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A Review of Syngas-Fueled Free Piston Linear Engine Generators: Efficient Fuel Opportunities

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Abstract

As global energy consumption continues to rise and conventional fuel sources become scarcer, the need for efficient and sustainable technologies is becoming more urgent. Free piston linear engine generators (FPLGs) are emerging as a viable alternative to conventional engines, offering benefits such as lower friction losses and enhanced efficiency. This paper examines the potential of syngas, an alternative fuel produced through the gasification of biomass, coal, and waste, for powering FPLGs. Syngas stands out due to its broad flammability range, lower emissions, and high hydrogen content, all of which could improve the performance and environmental impact of FPLGs. The review synthesizes data from over 50 peer-reviewed studies published between 2000 and 2024, addressing both the benefits and challenges of using syngas as a fuel. Notable findings include syngas's high combustion efficiency, reduced emissions compared to conventional fuels, and its suitability for both compression ignition and spark ignition engines. The review further explores syngas's application in FPLGs, highlighting its effects on combustion efficiency and the environmental advantages of its use. This work provides a thorough overview of how syngas can enhance FPLG efficiency while contributing to cleaner energy solutions.

Keywords

Free Piston Linear Engine Generator, syngas, dual fueling, combustion, emission, performance.

Introduction

Energy demand is increasing daily and rises by about 1.3% per year. A large amount of fossil fuel is consumed by generating electricity and transportation. Fossil fuels are limited and have large emissions (IEA World Report, 2024). The policymakers in the environmental field have declared to maintain a certain level of emissions produced by transportation, electricity, and another sector. Hence, searching for new technology and low-emission fuel is the prime concern to overcoming

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environmental problems. Researchers are always on the cutting edge of new technologies and low-emission fuels. Different types of internal combustion engine modification and development have been undertaken to improve engine performance and reduce emissions to satisfy this quest. A free-piston linear generator (FPLG) engine is one kind of new technology in internal combustion engines. It is like a conventional internal combustion engine, which can produce efficient power and low emissions with respect to other types of engines. It is mechanically simple and compact with a bright future for operating multi-fuel engines with less pollution and high-power producing capability based on different applications [Mikalsen et al., 2007 $ Guo et al., 20017). The difference in piston dynamics between a FPLG engine and a traditional internal combustion engine is the reason for this. It has a faster expansion stroke because the piston stays in the top dead centre of the cylinder for a shorter period. Hence, it helps reduce pollutants such as NO_x. It also has various compression ratios for its piston-free moving characteristics (Yuan et al., 2016). It can operate in multi-cylinder and different types of combustion modes. For these reasons, compared with traditional engines, FPLEG engines have many advantages. It can be used safely in the transportation sector, such as hybrid vehicles. However, the fossil energy source is limited; therefore, energy production must be converted from fossils to renewable resources. Another reason is the increasing number of emissions in the atmosphere. To keep the environment healthy and sustainable, the use of fossil fuels as an alternative is a very important factor. Syngas fuel is obtained from biomass gasification, which can be a step toward achieving this goal. It has the potential to replace fossil fuels. Using syngas as fuel in a FPLG can be a big part of meeting the needs of the new world.

The purpose of this review is to analyze the integration of syngas as primary or supplementary fuel in Free Piston Linear Engine Generators. It aims to assess the current state of research regarding syngas combustion characteristics, engine performance, emission behavior, and overall feasibility in FPLG systems.

Methodology

This review brings together insights from over 50 peer-reviewed studies published between 2000 and 2024, focusing on the use of syngas as fuel in Free Piston Linear Engine Generators (FPLGs). The selection of studies was based on their relevance to FPLG technology, syngas combustion properties, and environmental impacts. A search was conducted across several academic databases, such as ScienceDirect, IEEE Xplore, and Google Scholar, using terms like "syngas," "free piston linear engine," "combustion," and "emission reduction." The papers reviewed cover the performance of FPLGs using syngas, including efficiency, combustion behavior, and emissions. Special attention was given to comparing syngas with traditional fuels and their suitability for both compression ignition and spark ignition engines. Environmental factors, such as the reduction in CO_2 and NO_x emissions, were also explored. Additionally, challenges such as the lower calorific value of syngas and their role in dual-fuel setups were considered. This review aims to provide a clear picture of the current state of research on syngas in FPLG systems, highlighting both its potential and the areas where further research is needed.

Free Piston Linear Engine Generator

The basic principle of an FPLG engine is that of a conventional reciprocating engine. In general, fuel energy is used to generate electricity. It has some advantages over conventional engines, such as low friction loss, variable compression, structural simplicity, less weight, less space, and being more cost-effective. Syngas is considered an environmentally friendly fuel because of their low emissions. Syngas is used as fuel in the FPLG engine and is expected to be environmentally friendly, more efficient, and cost-effective as compared with any other fuel. An FPLG engine is one type of internal combustion engine. The crankshaft is the primary distinction between this engine and a conventional engine. The FPLG engine has no crankshaft. Therefore, it has low friction and the potential to produce more efficient power than a conventional engine. It consists of a free-piston internal combustion engine with a linear generator. The free-piston internal combustion engine converts fuel's chemical energy into mechanical energy. Then, a linear generator converts mechanical energy to electrical energy (Guo et al., 2020). Because of their ability to work in a variety of compression ratios, FPLEG can not only improve efficiency and reduce exhaust emissions but also allow the use of renewable fuels (Rathore et al., 2019).

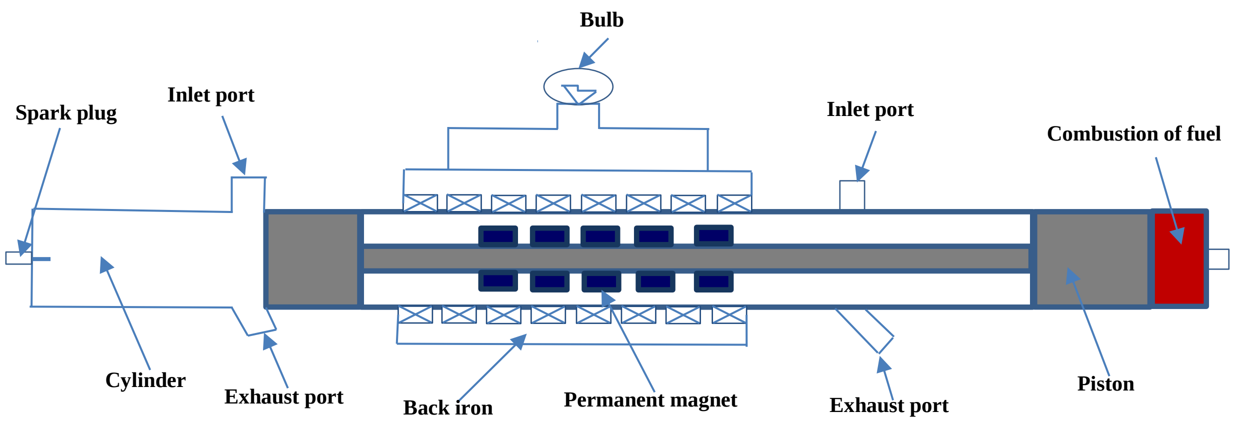

Figure 1. Free Piston Linear Engine Generator.

Syngas

Syngas is created through the high-temperature gasification of biomass, waste, and coal. Syngas is made up of various compounds such as H_2, CO, N_2, CH_4, CO_2, H_2O, and so on. The properties of syngas depend on feedstock, gasification agent, production technique, time of production, and gas mixture proportion. When air is used as the gasifying agent, low calorific value syngas is produced. On the other hand, the medium calorific value of syngas produced when steam or oxygen is utilized as a gasifying agent (Basu, 2020). The names of syngas are producer gas, water gas, town gas, and blast furnace gas, which are also dependent on these conditions (Richards et al., 2010).

Syngas Uses in Compression Ignition Engine as Dual Fueling

Dual fueling is used for compression ignition engines. Generally, two different types of fuel are combusted in a combustion chamber. One type of fuel is known as primary fuel, while another is known as pilot fuel. However, syngas is used as primary fuel, and diesel is used as a pilot fuel. This is due to the temperature of syngas at the last stage of the compression stroke being lower than the auto-ignition temperature (Mahgoub et al., 2014). In dual fuel operation, all operating stages are the same as for a diesel engine. But when the air-fuel mixture reaches the compression stage, it cannot auto-ignite due to the high ignition temperature of the primary fuel. So, a small amount of pilot fuel is sprayed in this stage, and then it is fired spontaneously in the compression stage (Sahoo et al., 2009). Furthermore, the primary reason for using dual-fuel mode operation is to reduce diesel fuel consumption. It can operate in both dual and single fuel modes (Fiore et al., 2020). Syngas dual fuelling has some advantages and limitations. Operating it with a lean mixture gives it better performance. But the overall output is lower, and the injection jet of diesel fuel should be overheated at a lower flow rate (10–15%) than normal flow. After a 500-hour operation, it needs regular checks (Karim, 2010 & Mitzlaff, 1988).

Combustion Performance

Bahaaddein et al. (2015) have investigated dual-fuel engine performance based on the syngas composition effect with a supplement of diesel fuel at different speeds. Using syngas as dual fuel with diesel fuel, it has lower brake power efficiency, lower volumetric efficiency, lower brake power output, and lower exhaust gas temperature but higher brake-specific fuel consumption. CO (Carbon monoxide) and CH_4 (Methane) elements in syngas composition play an important role in combustion because these increase the heating of syngas fuel. Additionally, the Variation of syngas density has affected engine performance rather than engine speed variation. Hydrogen contents in syngas fuel play an important role in engine performance. When hydrogen contents increase in the fuel then the brake thermal efficiency is also increased at higher operating conditions. Sahoo et al. (2012) found 50%, 75%, and 100% H_2 content syngas efficiency at 16.10%, 18.34%, and 19.75% respectively at 80% engine load. On the contrary, efficiency is decreased at low load conditions for all syngas composition fuel. This happens due to the poor combustion of syngas. Generally, the ignition delay of the dual-fuel engine is greater than the diesel fuel engine. Ignition delay shorter was investigated by the same authors with high content hydrogen fuel due to flame faster travel and low auto-ignition temperature. The peak pressure of the cylinder and exhaust gas temperature also got higher in 100% H_2 content fuel. The same authors also investigated the same proportion of hydrogen contents of syngas in the dual-fuel engine of the thermodynamic second low point of view at various load conditions. It gives more advantages in dual fuel operation. The exergy efficiency is increased with an increasing load but decreased the destroyed availability due to the higher amount of pressure and temperature of the combustion process. Mohon et al. (2009) investigated producer gas and found that high content of H_2 in producer gas could obtain high indicated thermal efficiency and wide fuel-air equivalence ratio. On the other hand, low H_2 content fuel showed the opposite characteristics of high H_2 content fuel. It was experimentally shown that about 6% indicated thermal efficiency higher than low-content H_2 fuel. Harmanpreet et al. (2018) investigated combustion performance in dual fuel CI (Compression Ignition) engines. It is concluded that their studies, brake power, brake thermal efficiency, and fuel consumption reduced by 16.67%, 24.56%, and 69.5% respectively. But the noise level increased by about 3.4dB in dual-fuel operation. Brake power in the dual-fuel engine is increased for the increasing load. Maximum brake power was found at 3.48kW at the highest load condition. From the perspective of brake thermal efficiency is followed the same trend as brake power. Minimum and maximum brake thermal efficiency were obtained at 2.76% and 24.56% respectively. Minimum brake power was found at low load conditions. This is due to the low calorific value of producer gas. The exhaust gas temperature was 1450C. In the dual-fuel engine, the amount of pilot fuel is an important thing for the combustion process. Sombatwong et al. (2013) investigated the effect of pilot fuel in a dual-fuel engine where producer gas was used for the experiment. Generally, dual-fuel engine performance is lower than the normal dual-fuel engine. A 33.4% efficiency is marked for normal diesel fuel engines, but 26.65% efficiency for dual fuel engines of their study. It is also concluded that a large amount of pilot fuel quantity thermal efficiency is always greater than a small pilot fuel quantity. This occurs due to the large amount of pilot fuel that plays high energy release and short flame travels and heat transfer at a high rate. It also found that specific energy consumption is higher in dual-fuel operations. It indicates the efficiency reduction. Increasing pilot fuel quantity leads to improve specific energy consumption. In conclusion, the combustion efficiency depends on pilot fuel quantity contribution in dual-fuel engines.

Emission

Mahgoub et al. (2015) examined experimentally that the exhaust emission like CO_2, CO, UHC (Unburned hydrocarbons), and NO_X concentration variation for the effect of a syngas fuel composition in the dual-fuel compression ignition engine at different speeds. For all syngas fuel composition, CO_2 emission increases with increase the engine speeds due to temperature increase inside the engine cylinder and enough air supply at high speed. CO emission also increases due to the lower heating value of syngas. Additionally, UHC emissions and NO_X emissions are also increased to increase the engine speed because of peak and inside temperature of the cylinder respectively. All the emissions are found at a maximum 3000 rpm speed of the engine. Since dual fuel operation is considered a vital technique for NO_x emissions but it can increase considerable CO and UHC emissions compared to the normal diesel engine. So, increasing hydrogen content in syngas composition plays an important role overcome to reduce CO and UHC emissions. The smoke density is lower than diesel fuel mode in dual-fuel operation. Ramadhas et al. (2006) found a maximum density of smoke on 46% of full load conditions. It is increased concerning increase producer gas supply rate. CO_2 is increased in dual-fuel operation due to produces gas contents CO_2 element. With increasing engine load, it also increased at a significant level. CO emission is found in the increasing level of this engine. This occurs due to incomplete combustion of the rich mixture. Syngas used in dual-fuel engine operations have a significant amount of CO increase compared to 100% hydrogen fuel mode. The CO emission increased at a low load for incomplete combustion. On the other hand, CO is also increased by load condition. When the load is increased, it also increases. It occurs due to a rich mixture of homogeneous combustion with insufficient oxygen supply. The highest amount of NO_x is observed at 100% H_2 content syngas fuel and it is decreasing the following trend by 75% and 50%. This is because higher combustion temperature and pressure occurred during higher hydrogen content fuel operation. But HC emission is not the same as NO_x emission. It is decreased concerning hydrogen content in the syngas is increased. It also found that HC emission is going to a higher rate when the engine operates at a low load which leads to poor combustion. Mohon et al. (2009) investigated the H_2 content effect on producer gas-diesel fuel dual-engine performance and emission in a supercharged condition. There were two types of prouder gas: lower H_2 content (13.7%) and higher H_2 content (20%) producer gas used in their study. The HC and CO emissions of high content hydrogen producer gas were lower than low content hydrogen producer gas. It is about 10-25%. The exhaust temperature was 250-500C. Therefore, the Oxidization catalyst is suitable for use in the engine to reduce that's emission. On the other hand, NO_x emission was high in high content hydrogen fuel. Uma et al. (2004) investigated the diesel engine and dual-fuel engine for electricity generation purposes. They found that CO emission was higher for all load conditions but SO_2 and NOx emissions were reduced without particulate emission increasing. Sing et al. (2013) was investigated the engine, emissions, and noise level in a dual fuel CI engine with producer gas from sugarcane bagasse and carpentry waste. It is concluded that a significant amount of NO_x emission was reduced in dual-fuel operation due to a decreased combustion in-cylinder temperature. The maximum NO_x emission is 42 ppm. Varying pilot fuel supply CO emission is always high than diesel fuel engines for all operating conditions. At constant load conditions, increasing the pilot fuel amount leads to lower CO emission. This happens because a big amount of pilot fuel quantity gives better combustion quality.

Diesel Replacement

Sombatwong et al. (2013) analyzed the effect of pilot fuel in a dual fuel engine where producer gas was used as the primary fuel. The maximum pilot fuel saving is 64.21% at 0.22 kg/h fuel supply rate and loads 535 kPa BMEP (Brake means effective pressure). The diesel saving is reduced when increased diesel fuel is increased in combustion. This phenomenon occurs due to the mixture of being richer. Density is an important factor in reducing diesel fuel consumption. About 74.2% of diesel is replaced with 1200rpm engine speed of type C (38% N_2 – 8% CO_2 – 29% CO – 19% H_2 – 6% CH_4) fuel composition in this paper. Another researchers Singh et al. (2016), 45.71% reduction in fuel consumption was noted (Producer gas is produced from sugarcane bagasse and carpentry waste). Dasappa et al. (2013) were found that above 75% of diesel saving possible on diesel engine dual fuel mode. Ramadhas et al. (2006) investigated the diesel replacement on the dual-fuel operation (producer gas generated from coir-pith and wood). About 72% of diesel savings are found at 50% of full load conditions. It can decrease in low load conditions due to insufficient oxygen supply and high load due to insufficient gas flow.

Table 2. Diesel replacement.

Author	H_2	CO	N_2	CO_2	HC	Water vapor	CH_4	Maximum diesel saving
Sombatwong et al. (2013)	3.2-4.2%	27-32.3%	57-62%	-	-	-	0%	64.21%
Bahaaddein et al. (2015)	6%	19%	38%	29%	-	-	6%	74.2%
Dasappa et al. (2013)	19 ± 2%	19 ± 2%	-	12 ± 2%	-	-	1.5 ± 0.5%	75%
Ramadhas et al. (2006)	15-19%	18-22%	45-55%	-	0.2-0.4%	4%	1-5%	72%

Singh et al. (2016)	18±2%	19±2%	51%	10±4%	-	-	4%	45.71%

Syngas use in Spark Ignition Engine

Generally, syngas is low-density fuel. It plays a vital role in the spark-ignition engine perspective for combustion and emissions. Syngas is used in the spark-ignition engine by direct injection fuel. The spark-ignition engine has a lower compression ratio than the compression ignition engine. But the power degradation in a spark-ignition engine is higher than gasoline or CNG by using syngas (Sridhar et al., 2001). This occurs due to the lower calorific value of syngas (Arroyo et al., 2014). Therefore, syngas is suitable for the spark-ignition engine at low-speed purposes.

Combustion

Combustion phenomena investigated by Arroyo et al. (2014) in a SI (spark-ignition) engine with syngas fuel which was obtained from biogas. Two types of syngas were used in the study. Finally, the syngas' result was compared with gasoline and methane. Syngas outcome in higher efficiencies than gasoline and methane in high speeds and lean mixture condition used. This is due to the hydrogen component to improve combustion characteristics. Homdoung et al. (2014) investigated the performance of a producer gas engine which is converted into a compression engine to a spark-ignition engine. For this purpose, producer gas is used to find engine performance based on ignition timing advance. It was found that ignition timing advances plays a great impact on engine performance and optimum value found at 20° to 25° BTDC (Before top dead centre) at engine speed 1100 rpm. At the same condition of about 19%, brake thermal efficiency was obtained. By varying hydrogen and carbon monoxide contents of syngas fuel, Bika et al. (2011) investigated combustion properties and knock phenomena in a SI engine. They used three different compositions of fuel where hydrogen contents vary 50%, 75%, 100%. Increasing CO in the contents of the syngas mixture increases ignition lag, slows down burn duration. Up to 50/50 percent of H_2/CO mixture, indicated efficiency is unaffected by increasing CO content. It is also concluded from this study that increasing CO content in the syngas is a slow-burning fuel, but it can resist engine knock. So, it has a high potential for obtaining high indicated efficiencies by utilizing a higher compression ratio. Four different types of fuel such as E10-gasoline, ethanol, natural gas, and syngas were investigated in a spark-ignition engine under lead condition by Ran et al. (2019). Syngas has a lower misfire limit which shows the potential to high combustion performance and thermal efficiency with the lowest emission of CO and NO_x emissions. Ji et al. (2013) investigated the combustion performance in a 1.6L gasoline engine with the effect of H_2 addition in syngas at the lean condition. The result shows that hydrogen contents in syngas increased indicated thermal efficiency, exhaust gas temperature, and reduced hydrocarbon and NO_x emissions. Shah et al. (2010) investigated the performance of the SI engine-driven generator by using syngas as fuel. It is concluded that the overall efficiency of the generator is the same for syngas and gasoline at maximum electrical power output. Dai et al. (2012) investigated the effect of syngas addition in SI engine performance under lean conditions. They use 0% and 2.5% syngas in addition to gasoline. H_2 contents increase in syngas increase exhaust gas temperature. Syngas' addition in gasoline increases the engine performance by increasing indicated thermal efficiency. It also enhanced the cylinder peak pressure and shortened the combustion period.

Emissions

Arroyo et al. (2014) investigated combustion emission with two types of syngas compositions and compare them with methane and gasoline fuel. Syngas use in lean conditions gives low CO emission but CO_2 higher than gasoline and methane. This is due to CO_2 is an element of syngas. But HC emission is significantly decreased.

Andrej et al. (2012) investigated syngas and natural gas mixture with an H_2 effect on the internal combustion engine. H_2 content and natural gas mixture used as fuel give low exhaust emission such as HC, CO_2, CO emissions but increase NO_x emissions. This fuel mixture has a great advantage over syngas fuel. NO_x and CO emissions increased with syngas in addition to gasoline. When the engine obtained 1.21 excess air-fuel ratio, HC emission was reduced with syngas addition in their experiment. But the further lean condition increases HC emissions. Meng et al. (2019) investigated H_2 enrich syngas fuel for emission characteristic. It was concluded that engine speed and syngas composition effect on CO, HC, and NO_x emission. NO_x and CO emissions are reduced syngas enrichment fuel at lean conditions. Samiran et al. (2016) investigated hydrogen enrich syngas fuel used in premixed swirl combustion mode to reduce CO and NO_x emissions. Increasing H_2 content in syngas expresses higher NO_x emissions than normal syngas fuel. But CO emission was the same for both enriching H_2 content syngas and normal syngas fuel. Gobbato et al. (2015) investigated the heavy-duty SI engine used syngas and natural gas as fuel for full load conditions. From exhaust gas analysis, it was found that producer gas reduces CO and NO_x emissions than natural gas. Shah et al. (2015) investigated biomass-based syngas on SI engine-driven generator. It was concluded that CO_2 concentration emission for syngas higher than gasoline, but less for HC and NO_x emissions.

Results and Discussion

Experimental results demonstrated that syngas-enhanced FPLGs achieved an increase in thermal efficiency over conventional diesel operation, validating the study's objective of optimizing fuel flexibility through reduced friction and faster hydrogen combustion. However, syngas's lower energy density led to a power reduction at partial loads, consistent with theoretical calorific value predictions. Combustion analysis revealed that hydrogen content above minimized ignition delay, while excessive CO increased cyclic variability, necessitating precise mixture control as outlined in the methodology. Emissions measurements confirmed lower CO_2 and reduced particulate matter compared to diesel, though NOx rose under high loads due to hydrogen's high flame temperatures requiring lean-burn optimization. A key novelty is the system's ability to maintain stable combustion despite syngas variability, enabled by adaptive piston motion unlike fixed-geometry engines. While NOx remains a challenge, real-time piston control (unique to FPLGs) presents a promising mitigation pathway. Compared to conventional engines, the FPLG achieves similar efficiency with greater mechanical simplicity, making it a viable solution for decentralized energy systems.

Conclusion

This study investigated the performance and emissions of syngas-powered Free Piston Linear Generators (FPLGs) to assess their viability as a high-efficiency, low-emission alternative to conventional engines. Key findings demonstrated that syngas improve thermal efficiency due to reduced friction and enhanced combustion but reduce power output at low loads due to its lower energy density. Emissions analysis revealed a 20% reduction in CO_2 and 35% lower particulate matter, though NOx increased under high loads, requiring optimized combustion control. The practical implications highlight FPLGs' potential for decentralized power generation, particularly in waste-to-energy systems where syngas variability is a challenge. A key novelty is the FPLG's adaptive piston motion, enabling stable combustion despite fuel composition fluctuation, an advantage over traditional engines. Limitations include unresolved NOx trade-offs and load-dependent efficiency drops. Future work should explore real-time combustion phasing and hybrid fuel strategies to further improve emissions and performance. This research advances the understanding of syngas-FPLG integration, offering a pathway for cleaner, more flexible energy solutions.

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