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The effect of Jatropha seed cake producer gas flow rates on a diesel engine operated on dual fuel mode at high engine speedMonorom Rith*,^{1, 2)}, H. W. Gitano-Briggs³⁾, Nechoh Arbon¹⁾, Jeremias A. Gonzaga¹⁾ and Jose Bievenido M. Biona^{1, 4)}¹⁾Department of Mechanical Engineering, De La Salle University, Taft Ave, Metro Manila, Philippines²⁾Research and Innovation Center, Institute of Technology of Cambodia, Russian Conf. Blvd, Phnom Penh, Cambodia³⁾Department of Mechanical Engineering, UniKL Malaysian-Spanish Institute, Kulim, Malaysia⁴⁾Center for Engineering and Sustainable Development, De La Salle University, Taft Ave, Metro Manila, Philippines

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Abstract

Jatropha seed cake is a byproduct of biodiesel production. The seed cake can be used to make a producer gas that can be fumigated into a diesel engine operated on dual fuel mode without major modification. This paper intends to investigate the impact of Jatropha seed cake-derived producer gas mass flow rate on the performance and emission characteristics of a diesel engine operated on a dual fuel mode at a high engine speed of 3,000 rpm. The results highlight that the maximum diesel replacement rate reached 60% at a 20 kg/h gas flow rate when the engine was operated at medium engine load. An increase in gas flow rate augments the diesel substitution rate but decreases the electrical-thermal efficiency (ETE). At 70% of the full engine load, the specific diesel consumption declined from 0.337 to 0.185 kg/kWh when the gas was increased from zero to 20 kg/h. At this engine load, the ETE sharply fell off from 25% to 10.6% and 6.6% when the gas flow rate increased from zero to 10 kg/h and 20 kg/h, respectively. The electrical specific fuel consumption and electrical specific energy consumption, exhaust hydrocarbon (HC), carbon monoxide (CO), and carbon dioxide (CO₂) emissions were found to be higher with an increase in gas flow rate. Unlike dual fuel engine operation at medium speed, the nitrogen oxides (NO_x) emissions were consistent with an increase in gas flow rate. Based on the empirical findings, the dual producer gas-diesel engine should be operated at high engine load but not at a high engine speed of 3,000 rpm with a maximum gas flow rate of 20 kg/h.

Keywords: Jatropha seed cake, Producer gas, Dual fuel mode, Diesel engine**1. Introduction**

The use of carbonaceous bio-waste as a feedstock for gasifier-engine systems contributes to the mitigation of the imported petroleum fuel dependency for power generation. This encourages the construction of decentralized power plants in remote rural areas that have little access to fossil fuels. Jatropha can be grown as a biodiesel energy crop. Its oil can be transesterified to biodiesel and burned in an internal combustion (IC) engine with minor modifications [1]. The solid organic material obtained from Jatropha oil production is the seed cake, considered a byproduct of Jatropha biodiesel production. The seed cake accounts for 62% of the Jatropha seed [2]. It can be used as an organic fertilizer for Jatropha plantations or as a feedstock for biogas production through anaerobic digestion [3]. However, the efficiency of Jatropha seed cake biogas production through the anaerobic digestion process is low, roughly 20%, and is impacted by input parameters [3]. Air gasification is also another pathway for utilization of the Jatropha byproduct because Jatropha seed

cake is a carbonaceous material. This conversion technique is a thermo-chemical process. The gasification efficiency is generally above 50% for all kinds of biomass feedstocks [4]. This value varies with biomass properties, as well as the specific design of a gasifier, gasification parameters, and the cleaning cum cooling unit [4-6]. A gaseous fuel converted through gasification technology is called producer gas. Its production rate is 2.857 kg per 1 kg of the Jatropha seed cake [7].

This type of gaseous fuel can be fumigated into a compression ignition (CI) engine to partially replace diesel fuel without internal modification of the engine [8-9]. A CI engine cannot run on 100% producer gas without modification as the gas cannot be auto-ignited in the engine owing to high auto-ignition temperature [10]. A small quantity of diesel is injected near the end of the compression stroke. Consequently, such gasifier-engine systems can be used to mitigate fossil fuel dependency for power generation. This technology has received growing interest in remote rural districts that have poor access to fossil fuels.

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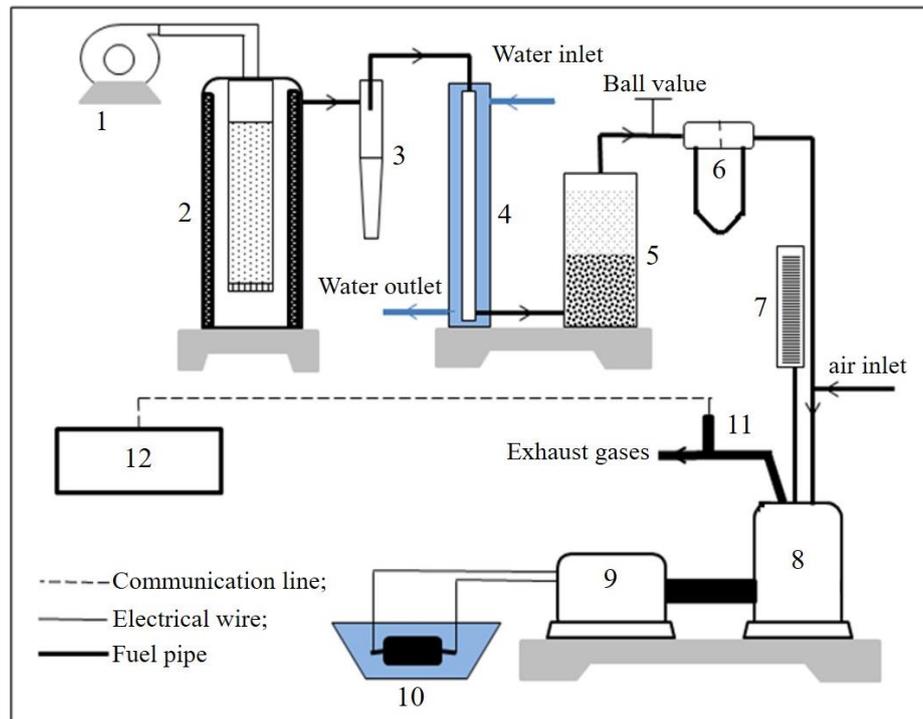


Figure 1 Flow chart of the experimental setup. 1-Air blower, 2-Gasifier, 3-Cyclone filter, 4-Heat exchanger, 5-Dried-bed filter, 6-Orifice and U-tube manometer, 7-Diesel glass burette, 8-Diesel engine, 9-Electric generator, 10-Water heaters, 11-Exhaust gas probe, and 12-Exhaust gas analyzer

Most of the previous studies investigated the performance and combustion characteristics of the dual producer gas-diesel engine at the maximum diesel replacement rate or one gas flow rate only [11-18]. Very few studies investigated the impact of gas flow rates on a dual fuel engine [8-9, 19-21]. For dual fuel mode relative to pure diesel operation, the brake thermal efficiency decreases due to less efficient combustion, while the brake specific energy and fuel consumption increase. Additionally, the concentrations of hydrocarbons (HC), carbon monoxide (CO) and carbon dioxide (CO₂) in the flue gases are significantly higher in the dual fuel mode compared to 100% diesel [19, 21]. Inversely, nitrogen oxides (NO_x) and sulfur dioxides (SO₂) are lower [22]. Other recent studies investigate the combustion characteristics of the dual fuel mode at a high engine speed of 3,000 rpm and only one gas flow rate, but did not consider the engine performance and emission characteristics [23-24]. Nayak et al. empirically investigated the effect of the geometry of the combustion chamber of a dual fuel engine at a medium engine speed and maximum diesel replacement rate [25]. To the best of our knowledge, the effect of varied gas mass flow on performance and emission characteristics of a dual producer gas-diesel engine has yet to be investigated at high engine speeds.

The thrust of this study, therefore, intends to explore the impact of producer gas flow rates on a diesel engine operated on a dual fuel mode at a maximum engine speed of 3,000 rpm. In this regard, it is beneficial to understand the overall performance by considering specific diesel fuel consumption, diesel fuel replacement rate, electrical-thermal efficiency, electrical-specific fuel consumption, and exhaust emissions (i.e., HC, CO, CO₂, NO_x). A gaseous fuel was produced from *Jatropha* seed cake through a gasification process with the air as the gasifying agent. The rest of the paper is structured as follows. Section 2 gives an overview of the experimental setup and procedures. Section 3 presents

the empirical results and discussion. The last section gives concluding thoughts and recommendations.

2. Methodology

A flowchart of the experimental setup is given in Figure 1. The setup consisted of a gasifier, a gas cleaning system, a diesel engine, and other instruments to measure experimental parameters. The basic characteristics of the designed gasifier are listed in Table 1. The gas cleaning system is comprised of a cyclone filter, a shell-tube heat exchanger, and a dried bed filter. A cyclone filter is usually used as a preliminary filter to collect dust and cool the high temperature gas. A heat exchanger was used to cool the gas to ambient temperature and condense the tar content. The dried bed filter was made of small-sized charcoal layered under a synthetic material. This filter is typically utilized to capture the remaining tar and smaller-sized particles. The key specifications of the engine used in the tests are tabulated in Table 2. The engine intake manifold was modified to mix the gas with air by connecting the gas inlet pipe to the air filter box (see Figure 2). The engine was coupled to an electric generator with a capacity of 3 kWe, and it was loaded with five 0.5 kWe electric heaters connected in series. The engine speed was measured using a microprocessor tachometer with an accuracy of ± 0.5 rpm. The diesel consumption rate was measured using a glass burette and a digital stopwatch. An orifice and a U-tube manometer were designed based on the Bernoulli's principle to indicate the producer gas flow rate. An MRU model DELTA 1600-L multi-exhaust gas emissions analyzer was employed to monitor the flue gases (i.e., HC, CO, CO₂, and NO_x). The measurement accuracy of this instrument is ± 12 ppm for HC, $\pm 0.06\%$ for CO, $\pm 0.5\%$ for CO₂ and ± 5 ppm for NO_x.

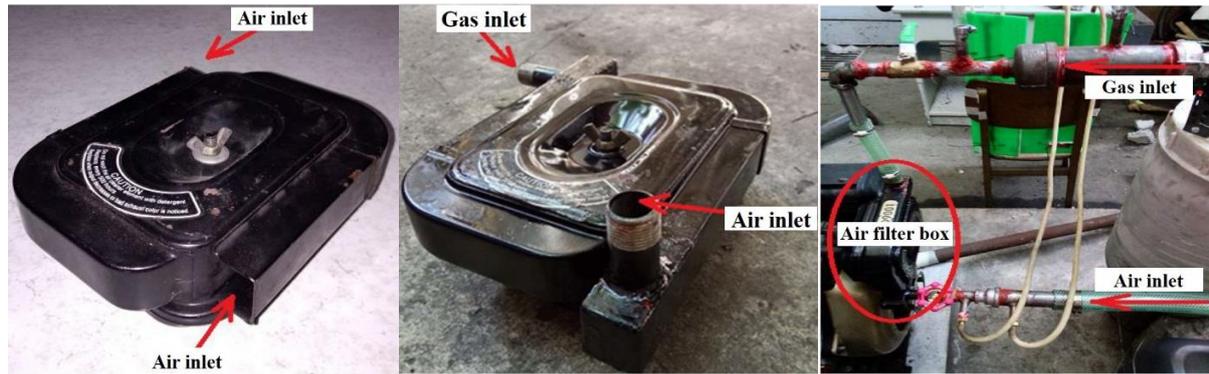


Figure 2 Air filter box: the initial box (left), the modified box (middle), and the modified box installed on the engine (right)

Table 1 Basic characteristics of the gasifier

Item	Description
Type	Close top, throatless, downdraft
Gasifying agent	Air
Gasifier's weight (kg)	30
Critical dimension (mm)	D = 350 / h = 1800
Capacity (kW _{th})	130
Fuel consumption rate (kg/h)	7 (approximately)
Biomass feedstock	Jatropha seed cake
Efficiency (%)	~74

Table 2 Specifications of the engine test

Item	Description
Model	KM 186F
Engine type	Single cylinder, 4-stroke, air-cooled, direct injection, naturally aspirated, diesel engine
Bore×stroke	86×70 (mm)
Connecting rod length	117.5 (mm)
Displacement	406 (cm ³)
Engine speed	3,000 (rpm)
Compression ratio	19:1
Diesel injection timing	BTDC 9° of crank angle
Rated output power	5.7 (kW)
Engine speed	3,000 (rpm)

Physical properties of producer gas and diesel fuel are listed in Table 3. The properties of the gas were analyzed using the standard test methods of ASTM D1946 to determine a volumetric percentage of each constituent and ASTM D3588 for heating value and density. Basic properties of diesel fuel have been published [26]. After 30 min of the gasification, gas production is stable and less dirty. The gasified Jatropha seed cake exiting the gasifier was cleaned and cooled to roughly 30 °C prior to its introduction into the engine. The properties of Jatropha seed cake are listed in Table 4.

Four different gas flow rates were used in the current study: no gas, PG 10 kg/h, PG 15 kg/h and PG 20 kg/h (PG denotes producer gas). No gas represented a 100% diesel fuel mode of operation. The engine speed was maintained constant at 3,000 rpm throughout the experiments. The engine loads were as follows: 18, 35, 53 and 70% of full load. It could not be operated at the full load in the dual fuel mode due to the power de-rating that resulted from the lower heating value of the combustible mixture [6]. The output parameters of specific diesel consumption (SDC), diesel replacement rate (DRR), electrical-thermal efficiency (ETE), electrical-specific energy consumption (ESEC) and electrical-specific

fuel consumption (ESFC) were determined using equations (1-5), respectively.

$$SDC = \frac{\dot{M}_{\text{Diesel}}}{\text{Load}} \quad (1)$$

$$DRR = 100 \times \left(\frac{\text{Diesel}_{\text{no gas}} - \text{Diesel}_{\text{with gas}}}{\text{Diesel}_{\text{no gas}}} \right) \quad (2)$$

$$ETE = \frac{\text{Load}}{(\dot{M}_{\text{Diesel}} \times CV_{\text{diesel}}) + (\dot{M}_{\text{PG}} \times CV_{\text{PG}})} \quad (3)$$

$$ESEC = \frac{(\dot{M}_{\text{Diesel}} \times CV_{\text{diesel}}) + (\dot{M}_{\text{PG}} \times CV_{\text{PG}})}{\text{Load (kWe)}} \quad (4)$$

$$ESFC = \frac{\dot{M}_{\text{Diesel}} + \dot{M}_{\text{PG}}}{\text{Load}} \quad (5)$$

where the units of SDC, DRR, ETE, ESEC, and ESFC are kg/kWh, percent, percent, MJ/kWh and kg/kWh, respectively. \dot{M}_{Diesel} is mass flow rate of diesel fuel (kg/h) and \dot{M}_{PG} is mass flow rate of producer gas (kg/h). Load is an electrical load placed on the engine (kWe). $\text{Diesel}_{\text{no gas}}$ and $\text{Diesel}_{\text{with gas}}$ are the diesel flow rates (kg/h) for the single

Table 3 Properties of the fuel

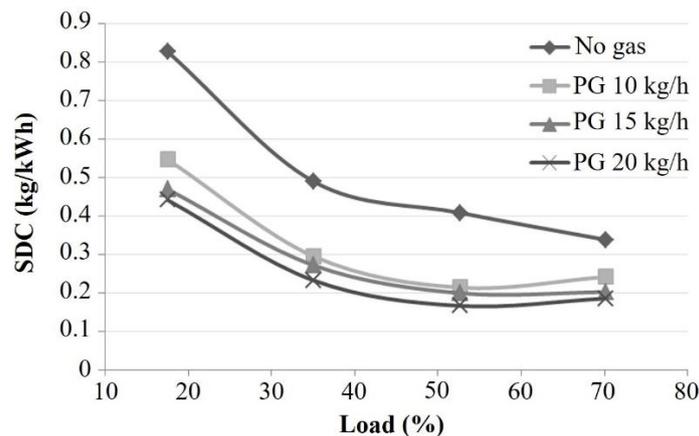
Properties	Producer gas [7]	Diesel [26]
H ₂	7.9 %	–
CO	8.8 %	–
CH ₄	2.1 %	–
CO ₂	18 %	–
N ₂	60 %	–
O ₂ /Air	3.8 %	–
Oxygen content	–	0 (% mass)
Sulfur content	–	0.595 (% mass)
Viscosity	–	2.5 (cSt at 40 °C)
Density	1.19 (kg/m ³)	837 (kg/m ³)
Carbon content	0.1266 (kg/kg Gas)	20.2 (kg/GJ)
Net heating value	4.69 (MJ/kg)	42.72MJ/kg)

Table 4 Properties of the Jatropha seed cake [3]

Solid content (%)	Volatile solid content (%)	Carbon content (%)	Nitrogen content (%)	C:N
88.00	72.70	26.00	2.88	9:1

Table 5 The standard errors of the output variables

Output Variable	SDC (kg/kWh)	ETE (%)	DRR (%)	ESEC (MJ/kWh)	ESFC (kg/kWh)	HC ppm	CO %	CO ₂ %	NO _x ppm
Standard Error	0.0442	1.6887	2.3902	13.4230	2.8367	4.4417	0.2867	0.3371	17.1449

**Figure 3** The effect of gas mass flow on the specific diesel consumption

diesel fuel mode and dual fuel mode, respectively. CV_{diesel} and CV_{PG} are the calorific values (MJ/kg) of diesel fuel and producer gas, respectively.

Data were gathered at each set of experimental settings in triplicate to ensure repeatability. Each experiment required 10 min. The standard errors of the output variables are tabulated in Table 5.

3. Results and discussion

3.1 Engine performance

The impact of the gas flow rate on the specific diesel consumption (SDC) is illustrated in Figure 3. Over the engine load range, the SDC sharply decreased with an increasing gas flow. The heating value of producer gas significantly contributed to this. However, the SDC slightly decreased when the producer gas flow rate was doubled from 10 to 20 kg/h. This is a clear indication of the high inefficiency of dual fuel combustion at the maximum diesel replacement rate. A reduced amount of air probably

constrained fuel combustion. For the 100% diesel fuel mode, the SDC exponentially declined with an increase in the engine load. For all dual fuel modes, the SDC considerably decreased as the engine load was increased, while the SDC slightly increased with the engine load. It is likely that for dual fuel engine operation at high loads, the peak combustion pressure is inherently higher and at a more advanced timing. Therefore, more pilot diesel fuel is injected to reduce the ignition delay. A limited SDC at the high engine load operation is probably a cause of power loss. Therefore, the dual producer gas-diesel engine cannot reach its rated power. A maximum value of power de-rating for the dual fuel mode in this study was 30% compared with 100% in diesel fuel mode. This value is higher than the power de-rating reported by Banapurmath et al. [15]. It is likely that a dual fuel engine operated at a high engine speed decreased the duration of combustion of the fuel-air mixture. It is noteworthy that at 70% of the full engine load, the SDC decreased from 0.337 to 0.241 and further to 0.185 kg/kWh when the gas was increased from zero to 10 and finally 20 kg/h, respectively.

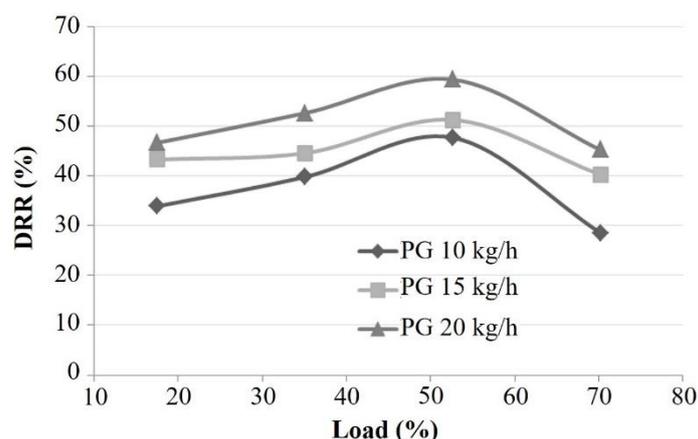


Figure 4 The effect of gas mass flow on the diesel replacement rate

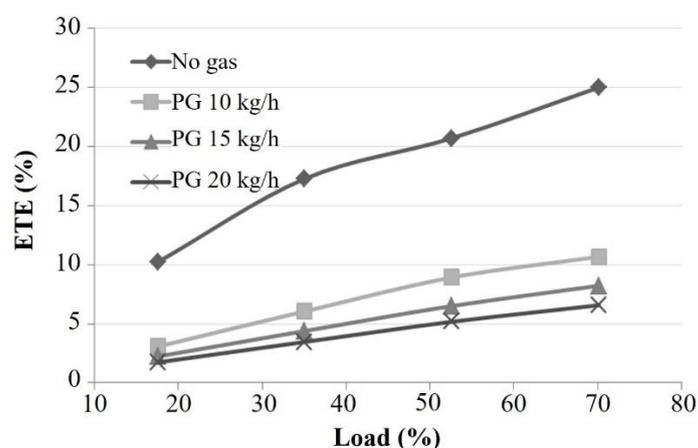


Figure 5 The effect of gas mass flow on electrical-thermal efficiency

Figure 4 shows the profiles of the diesel replacement rates. The diesel replacement rate (DRR) increased with the gas flow rate. For all engine loads, the DRR increased by about 12.5% when the gas flow was doubled from 10 to 20 kg/h. This implies that dual fuel engine operation at a higher diesel replacement rate was less efficient. For all the dual fuel modes, the DRRs initially increased with the engine load, and then they decreased when the engine load was further increased. Several other research groups also found this to be the case [8-9, 15, 18, 22]. The maximum diesel saving rate occurred at a medium engine loading. Similar results were reported in other studies [16, 18]. A maximum diesel saving rate of 60% was reached at a gas flow of 20 kg/h. Compared with a medium engine load operation, the DRR was found to be lower at low engine loads as a result of inherently inefficient combustion and high engine load. This resulted from the requirement for more pilot diesel fuel. At 70% of the full engine load, the gas flow rates of 10 kg/h and 20 kg/h replaced diesel fuel by 25.6% and 45.6%, respectively.

The effect of the gas flow rate on electrical-thermal efficiency (ETE) is apparent in Figure 5. At all gas flow rates, the ETE was found to be higher with an increase in engine load due to more complete combustion. The ETE was markedly lower in the dual fuel mode relative to the 100% diesel mode over the entire engine load range. This indicates inefficient combustion. At 70% of the full engine load, the ETE of the 100% diesel fuel mode was 25%, and this value dropped to about 10.7% when a gas flow rate of 10 kg/h was

fumigated into the engine. This considerable decrease is higher than the results of previous studies, probably since the engine speed in our study was controlled at the maximum value. The ETE further decreased with increased gas flow rates. This was caused by a reduced pilot diesel quantity that decreased the amount of ignitable fuel, thereby reducing the time available for combustion of the unburned producer gas-air mixture [10]. Additionally, an increase in the gas flow rate results in a reduced oxygen concentration and incomplete combustion. For high engine load operations, the ETE was 8.2% and 6.7% when the gas flow rate was 15 kg/h and 20 kg/h, respectively.

As is evident from Figure 6, the gas flow rate significantly affects electrical specific energy consumption (ESEC) over the entire engine load range. At low load operation, the ESEC increased greatly with the gas flow owing to the high use of gaseous fuel. The ESECs of all the dual fuel modes greatly declined with increased engine loads. This is attributed to a lower increase in diesel consumption compared the increase in engine load, while the gas flow rate of each dual fuel mode was fixed. However, over the entire engine load range, the ESEC of dual fuel mode was found to be greater at a higher gas flow rate, which is an indication of less efficient combustion. There was likely a lower natural adiabatic flame temperature using producer gas and restricted intake air for dual fuel combustion, which may narrow the effective flammability constraint. Additionally, an increase

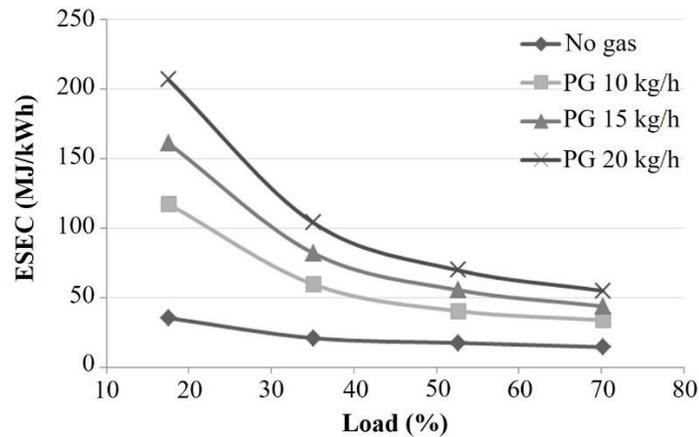


Figure 6 The effect of gas flow rate on electrical specific energy consumption

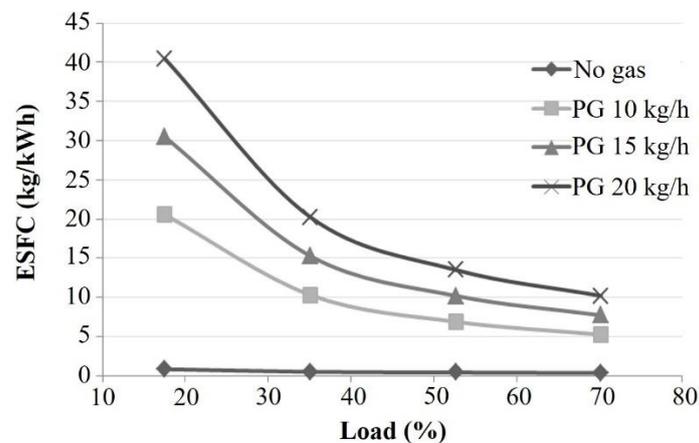


Figure 7 The effect of gas flow rate on electrical specific fuel consumption

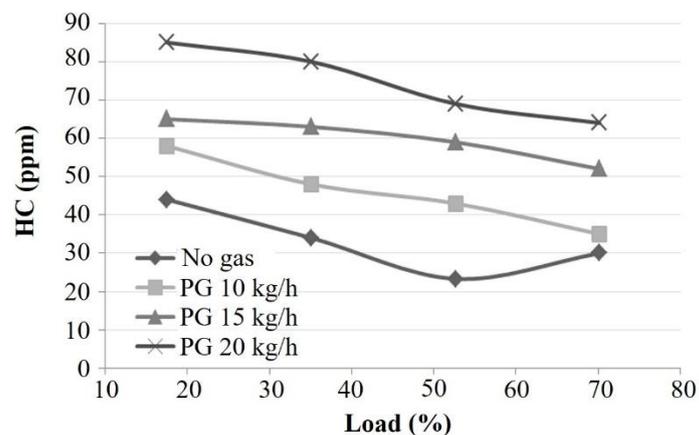


Figure 8 The effect of gas mass flow on HC emissions

in the amount of gaseous fuel concurrently reduces the pilot diesel quantity, thereby causing an improper ignition timing and degrading the ignition centers.

The electrical-specific fuel consumption (ESFC) was influenced by gas mass flow as is shown in Figure 7. For the fuel mode operations, the ESFC decreased with additional engine loading. At all engine loads, the ESFC was higher with increased gas flow rates as a result of the lower calorific value of the gas, along with inefficient fuel combustion. The lower energy density of producer gas is attributed to its high

content of inert gases (i.e., 18% NO_x and 60% CO_2). As is apparent from the figure, gas flow rate and engine load are interactive factors that significantly affected the ESFC.

3.2 Emission characteristics

Figure 8 and Figure 9 show the impact of gas flow rate on hydrocarbon (HC) and carbon monoxide (CO) emissions, respectively. The HC and CO concentrations were found to be higher with increased gas flow rates. The presence of HC

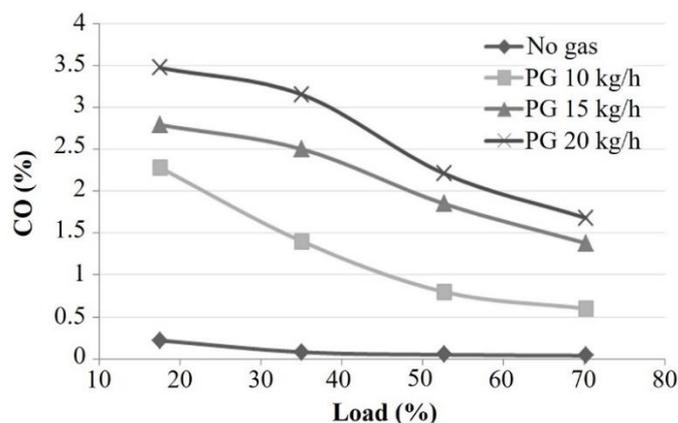


Figure 9 The effect of gas mass flow on CO emissions

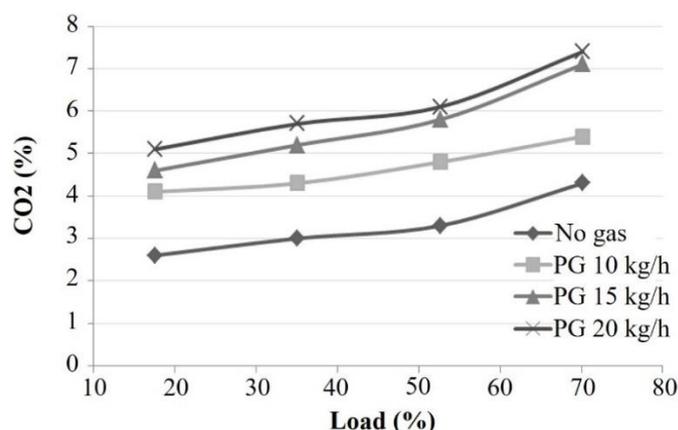


Figure 10 The effect of gas mass flow on CO₂ emissions

and CO exhaust gases indicates less efficient combustion in the dual fuel mode. The same results were also reported for a dual biogas-diesel engine [27]. The fumigation of producer gas into a diesel engine causes a longer ignition delay [14]. This is the main cause of the higher exhaust HC emission for a naturally aspirated direct injection engine [15]. Furthermore, the induction of gaseous fuel inherently suppressed the turbulent flame propagation from the ignition region of the pilot liquid fuel [27]. It is also obvious that a higher CO concentration is associated with the already high presence of a CO constituent in the producer gas [4]. Also, the gaseous fuel is forced into the crevice volume during the compression stroke to escape fuel oxidation during the combustion process. Then the unburned fuel is blown out during the exhaust process [27]. These exhaust gas emissions declined in response to an increased engine load in view of a higher combustion temperature that improved oxidation of the fuel. This empirical finding was shown by [22]. Furthermore, an increase in engine load required more diesel fuel that translates to a higher quantity of ignitable material, thereby reducing the ignition delay during the pre-mixed combustion phase. This empirical finding was previously reported [12].

The impact of the gas flow rate on CO₂ emissions is illustrated in Figure 10. A larger CO₂ concentration was apparent in the dual fuel mode compared with the 100% diesel fuel mode as a result of the CO₂ content of the producer gas. The exhaust gas concentration of CO₂ was observed with increased engine loads due to more complete

combustion. This has been reported by other researchers [12].

According to previous studies using medium engine load operations, NO_x emissions were lower for the dual fuel mode compared with the 100% diesel fuel mode [9, 15, 22]. It was found that the NO_x emissions in the current study were higher with increased gas flow rates, as can be seen in Figure 11. One explanation might be that the gasifier used in this study is a forced-draft design (the pressure inside the gasifier is higher than atmospheric pressure) in which the gasifying agent is resident in the apparatus for a shorter time. This is unlike an induced-draft gasifier. The N₂ content of the producer gas was higher in the unit of the current study. Another reason is that the exhaust gas temperature is higher with an increase in gas flow rate [9]. A higher exhaust temperature is caused by a higher temperature in dual fuel oxidation resulting from the greater energy of the producer gas. The engine speed of our study was 3,000 rpm, which is associated with a higher combustion temperature. Nitrogen and oxygen are the two precursors for the formation of NO_x emissions in a CI engine [9]. The nitrogen is an inert gas at low temperature but reacts with the oxygen to form nitrogen oxides at temperatures above 1,100 °C [29].

4. Conclusions and recommendations

This study investigated the impact of producer gas flow rates on the engine performance and emission characteristics of a diesel engine operated on a dual fuel mode at a high engine speed. The results highlighted that the *Jatropha* seed cake can be used as a feedstock for a gasifier-engine

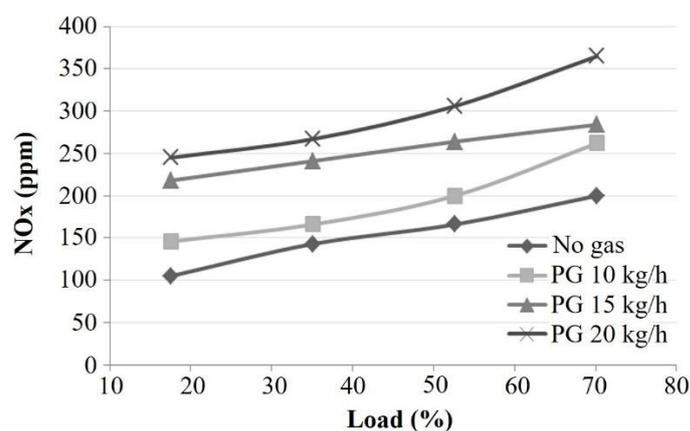


Figure 11 The effect of gas mass flow on NO_x emissions

system to partially reduce the diesel fuel requirements for decentralized power plants. However, a power de-rating of 30% was observed for the dual fuel mode relative to the 100% diesel fuel mode. The maximum diesel savings reached 60% at a gas flow rate of 20 kg/h when the engine was operated at a medium engine loading. At 70% of the full engine load, the specific diesel consumption declined from 0.337 to 0.185 kg/kWh when the gas flow rate was increased from zero to 20 kg/h. At the optimal engine load, the gas flow rates of 10 kg/h and 20 kg/h replaced diesel fuel by 28.6% and 45.2%, respectively, but the electrical specific energy consumption, electrical specific fuel consumption, and CO₂ emissions were doubled. This implies that an increase in gas flow from 10 to 20 kg/h produced less of an effect than an increase in gas flow rate from zero to 10 kg/h. Increased gas flow rates resulted in an increase in the diesel substitution rate, but the electrical-thermal efficiency declined. Furthermore, electrical specific energy consumption, electrical specific fuel consumption, and exhaust gases emissions (i.e., HC, CO, CO₂, NO_x) were greater at higher gas flow rates. The presence of higher HC and CO in the exhaust gas suggests that the combustion of dual producer gas-diesel fuel is less efficient when compared with the 100% diesel fuel mode.

From this empirical study, a producer gas-diesel engine should be operated at high engine loads but not at the maximum diesel replacement rate and a high engine speed of 3,000 rpm. Further research should focus on the cost-benefit and net energy analysis of the Jatropha seed cake producer gas for the gasifier-engine unit to address the economic and environmental benefits.

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