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Full Paper

Performance investigation of a modified small engine fueled with producer gas

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Abstract: Producer gas from biomass gasification can be used as a replacement fuel in spark-ignition engines. In this study, a small, single-cylinder, naturally aspirated diesel engine was modified into a spark-ignition engine. A conventional swirl chamber was replaced by a bath tube combustion chamber. Optimum spark ignition time was set for each engine speed to give maximum brake torque. It was fueled with 100% producer gas and coupled to a 5.0-kW dynamometer. A downdraft gasifier was used to generate producer gas from charcoal. Engine performance in terms of engine torque, brake power, brake thermal efficiency and brake specific fuel consumption were evaluated at variable compression ratios between 9.7:1-17:1. Engine speed and load were varied between 1100-1900 rpm and 20-100% respectively. At a certain combination of compression ratio, engine speed and load, deceleration and knocking were detected. Maximum engine torque and brake power were 18.6 Nm and 3.3 kW respectively, at a compression ratio of 14:1, full load and 1700 rpm. The best specific fuel consumption of 0.94 kg/kWh and maximum brake thermal efficiency of about 19% were obtained.

Keywords: small engine, producer gas, compression ratio, spark ignition, renewable energy

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INTRODUCTION

Escalating oil prices and increasingly scarce fossil fuels, coupled with an exploding population, have created an energy crisis, especially in developing countries where machines are used in food production. In Thailand, the agricultural sector commonly uses small, internal combustion engines, with power and speed mostly in the range of 2.2-10.4 kW and 1000-2000 rpm respectively [1]. Farms use them for mechanical work, pumping, power generation and plowing. Using producer gas in engines offers an alternative energy source, reducing dependence on fossil fuels. However, producer gas poses a problem as more combustible carbon monoxide content is needed to produce a similar output to gasoline. This is because the engine operates at a lower

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thermal efficiency with power de-rated by more than 30% due to the lower energy density of producer gas compared to that of gasoline and diesel fuels [2].

Attempts to develop internal combustion engines, especially for producer gas as fuel, are ongoing, with three primary types: (i) spark ignition (SI) engines using gas, (ii) compression ignition (CI) engines using gas and diesel in dual fuel mode, and (iii) engines converted from CI to SI using 100% gas. Based on previous researches, converting a CI engine into an SI engine operated at medium and high levels of compression ratio (CR) shows promise. A number of studies of SI engines fueled by producer gas have been carried out. Parke and Clark [3] and Martin and Wauters [4] showed that the engine power was 34-50% less than gasoline engines at conventional CR [5]. Munoz et al. [6] reported test results on a small SI engine at a CR of 8.2: 1. A power de-rating of 50% was observed. Ando et al. [7] reported that SI engines using producer gas at a CR of 9.4:1 caused a 45% average power reduction at all engine speeds. Shah et al. [8] found that a small SI engine using producer gas at a low CR had 1.8 times less power than using gasoline. Dasappa et al. [9] studied the use of producer gas with a 100-kW SI engine at a CR of 9.7:1. The maximum thermal efficiency was 18% and at low CR the engine power was reduced.

Ramachandra [10] studied medium and high CRs in a converted SI engine and found that the engine ran smoothly, with power output reduced by 20% compared to the original CI engine [5]. Shasikantra et al. [11] converted a CI engine to operate as an SI engine with producer gas as fuel at a CR of 11:1. They obtained a high thermal efficiency in the range of 20-24%. Aung [12] adapted a producer gas engine converted from a CI engine at a CR of 10:1. The power and torque output were 40% less than that with diesel mode. Raman and Ram [13] reported on an SI engine using producer gas at a CR of 12:1. The maximum thermal efficiency was 21% at 85% of full load. Sridhar et al. [5] modified a CI engine into an SI engine and used producer gas as fuel at a CR of 17:1. The engine brake power was reduced by 20% and the maximum overall efficiency obtained was 21%.

Most of these studies used medium to large engines. There have been very few studies on small engines. The objective of this research is to analyse the performance of a small engine fueled with 100% producer gas and determine the most appropriate CR, load and engine speed.

MATERIALS AND METHODS

Experimental Set-up

A schematic diagram of the gas generator system used in this study is shown in Figure 1. The gas generator design is based on a downdraft gasifier [14], and configured to operate on charcoal or wood. It consists of a gasifier, a gas conditioner and gas filters. The producer gas can be produced with a charcoal consumption rate between 5-6 kg/h. The efficiency of the gasification system is 70-75% and can generate up to 27 Nm^3/h of producer gas. The conditioning system improves the quality of the producer gas to ensure that the engine runs smoothly. The gas conditioning system consists of a heat exchanger, cyclone, Venturi scrubber, tar box, moisture separator, biomass filter, fabric filter and paper filter. The set-up also includes a water treatment plant for closed-loop water re-circulation.

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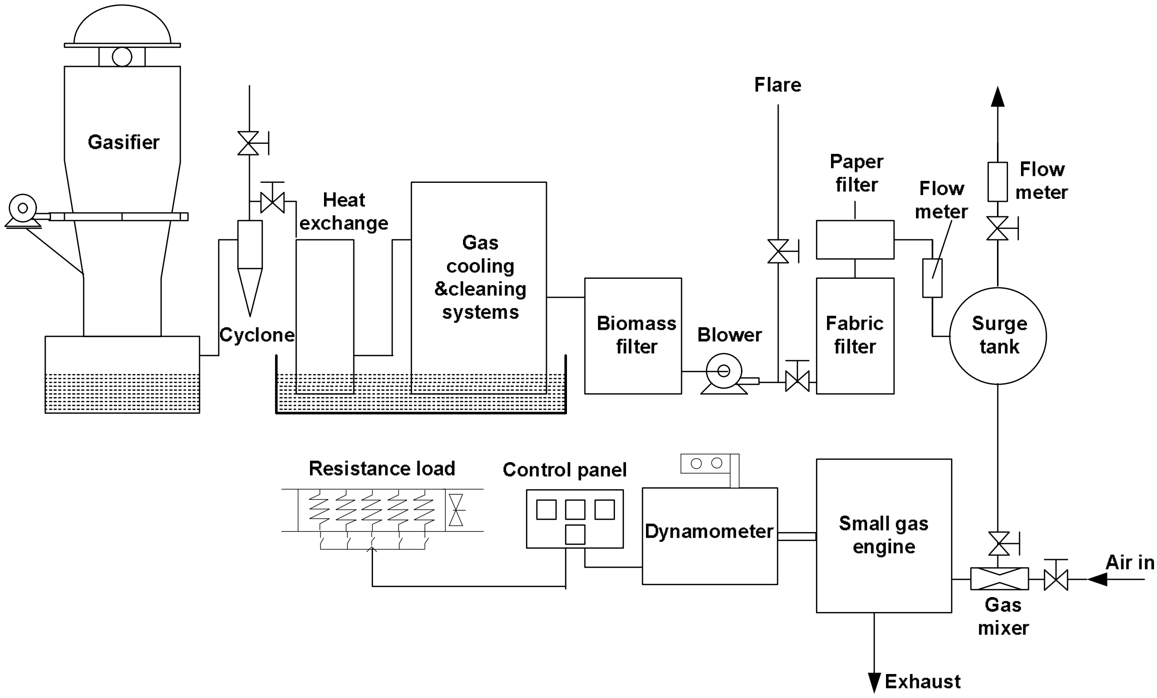
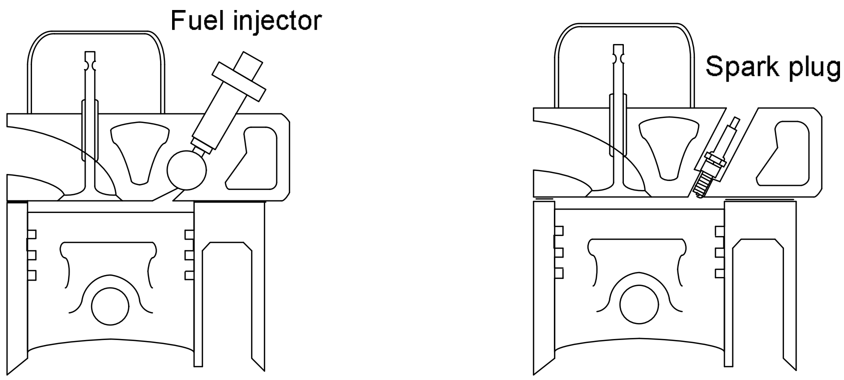


Figure 1. Schematic diagram of the experimental set-up for gas generator system



(a) before (b) after

Figure 2. Small producer gas engine before and after modification of cylinder head

Engine Modification

A conventional, small, agricultural, water-cooled diesel engine with a CR of 21:1 was used in this experiment. The four-stroke, single cylinder, indirect injection engine was capable of producing a maximum power output of 8.2 kW. The engine specifications are given in Table 1. For the producer gas feeding system, a gas mixer was designed, manufactured and installed. The original diesel injection system was replaced with a spark plug as shown in Figure 2. The distributor and ignition coil were taken from a Mitsubishi 4G15 engine. The vacuum and centrifugal advances were disabled because the engine ran at a constant speed. The distributor was modified by replacing the magnetic pick-up with a spark timing plate stuck to the flywheel. The spark-ignition timing could be adjusted between 0-60°. The CR was adjusted to a range of 9.7-17: 1. Variable CR was achieved by using a thicker head gasket (between 4.7-8.2 mm). The volumes of the cylinder head

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and piston head were measured using a hypodermic syringe with low-viscosity oil. The cylinder head bolts and push rods were modified and the stoichiometric ratio of air to producer gas was approximately 1: 1.2. This volume ratio was used in the design of the gas mixer, which was based on Janisch [15] and used to supply the engine operating between 1000-2000 rpm with the appropriate mixture of air and gas. The air mixer was a Venturi with a throat diameter of 25 mm. Producer gas and air could be controlled by adjusting two screws.

Table 1. Specifications of original engine dynamometer set-up

Engine make, model	Kubota, ET11
Engine power	8.2 kW
Bore × Stroke	92×90 mm^2
Number of cylinder	1
Engine arrangement	Horizontal
Type of cooling	Water, thermo siphon system
CR	21:1
Combustion chamber	Pre-chamber
Ignition system	Compression ignition
Alternator efficiency	85%

Experimental Apparatus and Procedure

All experiments involving the engine were performed only after the gasifier system stabilised, normally about 1 hour from start-up. The stability of the gasifier system was achieved when the temperatures of the gasification zone and burner flame stabilised. The gas generator was operated using charcoal (size 25×25×25–50×50×50 mm according FAO [2] and Shaw [16]) which was available locally. Its density and average moisture content were measured based on ASTM C373-88 and ASTM D 2016-74 [17] and were found to be 250-300 kg/m^3 and 7% respectively. The gas composition was determined at random intervals using a Shimadzu GC-8A gas chromatography fitted with a ShinCarbon ST Micropacked column and a thermal conductivity detector. The conditions used were similar to those reported previously [18, 19]. The average chemical composition was 30.5±2% CO, 8.5±2% H_2, 0.35% CH4, 4.8±1% CO_2, 6.3±0.5% O_2 and N_2 (balance). The calculated mean calorific value of the producer gas was 4.64 MJ/Nm^3. The tar and particulate matter in the producer gas was measured according to Hasler et al. [20] and found to be less than 50 mg/Nm^3. Experiments were conducted at CRs of 9.7:1, 14:1 and 17:1. A higher CR engine using producer gas is of interest as it might offer a higher efficiency with better tolerance to knocking. Modifying an engine to have a higher CR is straightforward by simply decreasing the thickness of the cylinder head gasket. Engine tests were carried out by varying engine speeds with rpm and loading range of 1100-1900 and 20-100% respectively. The data were acquired at the corresponding maximum brake torque timing for each 1100, 1300, 1500, 1700 and 1900 rpm of the engine speed test condition. The air and fuel were tuned to achieve maximum power and after a stable operation, several measurements were taken over an average of 10-min. interval. Charcoal consumption at different loads was monitored by weighing the amount fed into the gasifier. The producer gas and airflow rates were measured using a Lutron YK-80 flow meter. The electrical load consisted of ten 100W bulbs with ten 500W heaters; a F609 Chauvin Arnoux watt meter was used for monitoring the load. The engine torque was measured using a load cell. The brake power, thermal efficiency and fuel consumption were evaluated using the following equations [21]:

$$P = 2\pi N\tau \quad (1)$$

where P is the brake power, τ is the engine torque (Nm) and N is the engine speed (s^{-1});

$$BSFC = \frac{\dot{m}_f}{P} \quad (2)$$

where $BSFC$ is the brake specific fuel consumption and $\dot{m}_f$ is the mass flow rate of biomass (kg/h);

$$BTE = \frac{P}{\dot{V}_{pg} LHV_{pg}} \quad (3)$$

where BTE is the brake thermal efficiency, expressed as ratio of the output power to the power supplied by the fuel, $\dot{V}_{pg}$ is the producer gas flow rate (m^3/s) and LHV_{pg} is the lower heating value of the producer gas (MJ/Nm^3).

RESULTS AND DISCUSSION

Gas Engine Operation

Table 2 provides a general overview of operation of a small engine with producer gas. It is representative of the results of analysing the engine performance. It can be observed that, at a low CR (9.7:1), the engine was able to be gradually loaded and stabilised up to 1500 rpm. With increasing engine speed, acceleration was good and the engine power increased. The engine decelerated and became unstable when the speed was increased to 1700-1900 rpm. The observed deceleration might be due to a reduced energy density compared to gasoline. The low CR of the engine might cause a lower pressure inside the combustion chamber [22] and affect flammability of the producer gas [7]. The lower volumetric efficiency might be reduced for gaseous fuel operation compared to conventional liquid fuels [23]. At a medium CR (14:1), however, the engine was observed to have good acceleration stability and its power increased with speed, although knocking occurred at full load and 1900 rpm. Finally, at a high CR (17:1), the small engine operated well between 1100-1500 rpm, but severe knocking symptoms occurred at 1700-1900 rpm and 80-100% of full load. Knocking might result from the increasing compression ratio, as well as increasing load and engine speed, leading to an increase in gas density, temperature and ignition lag in the combustion chamber [21].

Engine Brake Torque

Figure 3 shows the variation in engine torque of the small producer gas engine at 1500 rpm with different engine loads and CRs. A maximum torque of 15.38 Nm was obtained at CR = 14:1 and full load. For all CRs, the brake torque was similar between 20-60% of load. Increasing load from 60 to 80% at medium CR increased brake torque significantly. The main reason for the increase in torque is that, compared to low CR, the work in expansion stroke exceeds that in the compression stroke [13]. At high CR, the engine torque was low due to abnormal combustion, leading to knocking [24]. Comparing engine torque versus speed at full load, the suitable CR for the small producer gas engine was found to be 14:1 at 1700 rpm and 18.61 Nm of maximum torque. At 1900 rpm, the engine was unable to operate due to severe knocking.

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Table 2. Operation of modified small engine fueled with producer gas at different test conditions

Compression ratio	Load (%)	Engine operation				
		1100 rpm	1300 rpm	1500 rpm	1700 rpm	1900 rpm
9.7:1	20	✓	✓	✓	x	x
	40	✓	✓	✓	x	x
	60	✓	✓	✓	x	x
	80	✓	✓	✓	x	x
	100	✓	✓	✓	x	x
14:1	20	✓	✓	✓	✓	✓
	40	✓	✓	✓	✓	✓
	60	✓	✓	✓	✓	✓
	80	✓	✓	✓	✓	✓
	100	✓	✓	✓	✓	xx
17:1	20	✓	✓	✓	✓	✓
	40	✓	✓	✓	✓	✓
	60	✓	✓	✓	✓	✓
	80	✓	✓	✓	xx	xx
	100	✓	✓	✓	xx	xx

Note: ✓ = OK; x = Erratic; xx = Knocking

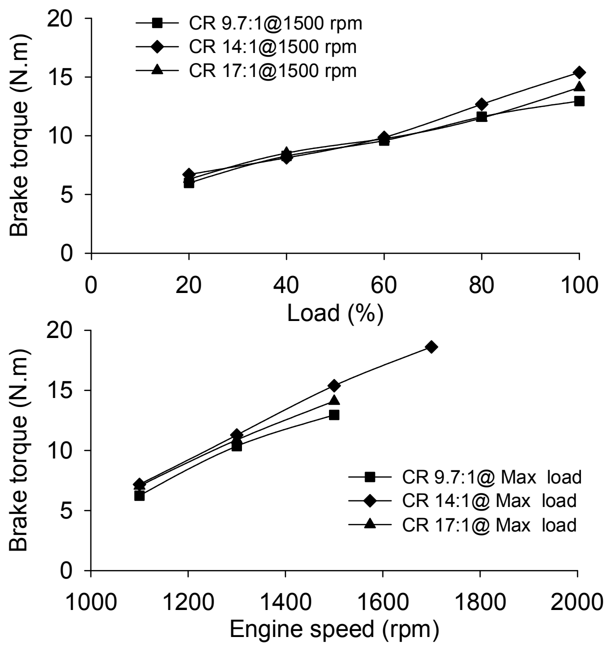

Figure 3. Engine brake torques at different loads and engine speeds

Brake Power

Figure 4 shows the effect of load and engine speed on the brake power for each CR considered. The engine brake power increased as engine load increased at all CRs. At 1500 rpm, an engine brake power of 2.41 kW was achieved at 14:1 of CR. The maximum engine brake power of 3.31 kW was achieved at 1700 rpm and medium CR.

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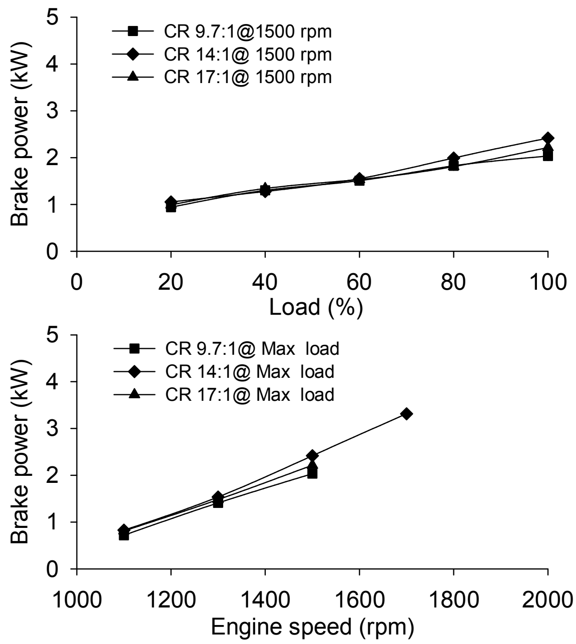

Figure 4. Engine brake power at different loads and engine speeds

Brake Thermal Efficiency

Figure 5 shows the BTE as a function of engine load and speed at different CRs. The efficiency tended to increase with engine load. This might be attributed to a better combustion of the relatively rich gas-air mixture at high loads. The BTE at medium CR was slightly higher than those at low and high CRs; reduction of BTE was due to a higher producer gas flow rate and poor combustion. At medium CR, a maximum BTE of 18.6% was obtained at full load. The small producer gas engine operated successfully at 1100-1500 rpm at both low and high CRs. The engine could operate up to 1700 rpm at medium CR, but at 1500-1700 rpm, the BTE tended to level off.

Brake Specific Fuel Consumption

The gasification rate from charcoal to producer gas was 25 Nm^3/h. The charcoal-to-gas conversion rate was arrived at by measuring the gas flow rate and fuel consumption rate. The specific charcoal consumption rate for the small producer gas engine was 0.94 kg/kWh. When the engine was operated at medium CR at full load (Figure 6), fuel consumption was reduced with increasing engine speed. The low and high CRs consumed more fuel than medium CR. Generally, the BSFC rate of the producer gas engine is in a range of 1.2-2 kg/kWh [9, 12]. At full load, the specific consumption rate decreased as engine speed increased. The lowest BSFC occurred between 1400-1500 rpm.

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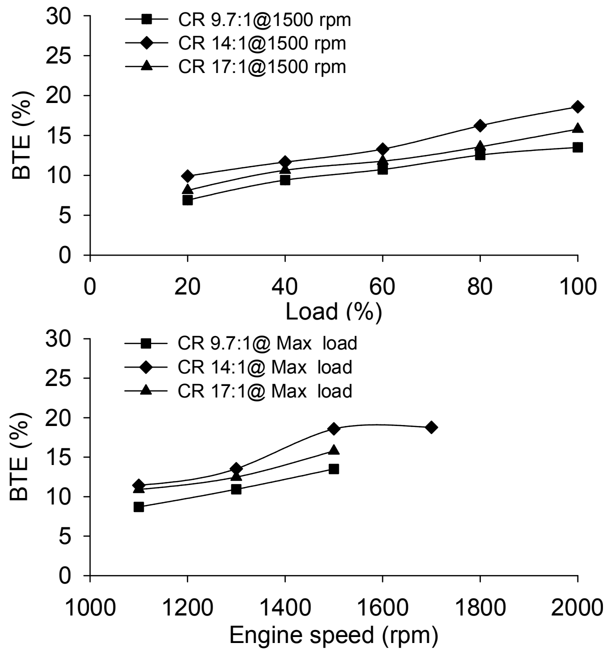

Figure 5. BTE at different loads and engine speeds

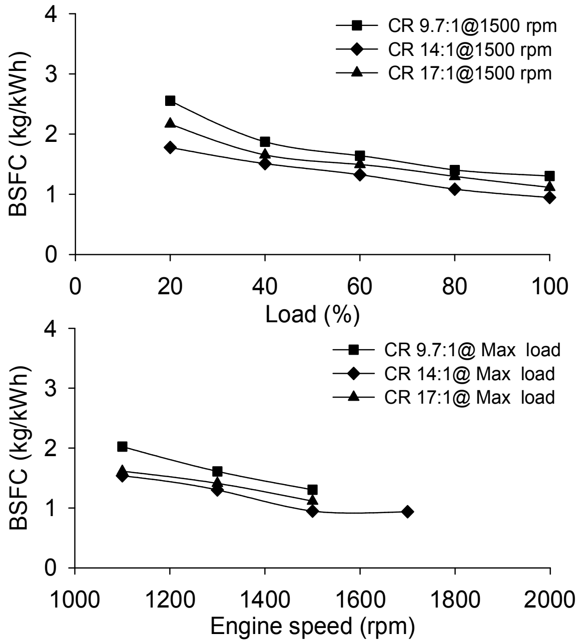

Figure 6. BSFC at different loads and engine speeds

Comparison with Previous Results

The performance of engines converted from CI or SI engines and fueled with producer gas at typical and high CRs, including that in this study, is summarised in Table 3. Most engines tested were large, with 2-6 cylinders and total engine displacement in the range of 1800-14000 cm^3, while that in this study was a small, single-cylinder engine with displacement of less than 600 cm^3. The CRs of the engines used were mostly low due to concerns about possible knocking [11] and the flexibility of using other fuels as primary fuel [12]. No sign of knocking at high CR was reported [9, 25]. Most reports on large engines did not provide information on torque and power. The overall

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efficiency of these large engines was in a range of 18-21%, which is similar to the efficiency values obtained in this work. The BSFC of our small engine was lower than those reported for the large engines.

Table 3. Performance of modified engines operated on producer gas

Performance specifications	[5]	[9]	[12]	[13]	This study
Engine power (kW)	28	283.48	26.5	99.2	8.2
Total displacement (cm^3)	3307	14000	1853	12316	598
Bore x Stroke (mm)	110x116	140x152	100x118	132x150	92x90
Number of cylinder	3	6	2	6	1
CR	17:1	8.5	10:1	12:1	14:1
Max torque/engine speed (Nm/rpm)	-	-	64/1400	-	18.6/1700
Max brake power/engine speed (kW/rpm)	-	-	12/1400	-	3.3/1700
BTE (%)	21	18	-	20.7	18.58
BSFC (kg/kWh)	-	1.36	2	1.2	0.94

Note: '-' = not available

CONCLUSIONS

We converted a small diesel engine into an SI gas engine. The modified engine successfully ran with 100% producer gas at high CRs. The most appropriate CR was 14:1 at full load with a maximum engine speed of 1700 rpm. The maximum engine torque and brake power was 18.61 Nm and 3.31 kW respectively.

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