Combustion and Performance of Syngas Dual Fueling in a CI Engine with Blended Biodiesel as Pilot Fuel

Bahaaddein K. M. Mahgoub,[a,]* Suhaimi Hassan,[a] S. A. Sulaiman,[a] R. Mamat,[b] A. Abdul Adam,[b] and Ftwi Y. Hagos [b]

Simulated syngas produced from biomass gasification was evaluated in a compression ignition (CI) engine under a dual fueling mode. Syngas is an economical solution with a carbon-neutral system that could replace petroleum diesel fuel. Syngas can be introduced into CI engines through a dual fueling process. However, syngas dual fueling combustion is very complicated because it consists of several combustion phases. In addition, CI engines operating under the syngas dual fueling mode suffer from low performance. Therefore, this study examined the performance of syngas dual fueling in a CI engine with blended biodiesel as pilot fuel. Two types of simulated syngas, namely typical syngas and high hydrogen syngas, were considered. The simulated high hydrogen syngas was assumed to be the product of biomass gasification with introduction of a carbon dioxide adsorption. The effect of carbon dioxide removal from syngas on the performance of syngas dual fueling in a CI engine at constant engine speed, half load, and different pilot fuel substitution rates was investigated. The combustion characteristics showed a maximum pilot fuel substitution of up to 47% with simulated syngas. Better engine performance was achieved with the simulated typical syngas in terms of brake specific energy consumption and brake thermal efficiency.

Keywords: Dual fuel; Syngas; Biodiesel; Combustion; Performance; Compression ignition

*Contact information: a: Department of Mechanical Engineering, Universiti Teknologi PETRONAS, 31750 Tronoh, Perak, Malaysia; b: Faculty of Mechanical Engineering, Universiti Malaysia Pahang, 26600, Pekan, Pahang, Malaysia; *Corresponding author: m.bahaa02@uofk.edu*

INTRODUCTION

The internal combustion engine (ICE) is a very important lightweight power source that generates useful power or heat. The operation of this particular engine requires attention for further improvement in its combustion and performance characteristics. The ICE has generally been dependent on fossil fuel to generate power. However, the current depletion of fossil fuel has resulted in the exploration of alternative fuels that also affect economic development and environmental protection. Gaseous fuels from biomass gasification are effective substitutes for fossil fuels due to their capability to generate cost-effective power, which produces very low level of greenhouse gases when combusted in an ICE (Henham and Makkar 1998; Bika 2010). Power production from biomass conversion is a cost-effective economical solution to produce power due to the availability of suitable renewable biomass feedstock for the gasification process (Bika 2010).

Synthesis gas or syngas is the product of solid biomass feedstock conversion, which is a mixture of about 40% combustible gases and 60% noncombustible gases. The conversion process, *i.e.*, gasification, involves incomplete combustion of biomass feedstock. The combustible biomass gases are mainly a combination of carbon monoxide

(CO) and hydrogen (H_2), with only a small amount of methane (CH_4). The non-combustible gases are mainly made up of nitrogen (N_2); however, a significant percentage of carbon dioxide (CO_2) is also included (Shilling and Lee 2003). Different types of feedstock can be used for syngas production; hence, fluctuating syngas compositions are produced (Bika 2010; Hagos *et al.* 2013; Hagos *et al.* 2014).

Biodiesel is a fuel that can be used as a substitute for petroleum diesel, and it is produced from biodegradable and toxic free biological materials such as vegetables and animal fat (Zhang *et al.* 1998). Biodiesel represents the long-chain fatty acids as monoalkyl ester oxygenated fuel (Ong *et al.* 2011). Biodiesel is an environmentally friendly fuel because it produces lower levels of carbon and smoke when combusted in a CI engine (Murayama *et al.* 1984). The use of higher cetane number of the biodiesel has made it possible to increase its level of substitution in blended fuel for CI engines (Ong *et al.* 2011). Furthermore, biodiesel is not aromatic, and it contains around 10 to 11% oxygen on a mass basis. Therefore, biodiesel can be utilized in a diesel engine with little or no modification of the equipment (Ong *et al.* 2011). However, biodiesel has a higher viscosity, which can lead to injector coking, biodiesel cloud point, and pour point that are higher than with petroleum diesel fuel. The disadvantage of biodiesel is its lower heating value or energy content compared with petroleum diesel (Ng *et al.* 2011). In addition, biodiesel produces reduced performance with a higher level of nitrogen oxides (NOx) emission when combusted in CI engine, compared to petroleum diesel fuel. Furthermore, biodiesel is less efficient than petroleum diesel, and its price is high (Nettles-Anderson and Olsen 2009).

Dual fuel combustion is very complicated, as the process involves several modes of combustion. The diesel fuel auto-ignites first, followed by the gaseous fuel mixture flame propagation, in which the mixture auto-ignites at the end gas. The operation of a syngas-diesel-dual fuel engine negatively affects the engine’s efficiency due to the lower heating value of syngas as compared to petroleum diesel. Therefore, improvements are highly needed to optimize the dual fuel combustion of syngas-diesel fuels in CI engines in order to achieve a better performance. The effect of using blended diesel-palm oil biodiesel and syngas fuel on the combustion performance of a CI engine operating under dual fuel mode was studied as an alternative to improve engine efficiency.

In a dual fuel process, two different fuels are used to operate the engine, namely primary gaseous fuel and secondary pilot fuel. The gaseous fuel, such as gasification gas, hydrogen, or natural gas, is mixed with air and carbureted into the air intake. The mixture is then compressed inside the combustion chamber similar to the normal CI engines, and it is combusted after injecting a small amount of pilot fuel at the end of the compression stage (Lambe and Watson 1992; Bika *et al.* 2009; Saravanan and Nagarajan 2009). The combustibility of the two used fuels in the dual fuel mode provides substantial energy with stable ignition. Furthermore, the combustion system can be exchanged from the dual fuel to the normal pilot mode at any time. The dual fuel concept is a possible way for using gasification gas in CI engines, but most of the recently developed dual fuel engines use the spark ignition (SI) system for combustion purposes (Von Mitzlaff 1988; Ando *et al.* 2005; Pushp and Mande 2008). Dual fuel combustion in SI engines is not stable, especially at a high engine load due to gasification gas fluctuation. Therefore, dual fuel combustion cannot be applied to all diesel engines. For example, knocking and ignition delay occur when gasification gas is combusted in diesel engines with high compression ratios due to very high pressures (Kaupp and Goss 1981). Furthermore, direct injection (DI) diesel engines can be normally converted into dual fuel engines, due to its low compression ratios.

Among the engine side modifications adopted in diesel engines, dual fueling is popular in recent research. Dual fueling is mainly preferred over the others due to combustion temperature stabilization and controlling of emissions. Few researchers have performed syngas dual fueling in CI engines operating with other pilot fuels such as biodiesel instead of petroleum diesel. Ramadhas *et al.* (2008) used producer gas from coir-pith for the dual fueling of a CI engine running with rubber seed oil as the pilot fuel. The purpose was to investigate the engine performance at different substitution rates and load cases. It was found that specific energy consumption is higher when the engine operates under the dual fueling process rather than the single diesel operation for all load levels. At higher levels of engine loading, the achieved pilot fuel substitution rate was greater.

Honge oil and honge oil methyl ester (HOME) have also been used as pilot fuels in a CI engine under producer gas dual fueling (Banapurmath *et al.* 2008; Banapurmath and Tewari 2009). The study was conducted to evaluate the performance of producer gas dual fueling in a CI engine operating with honge oil and HOME, with and without a gas carburetor for various injection pressure and timing. The engine performance improved with the combination of all the tested fuels and the application of a producer gas carburetor. Timing is important in this process; thus improved engine efficiency was obtained when the injection timing was advanced, with or without the producer gas carburetor. Operating the engine under producer gas dual fueling with HOME as the pilot fuel produced higher efficiency than using honge oil, but still lower than a petroleum diesel operation.

Deshmukh *et al.* (2008) investigated the performance of producer gas dual fueling in a CI engine operating with diesel and esters of hingan oil as the pilot fuel for different load cases and pilot fuel substitution rates. The engine performance was analyzed with the use of producer gas produced from biomass gasification (hingan shell). Higher specific energy consumption was noticeable with an engine dual fueling operation rather than a single liquid fuel operation for all load levels, but the part loading case was the best for the dual fueling case. The engine thermal efficiency was lower with the producer gas dual fueling, when compared to the normal liquid operation, be it diesel or HOME.

In the study conducted by Singh *et al.* (2007), producer gas dual fueling showed better thermal efficiency when biodiesel was used in a CI engine as the pilot fuel, rather than diesel at two different compression ratios. Biodiesel was produced from three different sources including jatropha, karanja, and rice bran oil. The use of the rice bran oil as the pilot fuel has resulted in higher brake thermal efficiency with a lower NOx emission compared with other biodiesel sources, either in single fueling mode or in a producer gas dual fueling operation. The maximum pilot fuel substitution up to 86% was obtained with the producer gas dual fueling operation when biodiesel was used as the pilot fuel. A higher pilot fuel substitution rate (78.34%) was presented with producer gas dual fueling when biodiesel from karangan oil was used as the pilot fuel at medium engine load (63%).

Hassan *et al.* (2011) conducted an experimental study to compare the performance when different blends of vegetable oil and diesel were used as pilot fuel rather than diesel, under a producer gas dual fueling operation with the variations of engine load and pilot fuel injection timing. The engine operation with blended vegetable oil and diesel under producer gas dual fueling led to lower brake thermal efficiency and diesel replacement ratio, including higher specific energy consumption, compared with the engine operating with diesel as the pilot fuel under producer gas dual fueling.

The main objective of this study was to investigate the effect of CO_2 removal from syngas on the performance characteristic of syngas dual fueling in a CI engine operating with B50 as the pilot fuel. A simulated syngas was used rather than a producer gas obtained from real biomass gasification because the constituents of syngas are affected by many factors during the gasification process. Hence, it would be difficult to examine the effect of using real syngas in a CI engine under a dual fueling operation. The CO_2 component was excluded from the simulated syngas because it does not support the combustion but instead absorbs more heat released, which reduces the cylinder gas temperature as well as the engine performance.

EXPERIMENTAL

Setup

This section describes the engine test bed and equipment utilized in this study. It also includes the fuel selection, fuel preparation, and device calibration. Moreover, engine testing operation conditions along with testing fuel matrix and theory and calculation that were used to obtain the test data are presented in detail.

Engine test bed

A single cylinder water cooled direct injection four stroke CI engine was used in this study. The engine specifications are listed in Table 1.

Table 1. Engine Technical Data

Parameters	Specification
Continuous Rating Output	10.5hp @ 2400 rpm
1-Hour Rating Output	12.0hp @ 2400 rpm
Cylinders	1
Combustion	Direct Injection
Cooling System	Water - Radiator
Injection timing	BTDC 17°
Maximum torque kg.fm / rpm	4.42 / 1800
Compression ratio	17.7
Specific fuel consumption g/hp.hr	169 @ 2400 rpm
Bore x Stroke	92 x 96 mm
Displacement	0.638 L
F.O. tank capacity	11.0 L

The engine was coupled to a hydraulic gear pump, which acted as a dynamometer to brake the engine. The load exerted on the engine was obtained through the hydraulic pressure reading by using a pressure gauge located in between a screw type valve and the gear pump. An 'S' type load cell was mounted to the lever arm that was bolted to the dynamometer in order to measure the brake torque exerted by the engine.

An external fuel tank, made from two 1-L beakers, was used to supply the tested liquid fuel to the engine fuel pump. The liquid fuel was supplied into the fuel pump through a transparent 3/4" hose from the beaker to ensure that the flow of the fuel could easily be observed during the experiment. The fuel tanks were placed at a height of one meter above the injector to enable the fuel to flow into the fuel pump by gravitational force. The liquid fuel flow rate was determined by measuring the time taken for the engine to consume 5 mL of fuel. The air intake was modified by removing the air tank and pipes connected to reduce the air pressure losses and increase the volumetric efficiency, long pipe was connected to introduce the air-syngas mixture into the engine through the air intake. Higher volumetric efficiency was obtained after the air intake modification.

The engine's combustion characteristics were determined by using a cylinder pressure sensor mounted to the engine head using a customized adapter. A magnetic type crank angle sensor mounted to the engine was used to measure the crank angle for every crank rotation. The pressure and crank angle sensors were connected to a sensor interface and data logger, respectively. The engine speed was measured by using a photoelectric sensor through the flywheel rotation, and the reading was displayed through a digital tachometer. For the temperature measurements, the engine was fitted with three units of type-K thermocouples to measure the intake, exhaust, and ambient temperatures. The experiment test bed is shown in Fig. 1.

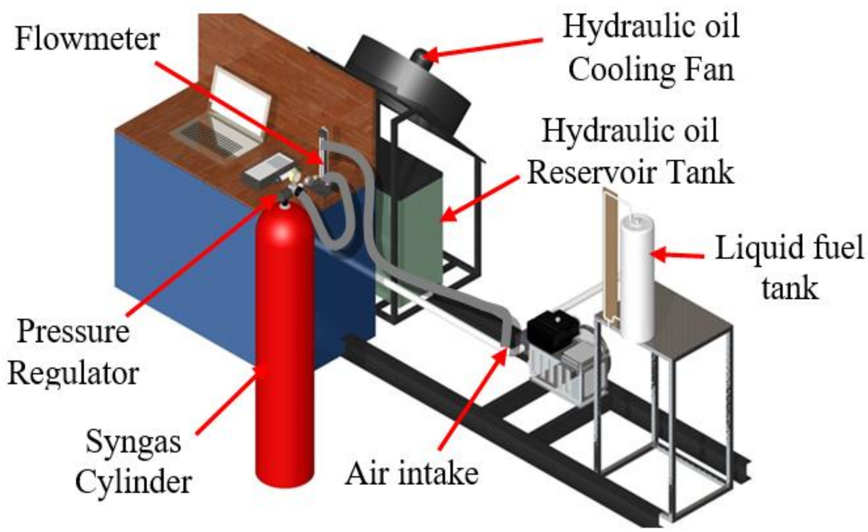

Fig. 1. Experimental test bed

To deliver a homogeneous syngas air mixture into the combustion chamber, various mixing system designs were reviewed, and the design of the mixing device recommended by Von Mitzlaff (1988) was selected. An air-gas mixing device was developed and connected into the engine setup for syngas dual fueling operation. It was composed of two pipes in a T shape; the gas pipe protruded into the air/gas pipe with an oblique cut in order to increase the active pressure drop for the gas to flow into the mixing device. The oblique cut was facing the engine inlet. A turbulence grid was attached to the mixer to enhance the mixing process.

Additional components, such as a non-return valve, pressure regulator, and flow meter, were incorporated into the diesel engine setup to control the supply of syngas for the dual fuel operation. The syngas flow rate was calibrated by using a Defender 510 calibrator (Bios International Corporation, Butler, NJ, USA) connected to a water displacement tank.

Fuel preparation and tested fuel matrix

The four different types of fuels included petroleum diesel, biodiesel, and two compositions of simulated syngas. The biodiesel was a commercial fuel derived from palm oil. Properties of used biodiesel fuel is shown in Table 2.

Table 2. Properties of Biodiesel Fuel

Properties	**Value**
Fuel	Biodiesel
Density @ 15 °C (kg/L) ASTM D4052 (1988)	0.875
Sulfur content (wt.%) IP 242/83 (1995)	< 0.04
Viscosity at 40 °C (CST) ASTM D445 (2009)	4.5
Pour point (°C) ASTM D97 (1996)	+ 15
Flash point (°C) ASTM D93 (2002)	174
Cetane number ASTM D613 (2008)	62.4
Gross heat of combustion (kJ/kg) ASTM D4809 (2013)	40,335
Conradson carbon residue (%wt) ASTM D189 (2014)	0.02

Two syngas compositions were used in this study. The main composition was selected to represent the typical syngas produced from the biomass gasification, and the second was selected to represent a syngas with a high hydrogen content produced through the biomass gasification and CO_2 removal processes. The density (ρ), lower heating value (LHV) and low flammability limit (LFL) of each syngas composition were calculated based on the syngas constituents. The properties of selected syngas compositions are presented in Table 3.

Table 3. Properties of Selected Syngas Compositions

	Syngas components (%)					Syngas Properties			
	CO	H_2	CH_4	CO_2	N_2	ρ (kg/m^3)	LHV (kJ/kg)	LFL (%)	C:H:O content
Typical syngas	15.00	33.00	3.00	14.00	35.00	1.32	6849.61	9.90	18.0 : 3.7 : 32.3
High H_2 syngas	16.57	42.61	3.85	0.00	36.97	1.09	10949.97	7.81	14.6 : 6.1 : 16.1

Table 4. Test Fuels Matrix

Case Number	Pilot fuel	Gaseous fuel	Composition of gaseous fuel (%)					ϕ
			CO	H_2	CH_4	CO_2	N_2	
I.	Diesel	-	-					0.2
II.	B50	-	-					0.3
III.	B50	Typical syngas	15.00	35.00	3.00	13.00	34.00	0.7, 1.1, 1.5, 1.9
IV.	B50	High H_2 syngas	16.57	42.61	3.85	0.00	36.97	0.6, 1.0, 1.4, 1.8

Petroleum diesel fuel was used for basic engine testing under a normal diesel operation without any modification being made to the engine. A blend of B50 was the pilot fuel for the engine operation under syngas dual fueling. The amount of syngas provided for the dual fueling process was controlled to vary the equivalence ratio. The increase of pilot fuel substitution is related by an increase of the total fuel/air equivalence ratio, as the increased mass flow rate of the syngas introduced into the air intake considerably decreases the inhaled air for combustion. Therefore, the fuel/air equivalence ratio was used to represent the pilot fuel substitution in order to take into account both the syngas and diesel fuel masses. The test fuels matrix is given in Table 4.

Engine Test and Operation Conditions

The ambient temperature and humidity were recorded for all examined test cases to correct the performance readings based on the SAE J1349 (1995). The air inlet temperature was maintained at 25 °C, and the fuel line temperature was approximately 40 °C. Measurements were recorded at 1850 rpm and a constant half load with variation made to the fuel/air equivalence ratio (ϕ) under both a normal liquid fuel operation (PF_{SR} = 0%) and syngas dual fuel operation (PF_{SR} > 0%).

The engine was started at 1850 rpm under pure liquid fuel operation. The engine speed was increased when a small amount of syngas was provided for the dual fuel mode operation. The liquid fuel was controlled to return the engine speed to 1850 rpm, and all measurements were recorded. The previous steps were repeated by providing higher amounts of syngas fuel for the variation of the PF_{SR}.

RESULTS AND DISCUSSION

The combustion and performance characteristics of the CI engine operating at the constant engine speed of 1850 rpm, half load, and injection timing of 17° BTDC under syngas dual fueling are presented for two types of syngas composition and different equivalence ratios. The main focus of the study was to experimentally investigate the effect of CO_2 removal from syngas on the performance characteristics of syngas dual fueling in a CI engine operating with blended diesel-biodiesel fuel. The effect of syngas dual fueling on the following parameters was examined: cylinder pressure, heat release rate, maximum combustion pressure (P_{max}), and ignition delay. In addition, the brake specific energy consumption (BSEC), brake thermal efficiency (BTE), and exhaust temperature ($T_{exh.}$) were observed in relation to the engine performance.

Measured Data Accuracy and Repeatability

Measurements were repeated five times for each point either for the operation under normal liquid mode or dual fuel mode in order to determine the repeatability and accuracy of the measured data. The devices were calibrated before the engine test to minimize error and to achieve a good research basis. The syngas flowmeter was calibrated using a water displacement container and “Defender 510” calibrator in order to minimize the measurement error for the fuel consumption and engine performance. The mean values were calculated from all of the repeated measurements for all of the examined parameters. Next, the coefficient of variation (COV) for each measured parameter was determined to estimate the accuracy of the measurements. Considering the COV values, it was detected that the measurements were accurate because the COV for the maximum combustion pressure, fuel consumption, and exhaust temperature measurements were 0.69%, 1.67%, and 0.18%, respectively.

Effect of Syngas Dual Fueling on the Combustion Characteristics

The analysis of in-cylinder pressure and heat release rate data obtained during the operation of a CI engine with modified air intake under syngas dual fueling with introducing blended fuel (B50) and two different compositions of syngas at different equivalence ratios are presented in this section.

Figure 2 presents the in-cylinder pressure and heat release rate traces of diesel and blended fuel B50 as well as B50 with different syngas compositions at 1850 rpm and 50% load. A total of 200 consecutive cycles were averaged to reduce the engine cyclic variation effects.

The in-cylinder pressure and heat release rate traces for blended fuel B50 with typical syngas at different equivalence ratios (0.7, 1.1, 1.5, and 1.9) are shown in Fig. 2 (a). The maximum pressure was 65.32 bar for the diesel, while it increased to 67.42 bar for blended fuel B50.

The increase in the maximum in-cylinder pressure (3.21%) was due to the high oxygen content and cetane number of blended fuel B50. Similar results were obtained from previous studies (Qi *et al.* 2010; Sharon *et al.* 2012; Yasin *et al.* 2014), which reported that maximum in-cylinder pressure increased with the increase of palm oil biodiesel ratio in the blended fuel.

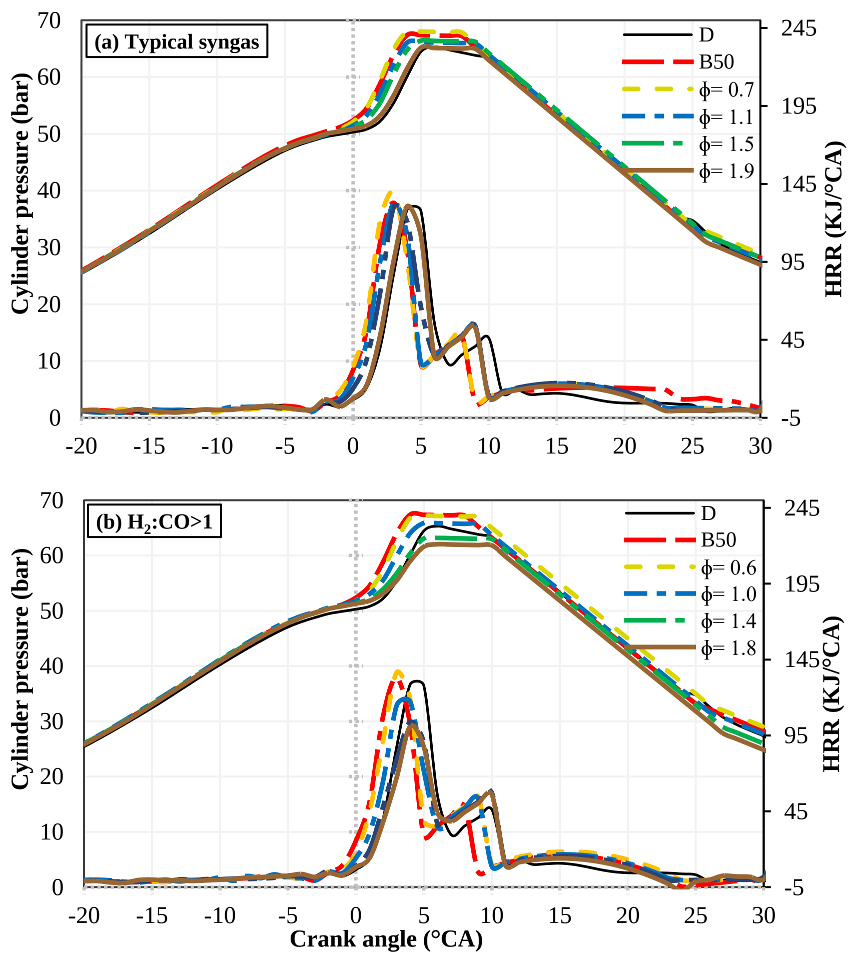

Fig. 2. In-cylinder pressure and HRR for typical syngas and syngas containing H_2:CO > 1

For the engine operation under dual fuel mode with blended fuel B50 and typical syngas, the in-cylinder pressure was reduced to 66.6 bar at an equivalence ratio of 0.7. Further reductions in the maximum in-cylinder pressure occurred with increased syngas concentration, with its lowest value of 63.6 bar at the maximum examined equivalence ratio of 1.9. The reduction in the maximum in-cylinder pressure at an equivalence ratio of 1.9 was about 2.63% compared with the normal diesel operation. This result indicated a lower heating value at higher syngas concentration and lower oxygen content.

Figure 2 (b) shows the in-cylinder pressure and heat release rate traces for the engine operation under dual fuel mode with blended fuel B50 and syngas containing H_2 : CO > 1 at different equivalence ratios (0.6, 1.0, 1.4, and 1.8). The in-cylinder pressure was reduced to 65.4 bar for equivalence ratio of 0.6. Further reductions in the maximum in-cylinder pressure occurred with increased syngas concentration, with its lowest value of 60.5 bar at the maximum examined equivalence ratio of 1.8. The reduction in the maximum in-cylinder pressure at equivalence ratio of 1.8 was about 7.38% compared with the normal diesel operation.

The heat release rate (HRR) is an informative parameter used to investigate combustion in CI engines (Heywood 1988). However, the estimations for both combustion duration and ignition delay were obtained from the heat release data by calculating the in-cylinder pressure results.

The combustion process when diesel and simulated typical syngas were used to run a CI engine with modified air intake under dual fuel mode occurred in three stages, including premixed combustion of the diesel and part of the simulated typical syngas, followed by premixed combustion of the simulated typical syngas and the rest of the diesel fuel; the process then ended by the diffusion stage. Negative heat release values were observed in all examined cases due to the heat transfer onto the cylinder surfaces and the cooling effect that caused by the liquid fuel injection.

Figure 2 shows that the maximum heat release rate was higher during the normal blended fuel B50 operation compared with the normal diesel operation. As shown in Fig. 2 (a), the maximum heat release rate during the first stage for the engine operation under dual mode with blended fuel (B50) and simulated typical syngas at minimum examined equivalence ratio of 0.7 was similar to the one at normal engine operation with blended fuel (B50) only. The maximum heat release rate during the first stage started to decrease with increase of simulated typical syngas inside the combustion charge, recording its lowest value of 130.77 kJ/kg. The syngas combustion improved during the second stage and diffusion stage where the maximum heat release rate was higher for the engine operation under dual mode with blended fuel (B50) and simulated typical syngas rather than with blended fuel (B50) only.

Figure 3 shows the variation of maximum in-cylinder pressure (P_{max}) for normal diesel operation (ND), normal blended B50 operation and dual fuel operation with blended B50 and the examined simulated syngas compositions at various equivalence ratios. Typical syngas resulted in higher maximum values of in-cylinder pressure at all examined equivalence ratios compared to the one with blended fuel (B50) and simulated syngas containing H_2 : CO > 1. The reduction in maximum cylinder pressure for engine operation under dual fuel mode with blended fuel (B50) and simulated syngas containing H_2 : CO > 1 was clearer at higher equivalence ratios. This result indicated that hydrogen combustion progressed well at leaner modes (Shrestha and Karim 1999).

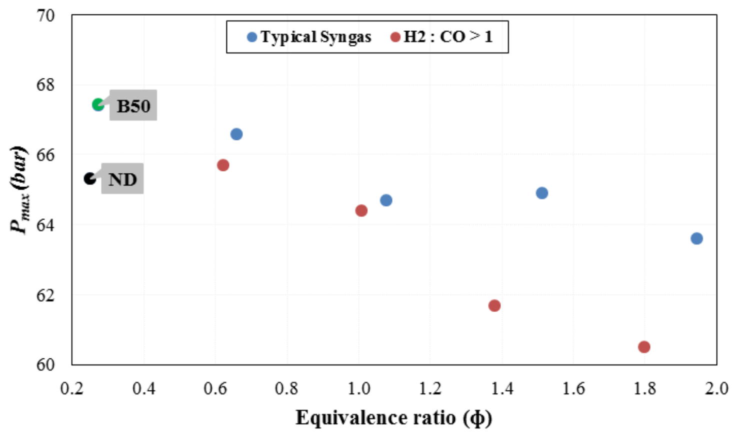

Fig. 3. P_{max} for different equivalence ratios

Effect of Syngas Dual Fueling on Performance of the Engine

The analysis of engine performance for the operation of a CI engine with modified air intake under syngas dual fueling with introducing blended fuel (B50) and two different compositions of syngas at different equivalence ratios was considered in terms of brake specific energy consumption (BSEC), brake thermal efficiency (BTE), and exhaust gas temperature ($T_{exh.}$). BSEC in dual fuel mode was estimated from the brake power output of the engine and the measured mass flow rate of fuels with considering the correction made to the difference in caloric value between the gaseous fuel (simulated syngas) and the pilot fuel (B50). Because comparing two fuels with different calorific values and density by using the brake specific fuel consumption parameter is not reliable, brake specific energy consumption was used to compare the performance of the engine.

Figure 4 illustrates the variation of total brake specific energy consumption as a function of equivalence ratio in a CI engine with modified air intake for normal diesel operation (ND), normal blended B50 operation and dual fueling operation with blended B50 and the examined simulated syngas compositions at 1850 rpm and 50% load. The results showed that diesel fuel had the lowest BSEC of 3.04 kJ/kWh, while it increased to 3.125 kJ/kWh for blended fuel (B50) at the same engine load. This difference in BSEC was due to the high heating value of diesel or the lower energy content of the blended fuel.

BSEC in dual fuel mode increased with the increase of syngas concentration in the combustion chamber. This was mainly due to the lower temperature and air fuel ratio inside the combustion chamber of the engine, resulting in a slower combustion rate, as observed in the heat release rate analysis. The engine operation under dual fuel mode with simulated typical syngas showed lower BSEC than that for simulated syngas containing $H_2 : CO > 1$. This may have been due to the high oxygen content in the simulated typical syngas concentration that accelerated the combustion rate.

BTE is the ratio between the power output and the energy introduced through fuel injection. The BTE is a more appropriate parameter for comparing the performance of different fuels. The variation of the BTE for various equivalence ratios is shown in Fig. 5. The BTE of the blended fuel (B50) was 33%, while it was slightly higher than that of the diesel by about 3.03%. This difference might have been due to the high oxygen content in blended fuel (B50) conentration, which facilitated the combustion. These results were in agreement with previous study (Buyukkaya 2010). BTE in dual fuel mode decreased with increasing syngas concentration in the combustion chamber. This was mainly due to the lower heating value of the two simulated syngas compositions compared with diesel and blended fuel (B50).

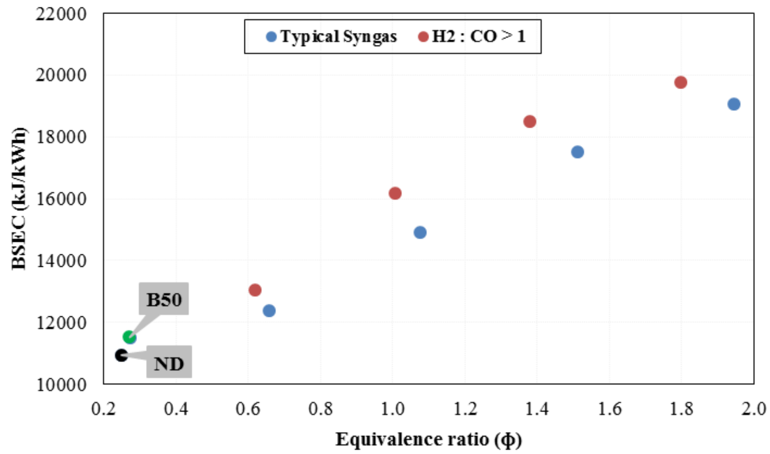

Fig. 4. BSEC for different equivalence ratios

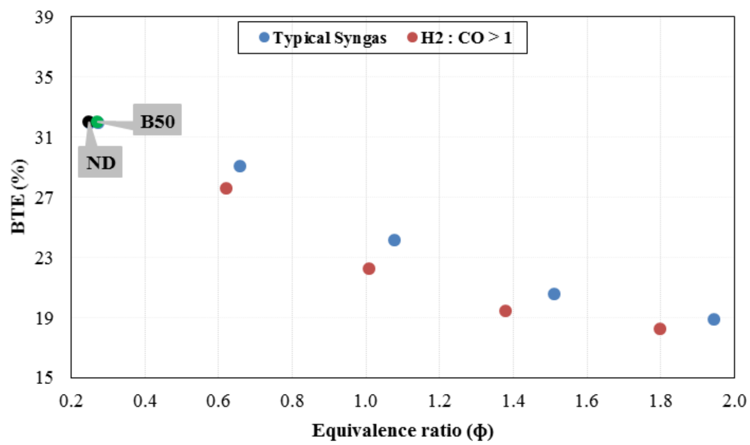

Fig. 5. BTE for different equivalence ratios

The engine operation under dual fuel mode with simulated typical syngas showed lower BTE than that for simulated syngas containing H_2 : CO > 1. This was due to the lowered heating value. The syngas with a high H_2 content showed higher BTE caused by the higher heating value owing to the high presence of H_2 in the syngas composition, which accelerated the flame propagation, extended the lean operational region, and enhanced the combustion stability with the lean operation. A similar result was obtained when the performance of supercharged syngas in a dual-fuel engine with micro-pilot ignition was examined (Tomita *et al.* 2007).

The variation of exhaust temperature for various equivalence ratios is shown in Fig. 6. The normal diesel operation resulted in higher exhaust temperature compared to the normal blended fuel (B50) operation. This was due to oxygen content in blended fuel, which promoted the combustion process and, thus, resulting in increased peak temperature leading to increased exhaust gas temperature.

The results showed that the engine operation under dual fuel mode at medium load led to an increase of the exhaust gas temperature. A high concentration of syngas into the cylinder charge led to an improvement in the conditions inside the cylinder, which affected the existence and spread of the flame front surrounding the burning zone, resulting in a considerable increase in the combustion temperature.

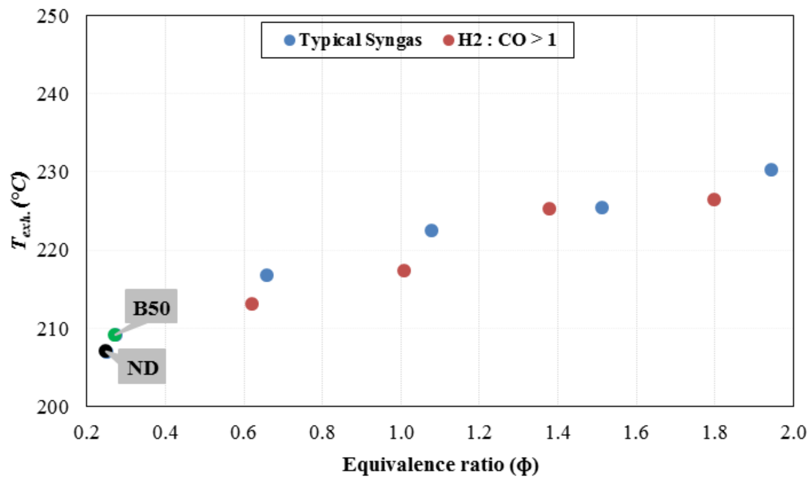

Fig. 6. Exhaust temperature for different equivalence ratios

CONCLUSIONS

1. This study investigated the performance characteristics of normal diesel operation, normal blended fuel (B50) operation and dual fueling operation with B50 and two simulated syngas compositions in a CI engine with modified air intake.
2. The normal engine operation with blended fuel (B50) showed better performance than diesel with 3.03% higher in BTE while the BSEC increased by 0.085.
3. In the dual fuel operation, both examined syngas fuels produced higher maximum combustion pressure rather than diesel operation with an increase of 2.1 bar, while the engine efficiency was negatively affected (reduction).
4. The typical syngas showed better performance than the high H_2 syngas with 7.8% lower BSEC, and 8.4% higher BTE at relative fuel air equivalence ratio of 1.1.

REFERENCES CITED

Ando, Y., Yoshikawa, K., Beck, M., and Endo, H. (2005). "Research and development of a low-BTU gas-driven engine for waste gasification and power generation," *Energy* 30(11), 2206-2218. DOI: 10.1016/j.energy.2004.08.024

ASTM D4052 (1988). "Standard test method for density and relative density of liquids by digital density meter," ASTM International, West Conshohocken, PA.

ASTM D445 (2009). "Standard test method for kinematic viscosity of transparent and opaque liquids (and calculation of dynamic viscosity)," ASTM International, West Conshohocken, PA.

ASTM D97 (1996). "Standard test method of pour point of petroleum products," ASTM International, West Conshohocken, PA.

ASTM D93 (2002). "Standard test methods for flash-point by Pensky-Martens closed cup tester," ASTM International, West Conshohocken, PA.

ASTM D613 (2008). "Standard test method for cetane number of diesel fuel oil," ASTM

International, West Conshohocken, PA.
ASTM D4809-13 (2013). “Standard test method for heat of combustion of liquid hydrocarbon fuels by bomb calorimeter (precision method),” ASTM International, West Conshohocken, PA.
ASTM D189 (2014). “Standard test method for Conradson carbon residue of petroleum products,” ASTM International, West Conshohocken, PA.
Banapurmath, N. R., and Tewari, P. G. (2009). "Comparative performance studies of a 4-stroke CI engine operated on dual fuel mode with producer gas and honge oil and its methyl ester (HOME) with and without carburetor," *Renewable Energy* 34(4), 1009-1015. DOI: 10.1016/j.renene.2008.08.005
Banapurmath, N. R., Tewari, P. G., and Hosmath, R. S. (2008). "Experimental investigations of a four-stroke single cylinder direct injection diesel engine operated on dual fuel mode with producer gas as inducted fuel and honge oil and its methyl ester (HOME) as injected fuels," *Renewable Energy* 33(9), 2007-2018. DOI: 10.1016/j.renene.2007.11.017
Bika, A. S. (2010). *Synthesis Gas Use in Internal Combustion Engines*, Ph.D. Dissertation, University of Minnesota, Minneapolis, MN, USA.
Bika, A. S., Franklin, L. M., and Kittelson, D. B. (2009). “Hydrogen as a combustion modifier of ethanol in compression ignition engines (SAE Technical Paper 2009-01-2814),” *SAE 2009 Powertrains Fuels and Lubricants Meeting*, San Antonio, TX, USA. DOI: 10.4271/2009-01-2814
Buyukkaya, E. (2010). "Effects of biodiesel on a DI diesel engine performance, emission and combustion characteristics," *Fuel* 89(10), 3099-3105. DOI: 10.1016/j.fuel.2010.05.034
Deshmukh, S. J., Bhuyar, L. B., and Thakre, S. B. (2008). "Investigation on performance and emission characteristics of CI engine fueled with producer gas and esters of hingan (*Balanites*) oil in dual fuel mode," *International Journal of Mechanical, Industrial and Aerospace Engineering* 2(2), 206-211.
Hagos, F. Y., Aziz, A. R. A., and Sulaiman, S. A. (2013). "Study of syngas combustion parameters effect on internal combustion engine," *Asian Journal of Scientific Research* 6(2), 187-196. DOI: 10.3923/ajsr.2013.187.196
Hagos, F. Y., Aziz, A. R. A., and Sulaiman, S. A. (2014). "Trends of syngas as a fuel in internal combustion engines," *Advances in Mechanical Engineering* 6, 401587. DOI: 10.1155/2014/401587
Hassan, S., Zainal Z. A., Aizat, S., and Miskam, M. A. (2011). "The effects of supercharging on the performance and exhaust gas emissions of a dual-fuel engine fueled with producer gas-diesel and palm oil blends," *Middle-East Journal of Scientific Research* 7(2), 162-169.
Henham, A. and Makkar, M. (1998). "Combustion of simulated biogas in a dual-fuel diesel engine," *Energy Conversion and Management* Vol. 39, No. 16-18, pp. 2001-2009.
Heywood, J. B. (1988). *Internal Combustion Engine Fundamentals*, McGraw-Hill, New York, NY, USA.
IP 242/83 (1995). “Determination of sulfur content in petroleum products by the flask combustion method,” Institute of Petroleum, London, UK.
Kaupp, A., and Goss, J. (1981). *State-of-the-art Report for Small Scale (to 50 kw) Gas Producer-engine Systems (No. PB-85-102002/XAD)*, University of California-Davis, Davis, CA, USA.

Lambe, S. and Watson, H. (1992). "Low polluting, energy efficient CI hydrogen engine," *International Journal of Hydrogen Energy* 17(7), 513-525. DOI: 10.1016/0360-3199(92)90151-L

Murayama, T., Oh, Y.-t., Miyamoto, N., Chikahisa, T., Takagi, N., and Itow, K. (1984). "Low carbon flower buildup, low smoke, and efficient diesel operation with vegetable oils by conversion to mono-esters and blending with diesel oil or alcohols (SAE Technical Paper 841161)," *1984 SAE International Off-Highway and Powerplant Congress and Exposition*, Milwaukee, WI, USA. DOI: 10.4271/841161

Nettles-Anderson, S. L., and Olsen, D. B. (2009). "Survey of straight vegetable oil composition impact on combustion properties (SAE Technical Paper 2009-01-0487)," *SAE World Congress & Exhibition*, Detroit, MI, USA. DOI: 10.4271/2009-01-0487

Ng, J.-H., Ng, H. K., and Gan, S. (2011). "Engine-out characterisation using speed–load mapping and reduced test cycle for a light-duty diesel engine fueled with biodiesel blends," *Fuel* 90, 2700-2709. DOI: 10.1016/j.fuel.2011.03.034

Ong, H., Mahlia, T., Masjuki, H., and Norhasyima, R. (2011). "Comparison of palm oil, *Jatropha curcas* and *Calophyllum inophyllum* for biodiesel: A review," *Renewable and Sustainable Energy Reviews* 15, 3501-3515. DOI: 10.1016/j.rser.2011.05.005

Pushp, M., and Mande, S. (2008). "Development of 100% producer gas engine and field testing with PID governor mechanism for variable load operation (SAE Technical Paper 2008-28-0035)," *SAE World Congress & Exhibition*, Warrendale, PA, USA. DOI: 10.4271/2008-28-0035

Qi, D., Chen, H., Geng, L., and Bian, Y. Z. (2010). "Experimental studies on the combustion characteristics and performance of a direct injection engine fueled with biodiesel/diesel blends," *Energy Conversion and Management* 51(12), 2985-2992. DOI: 10.1016/j.enconman.2010.06.042

Ramadhas, A. S., Jayaraj, S., and Muraleedharan, C. (2008). "Dual fuel mode operation in diesel engines using renewable fuels: Rubber seed oil and coir-pith producer gas," *Renewable Energy* 33(9), 2077-2083. DOI: 10.1016/j.renene.2007.11.013

SAE J1349_200803 (1995). "Engine power test code – Spark ignition and compression ignition – Net power rating," SAE International, Warrendale, PA, USA.

Saravanan, N., and Nagarajan, G. (2009). "An insight on hydrogen fuel injection techniques with SCR system for NOx reduction in a hydrogen–diesel dual fuel engine," *International Journal of Hydrogen Energy* 34(21), 9019-9032. DOI: 10.1016/j.ijhydene.2009.08.063

Sharon, H., Karuppasamy, K., Kumar, D. S., and Sundaresan, A. (2012). "A test on DI diesel engine fueled with methyl esters of used palm oil," *Renewable Energy* 47, 160-166. DOI: 10.1016/j.renene.2012.04.032

Shilling, N. Z., and Lee, D. T. (2003). "IGCC: Clean power generation alternative for solid fuels," *PowerGen Asia*, Ho Chi Minh City, Vietnam, pp. 23-25.

Shrestha, S. O. B., and Karim, G. A. (1999). "Hydrogen as an additive to methane for spark ignition engine applications," *International Journal of Hydrogen Energy* 24(6), 577-586.

Singh, R. N., Singh, S. P., and Pathak, B. S. (2007). "Performance of renewable fuel based CI engine," *Agricultural Engineering International: The CIGR Ejournal*, Manuscript EE 0014. Vol. IX April 2007.

Tomita, E., Fukatani, N., Kawahara, N., Maruyama, K., and Komoda, T. (2007). "Combustion in a supercharged biomass gas engine with micro-pilot ignition-Effects of injection pressure and amount of diesel fuel," *Journal of KONES* 14 (2), 513-520.

Von Mitzlaff, K. H. (1988). “Engines for biogas,” A Publication of the German Appropriate Technology Exchange (GATE), Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ), Vieweg Verlag, Wiesbaden, Germany. ISBN 3-528-02032-6

Yasin, M. M., Yusaf, T., Mamat, R., and Yusop, A. F. (2014). "Characterization of a diesel engine operating with a small proportion of methanol as a fuel additive in biodiesel blend," *Applied Energy* 114, 865-873. DOI: 10.1016/j.apenergy.2013.06.012

Zhang, X., Peterson, C., Reece, D., Haws, R., and Moller, G. (1998). "Biodegradability of biodiesel in the aquatic environment," *Transactions of the ASAE* 41(5), 1423-1430.

Article submitted: March 6, 2017; Peer review completed: May 22, 2017; Revised version received and accepted: June 6, 2017; Published: June 21, 2017.
DOI: 10.15376/biores.12.3.5617-5631