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Gaseous alternative fuels for Spark Ignition Engines-A technical review

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ABSTRACT

More stringent emission norms and the need to conserve fossil fuel depletion have forced the researchers to focus their attention towards the usage of alternative fuels. Also the utmost priority lies in protecting the environment from transportation emissions. To overcome these problems, gaseous alternative fuels which had proven effective are being sought after. Among the renewable energy sources, gaseous alternate fuels offer a promising opportunity for sustainable development in the energy and transportation sectors. The following work discusses the different gaseous alternative fuels available for SI engines. The use of Hydrogen, Biogas, CNG, LPG, and Syngas in SI engines is being reviewed. This paper contains information regarding the application of syngas in SI engines and comparison of Syngas with the other gaseous fuels.

KEY WORDS: Hydrogen, Biogas, CNG, LPG, Syngas.

1. INTRODUCTION TO ALTERNATE FUELS

The scarcity of petroleum based fuels and increase in carbon monoxide hydrocarbons, nitrogen oxides particulates emissions and carbon dioxide lead to development of clean burning renewable alternatives fuels. In general, gaseous fuels result in extremely low pollutant levels and can be effectively utilized in both SI (Spark Ignition) and CI (Compression Ignition) engines. Gaseous fuels exhibit wide ignition limits and can easily form homogeneous mixtures with air to promote complete combustion. Even very lean mixtures can be used. Moreover, gaseous fuels have high hydrogen to carbon ratios, which will lead to low carbon-based emissions. Promising alternate gaseous fuels for internal combustion engines are hydrogen, CNG (Compressed Natural Gas), LPG (Liquefied Petroleum Gas), biogas and syngas. Each of these has its own advantages and is suitable for specific applications. Natural gas and LPG are the readily available petroleum- based fuels, while hydrogen, biogas and syngas can be obtained from renewable sources. LPG and CNG are mainly used for public transportation in urban areas where the distribution network is established. CNG is also used for industrial purposes apart from stationary power generation. Syngas is a useful source of energy which can be used in rural parts where infrastructure is not developed for distribution of electricity and petroleum products in irrigation, standalone power generation and transportation sectors.

Hydrogen: Hydrogen is a virtually a non- polluting fuel and its combustion in engines results in low CO and HC emission (mainly produced by the combustion of lubricating oil). Recently developed lean-burn hydrogen operated engines produce nothing but nominal amounts of NO_x as pollutants. Hydrogen can be produced from various sources including coal, crude oil and natural gas. It can be produced by electrolysis of water using a renewable and pollution free electricity source, such as solar or hydro power. Employing electrical power generation using a conventional hydrocarbon fuels would shift the pollution problem to the power stations where it can be controlled easily. Hydrogen has a very high flame speed which results in instantaneous combustion, which is good from the thermodynamic point of view. Its ignition limits are very wide and hence load control can be done on the qualitative basis with little or no throttling of the intake air. Its high auto-ignition temperature helps the engine to operate at fairly high compression ratios with good thermal efficiency. It can be observed that incase of SI engines, hydrogen is very advantageous on account of its wide flammability limits, high octane number, low ignition energy requirement, high flame speed and high self-ignition temperature which are most favorable properties. Additionally, faster combustion causes an increase of the engine’s efficiency (Welch, 1990; Saravanan, 2008; Munoz, 2000; Sridhar, 2001). However, the unfavorable properties are its low calorific value on the volume basis, low density and colour less flame. Other problems associated with hydrogen usage such as vehicle engine modification and its cost, safety, handling and distribution remain to be tackled before it becomes viable for use in vehicles.

Changwei Ji and Shuofeng Wang (2011) studied how the enrichment of H_2 was used to improve the performance of a SI engine operating under low speed and low load conditions. A hydrogen port-injection system was mounted on the intake manifolds for the sequential introduction of H_2without altering the original gasoline injection system. For a specified excess air ratio, brake thermal efficiency and torque increased with the addition of hydrogen. HC emissions were reduced whereas NO_x emissions increased with the increase of hydrogen addition. CO emission decreased with the increase of hydrogen enrichment level at lean conditions.

Yasin, (2015) investigated the emission, performance and combustion characteristics of a single-cylinder CFR engine running at constant speed by varying hydrogen levels. There was a significant drop in the emission levels of CO and smoke with increasing proportion of hydrogen. Juan J. Hernandez (2016), investigated the effect of H_2, CO_2 and CH_4individually on the emission, performance, combustion and characteristics of a diesel engine. The indicated thermal efficiency was reduced with increased diesel replacement because the amount of unburnt gaseous fuel also increased. This was identified by rise in HC and CO emissions when CO and CH_4 were used. However, a significant decrease in the particulate matter was achieved, while NO_x emissions were slightly affected by the diesel replacement.

Shuofeng Wang (2010), experimentally investigated the combined effect of and hydrogen addition and cylinder cutoff on the performance of a gasoline operated SI engine. For every cylinder closing strategy, the fraction of hydrogen was increased from 0% to 20%. Reduction of HC, CO and CO_2 emissions at low operating conditions was observed. However, because of the high flame temperature of H_2, NO_x emissions increased with blending ratio of $H_2$for a specified cylinder cutoff mode. For a specific H_2 addition fraction, NO_x emissions increased on cylinder cutoff due to rise in peak combustion temperature.

Biogas: Biogas is an excellent source of energy for rural areas. Also called 'gobar gas', it is generated during the anaerobic digestion of cow dung and other animal wastes and also from plant matter such as leaves, all of which are renewable and available in the countryside. Biogas can be produced in rural areas for small-scale consumption in engines powering pump sets and generators. Biogas is becoming a promising source of energy all around the globe as it can be used to run cars or city buses. It has been widely used for heating purposes and generation of electricity. (Pohare, 2010; Henham, 1998). It is approximately two thirds (by volume) methane and the rest carbon dioxide.

Biogas can be used in IC engines by appropriate modification of the desired engine. Biogas is suitable for engines with high compression ratio due to the high Octane number of biogas which increases the thermal efficiency (Yoon, 2011). The carbon content in biogas is lower compared to conventional diesel fuel, resulting in lower pollutants (Walsh 1989). The most important feature that in the usage of biogas in CI engine is that there is no de-rating of power which is present in case of Spark Ignition engines (Bari, 1996; Bedoya, 2012). The reason behind this fact is that SI engines are highly sensitive to composition of biogas resulting in high cycle to cycle variations **(**Bedoya, 2012). Biogas is used in the CI engines in dual fuel mode. Biogas has low energy density due to high CO_2 content. It also needs less amount of air for combustion per unit mass. The flammability limits of biogas are small; hence there is a need to maintain a close control over the air fuel ratio for good performance. The large CO_2 content of biogas leads to a high self-ignition temperature and it also resists knocking, which is desirable in SI engines. Thus biogas has a high anti-knock index as indicated by its high octane number. It also contains a small percentage of H_2S, which can cause corrosion of metal parts such as those in engines or burners.

Porpatham (2008), studied the effect of reduction of CO_2 content in biogas on the performance, emissions and combustion in a constant speed SI engine. The tests were carried for equivalence ratios ranging from rich to lean operating conditions at a constant speed of 1500 rpm and at compression ratio of 13:1. Reductions in the CO_2 and HC emissions were seen in case of lean mixtures. The test results showed that the increase in combustion rates resulted in the improvement in thermal efficiency. Porpatham (2012), conducted experiments on a biogas fuelled SI engine with hydrogen proportions (5%, 10% and 15%) on the energy basis. They found that with the addition of hydrogen, biogas can improve power and thermal efficiency and reduce hydrocarbon missions. When the hydrogen content exceeded 15%, the ignition timing needed to be retarded to control knock. In addition there was a reduction in cycle by cycle variations in combustion of lean mixtures.

Nagalingam (1983), claimed that hydrogen addition increased the lean limit of natural gas combustion, but it decreased the power due to low volumetric heating value. Due to a decrease in brake power to friction power ratio and increase in heating value of the fuel, the indicated thermal efficiency reduced on H_2addition. The optimum spark advance decreased up to 20°bTDC for mixtures of natural gas and 100% hydrogen operation. NO_x emission levels were seen to increase for pure hydrogen operation.

LPG: The use of liquefied petroleum gas (LPG) is a favorable method of lowering the CO_2 emissions and other pollutants from SI engine (Selim, 2009). LPG is a feasible alternative fuel which is a product of petroleum refining process primarily consisting of propane, butane and other hydrocarbons. It can be liquefied at a low pressure range of 0.7–0.8 Mpa at atmospheric temperature. Therefore the storage and transportation of LPG is more convenient than other gaseous fuels. The calorific value and octane number of LPG is higher compared to other gaseous fuels but it has a lower cetane number. Due to the high octane number it is suitable for SI engines. Low cetane number makes LPG difficult to be used in large quantities in CI engines. (Tira, 2012; Ogumo, 2003; Negurescu, 2013).

The use of LPG as alternative fuel to petrol is commonly used in SI engines. The main advantages of the LPG are low cost for the user, lower emission levels, particularly CO_2. Massimo Masi (2012), found that the deterioration in the performance of LPG operation is due to drop in volumetric efficiency and inadequate fuel delivery. Excessive LPG super heating leads to less volumetric efficiency.

Chunming Hu (2006), tested LPG engine with a LPG-fueled port fuel injection system for the steady lean operation. An analysis system for engine combustion was developed. Test results showed that the flame propagation of the lean mixture was improved by the increase in ignition energy intensity in this system. The advantages of LPG fuelling on burn rate, lean mixture limit, anti-knock performance and emissions levels were studied by Campbell, (2004). They conducted experimental study on a four-cylinder, four-stroke spark ignition engine modified to run on a single cylinder fed with gaseous LPG. Basic LPG conversion system design for gaseous fuel operation was explained.

CNG: Natural gas when used in diesel engine produces clean combustion as it contains a minimum quantity of impurities due to its gaseous state (Karabektas, 2014). It has a self-ignition temperature of 540°C. The natural gas used in vehicles is the same as that used in the domestic sector for cooking and heating. CNG is produced by compressing the conventional natural gas. It is stored and dispersed in a rigid container at a pressure of 200–248bar. Since the molar mass of gas o line is higher than natural gas, natural gas can produce better homogeneous air–fuel mixture. The atomizing and vapourizing time is more for liquid fuels to form a homogeneous air-fuel mixture (Jahirul, 2010). CNG being a gaseous fuel under Normal atmospheric conditions has high level of miscibility and diffusion with gaseous air, which is necessary for proper combustion. One major problem related with the CNG engine is the drop in volumetric efficiency up to 10% due to displacement of air available for proper combustion. (Shamekhi, 2008; Geok, 2009).

Musthafah Mohd. Tahira (2015), conducted study on the effect of CNG in a SI engine. A sensor was used to extract the data during the ignition stage for gasoline and CNG. The heat generated by both fuels had been extracted from the engine to find out which fuel would cause higher heat transfer to the engine. The obtained results explained why there was 18.5% less power for CNG compared to gasoline.

Yadollahi (2013), converted an existing MPFI gasoline engine to a direct injection natural gas engine with small changes. In the first part of this study, numerical modeling of transient gas injection had been performed. Upon validation, it was seen that the models were capable of handling all the essential physical phenomena. In the second part, a validated model was developed which included methane into the cylinder of direct injection engine for various combustion chamber geometries. The effects of geometry of combustion chamber, injection parameters, type of injector and cylinder head shape had been studied on mixing of air–fuel inside cylinder. From the obtained results, an appropriate geometrical configuration for the new natural gas DI engine had been discussed.

Syngas: Scarcity of conventional petroleum resources and advancement of solid to gas conversion technologies has resulted in increased use of solid fuels. Among the conversion technologies, gasification is the most reliable and energy efficient with advantages in both upstream and downstream flexibility (Stiegel, 2001). Gasification is a thermo chemical conversion process in which the hydrogen to carbon ratio of the feedstock is increased by breaking carbon bonds and adding hydrogen to the gaseous product (Basu, 2010). When high carbon solid fuel reacts with a controlled amount of gasifying agent at a temperature higher than 600°C, carbon monoxide and hydrogen are formed. The produced gas is called syngas. Syngas, also known as synthesis gas, is an end product of gasification. It is a name given for a mixture consisting of CO and H_2 at varying proportions. Gasifying agent has an influence on the quality of syngas produced. The main gasifying agents used in the process are oxygen, steam, and air. Syngas produced using steam or oxygen as a gasifying agent is known as medium calorific value syngas. It is also called simply syngas with its heating value range of 10–28 MJ/Nm^3. The syngas which is produced using air as a gasifying agent is known as lower calorific value gas. It is also called producer gas having heating value from 4 to 7 MJ/Nm^3.

Syngas has low energy density and SI engine has low compression ratios in the range of 8 to 12. Therefore the power degradation in SI engine is very high compared to gasoline and natural gas (Munoz, 2000). The reduction in power of an engine run on syngas is mainly due to the lower net calorific value of the air/fuel mixture (Sridhar, 2001). The power de-rated to around 40 to 50%. 30% of the power loss is due to low energy density of syngas and the rest from the pressure drop in the intake valves and piping. Slight modification of spark ignition engine is required to run on producer gas.

Changwei (2012), studied the effect of syngas addition in a petrol engine on its performance at lean conditions. The test was carried out at 1800 rpm and at manifold absolute pressure of 61.5 kPa. The volume fraction of syngas in the total intake gas was kept at 0% and 2.5%. The results showed an improvement in the peak cylinder pressure and indicated thermal efficiency on syngas addition. A small increase in CO and NO_x emissions was seen in case of syngas operation. The HC emissions first reduced and then increased on syngas blending**.** Changwei (2011), produced syngas by onboard steam reforming of ethanol. They conducted similar experimental study on SI engine to study effect of syngas addition. There was an increase in hydrogen concentration and decrease in carbon monoxide concentration in the syngas with the increase of the feedstock supply. Due to the better combustion on syngas enrichment, there was an increase in indicated thermal efficiency. Reduction in HC and NO_x emissions and increase in CO emission was observed by increasing concentration of syngas.

Stanislaw Szwaja (2013), conducted test on SI engine which drives a power generator. They found that the syngas operated engine will run unstably due to the engine misfiring caused by the low calorific value of syngas. To overcome this problem, the syngas was enriched with methane by varying ratios from 0% to 60% by volume. It was seen that 40% methane enrichment in syngas was producing reasonable results. Raman and Ram (2013**),** studied the performance of SI engine with 100% producer gas at variable load conditions. The engine was coupled to a power generator. Syngas generated from a downdraft gasifier system was supplied to the engine. The efficiency of power generation of the producer gas engine was calculated at variable loading conditions. A relation between compression ratio, thermal efficiency volumetric efficiency and expansion ratio was established and proved.

Sridhar (2003), conducted experimental and numerical analysis on utilization of biomass derived producer gas in a SI engine. Compression ratio was optimized to obtain the maximum brake power and efficiency by changing the compression ratios from 11.5:1 to 17:1. A smooth combustion process with a low cyclic pressure variation was the output. Maximum NO emission was observed at the highest compression ratio and advanced ignition timing. However, minimum CO emission was observed at the highest compression ratio. Ahrenfeldt (2007), studied the effect of fuelling biomass producer gas on a combined heat and power engine. Producer gas produced from various gasification plants with low heating values was used. Ignition timing was observed to affect the emission level of NO_x. The emission level of NO_x was reported to be less, whereas CO emission was seen to be high due to the presence of higher CO content in the fuel. The coefficient of variation of the IMEP and mass fraction burn remained constant for the producer gas even when λ increased.

Comparison of Syngas with other gaseous Fuels: Ftwi Yohaness Hagos (2014), investigated combustion, performance, and emission characteristics of syngas in a four-stroke, direct injection, spark-ignition engine. Engine rpm was varied from 1500 to 2400 rev/min, with the throttle in the wide-open position. The air/fuel ratio was varied from lowest possible value to lean operation limits. It has been reported that the in-cylinder peak pressure, heat-release rate are higher in syngas than CNG. However, CNG produced a higher brake thermal efficiency and lower brake specific fuel consumption. In the case of syngas, the total hydrocarbon and carbon monoxide emission levels were extremely small at higher loads. However, NO_x emission levels were found to be increasing with load as shown in Fig.1.

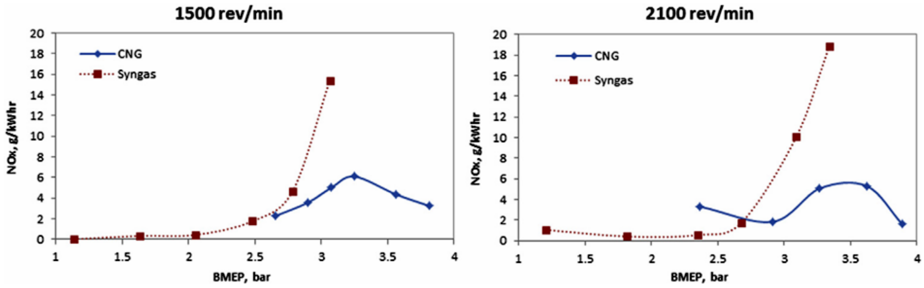

Figure.1. Brake specific NOx emissions versus BMEP for syngas and CNG

Ftwi Yohaness (2014), studied effect of air-fuel ratio on the combustion characteristics of SI engine operating on syngas having H_2 or CO composition of equal molar ratio. The throttle was kept in fully open position and the fuel injection started 180^o before top dead center. The results show that syngas operated in a wider excess air ratio (λ) as compared to CNG at the same engine speed. The smallest ignition advance for obtaining the maximum brake torque and combustion duration was observed to increase with an increase in λ. The effect of air-fuel ratio was more prominent in the initial stage of combustion at lower speeds and in the rapid burning stage at higher speeds.

Shah (2010), investigated the performance of a naturally aspirated, single-cylinder, four-stroke, SI engine fuelled with syngas. compared the results of commercial generator modified for operation with 100% syngas at different syngas flows with the results of gasoline operation Syngas used in this test was having a lower heating value of 5.79 MJ/Nm^3. Reduction of CO levels of 30 to 96% was obtained with syngas when compared to petrol as shown in Fig.5. This was due to high carbon content and rich operation in gasoline. The significant rise in CO_2 concentration was seen in syngas than gasoline operation. This was due to the presence of CO_2 in syngas and the transformation of CO present in the fuel during combustion. NO_x emission was found to be 54–94% lower than gasoline operation. They concluded that improvement in electrical power output and recovery of exhaust heat are important in the production of possible syngas operated systems. Sridhar and Yarasu (2010), claimed that the comparison of gaseous fuel with liquid fuel in IC engines had some difficulties.

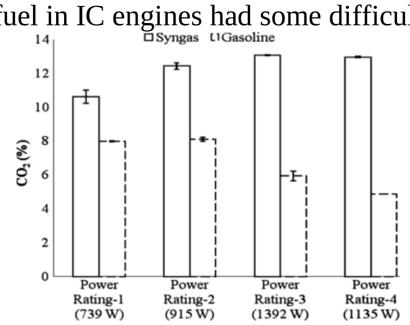

Figure.2. Exhaust emissions concentrations of CO_2 from generator for syngas and gasoline operations at different power ratings

Soid (2014), evaluated combustion characteristics of SI engine operating on CPG (compressed producer gas) by varying equivalence ratios using optical technique. The combustion characteristics of gasoline, CNG and LPG were compared. The amount of air required for each of the alternative fuels was determined based on the injected mass of gasoline. Test was carried out by varying the mass increase factors. The obtained results shows that the flame speed and peak pressure of CPG were found to be lower compared to gasoline, LPG and CNG. The peak pressure of CPG was found to be similar to gasoline. Mustafi (2006), studied the emission and performance of power gas in SI engine by varying compression ratios and compared with the results of gasoline and CNG. The lower heating value of the syngas used was 15.3 MJ/kg. 22% improvement in the power output was obtained by the increase in compression ratio from 8:1 to 11:1 at a constant speed of 1500 rev/min. In addition, the brake torque of power gas was 30% and 23% less than gasoline and CNG respectively.

Arroyo (2013), conducted a comparative study between the results obtained from operation of SI engine fueled with two synthetic gases obtained from catalytic decomposition of biogas**.** Experimental tests were carried out under a wide range of speeds and at three different equivalence ratios. It was seen that the fraction of H_2 in the synthetic gases increased the peak cylinder pressures. CO and its content present in the synthetic gases resulted in increase of the CO emissions compared to other fuels, while HC decreased due to the fact that small fraction of CH_4 was unburned. High fraction of hydrogen in composition of syngas raised NO_x emissions due to the increase in flame temperature.

2. CONCLUSION

This paper reviewed the different gaseous fuels which are being used in SI engines. The use of hydrogen, biogas, CNG, LPG, Syngas were discussed. Based on the review some conclusions have been arrived

- Knock can occur only when the hydrogen enrichment equals 50% or more at full load condition. The optimal hydrogen enrichment with the primary fuel was around 30%.
- The ignition delay period in the dual fuel mode is longer for SI engine than in the diesel mode for LPG.
- The injection strategy and quantity of the pilot fuel was capable of determining NO_x emissions for CNG operation in dual fuel mode.
- NO_x emissions reduced by usage of lower calorific value syngas.

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