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Experimental studies on the effects of enhancing the concentration of oxygen in the inducted charge of a biogas fuelled spark ignition engine

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A B S T R A C T

A biogas fuelled constant speed spark ignition engine was studied experimentally for its performance, emissions and combustion, under the influence of an increased oxygen concentration in the intake air and results were compared. A single cylinder diesel engine was modified for the purpose and was operated at 1500 rpm, maintaining the throttle opening at 25% and 100% for various equivalence ratios. The oxygen level in the intake air was kept at 21%, 22% and 23% by volume and the tests also maintained a compression ratio of 13:1 with a masked valve. A significant improvement in the brake thermal efficiency and brake power was observed at higher oxygen levels. The peak brake thermal efficiencies with 22% and 23% oxygen levels are 27% and 28% respectively, whereas with 21% oxygen level at the same equivalence ratio the efficiency to be 26.2%. The lean limit also got extended and at higher oxygen levels increased NOx, reduced HC and CO emissions were measured. Heat release rates showed enhanced combustion rates, which in turn were indicators for improvised thermal efficiencies. To maintain the NOx emissions well inside the set standards, a mere increase of 1%–2% oxygen level was observed to be ideal.

1. Introduction

Active researchers all over the globe are turning towards renewable clean fuels to address the environmental considerations and to reduce the burden of fossil fuel import. Commercially, these fuels are capable to power Internal Combustion (IC) engines which have become inevitable. Fuels such as alcohols, vegetable oils, natural gas, Liquefied Petroleum Gas (LPG), biogas and producer gas have been explored as viable alternatives to petrol and diesel. These fuels are attractive owing to its wide ignition limits, high hydrogen-to-carbon ratio leading to very low pollutant emissions, capability to burn very lean blends and to form homogeneous mixtures. Therefore, it can be effectively utilized in both Spark Ignition (SI) and Compression Ignition (CI) engines. While both Natural gas and LPG are the readily available petroleum-based fuels, renewable sources can be harnessed to yield biogas (gobar gas) and producer gas. The former is indeed an attractive source of energy for rural areas because; it can be produced from cow dung, animal wastes and also from leaves and water hyacinth during anaerobic digestion. Biogas plants can be installed even on portable frames to power the agricultural pump sets and generators in rural areas. Its commercial application includes the effective utilization of biodegradable urban waste materials to generate electricity, benefiting the smaller locales. It consists of methane (CH_4) and carbon dioxide (CO_2) in the ratio 2:1 by volume. The concentration of the latter reduces the oxygen concentration in the charge and leads to slow combustion. However, it increases the knock limit of biogas which in turn promotes high compression ratios.

As a fuel, biogas on account of its high CO_2 content, has a few disadvantages such as (i) extremely low energy density on volume basis, (ii) low calorific value and flammability range and (iii) lesser flame speed (25 cm/s) when compared with LPG (38 cm/s) [1], which is shown in Table 1.

The high value of self-ignition temperature results in high anti-knock index. It permits the biogas engine to accommodate higher compression ratios to improve its thermal efficiency. It also contains a small percentage of H_2S, which can cause corrosion in engines metal parts. The high self-ignition temperature prevents the direct use of Biogas in CI engines. However, it can be used in CI engines with a dual fuelling approach. A mixture of air and biogas (or any other gaseous fuel) is sucked into the cylinder, compressed,

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Table 1
Fuel Properties [1].

Property	LPG	Natural Gas	Hydrogen	Biogas	Producer Gas
Composition (% vol)	C_3H_8-30% C_4H_{10}-70%	CH_4-85% C_2H_6-7% C_3H_8-2% N_2-1% CO_2-5%	H_2	CH_4-57% CO_2-41% CO-0.18% H_2-0.18% Traces of other gases	CO-24.3% H_2-22.6% CH_4-2.2% CO_2-9.3% N_2-41.2%
Lower heating value at 1atm & 15 °C (MJ/kg)—————	45.7	50	120	17	5
Density at 1 atm & 15 °C	2.26	0.79	0.08	1.2	1.05
Flame speed (cm/s)	44	34	275	25	50
Stoichiometric A/F (kg of air/kg of fuel)	15.5	17.3	34.2	5.8	1.4
Flammability limits (vol% in air)	2.15	5	4	7.5	7
Leaner——————	9.6	15	75	14	21.6
Richer——————					
Octane number	103–105	120	130	130	100–105
Research————	90–97	120	130	–	–
Motor—————————					
Auto ignition temperature (°C)	405–450	540	585	650	625

and then ignited by spraying a mandatory pilot fuel which has low self-ignition temperature - diesel, vegetable oil or biodiesel are used as pilot fuels [2–4]. As similar in all SI engines, it is necessary to maintain a proper ‘fuel – air’ ratio to attain good combustion. Nowadays, to meet the stringent environmental regulations, the engine manufacturers and researchers have attempted to improve thermal efficiency and power output, ensuring least emissions. Increasing the in-cylinder oxygen availability improves the combustion efficiency, and particularly in biogas, it reduces the emissions. This can be attained by enhancing the oxygen concentration in the intake air.

Air can be separated into its constituents using a variety of techniques. They are cryogenic separation, pressure swing adsorption, membrane technology and by-product methods of oxygen generation [5]. Each air separation technology produces oxygen at different purities, pressures, and volumetric flow rates. Furthermore, each technology has different running costs. Cryogenic plants produce nitrogen, oxygen and argon as gas (and liquid) products using very low temperature distillation to separate and purify the desired products. Cryogenic plants are most commonly used to produce high purity products at medium to high production rates. They can produce products as gases or as liquids. Non-cryogenic plants produce gaseous nitrogen or oxygen products using near-ambient-temperature separation processes. Pressure Swing Adsorbers (PSA) is a much newer as compared to cryogenic air separation units. PSA units are best suited for processes that do not require extremely high purities of oxygen ($\leq$ 95). It is best suitable for small volumes of oxygen production. A mid-sized PSA plant requires power cost of 0.75 kW/Nm^3.

Conventional membrane technology involves passing air over a membrane filter. The filter will allow fast gasses to pass and slow gasses will stay. Oxygen is considered a fast gas and nitrogen and argon are considered slow gasses. Varying levels of purity can be achieved by varying the time that the gas spends undergoing filtration. Previous membrane technology could only produce purity levels of less than 50%. Membrane technology has quick start-up times and operates at near ambient conditions. However, recently there has been a significant technological break-through in membrane technology. The Ion Transport Membrane (ITM) was developed by Air Products and Chemicals, in conjunction with the United States Department of Energy and Ceramatec. Reports have shown that this technology can produce greater than 99% purity oxygen at much lower costs than cryogenic separation. ITM Syngas is a process still under development. The technology will pass air on one side of a membrane and natural gas and steam on the other. The two by-product streams will be syngas and oxygen depleted air [6]. In some of the processes mentioned above, high volumes of nitrogen will be available to the user for use in another process. Similarly, in processes that produce nitrogen, large volumes of oxygen are readily available. Similarly, hydrogen production results in waste oxygen. All over the world, countries have set measures to increase the amount of energy derived from hydrogen, meaning that the hydrogen economy is certain to grow. Consequently, if a use can be found for the left over oxygen, an overall increase in the hydrogen production process efficiency would lead to potentially large energy savings. Finally, it was concluded that Pressure Swing Absorbers/Vacuum Pressure Swing Absorbers (VPSA) is suitable for low volumes and low purity oxygen requirements. Cryogenic separation is best suited for high flow rates and when high purity oxygen is required.

Oxygen enriched air has numerous applications in various fields such as chemical processing, hazardous waste destruction, biotechnology, aircraft propulsion and marine engines. Nearly pure oxygen is considered for industrial furnace applications to improve the furnace productivity and to minimize the NOx (Oxides of Nitrogen) emissions. Literature indicate that researchers have improved the performance of SI and CI engines by enhancing the percentage of oxygen in the intake charge. Membranes are available to separate the nitrogen so that the percentage of oxygen concentrations improve, and are higher than the atmosphere. To negate the effect of large amount of CO_2 in biogas, this method can be used to enhance combustion.

Several studies related to oxygen enrichment (up to 35% by volume) in diesel engines (both direct injection and indirect injection) have been done with the objective of reducing smoke, particulates, HC (Hydrocarbon) and CO (Carbon monoxide) emissions [7–10]. Most of these studies reveal significant reductions in exhaust emissions, except NOx. With the increased oxygen content in the combustion air, power output can be increased by burning additional fuel. Oxygen enrichment of combustion air reduces the ignition delay period by allowing the ignition with minimum amount of premixed fuel [11]. As a result, both the rate of pressure rise and the peak cylinder pressure are low. Watson's [12] experiment on diesel engines with enhanced oxygen concentrations (ranging up to 30% by volume) indicate the potential to reduce particulates up to 80%. However, there is a threefold increase in NOx emissions above an oxygen level of 27%. The performance and NOx emissions of a diesel locomotive were studied by Ramesh B.Poola et al. [13] incorporating both oxygen enriched combustion air and thermodynamic simulations. It is found that with 4°