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GASEOUS ALTERNATIVE FUELS FOR CI ENGINES - A TECHNICAL REVIEW

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Highlights

- Review of Gaseous alternative fuels used in CI engines
- Discussed potential application of syngas in CI and HCCI engine
- Comparison of syngas with other gaseous fuels

Abstract

In this century, it is believed that the crude oil and petroleum products will become scarce and expensive. Moreover pollution from transport vehicles poses a threat to the environment. To overcome these problems, alternative fuels are being sought after. The following paper discusses the reliability of gaseous alternative fuels best suited for compression ignition (CI) engines. The use of Hydrogen, Biogas, CNG, LPG, and Syngas in CI engines is being reviewed. Among the renewable energy sources, gaseous alternate fuels offer a promising opportunity for sustainable development in the energy and transportation sectors. The review work also emphasizes the use of syngas as an environmental friendly future fuel in CI engine and HCCI engine in comparison with other gaseous fuels.

Keywords: Hydrogen, Biogas, CNG, LPG, Syngas, CI engine.

1. Introduction

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, stand alone power generation and transportation sectors.

2. 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. Smaller amount of hydrogen injected in CI engine decreases heterogeneity of diesel fuel spray making the combustible mixture more uniform (Welch et al. 1990). Additionally, faster combustion causes an increase of the engine’s efficiency (Welch et al. 1990, Saravanan et al. 2008, Munoz et al. 2000, Sridhar et al. 2001). However, the unfavorable properties are its low calorific value on the volume basis, low density and colourless 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. YasinKaragöz et al. (2015) studied the effect of hydrogen addition on the emission and performance of CI engine at constant speed. Reduction in brake thermal efficiency was observed with increasing amount of hydrogen. CO emission was seen to reduce with increasing hydrogen concentration. Hydrocarbon emission values were neglected. According to obtained results, a significant increase in NO_x emissions was seen on hydrogen enrichment compared with diesel fuel. Significant increase in maximum cylinder gas pressure and peak heat release rate was obtained of hydrogen addition compared to pure diesel fuel. It was concluded that the addition of hydrogen improved combustion characteristics and CO, HC emissions were reduced. Saravanan et al.(2008)investigated hydrogen-diesel co-combustion in a diesel engine. They experimented by changing hydrogen level from 10% to 90% by volume. It was observed that knock can occur only when the hydrogen enrichment equals 50% or more at full load condition. They concluded that the optimal hydrogen enrichment with diesel was 30%.

Osama Ghazal (2013) investigated the combustion of hydrogen and diesel fuel was conducted by varying hydrogen concentration from 0.05% to 50% by volume for engine speeds ranging from 1000 to 4000 rpm and air/fuel ratios from 10 to 80. For higher A/F ratio and engine speed, the maximum brake thermal efficiency occurs for hydrogen concentration around 40%. Fig. 1 shows the maximum thermal efficiency at a speed of 4000 rpm. The increase in efficiency is almost 30% compared to the diesel fuel. The increase in brake thermal efficiency is due to the ability of hydrogen to mix with air in a better way. It was found that the dual fuel engines were having higher brake thermal efficiencies.

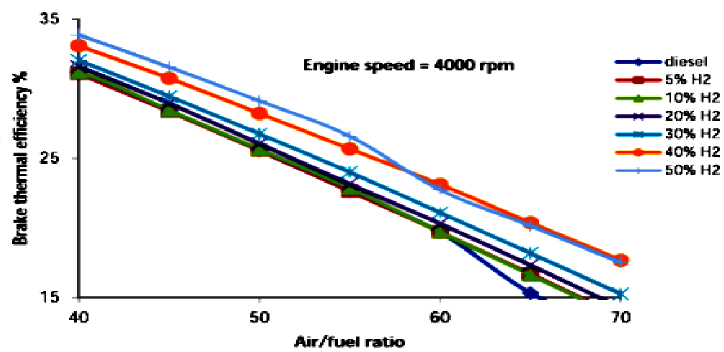

Fig.1.Brake thermal efficiency vs A/F ratio for different H_2 concentration.

3. 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 et al. 2010,Henham et al. 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 et al. 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 [Bari1996, Bedoya et al. 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 et al. 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. 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. Henham et al.(1998) studied the engine performance by experimenting with different compositions of simulated biogas. The study showed the possibility of 60% gas-oil substitution of pilot fuel without knocking. Yoon and Lee (2011) carried out an experimental study regarding the emission and combustion characteristics of biogas run dual fuel diesel engine using soybean biodiesel. It was seen that biogas-biodiesel combustion showed a better performance in reduction of soot emissions. Bari et al.(1996) experimentally studied the effect of CO_2 on the performance of a diesel engine running on biogas. It was observed that the presence of CO_2 in biogas up to 40% do not decline the engine performance. He explained the phenomenon of dissociation of carbon dioxide to carbon monoxide and oxygen could enhance the performance of the biogas run DFDE. It was seen that the increase in O_2 concentration reduced Ignition Delay whereas increase in carbon monoxide would increase the flame speed.

4. Liquefied Petroleum Gas (LPG)

The use of liquefied petroleum gas (LPG) is a favourable method of lowering the CO_2 emissions and other pollutants from CI engine (Selim et al. 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. (Tiraet al. 2012, Ogumo et al. 2003,Negurescu et al. 2013).

Emad Elnajjaret al. (2013) experimentally investigated the effect of LPG fuel on the performance of a dual compression engine by varying the composition and engine parameters. Few specific blends of LPG fuels with propane to butane volume ratio were considered for this study. A single cylinder, four stroke, indirectly injected, Ricardo E6 engine, was used for this study. Increase in the engine speed lead to decrease in the overall engine efficiency. Fuel having 25% propane was seen to provide the best performance with the highest efficiency and less noise. It was seen that higher pilot fuel mass flow rate produced higher overall efficiency. However the combustion noise levels are slightly decreased.

The effect of variation of pilot fuel quantity with different intake temperatures of the charges was investigated by Poonia et al. (1998) in a single cylinder constant speed diesel engine at different loads. It was observed that at high outputs, large quantity of pilot fuel leads to the high combustion rates. As load increased, brake thermal efficiency also increased. It was seen that the ignition delay period in the dual fuel mode is longer than in the diesel mode. The gaseous fuel added undergoes significant reactions during the compression stroke which leads to partial oxidation products which affects the pre-ignition processes of the pilot adversely.

5. Compressed Natural Gas (CNG)

Natural gas when used in diesel engine produces clean combustion as it contains a minimum quantity of impurities due toits gaseous state (Karabektaset al.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 200–248 bar. Since the molar mass of gasoline 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 et al 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 et al. 2008, Geok et al. 2009). Jie Liu et al.(2013)studied the effect of pilot fuel quantity and injection timing in the dual fuel mode on emission levels of SI engine. The CO emission levels under dual fuel mode are higher than under normal diesel operation conditions due to the flame quenching of natural gas and air. 30% drop in NO_x emissions was found in comparison to diesel mode due to low combustion temperature as shown in Fig. 2. Around 90% of the hydrocarbon emissions was unburned methane. Significant reduction in hydrocarbon emission levels and rise in PM emission levels was seen with the increase in the quantity of pilot diesel.

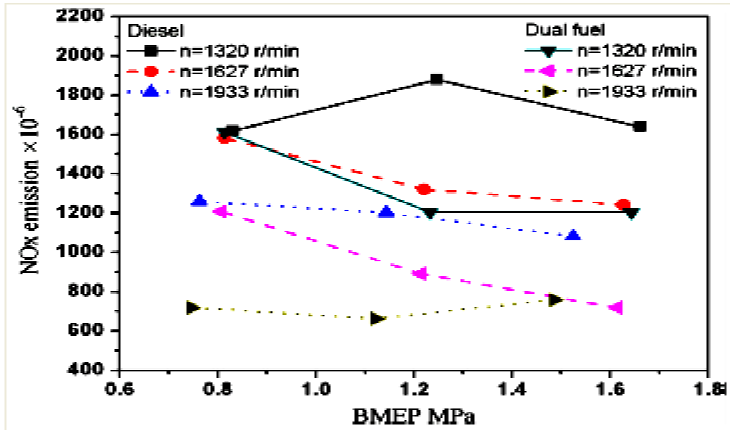

Fig. 2.NO_x emission characteristics.

Jie Liu et al**.** (2015) developed a dual fuel combustion model to simulate the combustion processes in the dual fuel engine. The developed model was capable of predicting propagation of flame and emission formation in the dual fuel engine. It was found that the injection strategy and quantity of the pilot fuel was capable of determining NO_x emissions during dual fuel operating conditions.

Abhishek Paul et al.(2013)presented a study consisting of a miscibility test of ethanol in diesel, experimental comparison between performance and emission characteristics of Diesel-Ethanol blends, Diesel-CNG combinations and Diesel-Ethanol blends with CNG addition. The results indicated that diesel-ethanol blend (95% diesel 5% ethanol) with low CNG enrichment produced better performance and emission characteristics as compared to diesel operation as well as diesel-ethanol blend operation.

Papagiannakis et al.(2008) showed that the peak pressure formed in a diesel ignited natural gas engine was lower than that of the normal diesel engine. Also at high loads, the combustion duration was shorter than that of the original diesel engine.

6. 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 et al. 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 (Basu2010). 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 andH_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 self-ignition temperature above 500◦C and as a result compression ignition will not be possible in CI engine. Syngas is utilized in the CI engine is by dual fuelling, where diesel is injected as a pilot fuel to initiate the ignition while syngas is injected into the induction system. (Garnier et al., 2005**)** Fig 3. shows the concept of dual fuel engine**.**

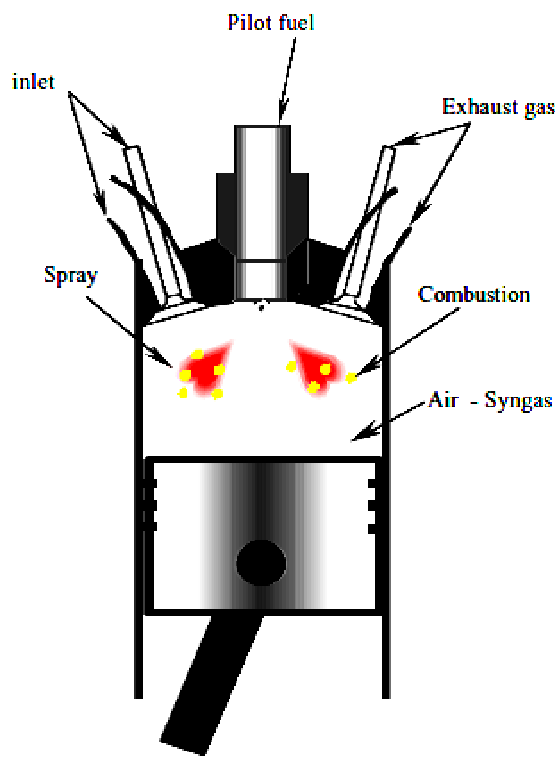

Fig.3. Concept of dual fuel engine.

Asimov (2011) studied the effect of H_2 and CO_2 present in the syngas on the performance and emission of a four-stroke single cylinder engine. Diesel used in assisting the auto-ignition of syngas was carried out in a pilot-fuel mode in the lean condition for wide range of equivalence ratio. It was observed that syngas reduced the main combustion time. Significant increase in the indicated mean effective pressure, mean combustion temperature and efficiency were observed. Sahoo et al.(2012) investigated effects of three different kinds of H_2:CO composition syngas fuel, 100:0, 75:25, and 50:50 on the engine performance, combustion and emission characteristics. Syngas having 100% H_2 composition presented an improved engine performance. However formation of high NO_x emissions was seen with increasing load. NO_x emissions reduced when 25% and 50% CO were added in the 100% H_2 composition syngas. At the maximum efficiency loading point, the maximum diesel replacement was found as 72.3% for 100% H_2 syngas mode.

6.1 Syngas in HCCI Engine

Onishi et al. (1979) performed the first work on HCCI engines. Combustion name was given as active thermo-atmosphere combustion (ATAC). A two-stroke SI engine with a 7.5:1 compression ratio was used. Onishi et al., Noguchi et al. (1979) also investigated HCCI engine. They used a horizontally opposed two-stroke SI engine. The name given to combustion was TS (Toyota-Soken) combustion. Njat and Foster (1983) investigated 4-stroke HCCI operation in a CFR engine. They used primary reference fuels and studied various parameters such as EGR, compression ratio and intake air heating. Their results showed that the HCCI combustion was regulated by global hydrocarbon kinetics. They also inferred that the low temperature kinetics was controlling the ignition of the fuel, while the high temperature kinetics regulated the heat release rate as well as duration of combustion. In 1989, Thring investigated 4-stroke HCCI operation in a single cylinder engine. He observed that for successful operation of HCCI engine, sufficient amount of EGR (30%) and intake air heating (370°C) were required. However, the process was limited to moderate and low loads. Yudai Yamasaki et al. (2014) studied effects of syngas components on auto-ignition and combustion. Simulations of the detailed reactions were also carried out. Syngas consisted of hydrogen and carbon monoxide (CO) as the main combustible components, nitrogen and carbon dioxide as incombustible components and a small amount of methane. The oxidation reaction process was analyzed numerically using CHEMKIN-PRO. It has been shown that the combustion rate after the auto-ignition is determined from the H_2 and CO_2 contents.

6.2 Comparison of Syngas with other gaseous Fuels

Wagemakers and Leermakers (2012) investigated the effect of dual fuelling of diesel and other gaseous fuels on the performance and emission characteristics of CI engines. Syngas, CNG, LPG, and hydrogen were used in this study. Results showed that all the fuels when used as dual fuel would decrease soot emissions except syngas. CNG and LPG were considered as the primary fuels for the comparison of NO_x reduction. Increase in NO_x level by the usage of syngas and hydrogen were observed compared to diesel. By dual fuelling of gaseous fuels, unburned hydrocarbons increased as compared to diesel in CI Engine. Dual fuel engine operation with syngas or varying gaseous hydrogen content was carried out researchers Abu-Jrai et al. (2007), Garnier et al. (2005) and Roy et al. (2009). Garnier established a predictive model for combustion. It was to determine the ignition delay of a dual fuel syngas-diesel engine. Roy varied the hydrogen concentration from 13.7% to 20% in syngas. The thermal efficiency and NO_x emission was found to increase with increase in hydrogen concentration of syngas.

Spaeth(2012) compared the performance of a dual fuel mode CI engine fueled by syngas with that of methane. For both mixtures, with reduction of the pilot diesel fuel there was a shift from diffusion flame combustion to propagation flame combustion. It was concluded that the performance of engine operated with methane was better compared to syngas in the duel fuel mode.

7. Conclusion

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

- Knock can occur only when the hydrogen enrichment equals 50% or more at full load condition. The optimal hydrogen enrichment with diesel was 30%.
- Biogas-biodiesel combustion showed a better performance in reduction of soot emissions. It was seen that the increase in O_2 concentration reduced Ignition Delay whereas increase in carbon monoxide would increase the flame speed in CI engines.
- The ignition delay period in the dual fuel mode is longer 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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