is suitable for engines with a relatively high compression ratio to maximize thermal efficiency. So it was suggested that biogas-diesel dual fuel may be applied to conventional direct-injection, compression ignition engines [5]. So it is very useful to develop a practical and efficient method of utilizing biogas, particularly raw biogas, on diesel engine in dual fuel mode. Otherwise, for a wide application in rural area, the engine after modification should be switched over smoothly without interruption to conventional diesel operation in case of a shortfall in biogas supply. It is concept of hybrid biogas-diesel dual fuel engine, the subject of study of this work.

In fumigated dual-fuel mode, the biogas is mixed with the air before entering the combustion chamber. At the end of the compression stroke a pilot quantity of diesel fuel is injected to ignite the mixture. The amount of diesel fuel injected is normally about 10-20% of the amount needed for operation on diesel alone at normal working loads (namely rated injection) and contributes only to a small fraction of the engine power output [6]. Operation of the engine at partial load usually requires a reduction of the biogas supply by means of a gas control valve [6].

Effects of biogas on dual fuel engine performance have been evaluated by some investigations [6], [7], [8]. Among these are the use of low substitution levels [9], modification of the pilot fuel injection factors [10], direct injection of gas into the combustion chamber [11]... Quality of injected pilot fuel is another factor that has an effect on dual fuel engine performance, since composition and cetane number of liquid fuels affect ignition delay period and premixed combustion duration [12].

The observed power reduction of compression ignition engine when converted into spark ignition engine were 31.8%, 35.6% and 46.3% on CNG, methane enriched biogas and raw biogas, respectively [13]. In dual fuel mode it was demonstrated that over 90% substitution rate by enriched biogas can be achieved. For limited engine speed range, analysis of the comparative results revealed that dual-fuel operation exhibited higher power output than that under normal diesel operation, especially at low speed but the magnitudes were not markedly different [8]. With biogas containing 65.6% CH_4, output power of dual fuel engine is slightly higher than that of normal diesel operation by about 7% on average [8].

The existing works concerns mainly output performance of dual fuel engines however, no experimental analysis of in cylinder pressure of the engines seem to be available. Otherwise most of the present application of gaseous fuel engines has been focused on medium or relatively high power, multi-cylinder engines, but the experiences on small biogas engines were rarely available. Furthermore, the available researches focused on biogas spark ignition engines or dual fuel engines converted form diesel engine. After conversion, the engines cannot operate on diesel alone. This obstacle limits the application of biogas engines in rural area with various biogas supply resources.

The present study was focused on hybrid biogas-diesel dual fuel engine converted from a low-power diesel engine to overcome the above advantages. We will present experimental results of different ways to improve engine performance as it is fueled with raw biogas by analysis of combustion via in cylinder pressure diagrams. The strategy of the research is as following:

- Study of biogas-air mixture preparation.
- Study of the effects of biogas quality, equivalence ratio, engine speed and pilot fuel injection on engine performance based on analysis of in cylinder pressure and output power of the engine.
- Concept of control system for hybrid biogas-diesel dual fuel engine converted from a diesel engine.

2. Experimental Setup and Experiments

Experimental study of hybrid biogas-diesel dual fuel engine was conducted at the AVL Laboratory of the University of Danang, Vietnam. Fig. 1 illustrated the schematic of the experimental setup. The main component of the testing system is the dynamometer APA204 controlled by Puma system. The cylinder head of the engine was drilled and fitted with an AVL GU12P piezo-electric pressure transducer enclosed in a air cooling jacket. The output signal of the transducer was fed, via a piezo charge amplifier 3067A01, to the computer. Engine speed is obtained with help of AVL encoder. System Indiset 620 connected to

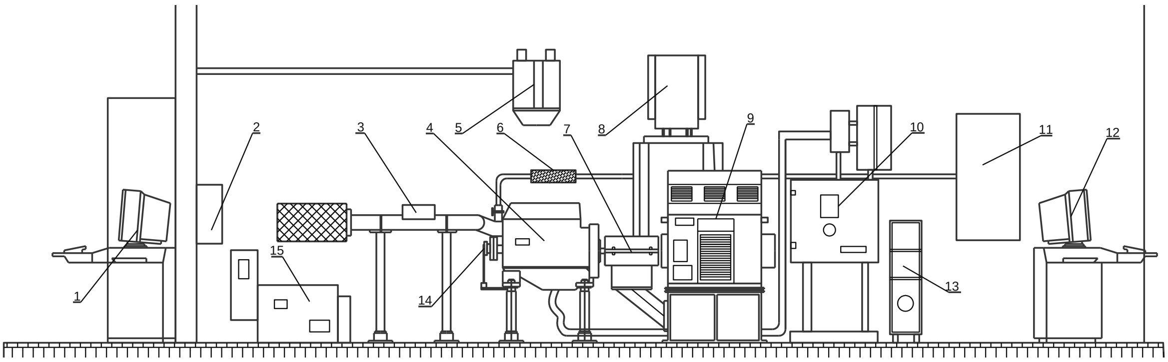


Fig. 1. Schematic of the experimental setup

1. Control computer; 2. AVL THA 100 throttle actuator; 3. Flowmeter for air; 4. Dual fuel engine; 5. System Indiset 620; 6. Flowmeter for biogas; 7.Cardan joint; 8. AVL Fuel Balance 733S; 9. Dynamometer APA; 10. Water cooler for the engine; 11. Biogas bag; 12. Computer; 13. Exhaust gas analyser; 14. Tachimeter; 15. Lubricating oil cooling system.

different sensors implemented to combustion chamber of the engine such as cylinder pressure sensor, advance injection sensor, TDC sensor... Data treatment and results exportation are performed by specialized software Concerto.

The diesel consumption are measured with help of AVL Fuel Balance 733S. Pilot injection is adjusted thanks to a limit screw retrofitted on the injection pump.

Raw biogas containing 61.2% CH_4, 37.9% CO_2, 0.3% H_2S and 0.6% other gas is treated chemically by NaOH solution for CO_2 and H_2S removal. After treatment, CH_4 composition in the biogas is up to 93.6%. It is than compressed to the cylinders at 100 bars pressure and carried to the laboratory. Biogas from the cylinder is filled to plastic bag at pressure slightly higher than atmospheric pressure where it is mixed with CO_2 to obtained desirable composition. This mixture is assumed to be raw biogas which contains only CH_4 and CO_2. Composition of biogas is determined by specialized biogas analyzer GFM435 before supplying to the engine. Biogas-air mixture is prepared by the mixer previously before induction into cylinder. The following mass flow rates were determined: (1) air, by ABB flow meter and (2) biogas, by means of rotameter.

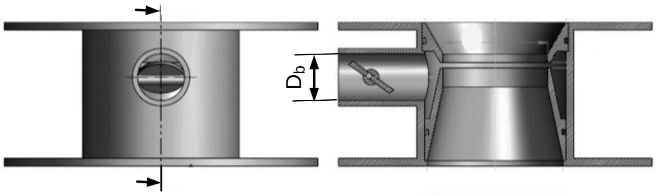


Fig. 2. Venturi-type biogas-air mixer

A venturi-type biogas-air mixer was retrofitted to the engine's air intake. Fuel-air equivalence ratio of the mixture could be set by means of a butterfly valve in the biogas inlet port as shown in Fig. 2. The AVL THA 100 throttle actuator controls the butterfly valve with pointer and scale arrangement indicating percentage of full throttle opening of the valve. The basic dimension of the mixer can be calculated at a given biogas composition and engine regime [14]. The diameter of biogas supply pipe is chosen 18mm for the poorest biogas containing 60% CH_4.

The experiments were carried out in the standard engine laboratory equipped by AVL, Austria, at normal atmospheric conditions of 755 mmHg pressure, 35°C temperature and 50% humidity. Pressure sensors and flow meters were calibrated before a series of measurement. For accuracy of experimental data, the in cylinder pressure is taken 10 samples of each 5 minutes at the same operating conditions. Pressure diagram used for analysis is the mean of these 10 samples. Output power of engine is the mean value of 20 measurements at the same conditions with cycle of 5 minutes after stable operation of the engine.

3. Results and Discussion

3.1. Mixture preparation

The study was carried out on hybrid biogas-diesel dual fuel engine converted from a base diesel engine Vikyno EV2600-NB. It is, a single-cylinder, four-stroke, with bore 118mm, stroke 108mm, having a swept volume of 1181cm^3 and a rated power output of 20HP at 2200rpm. The compression ratio of the engine is 16.5 and with an essentially fixed injection timing advance of φ_s=22.25° before TDC. The fuel consumption as engine operates on diesel alone is 165g/HP.h, i.e. 0.05g/cyc at rated regime (20HP, 2200rpm). As it operates in dual fuel mode, diesel pilot injection was maintained at 10% of rated injection, i.e. 0.005g/cyc by adjusting the limit screw retrofitted on injection pump. Air needed for complete combustion of this diesel pilot injection is 0.073g/cyc.

Biogas was inducted into the throat of the venturi. Biogas flow rate was controlled by the throttle of butterfly valve. Opening interval of butterfly valve from complete close to full open is graduated into 100 equal graduation marks. The valve was connected to the AVL THA 100 throttle actuator which was programmed to step 10 graduation marks for each measurement. Biogas-air equivalence ratio can be calculated via biogas flow and air flow with subtraction of air quantity needed for complete combustion of pilot injection.

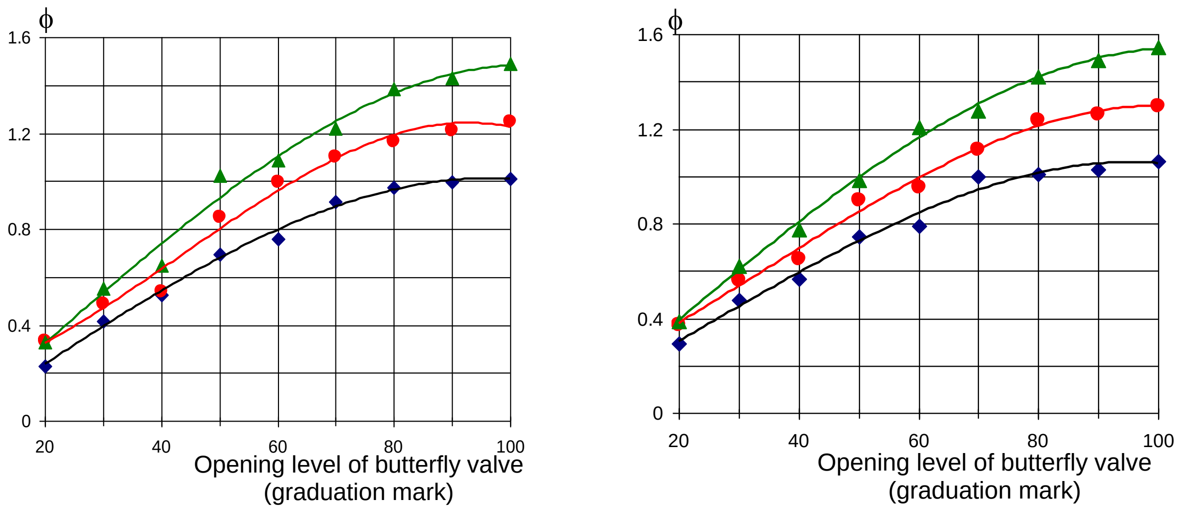
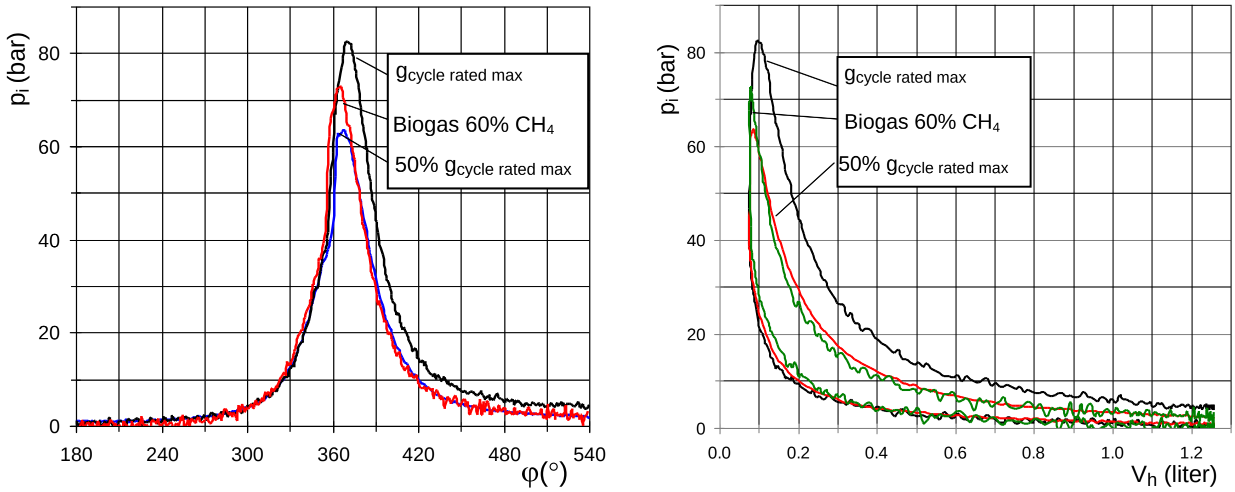


Fig. 3. Effect of CH_4 concentration in biogas to relationship between equivalence ratio and butterfly opening level at engine speed of 2000rpm (a) and 1800rm (b). Biogas containing 80% CH_4 (▲), 70% CH_4 (●) and 60% CH_4 (◆)

Fig. 3a and Fig. 3b present the variation of equivalence ratio ϕ with opening level of butterfly valve as engine fueled with biogas containing 60%, 70% and 80% CH_4 at two engine speeds of 2000rpm and 1800rpm. Each measurement is repeated 10 times. The deviation is about ±5% of mean value. The results show that with a given opening level of butterfly valve, equivalence ratio ϕ increases with CH_4 concentration in biogas. Stoichiometric equivalence ratio ϕ=1 was obtained for biogas containing 60% CH_4, 70% CH_4 and 80% CH_4 at opening level of butterfly valve 90, 65 and 55 graduation marks respectively. With a given biogas, equivalence ratio ϕ is proportional to flow section, i.e. to opening level of butterfly valve. It is a nonlinear relationship as shown in Fig. 3a and Fig. 3b.



a. *b.*

Fig. 4. Comparison of cylinder pressure diagrams (a) and indicated engine cycle work (b) at engine speed of 2000rpm operating in dual mode with biogas containing 60% CH_4, ϕ=1.1 and diesel mode with injection $g_{cycle\ rated\ max}$ and 50% $g_{cycle\ rated\ max}$

3.2. Comparison of diesel operation and dual fuel operation

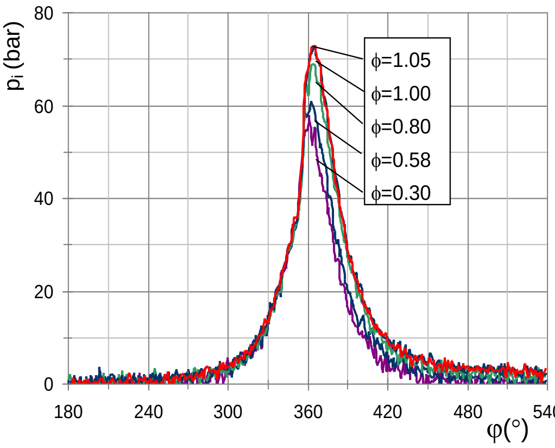


Fig. 5. Effect of equivalence ratio to cylinder pressure diagram as dual fuel engine fueled with biogas containing 60% CH_4 at engine speed of 2000rpm

The first test was performed with diesel alone. Quantity of diesel injection was 0.05g/cyc (rated injection) and 0.025g/cyc (50% of rated injection). The second test was performed on dual fuel mode with biogas containing 60% CH_4, ϕ=1.1 and pilot injection 0.005g/cyc. Engine speed remained constant at 2000rpm. Fig. 4a compares cylinder pressure diagrams of these 3 cases. It can be seen that peak of pressure of dual fuel case is intermediate of these two diesel cases. The difference in indicated engine cycle work can be seen clearly on p-v diagrams (Fig. 4b). Indicated cycle work of diesel engine was 1180.55J/cyc with rated injection and was 607.39J/cyc with 50% of rated injection, i.e. 51.45% value of the first case. Indicated cycle work of dual engine was 851.65J/cyc, equivalent to 72% indicated cycle work of diesel engine with rated injection.

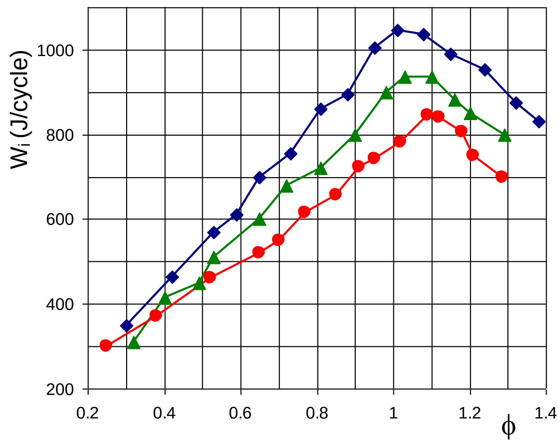


Fig. 6. Relationship between indicated cycle work and equivalence ratio ϕ of dual fuel engine fueled with biogas containing 60% CH_4 (◆), 70% CH_4 (▲) and 80% CH_4 (●) at engine speed of 2000rpm

3.3 Effect of equivalence ratio

Fig. 5 shows cylinder pressure diagrams of dual fuel engine fueled with biogas containing 60% CH_4 at engine speed of 1800rpm with different opening levels of butterfly valve at 20, 40, 60, 80 and 100 graduation marks corresponding to ϕ of 0.3, 0.58, 0.8, 1.0, 1.05 respectively. The results show that peak of cylinder pressure diagrams corresponding to ϕ=1.05 is the highest one. With the decrease in fuel air equivalence ratio, the flame propagation rate is reduced, leading to a longer combustion duration and a correspondingly lower maximum cylinder pressure.

Fig. 6 demonstrates variation of indicated engine cycle work with equivalence ratio as engine fueled with biogas containing 60% CH_4, 70% CH_4 and 80% CH_4. Engine speed remained constant at n=2000rpm. The results show that maximum indicated engine cycle work was found at the rich mixture side, at ϕ around 1.1, 1.06 and 1.02 with biogas containing 60% CH_4, 70% CH_4 and 80% CH_4 respectively. Mixtures richer or leaner than this point will cause incomplete combustion or slow the burning rate and hence lead to a drop in indicated cycle work. Theoretically burning rate reaches its highest value with stoichiometric mixture, hence theoretical maximum indicated engine cycle work is obtained at ϕ=1. However as biogas contains always an amount of CO_2 which is main factor to reduce burning rate so that the peak of indicated engine cycle work is obtained with a slightly rich mixture. With the increase in CH_4 concentration in biogas, the burning rate is enhanced leading to a better combustion and hence the peak of indicated engine cycle work moves toward theoretical stoichiometric mixture ϕ=1.

3.4. Effect of CH_4 concentration in biogas

Fig. 7 illustrates pressure diagrams of dual fuel engine at speed of 2200rpm fueled with biogas containing 60% CH_4, 70% CH_4 and 80% CH_4 at fixed equivalence ratio ϕ=1.05. The results confirm the above observation that increasing the CH_4 concentration in biogas increases the peak pressure due to increase in the combustion rate. Fig. 8 shows maximum output power curves of dual fuel engine fueled with biogas containing 60% CH_4, 70% CH_4 and 80% CH_4 in comparison with that of the engine operating on diesel alone. In diesel operation, maximum brake power should be distinguished with rated power which is limited by black smoke emission (Fig. 8). It can be seen that as the engine fueled with biogas containing 60% CH_4, maximum output power is lower than diesel rated power. With biogas containing 70% CH_4, maximum output power is higher than diesel rated power but lower than diesel maximum brake power. With biogas containing 80% CH_4, maximum output power of dual engine approaches to diesel maximum brake power. Thus as dual fuel engine fueled with biogas containing CH_4 concentration higher than 70%, it can supply maximum output power equivalent to diesel rated power, so no any change in external load system is needed. But as raw biogas is used, maximum output power of dual fuel engine is lower than diesel rated power. To ensure the need of external load, the engine performance should be improved.

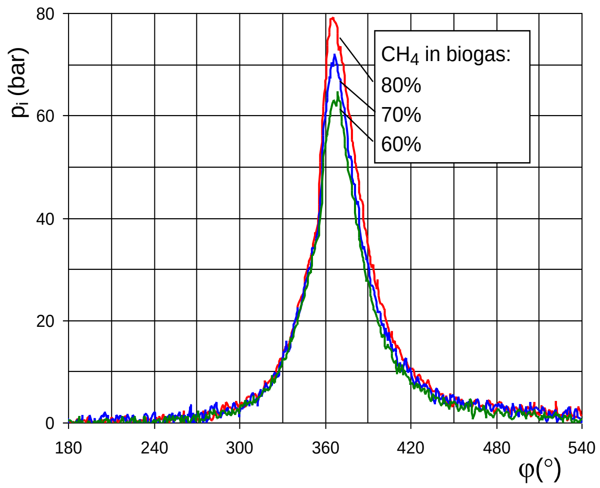


Fig. 7. Effect of CH_4 concentration in biogas to cylinder pressure diagram at engine speed of 2200rpm and ϕ=1.05

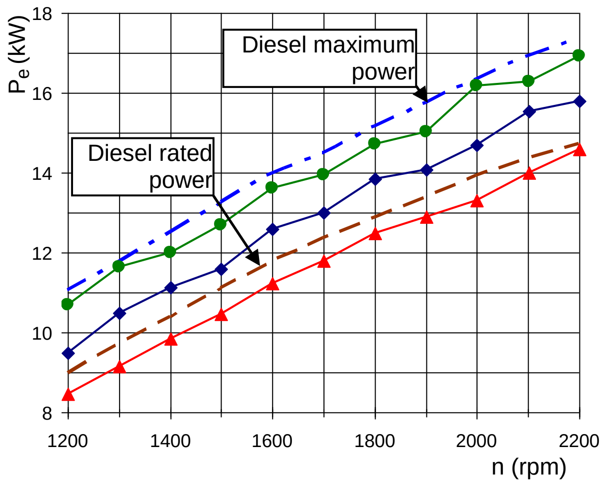


Fig. 8. Maximum output power of dual fuel engine fueled with biogas containing 60% CH_4 (▲, 70% CH_4 (◆) and 80% CH_4 (●) in comparison with diesel maximum brake power and diesel rated power

3.5. Effect of engine speed

Effect of engine speed to cylinder pressure diagram of dual fuel engine fueled with biogas containing 60% CH_4 and ϕ=1.1 is presented in Fig. 9. The results show that maximum pressure decreases as increasing engine speed. Fig. 10 shows variation of indicated engine cycle work with speed of hybrid dual fuel engine fueled with biogas containing 60% CH_4, 70% and 80% CH_4. Equivalence ratio was maintained constant at ϕ=1.05. The result shows that indicated engine cycle work decreases about 60J, 120J and 170J with biogas containing 60% CH_4, 70% CH_4 and 80% CH_4 respectively as engine speed increases from 1200rpm to 2200rpm. In fact the increase of engine speed lowers time available for combustion, thus fuel consumption during combustion process decreases, falling of indicated engine cycle work is as a result. For this reason, for high performance of dual fuel engine, advance injection timing should be increased as CH_4 concentration in biogas decreases or/and as engine speed increases. As we have mentioned in our previous research, the simulation shows that in order to fully utilize the fuel energy during the combustion stroke and to achieve a good combustion process with the pressure peak optimally after TDC, it is necessary to advance the ignition timing in

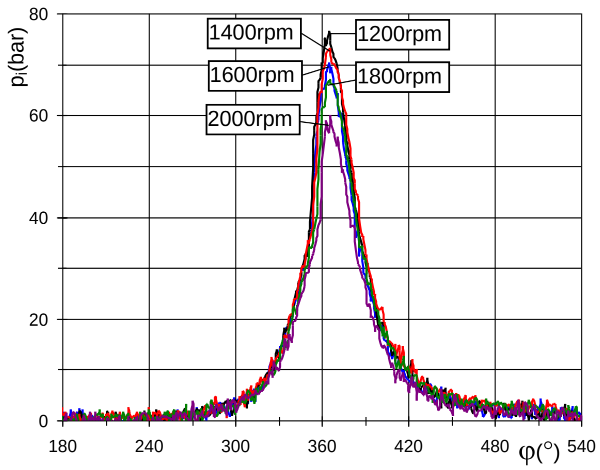


Fig. 9. Effect of engine speed to cylinder pressure diagram (Biogas containing 60% CH_4; ϕ=1.1)

engines when biogas is used as fuel [15]. The engine performance can be thus significantly improved by proper control of injection/ignition advance timings [5], [13]. This process, although effective, has not been found the most realistic way to apply on hybrid biogas-diesel dual fuel engine. In fact in most cases of stationary diesel engine, advance injection is fixed. Otherwise dual fuel engine needs a minimum diesel injection for ignition, so injection timing too early can deteriorate the ignition due to low air temperature. Further more in case of hybrid biogas-diesel engine, the engine can be switched to diesel alone in case of shortfall of biogas, so modification of injection advance timing can lead to abnormal operation of the engine. Thus injection advance timing of hybrid biogas-diesel engine should not be changed.

To enhance combustion process of biogas-diesel dual fuel engine, many researchers have focused on mixing biogas with gaseous fuels with high burning rates. Methane and

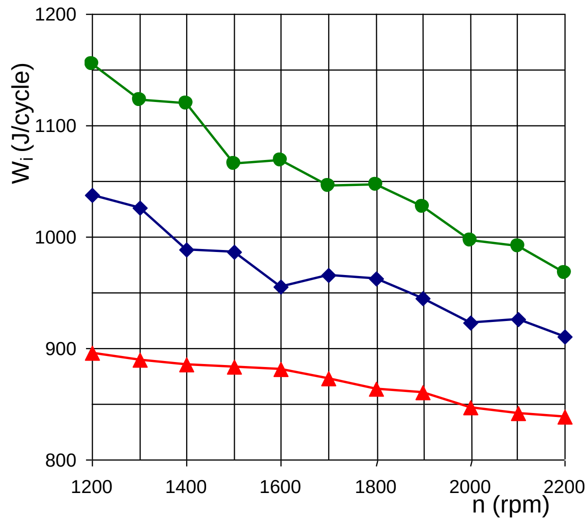
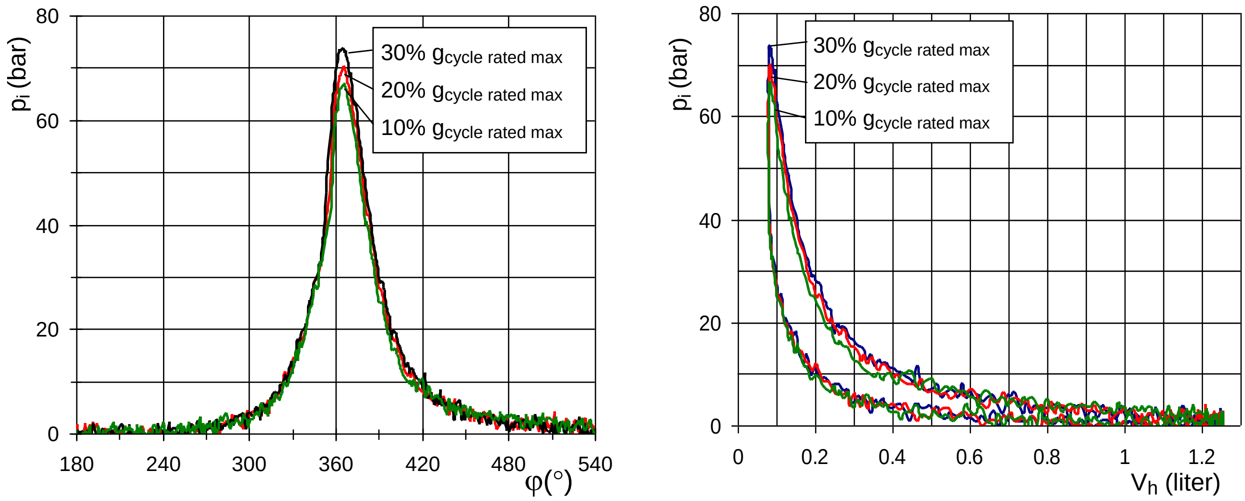


Fig. 10. Variation of indicated engine cycle work with engine speed of dual fuel engine fueled with biogas containing 60% CH_4 (▲, 70% CH_4 (◆) and 80% CH_4, (●), ϕ=1.05

hydrogen are the two gaseous fuels often used for this purpose [13], [16]. Their studies showed that increasing the hydrogen or methane concentration in biogas resulted in an increase in the burning velocity. However fraction of additional gas must be limited because of knock due to rapid combustion of gas mixture. Porpatham et al. [16] observed that on the whole the addition of hydrogen up to 10% seems to be desirable. This solution is effective for application of biogas on vehicle but it is not appropriate solution to stationary engines fueled directly with raw biogas.

3.6. Effect of pilot injection



a. *b.*

Fig. 11. Effect of pilot injection on cylinder pressure diagram (a) and on indicated engine cycle work (b) of dual fuel engine fueled with biogas containing 60% CH_4, ϕ=1.1, at engine speed of 1600rpm

For complete combustion of fuel air mixture, an increase of diesel injection conducts to a decrease of biogas supply. 740J/cyc, 775J/cyc and 801J/cyc as pilot injection is 10%,

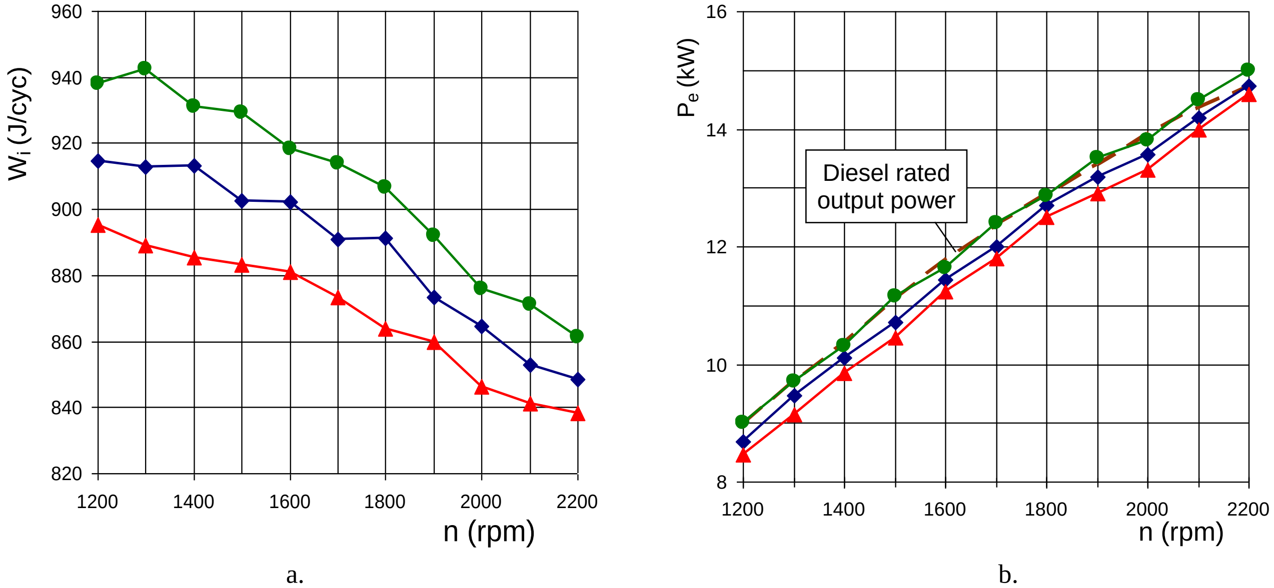


Fig. 12. Variation of indicated engine cycle work (a) and maximum output power with engine speed as dual fuel engine fueled with biogas containing 60% CH_4, ϕ=1.1, pilot injection 10% $g_{cycle\ rated\ max}$ (▲), 20% $g_{cycle\ rated\ max}$ (◆) and 30% $g_{cycle\ rated\ max}$ (●)

With a given air quantity, energy release by combustion of diesel and biogas can be calculated via low heating values and stoichiometric fuel air ratio. The calculation shows that energy release by combustion of biogas containing 60% CH_4 is about 79% energy release by combustion of diesel with a given air amount, i.e. engine indicated power increases only about 21% of diesel power imported to the engine.

Air needed for complete combustion of 0.005g/cyc (i.e. 10% of rated injection) is 0.073g/cyc. Energy release due to combustion of this diesel amount is 225J/cyc. Energy loss due to decrease of biogas supply is 210J/cyc. Thus with an increase in pilot injection of 10% of diesel rated injection, energy supplied to engine increases 15J/cyc. This means that indicated engine power gains 0.15kW and 0.28kW at engine speed of 1200rpm and 2200rpm respectively.

Fig. 11a shows effect of pilot injection on cylinder pressure diagram of dual fuel engine fueled with biogas containing 60% CH_4 at engine speed of 1600rpm. Pilot injection is 10%, 20% and 30% of rated injection. It can be seen that with the increase in pilot injection, the flame propagation rate is enhanced, leading to a shorter combustion duration and a correspondingly higher and earlier cylinder pressure. Fig. 11b compares p-v diagrams of dual fuel engine with various pilot injections. Indicated engine cycle work is 20% and 30% of rated injection respectively.

Fig. 12a indicates effect of pilot injection on variation of indicated engine cycle work with engine speed as dual engine fueled with biogas containing 60% CH_4 and ϕ=1.1. It can be seen that with an increase in pilot injection of 10% of rated injection, indicated cycle work of the dual fuel engine increases about 20J/cyc at engine speed of 1200rpm as against 10J/cyc at engine speed of 2200rpm. At low engine speed, increase of pilot injection contributes to increase of energy release and enhancement of burning velocity. This improves in whole combustion process and thus the increase of indicated cycle work is slightly higher than theoretical value. On the contrary at high engine speed, the increase of engine cycle work is slightly lower than theoretical value due to available time for combustion is reduced.

Fig.12b shows the effect of pilot injection on maximum output power of the dual fuel engine. It can be seen that maximum output power of dual engine fueled with biogas containing 60% CH_4 reaches to rated power of diesel engine as pilot injection is around 30% of rated injection. It means that 70% diesel substitution is possible by raw biogas without any deterioration of normal operation.

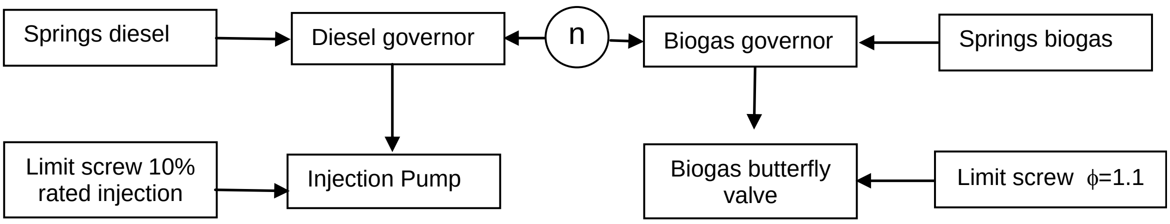


Fig. 13. Control schema of hybrid biogas-diesel dual fuel engine

4. Control Schema of Hybrid Biogas-Diesel Engine

As mention in previous section, output power of hybrid biogas-diesel dual fuel engine can be controlled by adjusting CH_4 concentration in biogas, by adjusting equivalence ratio ϕ or by adjusting pilot injection. At part load regime and in zone stability operation of the engine, the adjustment of biogas air equivalence ratio is priority for economic issue. At full load regime, particularly as the engine fueled with poor biogas, the adjustment of pilot injection is necessary to meet the requirements of external load as the engine is fueled with diesel alone. In case of shortfall of biogas supply, the engine is switched to diesel mode automatically without any interruption. With this concept, hybrid biogas-diesel dual fuel engine can operate and save fossil fuel even as it is fueled with raw biogas.

Bases on the results mentioned in the above section, the concept of hybrid biogas-diesel dual fuel engine can be described as following: (1) diesel mode (in case of shortfall of biogas), (2) biogas-diesel dual fuel mode with 10% rated injection (if CH_4 concentration in biogas is higher than 70%) and (3) hybrid diesel-biogas dual fuel mode with diesel injection up to 30% rated injection (if engine fueled with raw biogas).

Fig. 13 illustrates the concept of control schema of hybrid biogas-diesel dual fuel engine. The engine has two speed governors. The original speed governor controls injection pump with a retrofitted screw to limit pilot injection to 10% of rated injection. The second governor controls biogas supply valve with a screw to limit maximum opening so that ϕ=1.1 for a given CH_4 concentration in biogas. Combination of operation of the two speed governors allows the engine to operate under different biogas supply sources and there are no change in external load as the engine fueled with diesel alone. The concept of hybrid biogas-diesel dual fuel engine is applied successfully on Vikyno EV2600-NB diesel engine [17]. It can be applied generally on different other small power diesel engines which are widely used in rural area of developing countries.

5. Conclusions

The following conclusions may be drawn from the results of the present study:

- A hybrid biogas-diesel dual fuel engine operating either on diesel or on biogas with different CH_4 concentration can be developed based on a typical small power diesel engine Vikyno EV2600-NB by retrofitting speed governor system.
- For complete combustion, biogas supplied to the engine should be reduced as increasing diesel injection thus the engine can gain only 21% energy supplied by diesel injection. As increasing 10% diesel rated injection, indicated engine power increases 0.15kW at engine speeds of 1200rpm as against 0.28kW at engine speed of 2200rpm.
- To ensure the original rated output power as the hybrid biogas-diesel dual fuel engine fueled with diesel alone, pilot injection must increase up to 30% of rated injection as the engine fueled with raw biogas containing 60% CH_4.
- With rich biogas, diesel injection is needed only for ignition purpose, about 10% of rated injection. As the dual fuel engine fueled with biogas containing 70% CH_4, maximum output power is higher than diesel rated output power but lower than diesel maximum brake power. With biogas containing 80% CH_4, maximum output power of dual engine is close to diesel maximum brake power.
- Indicated efficiency of the engine decreases as increasing speed due to incomplete combustion. As advance injection timing of the engine remains constant, indicated engine cycle work decreases about 60J, 120J and 170J with biogas containing 60% CH_4, 70% CH_4 and 80% CH_4 respectively as engine speed increases from 1200rpm to 2200rpm.
- Maximum performance of hybrid biogas-diesel dual fuel engine is obtained with a slightly rich mixture. Indicated engine cycle work of hybrid biogas-diesel dual fuel engine fueled with biogas containing from 60% to 80% CH_4 reaches its maximum value at equivalence ratio in range from 1.10 to 1.02.
- Hybrid biogas-diesel dual fuel engine can operate and save fossil fuel with various biogas supplying conditions, particularly with raw biogas. It is appropriate solution for biogas application in rural area of developing countries.

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