Asian Journal of Scientific Research

ISSN 1992-1454

Asian Journal of Scientific Research 6 (3): 456-466, 2013
ISSN 1992-1454 / DOI: 10.3923/ajsr.2013.456.466

Performance of a Compression Ignition Engine Fuelled by Diesel and Imitated Syngas

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ABSTRACT

Biomass can be converted into a useful source of energy through gasification. The gasification product, which is a mixture of gases, is known as synthesis gas or syngas. The composition of syngas fluctuates due to many factors such as operational errors of the gasifier as well as the type of feedstock used or the feeding rate fluctuation. Therefore it is difficult to assess the effect of syngas composition and diesel replacement ratio to the performance when combusted in a compression ignition engine. In order to overcome this problem, controllable composition and conditions of imitated syngas is used in this study by selecting three compositions of syngas close to the real conditions. The objective of this study is to ascertain the possibility of using syngas as alternative to diesel fuel for an internal combustion engine while providing acceptable engine performance. The test results on syngas performance are compared with the results for diesel at engine speed of 2000 rpm. The results of the performance test of both fuels are examined in terms of the engine's power output, exhaust temperature, brake specific fuel consumption, brake thermal efficiency and volumetric efficiency. It is generally shown that the use of syngas leads to lower brake power and brake thermal efficiency. In addition, different syngas compositions are shown to respond differently to the engine performance.

Key words: Biomass, syngas, gasification, compression ignition engine

INTRODUCTION

Biomass is available in varying amounts throughout the developing world from densely forested areas in the temperate and tropical regions of the world. However, these amounts of biomass are considered wastes and are being disposed in an unrestricted manner. Thus, there is a need to introduce some technologies to convert these wastes into alternative fuel because the petroleum fuel is subject to depletion while biomass is a renewable energy source as its supplies are unlimited. There is also the ability to grow trees and crops and the waste will always exist.

Biomass can be converted into useful energy through the process of gasification and this process will in turn produce syngas. Conditions of syngas produced from the gasification process usually fluctuate due to many factors such as operational errors of the gasifier as well as the type of feedstock used or due to the feeding rate fluctuation (Tomishige *et al.*, 2004). Therefore, it is difficult to assess the effect of conditions to the performance when combusted in a compression ignition engine. In order to overcome the situation, imitated syngas may be used at different compositions as fuel in compression ignition engines.

The objective of this study is to determine the performance of a compression ignition engine fuelled with diesel and imitated syngas at different compositions and diesel replacement ratios.

This study involves experimental work for assessment of the effect of syngas composition and its amount to the performance of a compression ignition diesel engine.

Compression or spark ignition engines are often modified and used in most internal combustion engines; these are utilized for generating power, transportation and other uses and they use a variety of fuel types such as gaseous fuels including natural gas, liquefied petroleum gas and sometimes biogases.

The world looking for alternative solutions to transition from dependence on fossil sources of energy in order to rely on sources of more durable and less polluting to the environment.

Gasification is a process to convert carbonaceous materials such as biomass and coal using a controlled amount of oxygen at high temperature into carbon monoxide, hydrogen and other gases which are together known as synthesis gas (syngas). The main constituents of syngas are carbon monoxide, carbon dioxide, hydrogen, methane, nitrogen, water and contaminants like tars, small amount of char and ash particulates and other impurities (Chen *et al.*, 2007).

The syngas is influenced by many different processes so it can be expected that the gas produced will vary according to the biomass source used in production of the gas. Condition of the raw materials and the gasification in the plant play an important role in syngas composition. These variables have a considerable effect on engine performance (Roy *et al.*, 2009). A typical composition of bio-based fuel gas is as follows: hydrogen 20%, carbon monoxide 20%, carbon dioxide 7%, methane 2%, the balance is nitrogen 51% with a heating value of 5 MJ Nm^{-3} (Community Power Corporation).

Syngas that produced from gasification process can be used in several applications. One of them is in the operation of both compression and spark ignitions in internal combustion engines; another is in direct heat applications where it can replace furnace oil (Reed *et al.*, 1982).

Performance and emission characteristics of a gasifier-CI engine system fuelled with producer gas and esters of hingan (balanites) oil in dual fuel mode were investigated by Deshmukh *et al.* (2008). It is observed that the engine operation in dual fuel mode leads to maximum diesel savings and higher Specific Energy Consumption (SEC) at all load conditions. While the engine operation with liquid fuel mode presented higher brake thermal efficiency than that with dual fuel operation. Diesel replacement ratio of 60% was presented when the engine operated with hingan shell producer gas in dual fuel mode.

The performance and emission characteristics of the dual fuel engine using Rubber seed oil and coir-pith producer gas was studied by Ramadhas *et al.* (2008). The experimental results for seed oil and coir-pitch derived producer gas were compared with that for diesel fuel. The results showed that, the fuel consumption of rubber seed oil was higher than that of diesel in dual fuel mode.

It has been seen from literatures that syngas is a very good option to substitute diesel fuel showing acceptable engine performance. While, the problem is that syngas produced from biomass gasification fluctuates in the constituent's content and the most appropriate percentage of syngas constituents which will give the best performance is unknown. This study will give an idea on the effect of syngas constituent's presence that will lead to appropriate syngas composition giving the best performance.

MATERIALS AND METHODS

Engine test: The engine is naturally aspirated, two stroke, single cylinder Tecumseh 5 hp diesel engine with a displacement volume of 230 cc and a compression ratio of 17.6:1. This engine is being used to investigate its performance without load using different compositions of imitated syngas at engine speed of 2000 rpm and different diesel replacement ratios. The technical data of the engine used are provided in Table 1.

The engine was not modified; instead, an experimental rig was attached to it, so the engine can be easily switched over to operate on either pure diesel fuel mode or diesel and syngas (Dual fuel mode). Basic engine testing has been implemented using pure diesel fuel to obtain the baseline data without any modification done to the engine.

Syngas supply system: Syngas supply system is been used to introduce the syngas into the engine through the air intake valve. The system consists of five gas cylinders which are connected to the air intake valve of the engine, the cylinders contains: hydrogen, nitrogen, carbon dioxide, methane and carbon monoxide. The syngas fuel supply system is shown in Fig. 1.

Each gas cylinder connected to pressure regulator to reduce the pressure of the gases from tank which is 200 bars to 1 bar and let the gas flow into the engine. Volume flow meter is used to control the volume flow rate of each gas and obtain the required composition. The five gases were mixed on a five way mixer which was fabricated out of carbon steel. Pre-mixing of air and the gases occurred outside of the engine before entering the air intake valve.

Table 1: Engine technical data

Engine characteristics	Single cylinder
Bore×stroke (mm)	70×60
Piston displacement (cm^3)	230
Compression ratio	17.6:1
Maximum output [HP (kW rpm^{-1})]	4.8(3.5)/3600
Fuel	Diesel light oil
Fuel tank capacity (L)	3.2
Combustion system	Direct injection

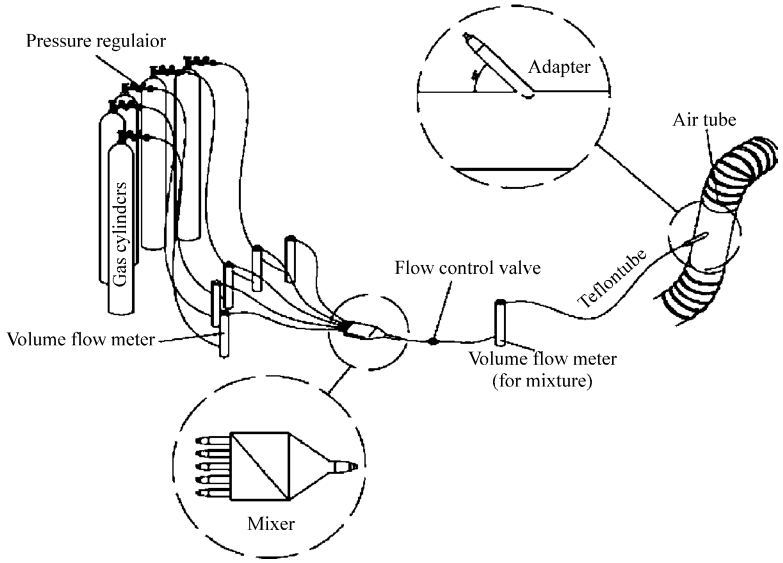

Fig. 1: Syngas fuel supply system

Table 2: Properties of syngas compositions

Syngas	N_2	CO_2	CO	H_2	CH_4	Heating value (kJ kg^{-1})	Density (kg m^{-3})
Composition A[1]	49	12	25	10	4	17146.8	1.10
Composition B[2]	51	6	22	18	3	28140.6	0.94
Composition C[3]	38	8	29	19	6	29773.0	0.93

[1]Ciferno and Marano (2002), [2]Deshmukh *et al*. (2008), [3]Papagiannakis (2007)

Selecting of syngas composition: Due to the fluctuation on syngas composition from biomass gasification, three compositions of syngas have been selected. Composition B and C were being selected from the previous studies to be close to the real condition and composition A has been selected to vary within the range of normal composition of syngas as described by Ciferno and Marano (2002). The syngas compositions are considered to be representative of biomass gasification process. The properties of syngas compositions that were used in the study are given in Table 2 along with the reference where these data have been taken from.

Engine testing with imitated syngas: The engine firstly was initiated at speed of 2000 rpm by adding diesel fuel only through the engine rack, when the imitated syngas was added, the engine speed has increased. Then the engine rack position was decreased to reduce the diesel fuel to obtain engine speed of 2000 rpm again, the reading from the instrumentation unit was recorded at constant engine speed of 2000 rpm and different diesel amount replacements by repeating the previous procedures by adding more syngas and reducing the diesel fuel amount up to obtain 2000 rpm engine speed.

Measurements and calculation: Engine speed is measured electronically by a pulse counting system. Engine torque is measured by a TD115 hydraulic dynamometer and transmitted to a torque meter located on a TD114 instrumentation unit. Exhaust gas temperature is measured by a chrome/alumel thermocouple conforming to BS1827. The thermocouple is located in a 1/8" BSP union brazed into the exhaust pipe close to the cylinder block of the engine.

Equation 1-11 were used to calculate the air flow rate, diesel flow rate, syngas flow rate, air to fuel ratio, syngas density and heating value in order to obtain the performance of the engine.

The specific gravity for diesel was 0.84 kg m^{-3}. Equation 1 was used to calculate the diesel flow rate:

$$\dot{m}_{\text{Diesel}} = \frac{sg_{\text{Diesel}} \times 8 \times 10^{-3}}{t} \times 3600 \tag{1}$$

where, $\dot{m}_{\text{Diesel}}$ is diesel mass flow rate (kg h^{-1}), sg_{Diesel} is diesel specific gravity (kg m^{-3}) and t is the time taken by the engine to consume 8 mL from the diesel fuel.

Air is drawn in through an inlet and flows through an element consisting of thousands of small bore tubes before entering the damping volume. For a given air density the mass flow rate of air is proportional to the average velocity, so that the pressure drop across the viscous element is directly proportional to the flow rate. The pressure drop was measured by an inclined tube manometer, calibrated in millimeters of water.

The temperature and pressure during the experiment were at 27°C and at 1.013 bar, respectively. The air mass flow rate was corrected by:

$$\dot{m}_{a,\,corrected} = \dot{m}_a \times 3546 P_a \times \frac{(T+114)}{T^2} .5 \tag{2}$$

where, $\dot{m}_{a,\ corrected}$ is corrected air mass flow rate (kg h^{-1}), $\dot{m}_a$ is air mass flow rate manometer reading (kg h^{-1}) and P_a is air pressure.

The air to fuel ratio is calculated from values of air and fuel mass flows obtained from the air flow manometer reading and the time to consume 8 mL of diesel fuel and syngas flow rate. Equations 3 and 4 explain how this is done:

$$\dot{m}_{f_{Total}} = \dot{m}_{Diesel} + \dot{m}_{Syngas} \tag{3}$$

$$A/F = \frac{\dot{m}_{a,corrected}}{\dot{m}_{f_{Total}}} \tag{4}$$

Calculation of density of syngas requires a few steps. First, the volume percent of each gas was given in volume basis so it has to be converted to mass fraction basis. Then, the density of the mixture will be the sum of the density of each gas multiplying by the mole fraction. Equations 5, 6, 7 and 8 were used to calculate the syngas density:

$$\dot{m}_g = \dot{V}_g \times \rho_g \tag{5}$$

$$n_g = \frac{\dot{m}_g}{n_T} \tag{6}$$

$$n_g (\%) = \frac{n_g}{n_T} \times 100 \tag{7}$$

$$\rho_{Syngas} = \sum \left(\% n_g \times \rho_g \right) \tag{8}$$

where, ρ_{Syngas} is syngas density, $\dot{m}_g$ is gas mass flow rate, $\dot{V}_g$ is gas volume flow rate, M_g is the gas molecular mass (kg/mole), n_g is number of moles (moles), n_T is total number of moles and ρ_g is density of each gas (kg m^{-3}).

The volume flow rate of syngas was obtained from the flow meter. The mass flow rate of mixture going into the engine was then calculated from Eq. 9:

$$\dot{m}_{Syngas} = \dot{V}_{Syngas} \times \rho_{Syngas} \tag{9}$$

where, $\dot{m}_{Syngas}$ is syngas mass flow rate (kg h^{-1}) and $\dot{V}_{Syngas}$ is syngas volume flow rate (m^3 h^{-1}).

The heating value of each syngas composition is calculated from the summation of heating value multiplying by the mole fraction of each gas as shown in Eq. 10:

$$HV_{Syngas} = \sum (\% n_g \times HV_g) \tag{10}$$

where, HV_{Syngas} is the syngas heating value, $\% n_g$ is the percentage of each gas in number of moles basis and HV_g is the heating value of each gas.

In this study, the heating value of examined syngas compositions were calculated according to the percentage of syngas constituents.

Diesel replacement ratio is calculated from the diesel consumption at diesel mode and the diesel consumption at dual fuel mode as shown in Eq. 11. The 0% R_D means the engine running with diesel fuel alone:

$$R_D\,(\%) = \frac{\dot{m}_{Diesel} - \dot{m}_{DF}}{\dot{m}_{Diesel}} \times 100 \tag{11}$$

where, R_D is diesel replacement ratio, $\dot{m}_{Diesel}$ is diesel mass flow rate at pure diesel fuel mode (kg h^{-1}) and $\dot{m}_{DF}$ is diesel mass flow rate at syngas dual fuel mode (kg h^{-1}).

RESULTS AND DISCUSSION

The test results on performance for syngas are compared with the results for diesel fuel only. The performance results of both fuels are examined in terms of the engine's exhaust temperature, brake power, brake specific fuel consumption, brake thermal efficiency, equivalence ratio and volumetric efficiency. Three compositions of syngas have been selected to resemble the real conditions and all the results varied as a function of diesel replacement ratio.

Figure 2 shows the exhaust gas temperature for the selected syngas compositions at engine speed of 2000 rpm. Exhaust gas temperature decreases as the amount of syngas increases for all syngas compositions due to the lower heating value of syngas compared to the one of diesel fuel. Therefore composition C showed the highest exhaust temperature due to its higher heating value compared to other compositions.

Even though composition B has a higher heating value than composition A, it exhibits a lower exhaust temperature. This because the combustion of composition B occurred earlier than that of composition A therefore causing a low exhaust temperature or due to limited presence of carbon monoxide and methane in the composition.

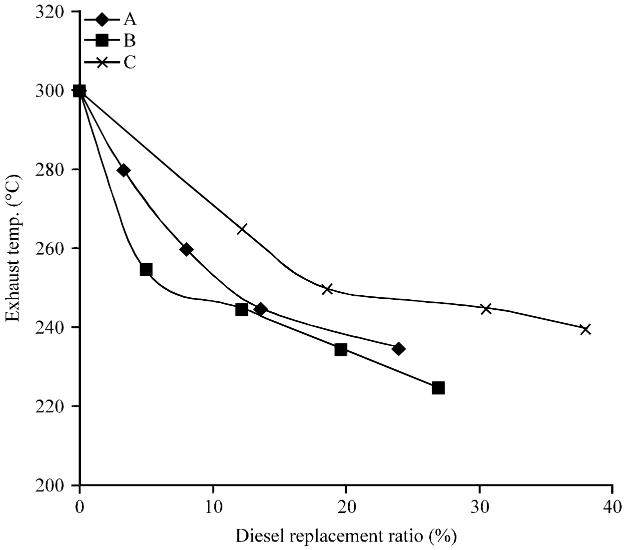

Fig. 2: Variations of exhaust gas temperature as function of diesel replacement ratios

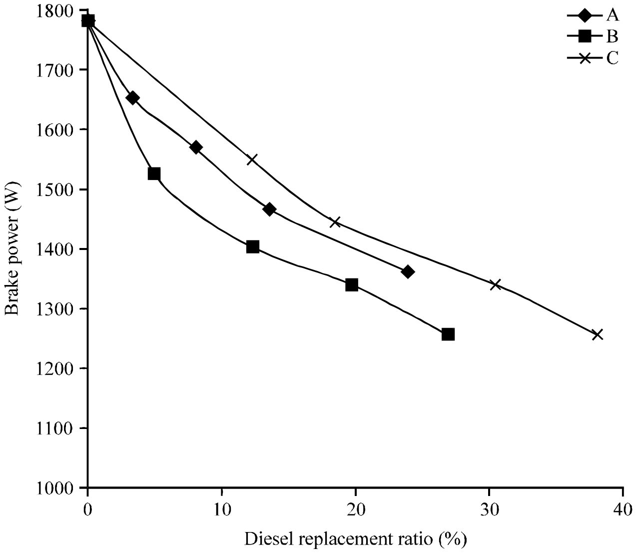

Fig. 3: Variations of brake power as function diesel replacement ratios

Likewise, highest exhaust gas temperature from composition C due to high presence of carbon monoxide and methane. Meanwhile, composition A and B showed lower exhaust gas temperature as a result of reduction in the presence of carbon monoxide and methane.

Variation of engine brake power as function of diesel replacement ratios is given in Fig. 3 for different syngas compositions at engine speed of 2000 rpm. The brake power in pure diesel fuel mode (RD = 0%) was higher than in syngas dual fuel mode due to the higher heating value of diesel than syngas. Therefore composition C produced the highest power output.

Although, composition B has a higher heating value than composition A, composition A produced higher power output than composition B due to its higher density compared with composition B. Furthermore; a pronounced improvement of brake power apparently is caused by adding more amount of carbon monoxide and methane which led to production of high power output for composition C, then B and A, respectively.

It is observed that from Fig. 3, the engine was able to run at higher diesel replacement ratio with composition C without penalty in brake power compared to other compositions. This is largely due to the lowest density of composition C compared to other compositions ensuring the availability of enough amount of oxygen to complete the combustion process without any penalty.

Figure 4 shows the brake specific fuel consumption versus diesel replacement ratio for the selected syngas compositions at engine speed of 2000 rpm. Because the heating value of syngas is lower than that of diesel fuel used, it is concluded that syngas require high fuel consumption, thus leading to high brake specific fuel consumption.

Composition A has the highest brake specific fuel consumption due its lower heating value. While other compositions B and C, respectively showing lower brake specific fuel consumption due to the rising in the heating value.

Brake thermal efficiency is the ratio between the power output and the energy introduced through fuel injection. Thus the inverse of brake thermal efficiency is brake specific fuel consumption. Besides their heating values, brake thermal efficiency is more appropriate to compare the performance of different fuels. Figure 5 depicts the behavior of the brake thermal efficiency

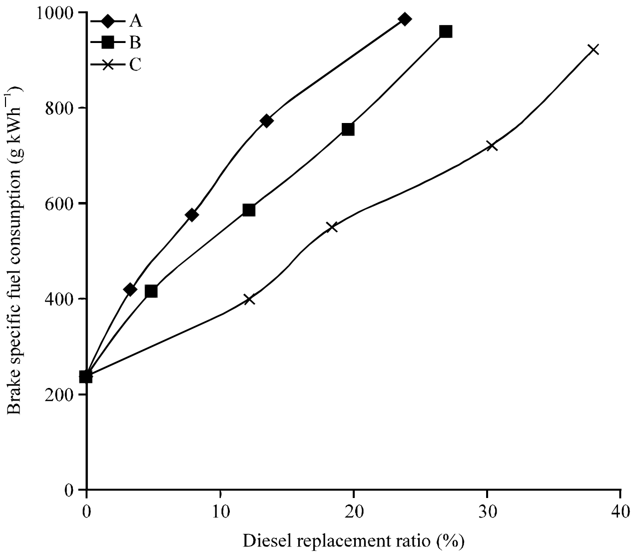

Fig. 4: Variation of brake specific fuel consumption as function of diesel replacement ratios

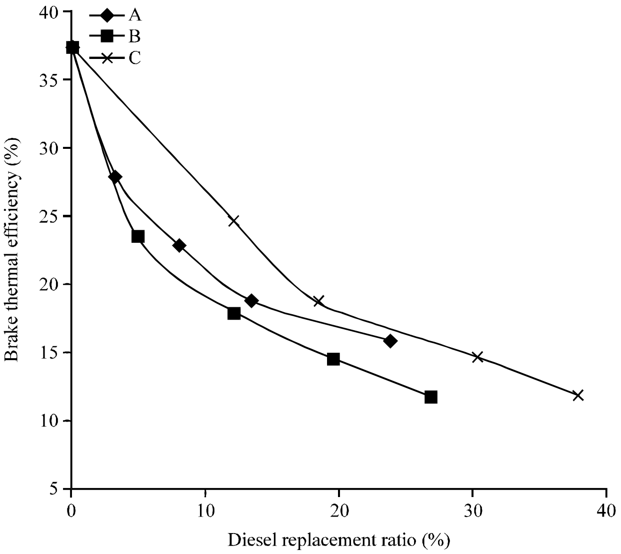

Fig. 5: Variation of engine brake thermal efficiency as function of diesel replacement ratios

with the diesel replacement ratios for the three selected syngas compositions at engine speed of 2000 rpm. The engine showed high brake thermal efficiency with pure diesel fuel due to its higher heating value. Syngas dual fuel engines generally have low thermal efficiencies due to the presence of CO_2 (Duc and Wattanavichien, 2007).

The highest brake thermal efficiency is presented with composition C due to the high presence of carbon monoxide and methane in composition C as compared to composition A and B, respectively.

Fuel air equivalence ratio (Φ) is a more informative parameter for defining mixture composition. For fuel-lean mixtures: $\Phi<1$, for stoichiometric mixtures: $\Phi = 1$ and for fuel-rich mixtures: s$\Phi>1$.

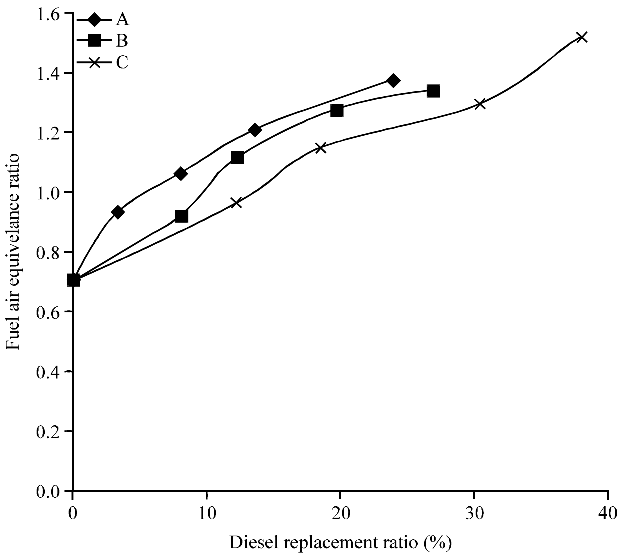

Fig. 6: Variation of fuel air equivalence ratio as function of diesel replacement ratios

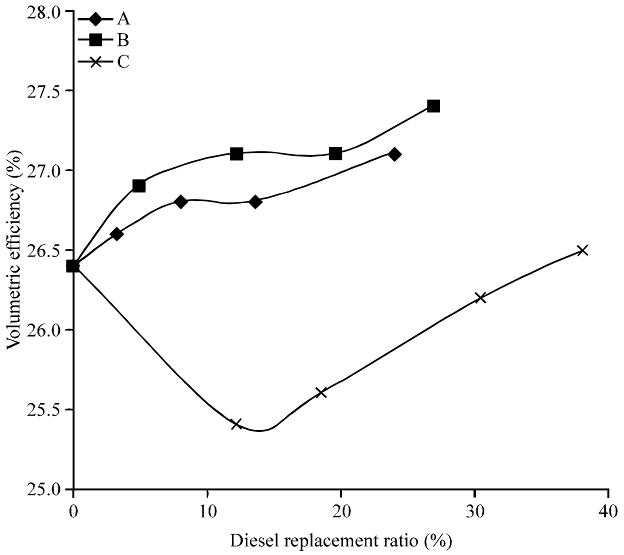

Fig. 7: Variation of engine volumetric efficiency as function of diesel replacement ratios

Figure 6 shows that, fuel air equivalence ratio increases as the diesel replacement ratio increases. This is due to replacing of oxygen by syngas which leads to increase the actual fuel air ratio causing richer combustion.

Figure 7 provides the variation of engine volumetric efficiency as function of diesel replacement ratios at engine speed of 2000 rpm for all syngas compositions examined. Volumetric efficiency is the amount of air that the engine can draw in or specifically the ratio of the actual mass flow of air to the ideal mass flow. In our case, the mixture of syngas and air was swept into the cylinder. The in-cylinder combustion temperatures are lowered in syngas dual fuel mode due to the lower heating value of syngas because less heat will be transferred to the engine parts, so the intake air temperatures decreases and increases the volumetric efficiency. Volumetric efficiency with composition B was the highest as shown in Fig. 7, which means more amount of mixture is sucked into the engine due to its low heating value compared to composition C.

Furthermore, lowest volumetric efficiency with composition C due to high presence of carbon monoxide and methane, while composition A and B, respectively showing higher volumetric efficiency due to lower carbon monoxide and methane presence.

The volumetric efficiency in pure diesel mode was higher than in syngas dual mode for composition C because the inducted amount of air input was greater compared to the inducted amount of mixture at the latter mode. This is the consequence of low density of composition C which led to a decrease in the mixture density and volumetric efficiency.

CONCLUSIONS

A system to operate a naturally-aspirated, two-stroke, single cylinder 5 hp compression ignition diesel engine with imitated syngas and diesel was assembled and run successfully. The main conclusions from the study are as follows:

- Dual fuel combustion using syngas as a supplement for diesel fuel leads to lower power output, exhaust gas temperature and brake thermal efficiency depending on the presence of carbon monoxide and methane in syngas composition
- The engine operating on composition C with highest diesel replacement of 38% showed the highest brake power output and the lowest brake specific fuel consumption without any penalties
- Engine performance depends more on the presence of syngas constituents which affect on density and heating value of the syngas

Regarding to the fluctuation of syngas composition in actual gasification system described above, using the product of biomass gasification from the gasifier directly into the compression ignition engines is not desirable because unstable performance will be obtained from the engine. In order to solve this problem, this research aims at studying of the diesel engine performance fueled with both imitated syngas and diesel. Thereby the stability problem will be solved and engine performance will be improved by knowing the most appropriate composition of syngas and diesel replacement ratio to operated compression ignition diesel engines without any penalties.

ACKNOWLEDGMENT

The authors are grateful for the contributions of Mr. M. Hazri B.A. Shahpin, technician at the Power Generation Laboratory in Universiti Teknologi PETRONAS.

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