Biogas Use As Fuel In Spark Ignition Engines

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Abstract - **This paper reviews the utilization of biogas in spark ignition engines with a view to making a case for it as an efficient substitute fuel for petrol. However, its gaseous nature which accounts for its low volumetric density implies that apart from the basic modification needed to accommodate the fuel, the engine might need further alterations to get the best from this relatively low cost and readily available fuel. Various modes of enhancing performance particularly methane enrichment, prechamber combustion, alteration of ignition parameters, increasing compression ratio and addition of hydrogen to improve performance and emissions were drawn from previous works to validate its efficiency as a viable substitute fuel in SI engines.**

Keywords - **Biogas, Spark ignition engines, Substitute fuel**

I. INTRODUCTION

The over dependence of humans on fossil fuels to improve their standard of living has led has led to massive depletion of these resources. We are currently past the peak production of these resources with reserves expected to be exhausted in few decades. Exploration, production and utilization of these fuels have directly caused global warming and pollution.

The transport sector has felt the pinch more with unstable fuel prices and governments continuing to set stricter fuel and emission standards. The transport sector consumes the largest fossil fuel portion after the industrial sector and accounts for a considerable percentage of the world's total greenhouse gas emissions [1]. 98% of the total energy used to power the different modes of transportation is from fossil sources [2]. The sector recently turned to natural gas which could be adapted to work in conventional spark ignition (SI) and perform better in dedicated engines. Natural gas though cheap, readily available and performs efficiently in internal combustion engines (ICE) is still of fossil origin [3, 4]. Hence, the need for a renewable substitute fuel to power our internal combustion engines.

Biogas, hydrogen and ethanol have been front runners in SI engine alternative fuels [5]. Hydrogen is often regarded as a futuristic fuel and its technologies are currently very expensive, ethanol on the other hand has been accepted for use more as an additive and is plagued by the food versus fuel argument, leaving biogas as a very viable candidate fuel. Biogas has a lower cost per unit energy when compared to petrol and hydrogen and can be upgraded to natural gas quality to be used in the already established natural gas vehicle market and systems [1, 6].

II. BIOGAS PRODUCTION

Biogas is a clean and renewable energy source, produced from the anaerobic digestion of a wide range of feedstock including wastes. Substrates may include diverse range of biomass, biodegradable waste. It is also generated from landfills and swamps. The bacteria which facilitates the process thrives within 25^0C - 40^0C (mesophilic temperatures) and 50^0C - 65^0C (thermophilic temperatures) [7]. The production through feedstock is done in controlled environments in anaerobic digesters (AD) and the quality of the biogas produced is determined by its methane content which is usually from 40% - 75% methane with carbon dioxide between 15% - 50% and other constituents taking minimal percentages. The digestion process is in 4 phases which are hydrolysis, acidogenesis, acetogenesis and methanisation [1]. The closer the methane content of the biogas produced is to natural gas the better its performance in spark ignition engines [5].

Biogas may be upgraded and cleaned by separating every other constituent from combustible methane as they have adverse effect on the engine and the biogas's burning properties. The purification process to create biomethane (methane enrichment) improves biogas's driving distance per unit volume while reducing the fuels affinity to corrode or damage engine components. The Burning of raw biogas directly in SI engines would require alteration of the engine's working parameters or change of components to accommodate unwanted constituents to make it perform as good as petrol [8].

Biogas is compressed to overcome storage requirement, improve volumetric density while easing handling and transportation. It is stored at 200-250 bars in pressure cylinders made from low cost steel and aluminum to more expensive metal and plastic liners wrapped with composites made of glass and carbon fibre for weight reduction. Biogas could also be cryogenically cooled at -161^{0}C to improve volumetric density [1].

III. BIOGAS IN SI ENGINES

Biogas is combustible in internal combustion engines, with simple modifications necessary on basic spark as their actual designs can accommodate the burning of biogas as a fuel to produce the energy required. Biogas, due to its high octane rating (MON=130), can attain higher compression ratios without knocking, allowing better engine performance [9, 10].

A very important factor to note in the utilization of biogas in SI engines is its wobbe index, which is the main indicator of the interchangeability of gases. Similar Wobbe indices signify that the gaseous fuels could be interchanged for a given pressure and valve settings with similar energy output [11]. However, a variation of 5-10% in performance is accepted [12]. Biomethane like natural gas is interchangeable with gasoline in conventional vehicle engines [9].

$$Q \div \sqrt{d} = W. \quad (1)$$

Wobbe index (W) is a function of the heating value as shown in equation 1.0 where (Q), also known as the calorific value is the amount of heat energy released when a given amount of fuel burns divided by the square root of its relative density (d). For biogas, the calorific value is directly proportional to its methane content, hence the need to ensure the efficiency of the AD. In fuels there are higher and lower heating values (HHV and LHV) and the efficiency of the engine when burning gaseous fuel is determined by these values.

Biogas in its purer state (more than 95% methane) has calorific values similar to that of natural gas and can be used in all existing natural gas applications [13]. Comparisons have been drawn in the performances of enriched biogas and natural gas at constant speed internal combustion engines with the experiments reporting similar engine performance in terms of brake power output, specific gas volume, thermal efficiency, fuel economy and emissions [11, 14].

When the fuel is to be incorporated to engine or vehicle design. It may be run in a mono-fuel (dedicated systems) mode and the bi-fuel mode in SI systems and a dual fuel mode in compression ignition systems. The fuel may be introduced into the combustion chamber via simple venturi gas mixer systems or the more efficient pressurised injection systems.

To accommodate biogas, the compressed fuel moves via the high pressure lines to the pressure regulator which reduced the high pressure fuel (about 250bars) to useable pressure (1.5 bar). The fuel is sucked into the intake manifold with atmospheric air via the gas mixer or streamed, via the gas injectors for combustion in the cylinders [1].

IV. PREVIOUS WORKS ON BIOGAS USE IN SI ENGINES

The utilization of biogas in automobiles commenced during the Second World War, as Germany and its Nazi territories found it challenging, sourcing fuel for their vehicles and farm machinery. They resorted to sewage gas and biogas produced from manure and digesters which were bottled and served as fuel during the crises [15].

Hickson in 1981 fuelled a diesel engine which was converted to a spark ignition engine with biogas and experienced a power loss of 40% when compared to the same engine using gasoline. Hickson's test of biogas usage was further investigated by Cunkel and Neyeloff in the same year with a research test engine which they operated with simulated biogas varying the compression ratios. This was the earliest record of an optimization test on a biogas fuelled engine and they concluded that 15:1 was the optimal compression ratio. It was identified that the major challenges associated with the use of use of biogas as its low calorific value, constituents that adversely affect combustion or aid corrosion and complexity with transportation and storage [16].

Thring in 1983 deduced that biogas utilization would be more attractive close to its source of production, also adding that biogas usage would be more efficient if enriched and used like natural gas or converted to liquid fuel like methanol to improve volumetric densities for use in gasoline applications. NC Macari reported excessive damage and quicker deterioration of lubricating oil after 400 hours of running a spark ignition engine on land fill gas [16].

In 1985, Wunshe reported that JENBACHER WERKE were able to vary the air-fuel ratios of the engines on a plant to induct more fuel into the combustion chamber of the engines, this was achieved by modifying the cylinder head to give room for a bigger inlet valve. With this, they were able to run rich or lean to produce electricity and heat. The low quality of the biogas necessitated the use of a knock detection sensor but even with the modification the still experienced low power output [16].

Roubaud et al in 2005 studied the prechamber combustion concept for biogas utilisation. They were able to deduce that the integration of prechamber ignition in the system was a cost effective way increasing efficiencies while having emissions at considerably low levels. They also proposed that further increasing compression ratios would further enhance performance [17]. In the same vein Muller had in 1995 stated that Caterpillar using similar prechamber concept and spark advance in a spark ignition engine powered by landfill gas recorded similar power, BMEP and BSFC when pitched with natural gas. Their experiments showed that tweaking operating conditions improved output and efficiency when an engine is fuelled with biogas with similar or lower exhaust emissions when compared with natural gas usage [18]. This makes biogas able to perform as good as or even better than petrol engines since there are documentations of natural gas performing better than petrol engines in dedicated engines.

E. Propatham et al in 2013 studied the effect of swirl to enhance the combustion characteristics of biogas in SI engines. They converted a single cylinder diesel engine to a biogas powered spark ignition engine. The engine was run at 1500 rpm at 25% and 100% throttle positions with different air-fuel ratios. They deduced that enhanced swirl caused a reduction in ignition delay, improved heat release rate, increased power output, brake thermal efficiency (especially at full throttle), extended lean limits and with respect to emissions, decreased HC levels while increased NOx levels were experienced [19]. Using the same engine with a modified combustion chamber (hemispherical shaped) to improve the combustion environment and ability to withstand high compression ratios, operating parameters where changed to include leaning mixtures with varying compression ratios of between 9.3:1 and 15:1. Brake thermal output and thermal efficiency improved with increase in compression ratio. Brake thermal efficiency of 23% was recorded at compression ratio of 9.31:1 with 26.8% at 15:1. The lean limit was extended with increase in compression ratios and reduction in ignition delay allowing a higher heat energy release. Power and thermal efficiency peaked between 13:1 and 15:1 and at equivalence ratios of 1.08 and 0.95 respectively. 13:1 was cited as the optimum compression ratios [20]. However, Thipse in 2010 stated that setting compression ratio at 12:1 and operating at 2000 to 7000 rpm full throttle, at lean conditions with ignition timing of 35^0 and 40^0 BTDC witnessed reduced CO and HC emissions [21].

With respect to ignition timing, Chandra et al experimenting in 2011 on a 5.9 KW modified CI to SI engine and compared the operations when fuelled with CNG, biomethane and biogas fixing the compression ratio at 12.65 while varying the ignition advance at TDC at 30^0, 35^0, 40^0. Advancing the spark by 35^0 recorded the maximum brake power but also showed significant power losses when compared to the engines original fuel which were 31.8%, 35.6% and 46.3% for natural gas, biomethane and biogas respectively. Biomethane scored similar values with respect to specific gas consumption, engine performance, thermal efficiency and brake power output as natural gas [8].

Huanga and Crooke in 1998 with a Richardo E6 Single Cylinder Spark Ignition Engine operated with a simulated biogas with different CO_2 concentrations by volume (0%-40%) at 4 speeds across different air-fuel ratios and varying compression ratios deciphered that increased CO_2 concentrations improves NOx emissions, lowers cylinder pressures, reduces power and thermal efficiency with increased HC emission experienced [22]. In a similar experiment Jawurek et al in 2015, substituting petrol for methane in an engine, noticed 10-20% reduction in power output though performance was relatively good. At high CO_2 concentrations typical of raw biogas, starting issues, uneven performance and power drop were noticed with engines running harshly at 42% and more and smoothly at 23% and below. At 41% CO_2, 45% power loss was recorded when compared with petrol. Initiating ignition (on only biogas) was only possible at 31% and below. Biogas with higher CO_2 (>31%) concentrations needed petrol to initiate burning [23].

Attilla and Valeria in 2010 similar to Huang and Crooke's work on simulated biogas, determined that the efficiency of biogas in internal combustion engines is a function of their methane content, increased CO_2 (the secondary constituent) reduces the performance and efficiency while narrowing working ranges in engines. Biogas with 40% CO_2 content requires specially designed engines able to specifically accommodate the excess air and CO_2 to properly combust. Narrowing the working range of the engine while continuously operating at regions of 1.2-1.6 excess air coefficient resulted in lower emissions [24]. Porpatham et al in 2007 also looked at the effect of reducing the percentage of CO_2 of biogas on a constant speed engine. The reduction was achieved with a lime water scrubber and 41%, 30% and 21% CO_2 concentrations in biogas were achieved. Swirl was improved with a marked valve; compression ratio was fixed at 13:1 with equivalence ratio varied across rich to lean with engine at a constant speed of 1500 rpm. Reduction in CO_2 levels directly improved performance, extended lean limits, emissions were reduced particularly HC at lean mixtures and an increase in thermal efficiency was experienced. When spark timing was retarded by 5^0 at 10% CO_2 level, significant HC reduction and slight increase in NOx levels were noticed [25].

Dave et al in 2013, cited that ignition parameters like spark plug design, spark intensity, spark gap as well as well as ignition timing may be altered to improve engine performance by compensating for the lower flame speed associated with this gaseous fuel. Altering the ignition system resulted in better flame kernel, increased lean-limits, improved cycle to cycle variation and higher maximum brake torques. Lean mixtures require high energy to ignite; hence the spark to be produced is to have high intensity to negate misfiring which occurs in excess air mixtures. The spark plug electrode was reduced; the spark plug centre electrode diameter was made smaller while electrode gap width and electrode temperature was increased. These reconfigurations increased lean limits and overall engine performance. The high intensity spark needed is created by spark plug modification and voltage increase from the ignition system [26]. Dave et al, to buttress the effect of spark plug gap (SPG) on performance looked at SPG's of 0.4mm, 0.6mm and 0.8mm at spark plug projections (SPP) of 0mm, 0.5mm and 1mm while varying loads (2kg, 4kg, 6kg and 8kg) at a constant speed of 3000rpm. SPG of 0.8mm and SPP of 1mm gave the maximum efficiency and minimum emission values. BSFC, volumetric efficiency, exhaust gas temperature (EGT) increase with increase in SPG and SPP with a reduction in HC and CO emissions [26]. In a related experiment, Park et al in 2012 improved thermal efficiency while extending the maximum tolerable EGR rate by increasing the spark gap. Projecting the spark gap further into the combustion chamber shortened flame propagation;

hence combustion duration reduced allowing quicker and more efficient burning of the fuel [27].

Lemke et al in 2011 retrofitted a 2009 Chevrolet 2500HD gasoline truck to run on both biomethane and petrol in bi-fuel mode. The vehicle's tail pipe emission showed that HC levels increased by 0.24g/mile while reduction of 170g/mile (105g/km), 0.02g/mile (0.0124g/km) and 0.8g/mile (0.0497g/km) for CO_2, NOx and CO respectively. A slight reduction in fuel economy was recorded as well as a not so significant performance reduction [28].

Tanoue et al in the year 2000, observed an improvement in the combustion performance of lean methane mixtures when hydrogen is added to improve turbulence in the combustion chamber as hydrogen's higher flame speed and wider flammability range enhanced the primary fuel's burning characteristics. In 2012, Mathai et al investigated the addition of 18% hydrogen by volume to CNG to make a fuel gas more potent than natural gas to power a bi-fuel gasoline generating set. Performance evaluation (power, emission, engine component appearance and lubricating oil quality) was done and compared for CNG and HCNG. The experiments carried out for an extended duration of 60 hours, recorded lower BSFC, HC, CO emissions and higher NOx values recorded for HCNG. Iron deposits on spark plugs and cylinder liners were more evident for HCNG with significantly lesser values for kinematic viscosity and total base number (TBN) leading to significant increase (higher concentrations) of wear metals in the oils [29]. With the similarity between enriched biogas and CNG, similar data is expected if biomethane is substituted for CNG with same operation conditions.

V. DEDUCTIONS ON PERFORMANCE

Biogas has been extensively researched in spark ignition engines as seen it the works cited above. System optimization has however taken various modes, from enrichment of the biogas to altering design and burning conditions to compensate for the deficiencies in the fuel (dilutuents). Getting better output from this fuel may require the addition of an enhancer (hydrogen) to improve flame qualities, prechamber concept design (increasing intake temperature), precise and controlled delivery of the fuel into the combustion chamber to compensate for low volumetric density of biogas (like most gaseous fuels), increasing compression ratios, changing ignition parameters or a combination of one or more of this methods [4, 16].

A. Combustion

During combustion to produce power, the dilutuents in biogas reduce the combustion heat causing a lower flame temperature and burning velocity. After the spark is introduced resulting in increased temperatures, a percentage of the heat is absorbed by the dilutuents especially CO_2 with a high combustion value which is further enhanced by temperature rise, impairing engine efficiency [16]. Removal of unwanted constituents especially H_2S which corrodes engine parts, causes rapid oil degradation, shorten engine's life span and CO_2 which reduces flammability would make the gas produced close to natural gas quality. The created gas burns as efficiently as petrol and cleanly to produce lower tail-pipe emission with little or no particulate matter in well-tuned engines except from lubricating oils and unburnt fuel attached to the cylinder walls which do not combust and find their way out through the exhaust valves [4, 16].

Apart from biogas purification, the challenge with burning biogas could be alleviated by the addition of hydrogen. Hydrogen with a laminar flame speed of 3.46m/s, minimum ignition energy of 0.02mJ and very high auto-ignition temperature is added to improve burning velocity. A faster flame development and propagation is observed with hydrogen addition improving engine performance [29, 30]. Preheating reactants before combustion in the chambers also improves overall burning velocity but at the expense of more CO emissions [16, 17].

Enhancing performance could also be done by increasing compression ratios in spark ignition engines by as much as 15:1 without damage to the engine. Extending compression ratios improves engine efficiency. The air-fuel charge is compressed at high pressures, like what is obtainable in CI engines, allowing lesser spaces just before the top dead centre for combustion. This allows better energy conversion and less thermal stress in the engine [16, 20].

Ignition parameters may also be tweaked like advancing spark timing to improve maximum brake power. Increasing the ignition energy intensity generated from the spark plug also improves combustion while reducing HC and CO emissions. Enhancing the ignition energy produced by the spark plugs might take the use of multiple spark plugs or altering the spark plug gap and projection amongst other means [16, 23].

A. Emissions

The advocacy for biogas utilization, apart from its performance in SI engines is also motivated by cleaner emissions and biogas is said to emit lesser nitrous oxides, carbon dioxide, carbon monoxide with little or no particulate matter and soot when compared to same engine using petrol. Nitrous oxides emission is reduced as a result of the low reaction temperature and lower oxygen levels available which has been displaced by a similar gaseous biogas (causing lower volumetric density) even for very rich and very lean mixtures. However, increasing compression ratio and spark timing to improve burning characteristics increases NOx emissions [16, 31, 32].

Biogas being a gaseous fuel is completely homogeneous in air even in cold starting operations. When fuels have mixability challenges, it results in incomplete combustion and CO emissions. Biogas mixability in air and it having lesser carbon atoms in its main constituent than petrol means combustion would yield less carbon oxides.

However, the CO_2 content in the biogas may influence the level of the carbon oxides emissions as it dissociates at high temperatures and exit through the exhaust valves unburnt [16, 23, 31].

Hydrocarbon emissions arise from incomplete combustion of the methane component of biogas. Low combustion temperature especially in lean conditions might tend to produce more hydrocarbon emissions at the exhaust as the energy generated in the combustion chamber is not adequate to burn all the air-fuel charge especially the ones near the cylinder walls where the flame front quenches. It is also a function of the available oxidant in the combustion reaction which is lesser in gaseous fuels [16, 31, 32].

Finally, most of the works related to emission showed that the combination of spark timing advance and increased compression ratio reduces HC and CO emissions; addition of hydrogen reduces HC and CO emissions while increasing NOx emissions. Scrubbing CO_2 from biogas reduces overall CO and CO_2 emission while EGR reduces NOx emission. However, in vehicle applications the 3-way catalytic converter remains a prime method of cutting down on all tail pipe emissions [16, 32].

VI. BIOGAS WITH OTHER ALTENATIVE FUELS

Apart from biogas's ability to perform efficiently in spark ignition engines. Other factors positively motivating its use includes; sustainability (derived from a wide range of available long-lasting sources), competitive price with petrol, safety of use, and its environmental compatibility.

Unlike liquefied petroleum gas (LPG) which is also an environmental friendly alternative fuel, it is not of a finite fossil origin while its raw materials are renewable and readily available. Biogas can be derived from an enormous waste reserve. Its ability to also supplement fossil fuel natural gas makes it easier to integrate into an already existing system cutting down on the overall cost of production [5].

Compared to ethanol, it is a more acceptable fuel. "The food versus fuel argument" has plagued the utilization of ethanol as a fuel because ethanol which is predominantly made from food or food crops is employed as a fuel at the detriment of having sufficient food supply across the world. This is evident in ethanol's use as an octane enhancer rather than a standalone fuel. Biogas can be produced cost effectively from waste and non-edible food crop so despite the argument still slightly evident with the use of arable land for energy crops, there are other way with which it can be acceptably produced [5, 33].

Though there are numerous citations of the lower cost of biogas as compared to petrol [13,34]. The cost on an energy equivalent base might be slightly higher than that of petrol with the recent crash in crude prices. Hence, the motivation should not be just cost but its many other favourable factors. However, government rebates, subsidies and tax wave or reductions in the production and utilization of biogas might further reduce the cost of biogas and make it cheaper than petrol on the energy market [34-37].

Hydrogen which is another fuel of interest outperforms biogas and petrol in dedicated engines. In a conventional SI system, hydrogen's use could be optimised for better efficiency in fuel economy and emissions primarily because of its lean burn properties and non-carbon constituent, its high cost on production remain a deterrent to wide-spread usage as its often referred to a futuristic fuel due to its efficiency in fuel cell systems. Presently the addition of hydrogen to remains prime at achieving optimum balance between performance, emissions and cost [1].

In stationery engines there have been works on modified systems to run on gaseous fuels by as much as 30% hydrogen mix in biogas with improved performance and emissions recorded when compared to biogas. In vehicles converted SI systems can utilize about 1-8% hydrogen mix in biogas without the negative attributes associated with hydrogen's usage, backfire and pre-ignition [37]. However, more works need to be done on the use of biogas rather than natural gas in vehicles despite their similarities. In the same vein, higher hydrogen-biogas mix in vehicles by as much as 30% hydrogen in modified SI systems which might be the optimum way of balancing performance and transient emissions in the systems.

VII. CONCLUSION

Biogas is a very efficient, sustainable and environmentally friendly fuel which performs optimally in modified spark ignition engines tuned with its specific properties in mind. It can be enhanced by methane enrichment or the addition of hydrogen to improve its flame quality.

ACKNOWLEDGMENT

The authors wish to acknowledge the City of Johannesburg and the University of Johannesburg for providing grants for this research work. The Process Energy and Environmental Technology Station (PEETS) and Botswana University of Science and Technology are acknowledged for technically support.

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