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A REVIEW ON THE USE OF BIOGAS AS A FUEL FOR INTERNAL COMBUSTION ENGINES

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Abstract. *The growing concern with the preservation of the environment has affected several areas of engineering sciences. The study and development of internal combustion engines, which are among the equipment considered to be major pollutant emitters, are also being greatly influenced by this concern. This causes a need to decrease the use of fossil fuels, which can be observed by the number of studies and research relating internal combustion engines and renewable energy sources. One of the energy sources that has been widely studied and analyzed as a viable alternative to the use of fossil fuels is biogas. Although recent, research involving the use of biogas as an engine fuel has grown considerably in the last 10 years. To analyze this scenario and thus conduct a literature review of the subject, searches were conducted in the Scopus database using keywords and appropriate filters. Articles not related or with little adherence to the subject were excluded from the review. The results were articles focused both on the composition of the biogas, which depends on the production process and may have effects on the combustion process, and on the efficiency of the use of biogas as a single or dual source of fuel for the engine. It was possible to verify, from the articles provided, good performance of the engines tested using biogas with different compositions, as well as analyses comparing emissions of pollutant gases. In general, these results are satisfactory, but leave room for further analysis under different conditions. Another parameter that is a point of concern are the hydrogen sulfide emissions, which, besides being highly toxic, can compromise the integrity of the engine components in the long term. Thus, the use of biogas as a fuel for internal combustion engines is proving to be a viable alternative and should continue to occupy more and more space in academic and industrial circles.*

Keywords: *internal combustion engine, biogas, biofuel, combustion, renewable energy*

1. INTRODUCTION

In the context of growing concern about carbon emissions and the harm to nature caused by the use of fossil fuels, the search for energy sources that can minimize or at least reduce these impacts is on the rise. Moreover, being petroleum a non-renewable natural resource, it is necessary to look for alternatives to its use. In several applications, the use of renewable energy sources is a viable alternative from an economic and energy point of view.

For electricity generation purposes, for example, the use of alternative energy sources, such as solar and wind power, has been expanding worldwide with intensity in recent years. In automotive engineering, the use of electrical energy as a power source for vehicles is also studied. However, the use of biofuels, such as bioethanol and biodiesel, can come as the solution for environmental problems, since the engines do not require modification, greenhouse effect gas emissions are lower, and they provide good lubricity (Hassan and Kalam, 2013). In addition to these energy sources, biogas also appears as a good alternative. Besides being efficiently used in applications such as cooking, heating and cooling, it has great potential with its use in internal combustion engines (Kurtgoz *et al.*, 2017). Biogas is composed mainly of methane and carbon dioxide, in addition to nitrogen and smaller quantities of sulfured hydrogen and carbon monoxide (Jiang *et al.*, 2009).

This paper aims to present the development of research on biogas engines. The objective is to present the state of the art and the methodology used to obtain articles to review the subject. Presenting some of the most relevant works according to pre-established criteria, it shows what the situation of biogas engines is today and what the future of this technology will likely be in the industrial environment.

2. METHODOLOGY

The key words used in the search were: TITLE-ABS-KEY (biogas AND engine) AND TITLE-ABS-KEY ((internal AND combustion)) AND TITLE-ABS-KEY (spark AND ignition). This returned a large number of articles, shown in Fig. 1. Figure 2 shows the keywords with the highest occurrence among the articles.

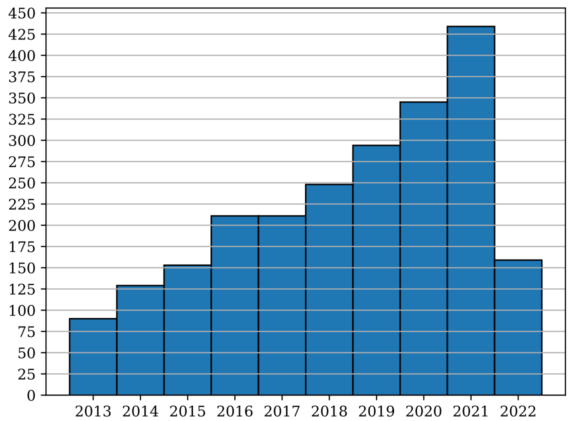

Figure 1. Histogram showing the number of publications per year on the subject.

Initially, a refinement was performed to return only results from articles and reviews published in journals. With this, 60 articles were returned. The most relevant information was exported in CSV format for analysis. A spreadsheet was created assigning ratings for comparison between the criteria.

The selected ratings were 6 (much more important), 3 (more important), and 1 (slightly more important). The criteria evaluated were year of publication (5 years $>$ year of publishing $>$ present; 10 years $\geq$ year of publishing $\geq$ 5 years; and year of publishing $>$ 10 years), CiteScore evaluation of the journal in which the article was published, and number of citations. In the end, the ratings were:

- 9 for publication year from 5 years onward;
- 3 for publication year between 5 and 10 years;
- 0 for publication year longer than 10 years;
- 18 for the CiteScore evaluation;
- 21 for the number of citations.

With the attributed ratings, those used for CiteScore evaluation and number of citations ended up greatly exceeding the values of the others. Therefore, they were normalized according to the highest values found, and these were used to divide all before multiplying the weights.

The next step was to add up all the parameters for each article. This gave a provisional ranking of each article in terms of relevance to the research. However, extra steps were taken. Groups related to the research topic are defined, and within these, subareas are established in which the articles should be placed. They are as follows:

- Combustion engines
  - Fuels (fossil, renewable, etc.)
  - Ignition type
- Thermodynamic analysis
  - Type of analysis (bench, numerical simulation, etc.)
  - Effects of parameter variation (mixtures, compression ratio, etc.)
  - Combustion power

Only one article was discarded because it did not adhere to any of the proposed subareas. Thus, 59 articles remain for use in the systematic review.

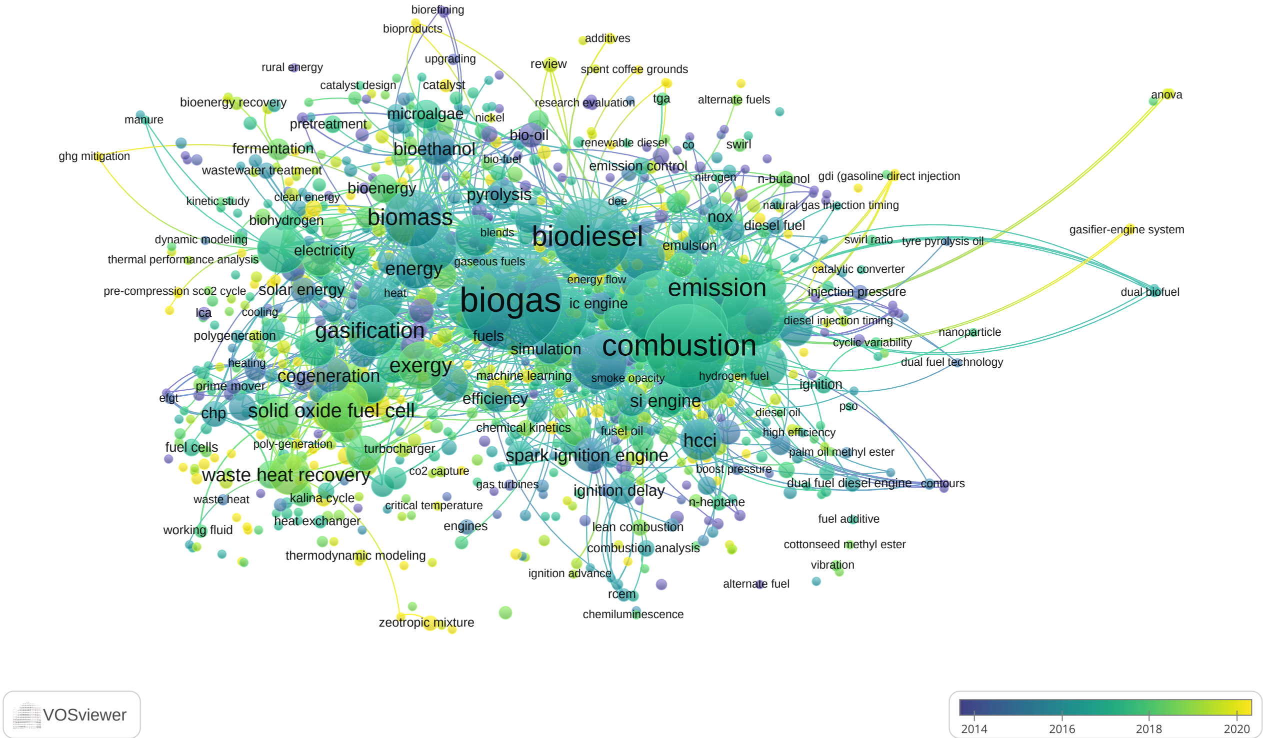

Figure 2. Map linking the keywords with the highest occurrence among the articles after the search.

3. STATE OF THE ART

Among the analyzed works, of great relevance is Kim *et al.* (2016), which deals with the effects of the composition of the biogas used on the combustion characteristics and the emission of NOx gases. Through an experimental analysis, using a three-cylinder engine and using different air/fuel ratios and compositions for the biogas, some results were recorded. One worth noting is that an increase in CO_2 in the fuel increased the fuel flow rate. Also, as the load was increased, the difference between 100% methane and 60% methane - 40% CO_2 fuels slowly decreased, until the methane consumption of the CO_2 containing fuel was less than that of the 100% methane fuel. Two factors were attributed to this: increased combustion efficiency and reduced pumping losses.

Furthermore, as the concentration of CO_2 was increased, NOx emissions decreased significantly regardless of the operating conditions. The reduction in NOx emissions due to the presence of CO_2 was most noticeable in the stoichiometric mixture.

The work by Yan *et al.* (2018), on the other hand, already presents a review of the development of technologies for the use of gas in engines and how they affect performance and emissions. Presenting an extensive number of papers and results, the authors show that adding nitrogen to gas can extend the operating limit of engines. This is a major advantage, since higher combustion performance results in higher thermal efficiency and lower NOx emissions.

However, in general, the addition of hydrogen to natural gas engines, when compared to pure natural gas engines, may even end up reducing emissions of gases such as CO and CO_2, but tend to lead to higher NOx gas emissions. The lower carbon emission is of course due to the lower carbon content when hydrogen is added. The increase in NOx emissions, on the other hand, is due to the higher combustion temperature.

Another aspect observed is how the addition of hydrogen can affect fuel consumption. This relationship between consumption and hydrogen content shows that the addition of hydrogen results in higher thermal efficiency of the engine in very poor mixtures, but this effect is negligible when approaching the stoichiometric mixture. In this type of engine, hydrogen content is the most relevant parameter in combustion performance and emissions. High hydrogen contents can lead to undesirable results, such as pre-ignition and knock. If the hydrogen content is too low, however, its benefits are not observed.

In his first work cited here, Porpatham *et al.* (2007) also adds small amounts of hydrogen, but to biogas. With tests on a single-cylinder engine at a constant speed of 1500 rpm and different mixtures, first only biogas was used; then hydrogen was admitted at 5%, 10% and 15% volume. It was observed that an increase in thermal efficiency and power occurs when using poor mixtures and hydrogen concentration of 15%. However, to avoid the occurrence of detonation with rich mixtures, the ignition time had to be delayed, which led to low thermal efficiency and lower power. It was also observed that the addition of hydrogen did not necessarily lead to a significant increase in NO levels, as CO_2 has the ability to dilute it. The addition of hydrogen up to 10 percent proved to be the most advantageous in the relationship between increased performance and reduced emissions. Furthermore, a strict control on ignition timing can be interesting for performance improvement at high hydrogen levels.

Still with great concern for CO_2 emissions, Porpatham *et al.* (2008) aimed to evaluate the effects of increasing the methane concentration in the biogas by removing CO_2 on engine performance, emissions, and combustion. The CO_2 contents were reduced to 30% and 20% of the commonly found volume of 41%. Using a single cylinder engine, rated at 4.4 kW at 1,500 rpm, compression ratio 13:1 and butterfly valve opening from 25% to 100%, a number of magnitudes were observed.

What was noted was that an increase in methane concentration increases performance and reduces hydrocarbon emissions. The greatest advantage of CO_2 removal from biogas is obtained when the engine operates at a lean mix regime. Removal of CO_2 results in higher methane and oxygen concentration, which leads to faster combustion and higher power output.

Also doing an experimental analysis with a one-cylinder engine, Crookes (2006) concluded that engines with biogas containing large contents of inert gases such as CO_2 and N_2 have their performance disadvantaged compared to biogas or gasoline. This can be overcome by increasing the compression ratio. In this case, NOx emissions increase. Overall, it has been presented that the emissions of compression engines with oil-derived biofuels can be reduced by means of emulsification with water. Furthermore, the specific fuel consumption is comparable to that of biogas engines, but with lower NOx emissions.

The work presented by da Costa *et al.* (2020) consisted of trials to analyze the potential of a dual biogas-ethanol combustion mode. Using a single cylinder engine with a 13.6:1 compression ratio, combustion, performance and emissions were analyzed. It was realized that the dual biogas-ethanol mode accelerated the burn rate, improving the combustion phase. In addition, at full load the fuels barred the occurrence of detonation, and the combustion efficiency was increased compared to pure biogas. This is due to the lower volume of unused methane, the more complete combustion, and the lower occurrence of flame cooling.

A numerical analysis of the theoretical performance of a biogas engine is presented in de Faria *et al.* (2017). The advantage of the simulation performed is the ease in adapting the code for different fuel compositions, which can help users in the optimization of the biogas to be used for engine operation. By varying the engine equivalence ratio and ignition time, the relative values of CO_2, CO, O_2, NOx and hydrocarbons were obtained. The results found converged with experimental data from the literature. The simulations made show more significant losses in engine performance than gains in emissions reduction. The major contribution of this work is the model, which proved to be reliable to reduce the need for adaptations and changes in benches to seek optimal operating conditions. In addition, there are not many papers in the literature involving biogas engine performance.

Using an experimental apparatus, Yamasaki *et al.* (2013) sought to develop an engine capable of using a mixture of natural and urban gas at any mixture ratio. Using a three-cylinder 1.6 engine, it sought to control NOx emissions and maintain a high thermal efficiency. Tests showed that the system worked properly, having the advantage of using an original controller, minimizing cost and time spent on modifications. Therefore, the proposed design can be useful in expanding the use of biogas.

The experimental results of a single cylinder spark ignition engine operated with raw biogas under wide open and part throttle conditions are analyzed and its performance is compared with a gasoline engine by Hotta *et al.* (2019). Break power was observed to be 17.5 and 37.5% lower on biogas at wide open throttle and part throttle, respectively. Besides, the average emission of carbon monoxide is reduced by 39.4% and 93% at wide open throttle and part throttle, respectively. This shows a major decrease in CO emissions for biogas fueled engines. However, they showed higher CO_2 production and higher unburnt hydrocarbon through the operating range of the gasoline fueled engine. Emissions of NOx were lower for biogas engine – on average, reductions of 81.5% at wide open throttle and 66% at part throttle conditions were observed.

Sudheesh and Mallikarjuna (2010) conducted an experimental investigation of a homogeneous charge compression ignition engine using biogas as fuel and diethyl ether as ignition improver in a single cylinder engine. Best brake thermal efficiency flow rate of diethyl ether was determined for each load condition. The used load range of operation was 0 to 4.52 bar BMEP. Biogas-diethyl ether at 25%, 50%, 75% and 100% loads showed an improvement of 29.5, 15.7, 19.3 and 9.2% respectively on brake thermal efficiency, as compared to spark ignition mode. For all observed load conditions, smoke emissions were found to be lower for biogas-diethyl ether in homogeneous charge compression ignition mode. This shows that operating the biogas engine in homogeneous charge compression ignition mode is advantageous for better performance and has better emission characteristics with diethyl ether as an ignition improver compared to other operating modes.

Hedfi *et al.* (2016) conducted experimental analyses of spark ignition engine fueled by unusual fuels, such as biogas, hydrogen, natural gas and liquid petroleum gas. The main goal was to improve the indicated thermal efficiency with respect to exhaust gas recirculation and fuel consumption for an engine running with these fuels. Another goal was to observe the possibility of using biogas mixed with hydrogen. The thermodynamic and kinetic analyses made it possible to establish a numerical code used to improve engine parameters. A mixture of biogas and hydrogen (50% each) was shown to be an operating blend. The thermal efficiency can be improved regarding both fuel consumption and exhaust gas recirculation. Highest efficiency values and lowest mass consumption were found with pure hydrogen and biogas-hydrogen mixture, when compared to gasoline, liquid petroleum gas and natural gas.

Sadiq Y and Iyer (2020) aimed to develop a dedicated biogas fueled spark ignition engine technology. The biogas used was provided by provided by Akshar Biotech Pvt. Ltd. Surat, India. Some elements of the plant are shown in Fig. 3. A gasoline single-cylinder engine was optimized to run on two types of biogas: scrubbed (93.8% CH_4) and raw (56.6% CH_4), making the necessary changes to the components. The tests were conducted at 3,000 rpm. Pistons with different crown geometries and cleavage on its crown were used. Scrubbed biogas and raw biogas showed inferior performance than petrol. The authors attribute this to biogas having lower volumetric efficiency.

Figure 3. Biogas scrubbing unit and four gas analyzers from Akshar Biotech Pvt. Ltd. Surat, India (Sadiq Y and Iyer, 2020).

Kruczek *et al.* (2019) conducted experimental and numerical analyses of a four-stroke single-cylinder engine running on methane and biogas. Excess air ratios of 0.95, 1.00, 1.05, 1.10, and 1,20 were used. Based on the numerical results, it was possible to conclude that fluid flow inside the cylinder has an influence on the development phase of the initial flame. In the case of biogas, the early flame phase is seen to be weak. This results in longer combustion, lower efficiency, and lower output of power. Disagreements were noted between numerical and experimental results for larger excess air ratios.

Marculescu *et al.* (2016) used biomass consisting of bones and meat residues from the food processing industry, with about 42% in mass of water. A waste to energy conversion using thermo-chemical processes was made. The influence of fuel properties of syngas was compared to methane and digestion biogas. An increase on the air excess ratio in combustion was seen to be necessary to prevent from detonation in engines using syngas.

Przybyla *et al.* (2016) used producer gas in a spark ignition engine and a homogeneous charge compression ignition engine. The spark ignition engine used a mixture equivalence ratio of $\phi = 1.0$, while the homogeneous charge compression ignition engine used a mixture of $\phi = 0.5$. Comparing the results, the peak pressure in the cylinder of the homogeneous charge compression ignition engine was 80 bar, while the peak pressure for the spark ignition engine was 16 bar. The maximum temperature of the spark ignition engine, however, is much higher than that of the homogeneous charge compression ignition engine – about 450 K. The indicated efficiency of both engines had close values. The spark ignition engine had an efficiency higher by only 3.5%. One advantage of this engine is that it can be more easily optimized in terms of ignition timing. In addition, it has lower losses by unburned fuel in exhaust (less than 2% of chemical energy of the fuel, against more than 10% in the case of homogeneous charge compression ignition engine). It was also noted that both engines had high emission levels of carbon monoxide.

Kwon *et al.* (2017) proposed and tested a small biogas-fueled spark ignition engine for supplying energy and decrease greenhouse gas emissions in remote areas of developing countries. A conversion kit, consisting of a regulator and an adapter, was used to make it possible to use three fuels. Compression ratio was increased to improve engine performance by a decrease on combustion chamber volume. An increase in compression ratio resulted on increasing brake power output and brake thermal efficiency, and brake specific fuel consumption decreased. The results obtained suggest that the performance of the engine improves at higher compression ratios, while it gets worse with an increasing carbon dioxide dilution.

Melaika *et al.* (2022) conducted an experimental investigation of inwards opening and spray-guided direct injection compressed natural gas injector in a spark ignition engine. 7 different nozzle head designs were used. Part load (6 bar) and wide open throttle conditions were used at 2000 rpm for testing. It was shown that the design of the injector nozzle head can influence engine performance and exhaust gas emissions. The results also depended on the pressure and injection timing of fuel injection.

Calam *et al.* (2015), instead of biogas, used fusel oil in a single cylinder spark ignition engine. Air/fuel ratio was kept at schoichiometric mixture for all speeds and loads tested. Engine torque was seen to increase in all engine speeds and loads with increasing ratio of fusel oil.

Zhang *et al.* (2018) studied combustion performance and emission characteristics of two-phase anaerobic digestion biogases modeled with CH_4/H_2/CO_2 mixtures in a small spark ignition engine, both experimentally and numerically. Increasing carbon dioxide volumetric ratio showed a lower engine power output, while increasing H_2/CH_4 ratio showed an increase on engine power output, particularly when excess air ratio was greater than 1.4. Working at high loads and excess air ratio between 1.2 and 1.4, no significant changes on engine power output, thermal efficiency, carbon monoxide emissions, and unburnt hydrocarbon were observed with an increase of H_2/CH_4 ratio. However, brake specific NOx emissions increased, as a result of increased cylinder temperature. The main conclusion was that the use of two-phase anaerobic digestion biogases is viable in spark ignition engines.

Guibert *et al.* (2022) proposes a concept that aims to avoid auto ignition by obtaining more control over the initiation of combustion. This is made through the introduction of biomass particles on the reactive gas mixture. This mixture gets a controlled amount of biomass powder injected by a specifically designed particle injector. The results showed that it is possible through this process to control ignition delay times of the mixtures. However, it is necessary to do further investigation on the interaction between gas and the solid particles. The properties of the gas mixture also has a large influence on the ignition of the solid particles. This means that better combustion processes could be obtained though the optimization of the characteristics of gas/particles.

The research conducted by De Llobet *et al.* (2013) aimed to study the influence of the conditions of catalytic decomposition of biogas on the yields and properties of the product, as well as the effect of the composition of syngases on emissions and engine performance compared with raw biogas. Better combustion was seen with the use of syngases than biogas, with higher engine break thermal efficiency (up to 32% against 27.2% with raw biogas) and lower exhaust emissions.

Biogas produced through biomass gasification using a catalyzer was simulated by Chen *et al.* (2012). The characteristics of combustion of H_2–CO blended fuel and the effect of the dilution of CO_2 on it on a spark ignition engine at wide open throttle, maximum break torque and at 1,500 rpm using these fuels were analyzed. The equivalence ratio was never let above 0.8. It was seen that brake mean effective pressure decreases as the dilution ratio increases, and lower NOx emissions could be obtained with CO_2 dilution, without significant losses in brake thermal efficiency. An operating range of H_2–CO mixture that led to 500 ppm of NOx emission and 26% brake thermal efficiency was reached.

Gupta and Mittal (2019) used biogas on a spark ignition engine to observe variations on the performance and the characteristics of combustion and emissions with varying biogas composition. With a single cylinder, the engine was cooled with water and operated at 1,500 rpm at various operation loads and compression ratio of 8.5:1. Again, an increase in CO_2 concentration led to lower brake thermal efficiency. An increase from 0% to 40% of CO_2 in methane-CO_2 mixture led to a decrease from 16.8% to 13.7% on brake thermal efficiency. Simultaneously, flame initiation and combustion duration were observed to be higher.

Biofuels in general as internal combustion engine fuels were observed by Awogbemi *et al.* (2021). Besides showing the benefits that the use of biofuels bring to the environment and potential gains on engine performance, they also highlight how it can improve the economy, providing employment, for example, and also solve energy security and poverty issues, providing energy at more stable and affordable prices. The authors also show the need to develop adequate policies and infrastructure to make a gradual change to the use of biofuels.

4. CONCLUSIONS

This paper aimed to show the academic studies on the use of biogas as a fuel for internal combustion engines, and with this, enlighten the state of the art of this subject, making it easier to understand the advantages and the associated problems found with the use of biogas. According to the research presented and the results found, it can be seen that biogas is an interesting alternative fuel for spark ignition engines. In addition to its clean origin, it can be used without major modifications. However, a disadvantageous factor is its low heat capacity.

Another parameter of concern is hydrogen sulfide emissions, which, besides being highly toxic, can compromise the integrity of engine components in the long term. It is still necessary to conduct studies on the optimal composition of biogas and the parameters with which the engines will have best results. Besides the benefits that it brings to the environment, the use of biogas can also have a positive impact on the economy, since it relieves the dependence on petrol and fossil fuels.

Either way, biofuels are a trend and it is likely that their use will increase in the next years because of the many advantages observed. Thus, the use of biogas as a fuel for internal combustion engines may be a viable alternative and should continue to occupy more and more space in academic and industrial spaces as its optimal operating parameters are found.

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