

Gaseous Emissions Using Producer Gas as Fuel in Reciprocating Engines

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ABSTRACT

In the recent times issues like the Green House Gas (GHG) emission reduction and carbon-trading through Clean Development Mechanism (CDM) have gained large prominence as a part of climate change. Biomass gasification is one such technology which is environmentally benign and holds large promise for the future. These technologies are currently being utilized for power generation applications at a number of industrial sites in India and abroad. This paper summarizes the work conducted using biomass derived producer gas in reciprocating internal combustion engines. The producer gas for the experimental work is derived from the well-established open top, re-burn, down draft gasification system, which is proven to generate consistent quality, ultra-clean producer gas. This paper discusses the actual emission measurements in terms of NO_x and CO on (a) dual-fuel engine (compression ignition engine) – using high speed diesel and producer gas fuel, (b) gas engine (spark ignited engine) – using 100% ultra clean producer gas. In the case of dual-fuel operation it is found that the NO_x levels are lower compared to operations with pure diesel fuel on account of lower peak flame temperature, whereas the CO levels were higher due to combustion inefficiencies. In the case of gas alone operation it is found to be environmentally benign in terms of emissions; NO_x and CO levels are found to be much lower than most of the existing emissions norms of various countries including the United States and European Union.

INTRODUCTION

In the recent times automobile and power generation systems are identified to be one of the largest contributors to atmospheric pollution. In order to mitigate this oxygenated doped petroleum fuels have been introduced in many countries. Likewise gaseous fuels are also receiving more prominence. Producer gas, a low energy density gas derived from biomass, holds large promise as an environment friendly fuel. This fuel gas, in addition to being CO₂ neutral, generates lower quantities of undesirable emissions such as nitric oxide and sulfur dioxide.

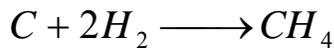
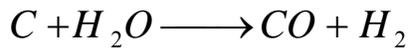
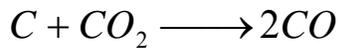
The thermo-chemical conversion of biomass leads to a gas generally termed as producer gas. The process is termed gasification implying that a solid fuel is converted to a gaseous fuel. Gasification is not a new technology but is known ever since World War II. During this period a number of vehicles in Europe were powered with charcoal gasifiers. It is estimated that over seven million vehicles in Europe, Australia, South America and Pacific Islands were converted to run on producer gas during World War II. These engines were spark ignition (SI) engines, mostly in the lower compression ratio (CR) bracket operating either on charcoal or biomass derived gas. It is appropriate to mention here the contribution of National Swedish Testing Institute of Agricultural Machinery, Sweden [1] whose extensive fieldwork conducted by mounting gas generator and engine set on truck and tractors has provided an important demonstration of the enormous possibilities.

Though there has been sporadic interest in biomass gasifiers whenever there has been an oil crisis, sustained global interest has got developed only in the recent times for reasons like Green House Gas (GHG) emission reduction and carbon trading through clean development mechanisms. In addition, steep rise in the oil prices has had a severe impact on the industrial economy and this has also forced many oil-importing countries to reconsider gasification technology and bring about improvements in them. Combustion, Gasification and Propulsion Laboratory (CGPL) at the Indian Institute of Science (IISc) has been addressing issues related to biomass gasification for over two decades. There has been extensive work carried out in this field involving more than 300 man-years. The outcome of this sustained effort is the design of open top, twin air entry, re-burn gasifier and its uniqueness in terms of generating superior quality producer gas provides a definite edge over other gasification technologies [2 - 4].

This paper addresses the work relating to application of biomass based gasification system for power generation. The overall performance and emission measurements in dual fuel and gas alone mode are presented in detail.

BIOMASS GASIFICATION PROCESS

Biomass is basically composed of carbon, hydrogen and oxygen, which are represented approximately by $CH_{1.4}O_{0.6}$. A proximate analysis of biomass indicates the volatile matter to be between 70 to 80% and rest carbon and ash. Gasification is a two-stage reaction consisting of oxidation and reduction processes. These processes occur under sub-stoichiometric conditions of air with biomass. The first part of sub-stoichiometric oxidation leads to the loss of volatiles from biomass and is exothermic; it results in peak temperatures of 1400 to 1500 K and generation of gaseous products like carbon monoxide, hydrogen in some proportions and carbon dioxide and water vapor which in turn are reduced to carbon monoxide and hydrogen by the hot bed of charcoal generated during the process of gasification. Reduction reaction is an endothermic reaction as indicated below to generate combustible products like CO, H_2 and CH_4 .



Since char is generated during the gasification process the entire operation is self-sustaining. The temperature of gas exiting the reactor is about 600 – 900 K. Typical composition of the gas after cooling to ambient temperature is about 18-20% H_2 , 18-20% CO, 2-3% CH_4 , 12% CO_2 , 2.5% H_2O and rest, N_2 [2 - 4]. The lower calorific value of the gas ranges is about $5.2 \pm 0.2 \text{ MJ/Nm}^3$, with a stoichiometry requirement of 1.2 to 1.4 kg of air for every kg of producer gas [5].

One of the pre-requisites for producer gas to be suitable for internal combustion application is the cleanliness of the gas apart from the composition. Conventionally, the gas purity is specified by quantifying the contaminant levels in terms of particulate and tar matter. The permissible levels of gas quality also differ with the nature of the engine's induction process. The permissible level for a naturally aspirated engine is around 50 mg/Nm^3 , whereas the same for a turbo-charged engine or a gas turbine is below a few mg/Nm^3 .

Producer gas can either be used in mono or dual fuel mode in reciprocating engines. In case of mono-fuel mode of operation, the gas is fuelled to a SI engine, whereas in dual-fuel mode it is operated along with small quantity of liquid fuel (high-speed diesel, furnace oil or bio-diesel) in a compression ignition (CI) engine. The choice of mode of operation is entirely dictated by the economics of operation, and of course on the availability of appropriate engines.

Conventionally, gasifiers can be classified as fixed bed and fluidized bed gasifiers. In a fixed bed gasifier, the charge is

held statically on a grate and the air moving through the fuel bed leads to gasification in the presence of heat. Fixed bed gasifiers can be classified as updraft, crossdraft and downdraft systems. Downdraft system is known to generate clean gas that is suitable for engine application. A new innovation in the downdraft design is the open top re-burn design developed at IISc. This design has certain inherent features that permit generation of a combustible gas with very low tar level [2 - 4]. It is proven to generate a gas with very low tar content and of reasonable calorific value. Typical producer gas composition is about $19 \pm 1\% H_2$, $20 \pm 1\% CO$, $2 \pm 0.5\% CH_4$ and rest being inert like CO_2 and N_2 , with lower calorific value (LCV) being $5.2 \pm 0.2 \text{ MJ/Nm}^3$. The properties of producer gas along with natural gas are shown in Table 1.

The stoichiometry air to fuel ratio is about 1.30 ± 0.1 on mass basis, with laminar burning velocity being higher than natural gas (0.5 m/s against 0.35 m/s) at ambient conditions [5]. This gas is amenable for engine applications, with particulate and tar content being less than 1 mg/Nm^3 .

DETAILS OF THE STUDY

This work addresses overall performance and emission with respect to usage of producer gas in reciprocating internal combustion engines in (1) dual-fuel mode and (2) gas alone mode of operation. The experimental set-up consisted of gasifier unit – reactor, gas cooling and cleaning sub-system coupled to either a diesel engine or a gas engine. The general arrangement of the experimental set-up is shown in Fig. 1.

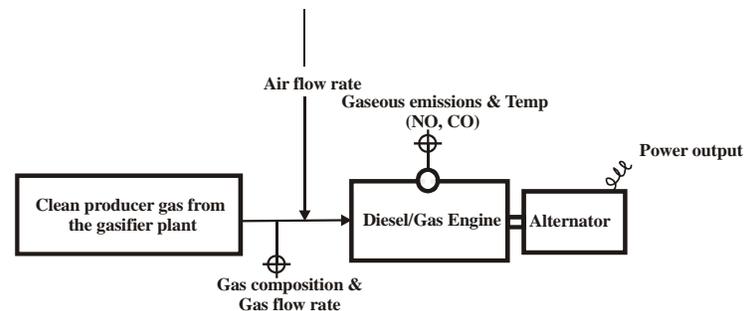


Fig. 1 Experimental set-up for diesel/gas engine.

Experiments were initiated on the engine only after the gasifier system stabilised i.e. attained steady state operation in terms of generation of consistent quality gas. Typical time scale for attaining steady state of operation from the cold start was 2 to 3 hours. During this period the gas was flared in a burner. The gas composition was determined using on-line gas analysers (Maihak gas analyzer), pre-calibrated using a known producer gas mixture. The calibrations of these analysers

Table 1: Properties of Producer Gas (PG)

Fuel + Air	Fuel LCV, MJ/Nm ³	Air/Fuel @ $\Phi = 1$ mole	Mixture, MJ/Nm ³	Φ , Limit		S_L (Limit), cm/s		S_L $\Phi = 1$, cm/s	Peak Flame Temp, K	Product/Reactant Mole Ratio
				Lean	Rich	Lean	Rich			
CH ₄ [6]	35.8	9.52	3.4	0.54	1.69	2.5	14	35	2210	1.00
PG [5]	5.6	1.12	2.6	0.47	1.60	10.3	12	50	1800	0.87

Φ =fuel-air equivalence ratio; S_L =Laminar burning velocity

were checked at random time intervals so as to minimise errors in long duration operation. Typically gas composition at the time of start of engine test was $19 \pm 1\%$ - H₂; $19 \pm 1\%$ - CO; 2% -CH₄; $12 \pm 1\%$ CO₂; 2% $\pm 0.5\%$ H₂O and rest, N₂ [7]. The feedstock used for gasification is Causurina species wood and coconut shells with moisture content between 12 to 15% on dry basis (sun dried wood). The details of the study are as presented below

DUAL-FUEL MODE

There is large experience gathered with respect to dual-fuel operations using producer gas fuel. Using IISc gasification technology, diesel engines of capacities between 3.5 to 700 kWe have been field tested and a cumulative experience in excess of 75,000 hours has been generated over a period of two decades [4]. This work reports the results of one such study conducted on a 96 kW @ 1500 rev/min (sea level) naturally aspirated diesel engine (Ashok Leyland make - ALU680 model) meant for power generation application. The engine though primarily designed for automotive use is also utilized as power generating system. The engine delivered a net output of 75 kWe (83 kW shaft power) at Bangalore (1000 m above the sea level). This engine was tested in dual-fuel mode (without any modifications) by inducting producer gas along with air at the intake manifold. The producer gas contained 18% H₂, 18% CO, 2-3% CH₄, 12% CO₂, 2.5% H₂O and rest, N₂, with lower calorific value being 5.2 MJ/Nm³. Measurements were made with respect to specific fuel consumption (sfc), and exhaust emissions – NO_x, O₂ and exhaust temperature (Kane exhaust analyzer). Fig 2 shows the variation of exhaust oxygen fraction with load. In case of diesel alone operations, the oxygen fraction drops to about 4% at 75 kWe, corresponding to maximum output delivered (at Bangalore – 1000m above seal level). Beyond 75 kWe the engine begins to smoke thereby indicating the upper limit for loading. The corresponding value in dual-fuel mode (producer gas + diesel) is 1% oxygen at 71 kWe load. Any further increase of the producer gas caused the engine to smoke and stall. Fig 3 shows the variation of sfc (diesel) in diesel and dual-fuel mode of operation. A maximum diesel substitution of 68% was recorded at a load of 65 kWe and the corresponding oxygen fraction in the exhaust was about 1.5%. Therefore maximum diesel replacement implied low concentration of oxygen in the exhaust - 1.5 to 2%. Any attempt to increase the gas flow caused the engine to stall; implying the energy input through the gas + diesel + air would

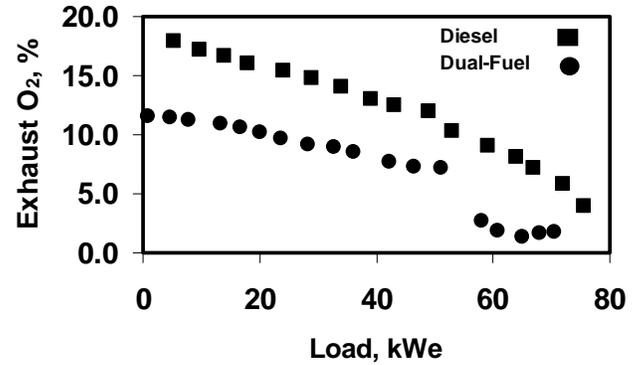


Fig. 2 Variation of exhaust O₂ with load.

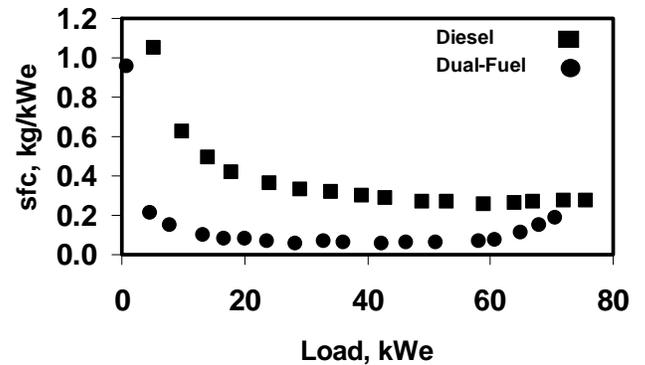


Fig. 3 Variation of sfc (diesel) with load. Maximum sfc (biomass) is 0.8 to 1.0 kg/kWe

not be adequate to take up the load. The maximum diesel substitution achieved at 71 kWe was 36% with oxygen concentration of 1.5 – 1.8%. The prime reason for low diesel substitution at higher loads is the low excess air availability on this engine. The excess air availability is about 17% in diesel mode at a nominal load of 75 kWe (1500 rev/min) and this therefore doesn't permit high diesel substitution at nominal ratings in dual-fuel mode. Fig. 4 shows the thermal efficiency in dual-fuel mode to be lower than diesel mode and one of the reasons for this is the higher exhaust temperatures, the temperature are higher by about 50 - 100° C in dual-fuel mode as compared to diesel mode as shown in Fig 5. This is reasoned to be arising due to lack of adequate combustion time between two competing fuels – liquid and gas.

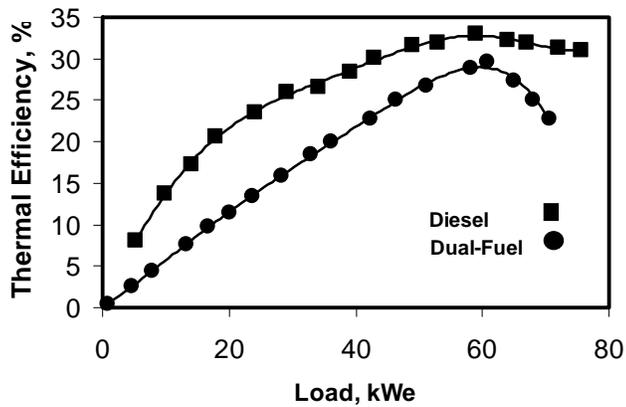


Fig. 4 Variation of efficiency with load

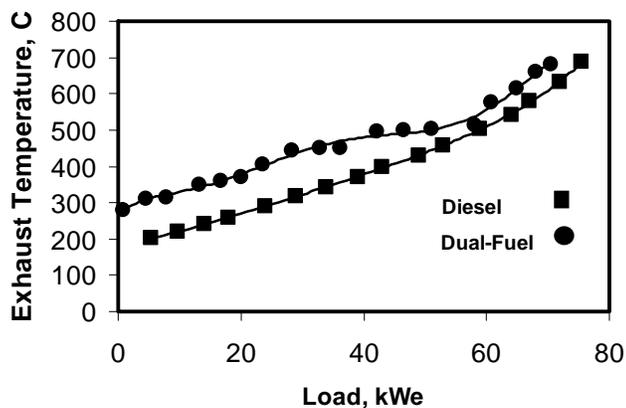


Fig. 5 Variation of exhaust temperature with load

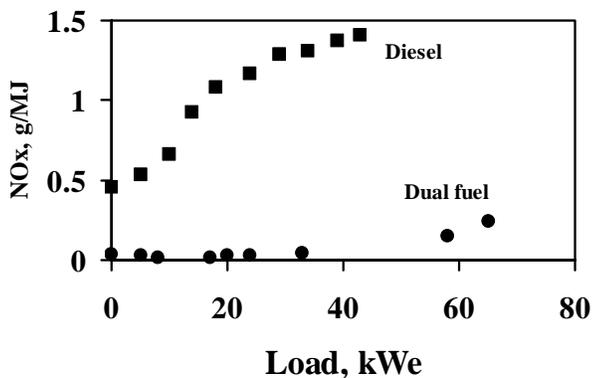


Fig. 6 Variation of NOx with load

Fig. 6 shows the variation of NOx with load. It is evident from the figure that NOx levels in dual-fuel mode are much lower and this attributed to lower combustion temperature occurring in the engine cylinder. Variation of CO with load was not measured, however at the rated load CO was found to about 3.1 – 3.5 g/MJ as against 0.6 – 1.2 g/MJ in diesel mode and this is reasoned to be due to combustion inefficiency.

Observations

Operation of diesel engine in dual-fuel mode resulted in a maximum diesel substitution of 68% at about 65 kWe. Further loading resulted in lower diesel substitution and reason for this to happen has been brought out. Also, the thermal efficiency is lower in dual-fuel mode on account of higher heat loss through the exhaust. It is however possible to improve the thermal efficiency by advancing the fuel injection timing. This could also result in reduction in CO level on account of higher combustion efficiency, where as, NOx level could increase due to the combined effect of increase in cylinder peak temperature and combustion duration.

GAS ALONE MODE

Producer gas can be utilized in reciprocating gas engine (spark ignited engine) using 100% ultra clean producer gas. This work relates performance of the above system in terms of performance and emissions. The gas engine chosen for experiments is a 12 cylinder (V-configuration), turbo-charged – after cooled engine, supplied originally to operate on dilute natural gas (biogas fuel). These engines are available as biogas engines and are serving as base load power plants in many parts of India. This engine is adopted to operate on producer gas along with a specially designed gas carburetor [7, 8]. This engine is basically built from a diesel engine frame (model no. TBD4V12, rated at 444 kW at CR of 15) at a modified CR of 12, to operate on gaseous fuels in a spark-ignited mode. The other modifications implemented on the engine are with respect to turbo-charger (model K-28 in place of K-36) and combustion chamber (simple cylindrical bowl in place of toroidal shape). The K-36 and K-28 turbo-charger are designed to generate a pressure ratio of 2.2 and 1.5 - 1.6 respectively. Therefore, the estimated power rating of the modified engine in diesel is between 290 - 310 kW (with the modified turbo-charger and lower CR ~ 2% reduction in power per unit CR assumed from Heywood [9]).

A 250-kg/hr-biomass gasifier formed the gas generator. Since the engine is of reasonably higher power level, the air-to-fuel control due to load variation assumed a major proposition. This called for design and development of a gas carburetor [7, 8] for producer gas application, as carburetors are not available for producer gas fuel. The carburetors available for other gaseous fuel, namely the natural gas, biogas and landfill gas are unsuitable due to widely different stoichiometric air-to-fuel requirement. The stoichiometric air-to-fuel ratio varies between 10 to 6 (on volume basis) for fuels such as natural gas and bio-gas/land fill gas based on methane content in the gas. However, stoichiometric air-to-fuel ratio for producer gas is about 1.2 to 1.4 (on volume basis) based on the constituents of the gas.

Experimental Procedure

The gas was made available at a higher pressure, typically 3000 to 5000 Pa, above the atmospheric pressure at the outlet of the gasifier. The gas pressure had to be reduced for proper functioning of the gas carburetor, and this was achieved using a zero-pressure regulator placed with the blower outlet and the entry to the carburetor. The arrangement of the zero pressure

regulator and producer gas carburetor is shown in Fig. 7 and the general arrangement for testing is shown in Fig. 1. The gasification process was initiated by lighting the reactor with an open flame at the air nozzles. The gas drawn by the blower was ducted to the flare. Within about ten to fifteen minutes, combustible gas was generated, with oxygen level in the product gas falling close to zero. This event marked the completion of gasification process, further to which the gasifier is operated in flare mode until the system reached steady state of operation. Typically, this was about 2-3 hours from the cold start. The producer gas composition was monitored during this period and at the time of start of the gas engine the composition was typically be $17\pm 1\%$ H_2 , $18\pm 1\%$ CO , $2\pm 0.5\%$ CH_4 , $12\pm 1\%$ CO_2 and the rest, N_2 , which corresponded to energy content of $4.8 - 5.0 \text{ MJ/Nm}^3$. Standard biomass namely, causerina with moisture content of 12-15% on dry basis (sun-dried biomass) was used as the feedstock to obtain consistent quality gas.

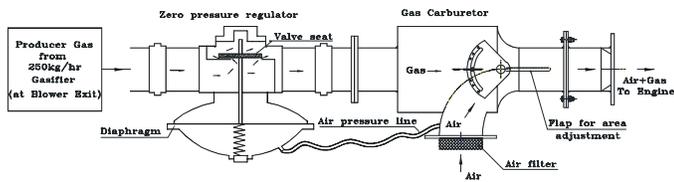


Fig 7 Schematic of Producer Gas Carburetor with Zero Pressure Regulator in the Gas-Air Line Circuit

Once the gas composition stabilized, the engine was operated for few minutes at 1500 rev/min under no-load condition. Subsequent operations on load were also conducted at 1500 ± 50 rev/min. The engine was tested at different ignition timing settings to determine the optimum ignition timing, referred as MBT (Minimum Advance for Brake Torque) at different CRs. With set ignition timing, the air and fuel were tuned to achieve maximum power. Measurements were initiated 10 to 15 minutes after attaining stable operation.

Results

A trace of the gas composition and the calorific value is shown in Fig. 8. The gas composition in these experiments was found to be lower than obtained in the earlier instances [3]. The LCV in these experiments is about $4.8 - 5.0 \text{ MJ/Nm}^3$ at the time maximum output from the engine. The reason this fact is brought out explicitly because the reduction in the mixture density has an implication on the maximum shaft output delivered and this is discussed subsequently. The performance results presented below pertain to CR of 12 and at various ignition settings. A maximum gross brake output of 194 kW (including 12 kW consumed by the radiator fan) was recorded with an ignition advance between 12 and 14° BTC (Before Top Centre) at $\Phi = 0.94$. The value of Φ was lower in the current case because of limitation coming from the gasification system. In fact, the gas composition in terms of combustibles deteriorated with increased supply of the gas to the engine. This therefore limited the input energy to the

engine. The maximum net brake output of the engine at various ignition timings is shown in Table 2.

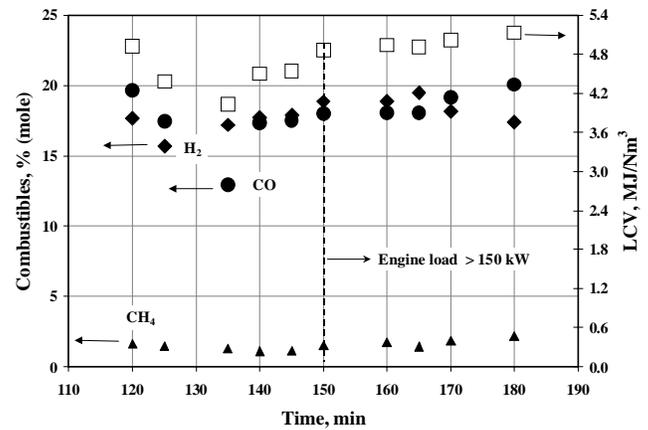


Fig 8 An on-Line Trace of Producer Gas Composition and LCV

The maximum net brake output was obtained at an ignition advance between 12 and 14° CA with gas-to-shaft efficiency being 28.3%. At relatively advanced ignition timing, the output was observed to reduce. Further, the performance of the engine is represented in terms of normalized value of brake specific fuel consumption (bsfc) in Fig 9. The bsfc at various ignition timing is normalized with bsfc at MBT, with all values corresponding to full throttle condition. A change in two degrees in ignition timing appeared to have modest effect on the fuel consumption, however with 5 to 10 degree change; the impact was much more significant.

Table 2: Maximum Net Brake Power at Varying Ignition Timings

IGN, °BTC	Φ	Net Elec. Power, kWe	Net Brake* Power, kW	Efficiency : Gas-to-Shaft, %
24	0.97	154	167	27.4
18	0.96	160	174	27.6
14	0.94	165	182	28.3
12	0.94	165	182	28.3

* Excluding Radiator Fan Power

The variation of emission in terms of NO_x and CO is shown in Fig 10 as a function of ignition advance. There was a reduction in NO_x emission observed with retardation of ignition timing and this is attributed to reduction in residence time as in the earlier case. Similarly, there was also reduction in CO seen with retardation of the ignition setting implying completion of combustion even at MBT of 12° BTC.

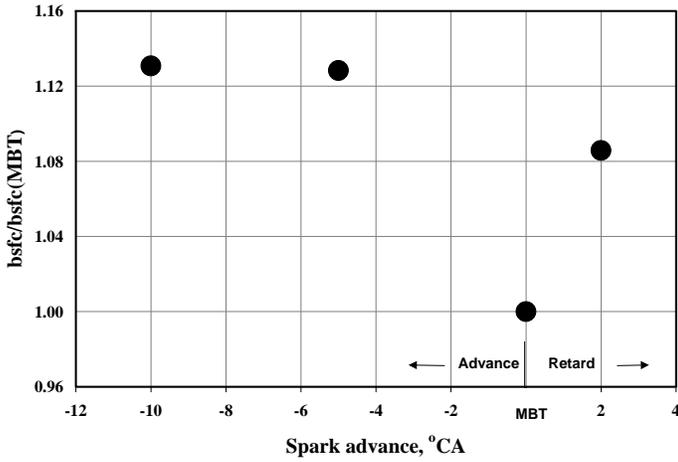


Fig. 9 Variation of bsfc with Ignition Advance. bsfc (MBT – 12° BTC) is 1.05 kg of Biomass or 2.8 kg of gas per kWe.

Observations

The engine operation with producer gas was found to be smooth. The engine and the gas carburetor system responded positively to the load changes. In addition, the carburetor was able to maintain the required air-to-fuel ratio with load changes. A gross brake output of 194 kW was obtained at an ignition advance of 12-14° CA, with $\Phi = 0.94$. Table 3 shows the comparison of delivered power using producer gas and diluted natural gas. The data with diluted natural gas (biogas) has been recorded on a field system comprising of a Greaves engine at UGAR Sugars Ltd, Belugum, Karnataka, India.

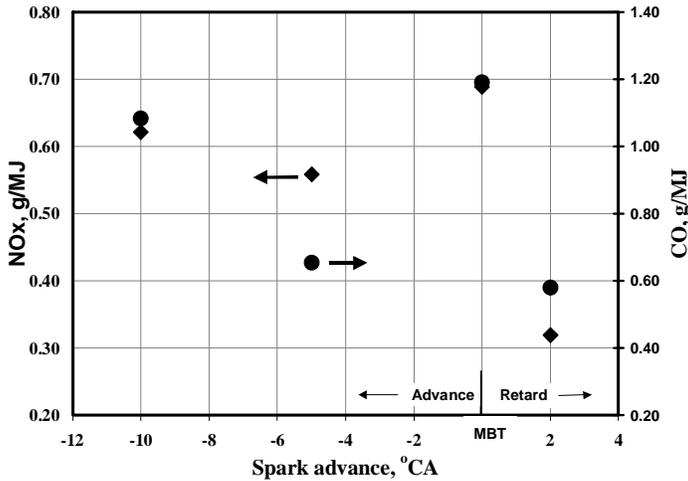


Fig. 10 Emissions at Varying Ignition Setting Corresponding to Peak Output. CPCB (Central Pollution Control Board) limit is NOx: 2.22 g/MJ, CO: 1.25 g/MJ.

With the boost pressure of the order of 1.47 measured against an expected pressure of 1.5 to 1.6 in diesel, the de-rating of power using producer gas as the fuel is about 37%. In the case of engine operation with gaseous fuel, derating occurs due to the resultant effect of reduction in the mixture energy density and the product-to-reactant mole ratio as shown in Table 1. The derating incase of producer gas should work out about 33%. But the de-rating reported above appears to be higher, and this is attributed to the mixture density. As indicated earlier, the calorific value of producer gas reported in this work is about 4.8 to 5.0 MJ/Nm³, which is about 10% lower than what has been measured on similar class gasifier [3]. This also would shift the operations from the currently achieved lean ($\Phi < 1.0$) towards richer limits. If an increment of 10% in the mixture density is considered the de-rating is reduced to 26-30%. The performance of producer gas against diluted natural gas ($\Phi=0.97$) fares slightly better with de-rating at 28%, and the de-rating further narrowing down to about 20% at the expected output of 214 kW with producer gas (LCV ~ 5.3 MJ/Nm³). The emission in terms of NOx and CO are found to be lower than the CPCB limits.

Further, the emissions in gas alone and dual fuel mode are compared against existing emission standards of various countries in Table 4. The standard given for Indian conditions correspond to that of diesel powered vehicle (Euro I) for gross vehicle weight > 3.5 tons [10] The data in the Table indicates that emission levels with gas alone operation to be lower than emission norms of EU and USA. However, in case of dual-fuel operation the CO levels are higher thus requiring exhaust gas treatment.

CONCLUSION

This study brings out the operation in dual-fuel and gas alone mode of operation using biomass derived producer gas. In case of dual-fuel mode of operation, the maximum diesel substitution achieved at rated load is limited by the oxygen availability. Whereas, in gas alone operation, there is loss of power to an extent of 20-30%. This loss in power is compensated to a much larger proportion as these technologies generate fewer amounts of toxic gases and zero towards Green House Gas emissions

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Table 3: Summary of Results at MBT

Fuel gas	Power (kW)* & Efficiency (%)	MBT, ° BTC	Mixture energy density, MJ/kg	Pressure- boost (turbo-charger)
Diesel (Estimated)	290 – 310 kW (<i>Base-line data</i>)	-	-	1.5 –1.6
Diluted Natural gas (75% CH ₄)	270 kW; 34%	28-30	2.48	1.5 - 1.6
PG	194 kW; 30 %	12 -14	1.90	1.47
<i>PG (Estimated)</i>	<i>214 kW (with 10% increase in LCV)</i>	<i>12 -14</i>	<i>2.10</i>	<i>Possibly > 1.47</i>

* Including Radiator Fan power

Table 4: Comparison of Emissions (g/MJ) with Producer Gas Operation against Existing Emission Norms in Various Countries

Parameter/Country [11]	EU	USA	India
CO	1.4 - 1.8	3.06	1.25
NO _x	2.56	2.56	2.22
HC	0.36	0.36	0.3
PM	0.15 - 0.24	0.15	0.1 –0.2
Emissions with Producer gas			
Component	Gas Alone	Dual-Fuel	
CO	0.58 – 1.2	3.1 – 3.5	
NO _x	0.32 – 0.7	< 0.25	
PM	< 0.0005	< 0.01	

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