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Performance and emissions characteristics of a direct injection diesel engine from compressing producer gas in a dual fuel mode

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Abstract

This research highlights the impact of compressed producer gas combined with diesel fuel in a dual fuel mode on performance and emission characteristics of a three-cylinder diesel engine connected to an AC generator. Producer gas was generated from a small downdraft gasifier using charcoal, and sent into the engine using a supercharger to increase the gas flow rate from 76 to 125 lpm. The engine speed was adjusted from 1,000 to 1,600 rpm, while operating at full load. All results of this investigation indicate that supercharging producer gas improved the diesel economy and engine performance characteristics, but it increased the amount of various pollutants. Engine performance testing results from compressing producer gas showed that the use of gas flow rates of 116 to 125 lpm increased the maximum diesel saving by 41%, electrical power by 1.88%, and thermal efficiency by 35.76% as compared to a diesel fuel only mode. Additionally, specific energy consumption decreased with increasing producer gas flow rate and engine speed. For measuring the emissions of the engine, exhaust gas temperature increased from 223 to 276 °C, CO_2 emissions increased from 21.59 to 33.90%, CO emissions increased from 0.36 to 0.59%, HC emissions increased from 23 to 58 ppm, and smoke opacity increased from 4.00 to 6.07 $K.m^{-1}$ compared with the diesel fuel only mode.

Keywords: Compressing producer gas, Diesel engine, Performance, Emissions

1. Introduction

Producer gas is generated from biomass gasification, a thermo-chemical process that converts solid fuel based carbonaceous materials into carbon monoxide (CO), hydrogen (H_2), carbon dioxide (CO_2) and methane (CH_4). Currently, producer gas is becoming an alternative fuel that can be used to relieve an increasing demand for energy and high levels of hazardous emissions [1]. Diesel engines are widely used in agricultural and the transport sector. In terms of diesel engines, there is a dual fuel mode in which diesel fuel is the primary fuel and producer gas is a secondary fuel. When producer gas was used in diesel engines, it could save up to 70% of the diesel fuel [2].

From 2007 to 2016, several researchers studied the performance and emissions of diesel engines by adjusting engine speed and load using producer gas as a secondary fuel derived from various biomass types. Shaw et al. [1], Yadav [2] and Brenneisen et al. [3] used wood chips and wood to generate producer gas that was used directly in an engine. Shrivastava et al. [4] produced this gas from 70% wood chips and 30% mustard oil cake in a down draft gasifier. They examined gas flow rates from 4 to 8 lpm. Rith et al. [5] using jatropha seed and press cake, while Hondoung et al. [6] used longan tree-derived charcoal, and Sombatwong et al. [7] chose charcoal to make procuder gas because it was the most widely used as a gasifier fuel and it released the lowest levels of tar. Dasappa et al. [8] tested the performance of producer gas and engine wear in a study lasting 60,000 hours using charcoal fed into a downdraft gasifier. Their results indicated that producer gas produced from charcoal had a lower humidity than from other biomasses. It gave the lowest tar, its ignition characteristics were very good, and the engine parts showed little damage.

Concurrently, many researchers modified diesel engines to use producer gas combined with diesel fuel in a dual fuel mode. In 2013, Shrivastava et al. [4] and Sombatwong et al. [7] studied the effect of the quantity of pilot diesel fuel on the performance and emissions of an engine modified to use producer gas as a secondary fuel. In 2008, Lekpradit et al. [9] investigated the effect of adjusting the injection timing on performance and emissions of a dual fuel engine using diesel fuel and producer gas. Both methods were very difficult. In 2015 and 2016, Yaliwal et al. [10] and Hadkar and Amarnath [11] used a mixing chamber or carburetor to send producer gas mixed with air into an intake manifold by combining it with biodiesel fuel in a combustion chamber with normal injection timing.

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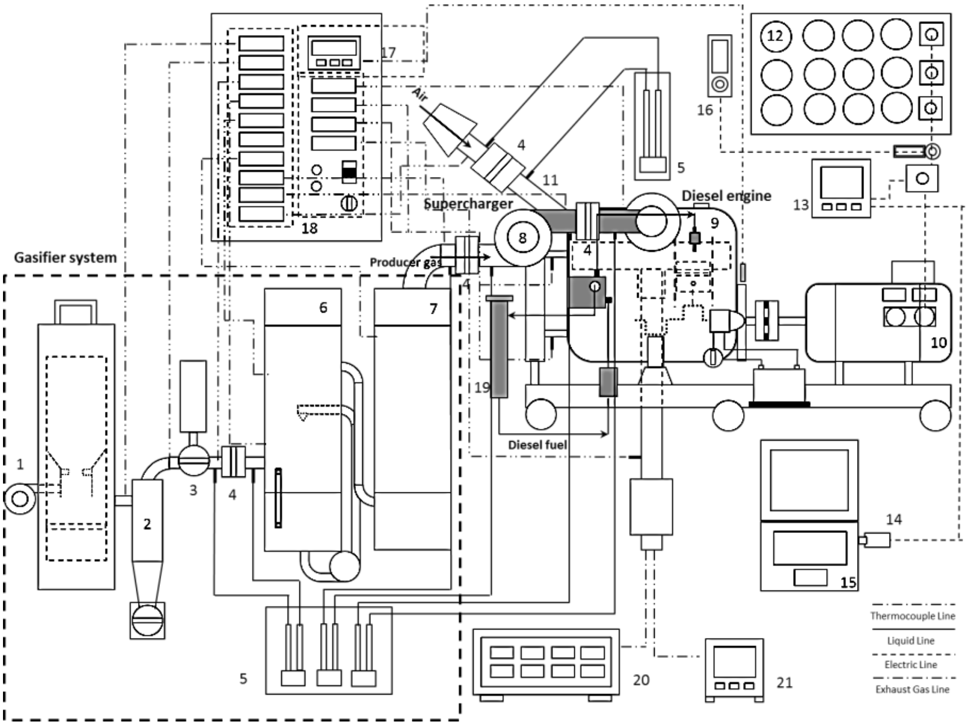
Since this is a simple method, it helped lower costs and non-modifications to either engines or operations. This method presents a disadvantage. A supercharger is required to compress the gas [12-13]. Additionally, other researches [10-16] operated using a dual fuel mode with producer gas and fuels such as biodiesels and vegetable oils, to reduce the exhaust gas emissions of diesel engine. However, the use of producer gas combined with their oils affected stability of engine operation. It yielded poorer engine performance than using only diesel fuel [8-16].

The objective of proposed work is to investigate supercharging producer gas combined with diesel fuel in a dual fuel mode on the performance and emissions characteristics of a low-speed direct injection diesel engine which is the non-modified engine. Producer gas was generated using a small downdraft gasifier with a capacity 75 kW_{th} using charcoal in the production process.

2. Materials and methods

2.1 Experimental setup

Investigation of performance and emission characteristics of a diesel engine using compressed producer gas was carried out at an automotive biofuels and combustion engineering research laboratory in the Department of Mechanical Engineering, Faculty of Engineering at Burapha University. A schematic diagram of the experimental setup is shown in Figure 1. Producer gas was generated within a gasifier system that consisted of a gasifier (1), a cyclone (2), a wet scrubber (6) and a sandbed filter (7), before it was sent into a Y-shaped mixing chamber (11) and an intake manifold of the engine. The gasifier was a small downdraft unit. Its specifications are shown in Table 1, and the producer gas properties are shown in Table 2.



Equipment and measuring instruments:

1. Downdraft gasifier
2. Cyclone
3. Producer gas valve
4. Orifice meter
5. Manometer
6. Wet scrubber
7. Sandbed filter
8. Supercharger
9. Diesel engine
10. AC generator
11. Mixing chamber
12. Electrical Load
13. Power meter
14. Hardlock
15. Computer
16. Clamp meter
17. Speed meter
18.Temperature meter
19. Fuel cylinder
20. Exhaust gas analyzer
21. Smoke meter

Figure 1 Schematic of the experimental setup

Table 1 Gasifier specifications

Item	Description
Type of gasifier	Closed top downdraft
Maximum Capacity (kW_{th})	75
Rate charcoal biomass consumption (kg/h)	5 to 6
Maximum rate gas flow (m^3/h)	96 (Charcoal)
Calorific value (MJ/kg)	29.60
Biomass size (mm)	10 to 30
Efficiency (%)	70 to 75
Equivalence ratio	0.12 to 0.16

Table 2 Producer gas properties

Properties	Volume percentage
Hydrogen (%)	7.5±2.5
Carbon monoxide (%)	29.5±1.5
Carbon dioxide (%)	1.5±0.5
Methane (%)	1.5±0.5
Nitrogen (%)	57.5±2.5
Calorific value (MJ/m^3)	5.08±0.48

Table 3 Engine specifications

Item	Description
Model	John Deere 3029DF150
Engine type and aspiration	In-line, 4-stroke, turbocharged, low speed engine
Number of cylinders (cyl)	3
Displacement (L)	2.9
Bore x Stroke (mm)	106 x 110
Compression ratio	17.2 : 1
Maximum power (kW)/ Maximum speed (rpm)	43 /2,500
Maximum torque (N.m)/ Maximum speed (rpm)	191 /1,600

Table 4 Specifications of the exhaust gas analyzer

Gas	Measured method	Resolution & Accuracy
Carbon monoxide (CO)	IR Bench	0.01±2%
Carbon dioxide (CO_2)	IR Bench	0.01±2%
Hydrocarbons (HC)	IR Bench	1±2%
Black smoke	Opacity	0.1±2%

To send producer gas into the diesel engine, producer gas was compressed by a supercharger, a Stanley STPT600 gas blower. The power consumption was 600 W_e and the gas flow rate varied from 0 to 3.5 m^3/min. The blower (8) was connected to a direct injection diesel engine (9) with the specifications shown in Table 3. For measuring the output power, a 20±5 kW_e AC generator (10) was used in this experiment. It was directly coupled to this engine using electric lamps to increase the electrical load (12).

Recorded output data of electrical power as a function of electrical load was analyzed using a Richtmass power meter, model RP-96EN (13), through a clamp IMARI-CT100/1A by converting the signal into an RS485 port with a USB data converter and hardlock (14) for an RP series to connect with a computer (15). Additionally, calibration was necessary for power-meter parameters of the Richtmass RP-96EN by comparing the readings obtained with a clamp meter. A fuel cylinder (19) was used for recording the diesel flow rate to calculate the diesel fuel saving.

To investigate the various engine temperatures, such as coolant, intake, exhaust gas and gasifier system, K-type thermocouples were used with temperature meters in a control box (18). Exhaust gas emissions, such as CO, CO_2 and HC, were measured using a MOTORSCAN: 8020 Eurogas Emission Analyzer (20) using an IR Bench (Infrared measuring) method. A MOTORSCAN: 9010 opacity meter/smoke detector (21) was used to measure black smoke in this experiment. Specifications of the exhaust gas analyzer are shown in Table 4.

2.2 Experimental procedure

A 10-15 kg mass of charcoal was fed into a small downdraft gasifier (1) through its top, while air was introduced through the side of the gasifier by adjusting the speed of an air blower to modulate the reaction rate of the gasification process. After the charcoal was transformed into the hot producer gas, it is entered a cyclone (2) and a wet scrubber (6) to decrease its temperature. Cooled gas with impurities was passed through a sandbed filter (7) to clean the producer gas, before it was sent through a valve in the filter pipe (7) and an orifice meter (4) connected to a manometer (5) for controlling the gas flow rate.

Producer gas was compressed and sent to the diesel engine (9) by adjusting the gas flow rate of the blower from 76 to 125 lpm, as measured using an orifice meter (4) and manometer (5) at entrance of the supercharger (8). As the supercharger compressed the producer gas into the diesel engine, it was mixed with air through a Y-shape mixing chamber (11), which was designed from work of Hadkar and Amarnath [11]. At this point, flow rate of producer gas and air was measured using a gas flow meter, before the mixture was sent into the intake manifold of the diesel engine.

For testing the performance and emission characteristics of the diesel engine, the engine was warmed for about 15-20 minutes. Room temperature was 32-35 ºC and all experiments were run for a period of 50 to 100 hours by reference to standard of engine testing [17]. After engine was operating at steady state, the experiments were started by adjusting the engine speed from 1,000 to 1,600 rpm with a full electrical load. The amount of fuel at 20 ml was applied for the investigation of diesel saving. Measurements of exhaust gas emissions, such as CO_2, CO, HC and black smoke were done at this time.

Next, there were openings in the filter pipe valve (7) and the supercharger (8) to input producer gas into the intake manifold of the diesel engine combining it with diesel fuel in a dual fuel mode. Producer gas was compressed into the Y-shape mixing chamber by adjusting the gas flow rate from 76 to 125 lpm. The engine was tested in a dual fuel mode as well as when it burned only diesel fuel at same speed and full load. Finally, all experiments using dual fuel and diesel fuel were analyzed to determine the engine performance characteristics.

2.3 Performance characteristics analysis

In this research, the power output was measured as electrical power. Engine performance analysis [18] was determined from thermal efficiency, specific fuel consumption and specific energy consumption. These were calculated as follows:

$$\eta_t = \frac{P_{ele}}{\dot{m}_{diesel} LHV_{diesel} + \dot{m}_{PG} LHV_{PG} + P_{Blower}\eta_{Blower}} x100 \quad (1)$$

$$\eta_{Blower} = \frac{\dot{V}_{PG}\Delta p_t}{102P_{Blower}} x100 \quad (2)$$

$$SEC = \frac{\dot{m}_{diesel}.LHV_{diesel} + \dot{m}_{PG} LHV_{PG} + P_{Blower}\eta_{Blower}}{P_{ele}} \quad (3)$$

where:

η_t : Thermal efficiency (%)
η_{Blower} : Blower efficiency (%)
SEC : Specific energy consumption (MJ/kW$_e$.h)
P_{ele} : Electrical power (kW$_e$)
P_{Blower} : Blower power (kW$_e$)
$\dot{V}_{PG}$: Volume flow rate of producer gas (m^3/sec)
$\dot{m}_{diesel}$: Mass flow rate of diesel fuel (kg/sec)
$\dot{m}_{PG}$: Mass flow rate of producer gas (kg/sec)
Δp_t : Total differential pressure (mm$_{WC}$)
LHV_{diesel} : Low heating value of diesel fuel (MJ/kg)
LHV_{PG} : Low heating value of producer gas (MJ/kg)

3. Results and discussion

In the performance and emissions testing of a diesel engine, the ratio of diesel fuel (D) and producer gas (PG) injected into the engine in a dual fuel mode was defined by diesel fuel was the primary fuel and producer gas compressed and flowing at 76 lpm, 79 lpm, 85 lpm, 93 lpm, 103 lpm, 116 lpm and 125 lpm was the secondary fuel. Terms are demonstrated as D+PG76 lpm, D+PG79 lpm, D+PG85 lpm, D+PG93 lpm, D+PG103 lpm, D+PG116 lpm and D+PG125 lpm, while the volume flow rates of producer gas are indicated after PG. Results of the testing are described below.

3.1 Performance characteristics

3.1.1. Diesel saving

Diesel fuel saving was analyzed from the diesel consumption rate calculated from the amount of diesel oil at 20 ml divided by the real time as experiment. This investigation examined the dual fuel mode, which was the ratio of diesel fuel as a primary fuel and compressed producer gas at levels from 76 to 125 lpm as a secondary fuel. This was compared with using only diesel fuel as shown in Figure 2. This figure indicates that the diesel consumption rate increased with increasing engine speed.

However, increasing the quantity of producer gas from 76 to 125 lpm in dual fuel mode decreased the diesel consumption rate as compared with only diesel fuel mode. The maximum diesel saving was 41% at and engine speed of 1,600 rpm and a gas flow rate 125 lpm. This result is compared with Brenneisen et al. [3] demonstrating a diesel fuel savings of 33.6%. This is consistent with the research work of Brenneisen et al. [3] and Nayak [15] since there was more energy supplied by the gaseous fuel as the flow rate of gas increased. To keep total energy constant, the rate of diesel fuel consumption rate must decrease.

3.1.2 Electrical power

Figure 3 shows the variation of electrical power at various gas flow rates and engine speeds. Electrical power using both modes increased with increasing engine speed, whereas the electrical power was similarly at comparable engine speeds. However, a considerable variation in electrical power was observed in dual fuel mode compared use of only diesel fuel at an engine speed 1,600 rpm and a gas flow rate 125 lpm. Electrical power increased by 1.88%. When this result is compared with Brenneisen et al. [3], it indicates that electrical power was lowered to 91.1%.

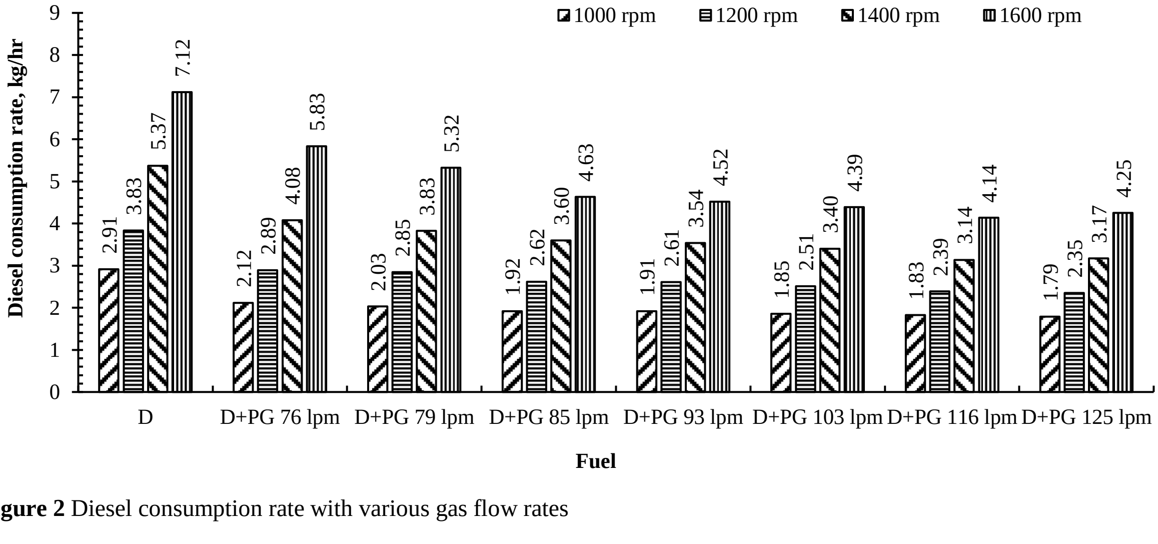


Figure 2 Diesel consumption rate with various gas flow rates

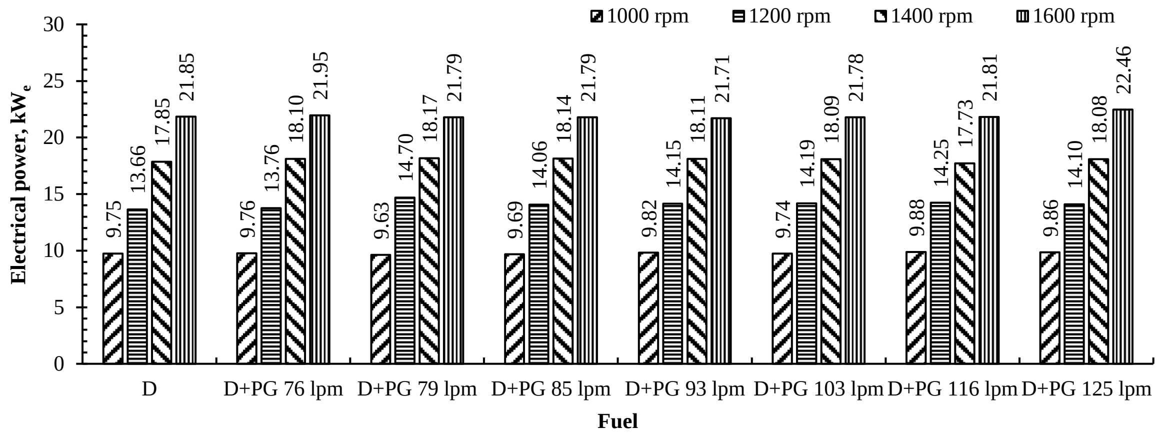


Figure 3 Electrical power with various gas flow rates

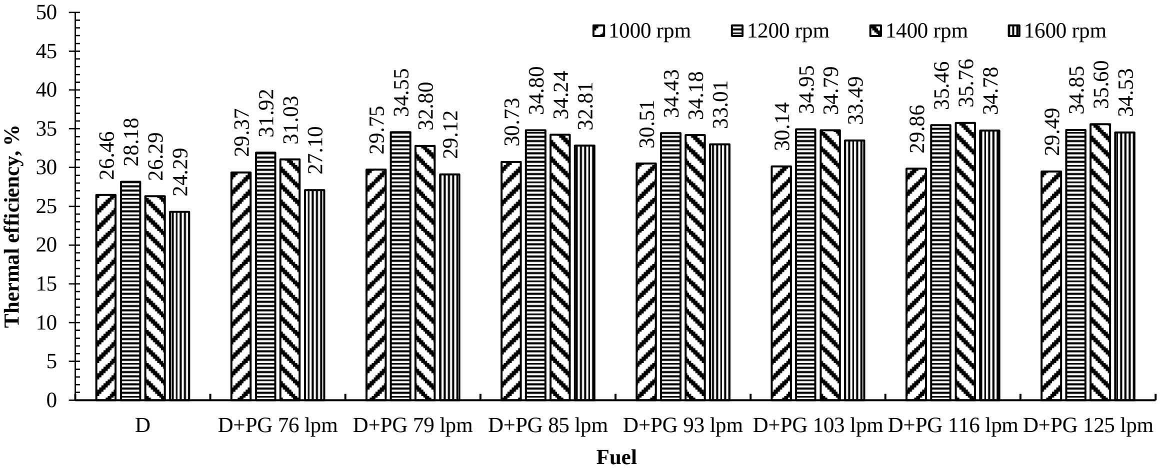


Figure 4 Thermal efficiency with various gas flow rates

The power was lower since Brenneisen et al. [3] used a single-cylinder 5 kWe engine. The current study used a three-cylinder 20 kWe engine. However, this is consistent with research work of Brenneisen et al. [3] and Sombatwong et al. [7] since using compressed producer gas at 125 lpm increases the hydrogen content. This results in faster combustion than in a diesel fuel only mode. Additionally, the increased quantity of producer gas enriched the mixture with fuel and then there was insufficient oxygen to complete the combustion process [19].

3.1.3 Thermal efficiency

Figure 4 shows the variation of thermal efficiency with various gas flow rates and engine speeds. While the compressed producer gas in dual fuel mode increased the thermal efficiency at all speeds of this engine, the maximum thermal efficiency was at 1,200 and 1,400 rpm.

To compare the diesel fuel only mode at 1,200 and 1,400 rpm, the thermal efficiency when using compressed producer gas in dual fuel mode increased from 31.92 to 34.85% and from 31.03 to 35.60% respectively. A maximum thermal efficiency of 35.76% at 1,400 rpm and a gas flow rate of 116 lpm was compared with Yaliwal et al. [10] demonstrating a thermal efficiency higher than 15.51%. This is consistent with research work of Shaw et al. [1], Yadav [2] and Yaliwal et al. [10] since compressed producer gas was mixed with air within the Y-shaped mixing chamber to generate turbulence in the air-producer gas mixture. Additionally, compressed gas increased the energy in the air stream sent to the combustion chamber so that combustion was faster and thereby improved thermal efficiency [11-12]. From Eq. 1, the use of a dual fuel mode had a lower energy input than using diesel fuel alone because producer gas has a lower heating value than diesel fuel. Although increasing the blower power improves efficiency, the resulting electrical power was similar. Results showed that the use of a dual fuel mode has higher thermal efficiency than using a diesel fuel only mode.

3.1.4 Specific energy consumption

Figure 5 shows the variation between SEC with various gas flow rates and engine speeds. SEC using a dual fuel mode was calculated using Eq. 3. While the compressed producer gas in dual fuel mode decreased the SEC in all engine speeds, the minimum of SEC was at 1,200 and 1400 rpm. To compare with use of a diesel fuel only mode at 1,200 and 1,400 rpm, the SEC decreased from 11.74 to 19.17% and from 15.33 to 26.20% at these respective engine speeds. The minimum SEC was 10.07 MJ/kWe.hr at 1,400 rpm and a producer gas flow rate 116 lpm. This result compared with Yadav [2] demonstrates that there was an SEC lower than 53.53%. This is consistent with the work of Yadav [2] since compressed producer gas decreased the quantity of diesel fuel injected whereas producer gas combined with diesel fuel

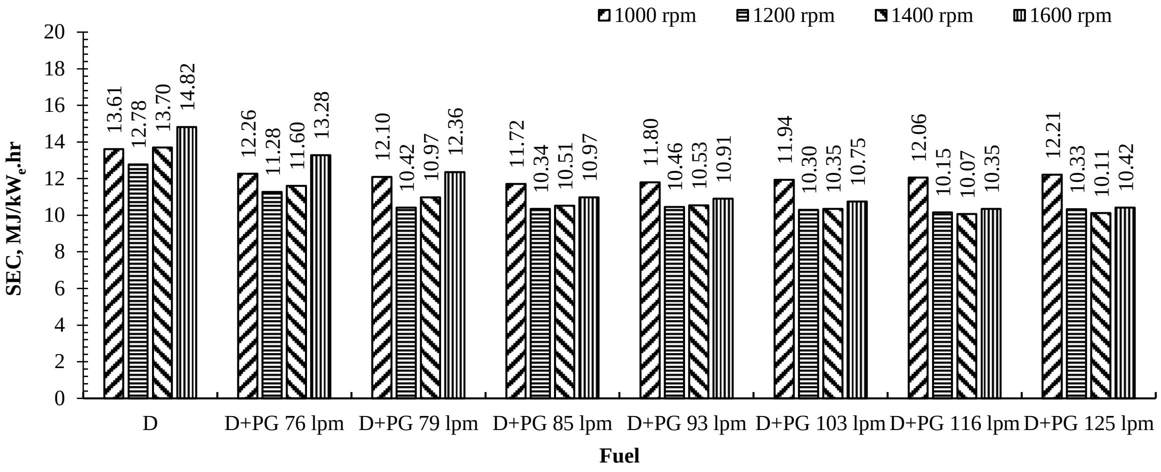


Figure 5 SEC with various gas flow rates

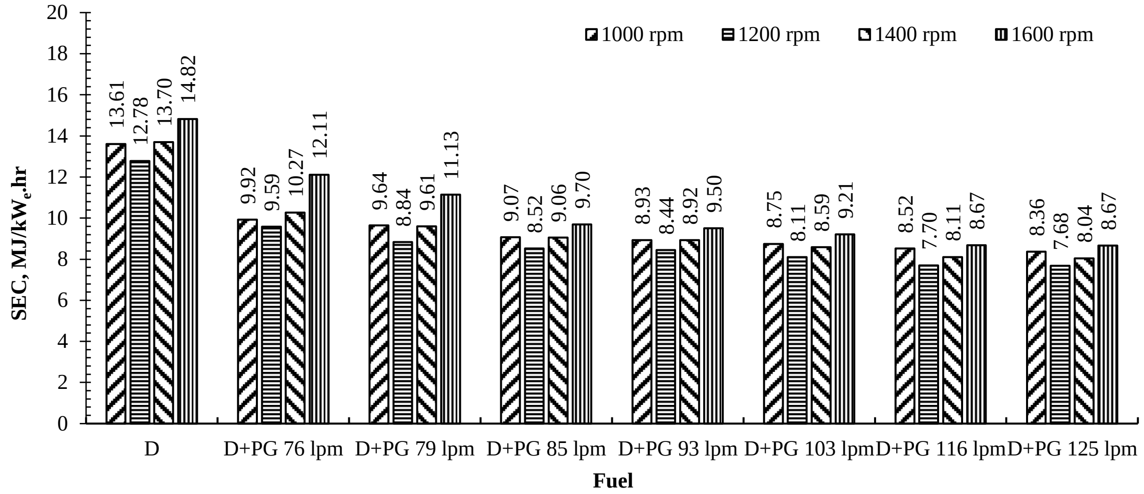


Figure 6 Variation of SEC to depend on rate charcoal biomass consumption

improved combustion efficiency. Additionally, the SEC in a dual fuel mode was found to be lower than that of a diesel fuel only mode at all engine speeds. The SEC was inversely proportional to the thermal efficiency. Increasing the producer gas flow rate reduces the SEC in proportion to the flow rate of producer gas [4].

Figure 6 shows the variation of SEC from the sum of the mass flow rates and heating values of diesel fuel and charcoal, and blower power and efficiency per unit of electrical power at producer gas flow rates of 76 to 125 lpm.

SEC decreased with various gas flow rates and engine speeds. This is consistent with the work of Yadav [2]. The minimum of SEC was when the engine speed was 1,200 rpm. To compare the SEC calculated from the mass flow rate and heating value of diesel fuel per unit of electrical power, the SEC was reduced from 24.96 to 39.91%. The minimum of SEC was 7.68 MJ/kW$_e$.hr at 1,200 rpm and a producer gas flow rate 125 lpm. This result can be compared with Yadav [2], who observed an SEC lower than 64.56%.

3.2 Emissions characteristics

3.2.1 Exhaust gas temperature

The variation of exhaust gas temperature (EGT) with gas flow rate and engine speed using diesel fuel and compressed producer gas in a dual fuel mode compared with a diesel fuel only mode at full load is shown in Figure 7. This figure indicates that the EGT of all fuels increased with increasing engine speed. The use of compressed producer gas in a dual fuel mode resulted in higher EGT values than a diesel fuel only mode.

This is consistent with research work of Brenneisen et al. [3] and Shrivastava et al. [4] since the use of diesel fuel and compressing producer gas in a dual fuel mode has a higher combustion rate than a diesel fuel only mode. This leads to higher exhaust gas temperatures. Considering an engine speed of 1,600 rpm and increasing the flow rate of producer gas from 76 to 125 lpm, the EGT increased from 17.99 to 46.03% to compare with only diesel fuel. The maximum EGT was 276 °C at a producer gas flow rate 125 lpm. This result can be compared with Shrivastava et al. [4], who demonstrated an EGT lower than 28.87%.

3.2.2 Carbon dioxide emission

Figure 8 shows the variation of CO_2 emissions as a function of gas flow rates and engine speeds. It can be seen that the use of compressed producer gas in a dual fuel mode increased the CO_2 emissions with increasing engine speed. This is consistent with Rith et al. [5] since producer gas has

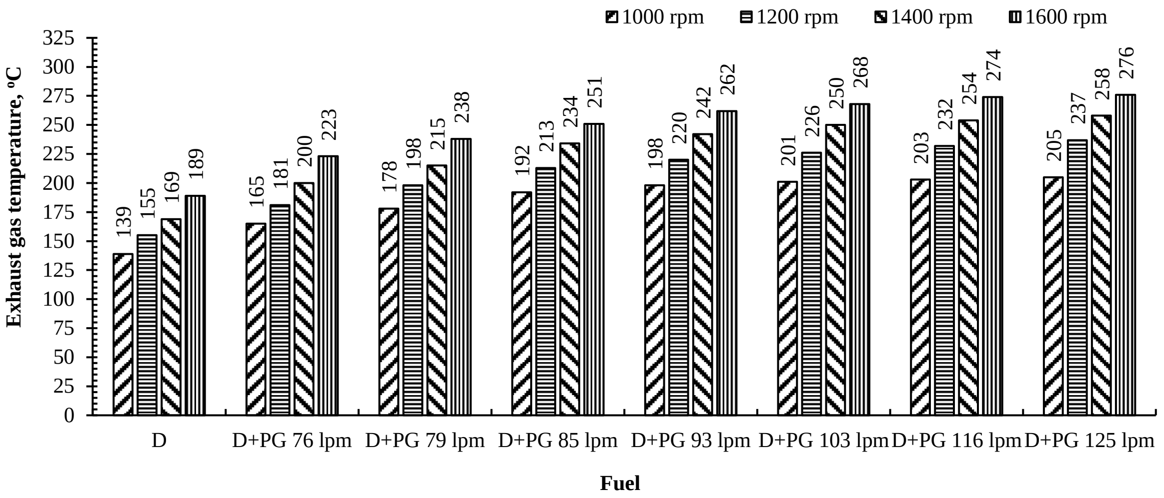


Figure 7 Exhaust gas temperatures with various gas flow rates

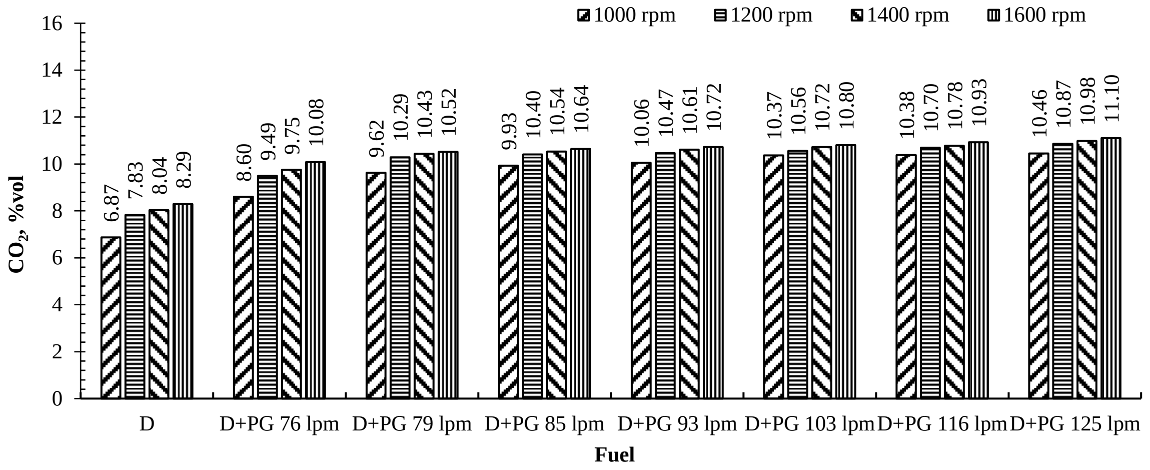


Figure 8 Carbon dioxide levels at various gas flow rates

its own CO_2 concentration before combustion. While the compressed producer gas increased the quantity of CO_2 entering the combustion chamber, it elevated the levels of CO_2 in the exhaust gas also.

At an engine speed 1,600 rpm, which is the speed that yielded the highest CO_2 emissions at producer gas flow rates from 76 to 125 lpm, the CO_2 emission increased from 21.59 to 33.90% over those of the diesel fuel only mode. The maximum of CO_2 emission was 11.10% by volume at a producer gas flow rate of 125 lpm. This result can be compared with Rith et al. [5] who observed higher CO_2 emission higher than 79.03%.

3.2.3 Carbon monoxide emission

Figure 9 shows the variation of CO emissions as a function gas flow rates and engine speeds using diesel fuel and compressed producer gas in a dual fuel mode compared with a diesel fuel only mode.

This figure indicates that compressed producer gas increased CO emissions with increasing engine speed. The reason for this may be due to the presence of CO in the producer gas before combustion. These levels were increased by supercharging. This is consistent with Shrivastava et al. [4], Rith et al. [5], Hassan et al. [13] and Nayak and Acharya [14] since there was incomplete combustion due to insufficient oxygen in the combustion mixture resulting in elevated CO emissions in the exhaust gas. At 1,000 rpm, the highest CO emission levels were observed because this condition had the lowest oxygen level in the combustion chamber. At this speed, compressed producer gas at flow rates from 76 to 125 lpm had increased CO emission from 0.62 to 1.69% by volume. At 1,600 rpm, the lowest CO levels were observed because there was sufficient oxygen for complete combustion. Increasing the flow rate of producer gas from 76 to 125 lpm, increased CO emissions from 0.36 to 0.59% by volume. The maximum CO emissions, 1.72% by volume, were observed at 1,000 rpm and a producer gas flow rate 125 lpm. This result can be compared with Rith et al. [5] at same speed demonstrating a CO emission lower than 25.23%.

3.2.4 Hydrocarbon emission

The variation of HC emission at various gas flow rates and engine speeds using different fuels is shown in Figure 10. This figure indicates that combustion of compressed producer gas increased the HC emissions with increasing engine speed. This is consistent with Banapurmath and Tewari [12], Nayak and Acharya [14] and Nayak [15] since

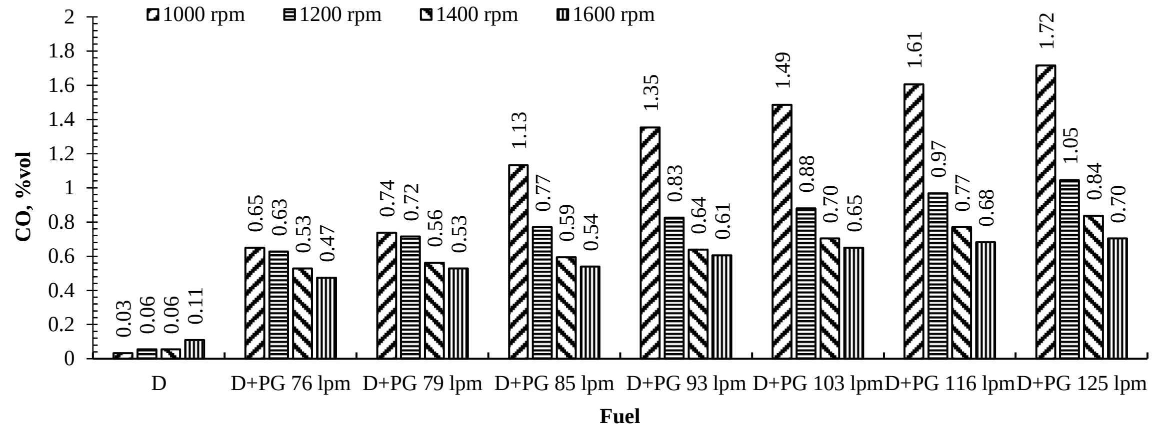


Figure 9 Carbon monoxide levels at various gas flow rates

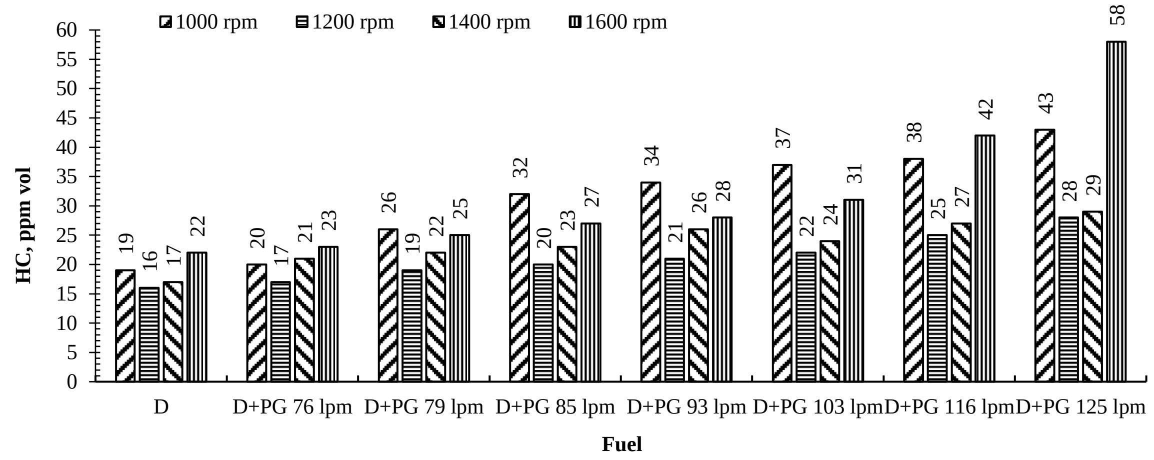


Figure 10 Hydrocarbon levels at various gas flow rates

there is increasingly incomplete combustion as a result of the slower burning velocity of producer gas and a decrease in oxygen levels in the mixture at increasing gas flow rates. At 1,000 rpm, increasing the flow of compressed producer gas from 76 to 125 lpm increased HC emissions from 20 to 43 ppm. At 1,600 rpm, the HC emissions increased from 23 to 58 ppm. The maximum HC emissions, 58 ppm, were observed at 1,600 rpm and a producer gas flow rate 125 lpm. This result can be compared with Nayak and Acharya [14] and Nayak [15] at same speed showing HC emissions lower than 10.77%.

3.2.5 Smoke opacity

The variation of smoke opacity emission with producer gas flow rate and engine speed is shown in Figure 11. From this figure, it can be observed that smoke opacity increased with increasing gas flow rates and engine speeds. This is consistent with research Shrivastava et al [4], since increasingly incomplete combustion as result of an over-rich combustion mixture with increasing producer gas flow.

At 1,000 rpm, compressed producer gas flowing at 76 to 125 lpm showed that smoke opacity increase from 2.74 to 3.97 $K.m^{-1}$. At 1,600 rpm, the smoke opacity increased from 4.00 to 6.07 $K.m^{-1}$ as the flow rate of producer gas was increased in the same manner. The maximum smoke opacity, 6.07 $K.m^{-1}$, was at 1,600 rpm and a producer gas flow rate 125 lpm. This result can be compared with Shrivastava et al. [4] indicating a smoke opacity higher than 39.69%.

4. Conclusions

From this investigation of the performance and exhaust emission characteristics of a low speed direct injection diesel engine operating with compressed producer gas in dual fuel mode, the following conclusions can be made:

1) The use of diesel fuel as primary fuel and compressed producer gas at 125 lpm as secondary fuel resulted in a diesel saving of 41%, while the output electrical power increased by 1.88%. The maximum thermal efficiency was 35.76% at a gas flow rate 116 lpm.

2) Specific energy consumption was found to decrease when there was the increase in the producer gas flow rate from 76 to 125 lpm. Specific energy consumption decreased from 11.74 to 19.17% compared with a diesel fuel only mode.

3) Exhaust gas temperature was found to increase when there was an increase in the producer gas flow rate from 76 to 125 lpm with concurrently increased engine speeds.

4) The amount of CO_2, CO and HC emissions were always higher with increasing producer gas flow rates in a dual fuel mode as compared with a diesel fuel only mode. Similarly, the quantity of black smoke increased with increasing producer gas flow rates.

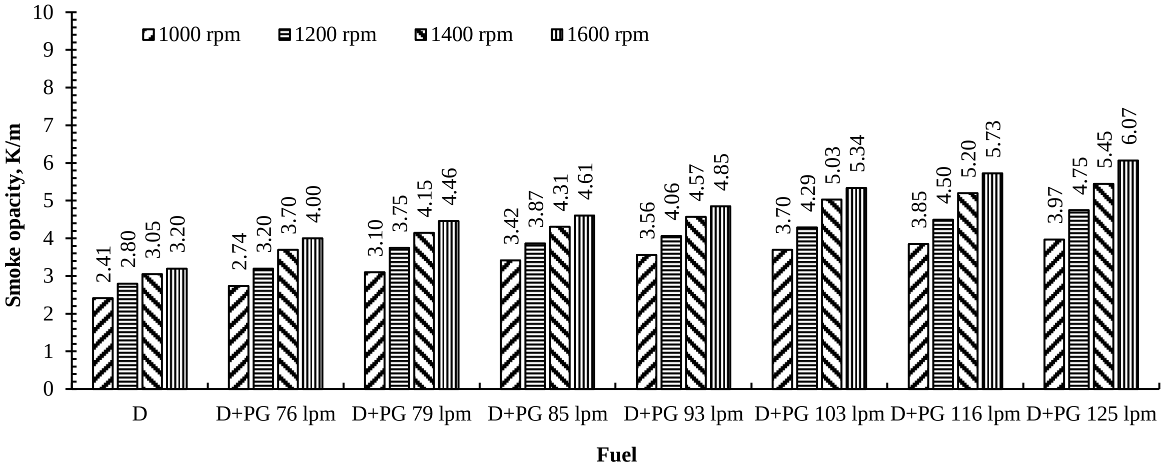


Figure 11 Smoke opacity at various gas flow rates

5) All results of engine performance and emissions testing indicated that increasing the compressed producer gas flow rate from 116 to 125 lpm not only improved the diesel savings and engine performance characteristics, but also increase the levels of exhaust gas emissions.

5. Acknowledgements

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