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PERFORMANCE ATTRIBUTES OF A FREE PISTON LINEAR GENERATOR FUELLED USING SYNGAS

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ABSTRACT

In this paper, the experimental test rig working on a single-cylinder principle has been developed and operated as a free-piston linear generator (FPLG). The engine was powered using syngas as the fuel and the results obtained from the experimental tests are presented. The

Introduction

Presently, the energy consumption of the transport sector in the USA is about 26% of the world's total energy (IEO, 2016). The majority of this energy comes from petroleum-based fuels (Mohon Roy et al., 2009). This situation, therefore, raised two major concerns: energy source depletion and environmental impact. Based on projection, the worldwide oil reserves, at the current consumption rate, can only last 40-50 years before depletion. Meanwhile, the combustion of fossil fuels in the transportation sector results in almost 22% of global greenhouse gas (GHG) emissions

performance and combustion attributes of the engine were investigated under a steady-state and at the best operating performance. Experimental results reveal the optimal conditions at which the rarely combusted fuel could operate thereby exhibiting the capability and flexibility of free-piston engines to utilize various fuels. The engine demonstrates low incylinder pressure of 14.34 bar due to the slow flame propagation speed caused by the noncombustible components of the mixture thereby diminishing the flame front surface that led to the 111.37 kJ/s rate of heat release obtained. The maximum piston velocity of 3.75 m/s generates a lower peak output power of 518.6 W due to the lower energy content available to drive the translator. The combustion and indicated efficiencies attained by the engine are 22.56% and 10%, respectively.

Keywords— *free-piston engine, syngas, combustion, engine performance, linear generator.*

(Jean-Paul, 2020). As the energy demand for transportation continues to grow, the emission crisis is expected to be even more aggravating than it is in the future despite the sharp decline during the pandemic period. Consequently, lots of automotive technologies are proposed including adopting renewable fuels such as biogas, syngas, etc., as alternative fuels to replace fossil fuels. The implementation of renewable fuels is still faced with challenges of the high cost of feedstock and processing expenditure, which later led to the discovery of other forms of renewable fuels e.g., ethanol and biodiesel produced with the help of advanced technologies from valuable crops or animal fats that serve as feedstock. The shortage of food for the ever-increasing population is the topmost concern raised against this option. For this reason, a low-cost feedstock for example lignocellulose, algae, waste vegetable oil, and municipal solid waste are then proposed. However, because of the complex pretreatment and purification processes necessary for this type of feedstock, the processing expenditure, undoubtedly, increased. So, on the ground of the high cost of feedstock and its consequent high cost of renewable fuels, the research on renewable fuels is significantly hindered. The other option available is exploring the engine technology, hence, the need for a new flexible engine that can measure up to renewable fuels. Various technologies such as fuel cells, micro-gas turbines, Otto/Wankel system, and free-piston engine (FPE) are being researched to tackle the fossil fuel challenges.

FPE is a new device that has received a lot of attention from researchers all over the world because of its unique features of simplicity, potential to reduce cost, high power density, and perhaps high thermal efficiency (Achten, 1994; Woo & Lee, 2014). FPE is a 'crankless' internal combustion engine with no restriction of piston motion by crankshaft thereby making the piston 'free' to move. It can operate a variable compression ratio considered a potentially valuable feature to allow for different fuels to be used. Different load devices such as air compressors, linear generators, etc. can be coupled to an FPE to become a free-piston linear generator (FPLG) in the case of a linear generator (Mikalsen & Roskilly, 2007). It is capable of generating higher mechanical and thermal efficiencies when compared with equivalent and more conventional reciprocating engines (Hung & Lim, 2016; Virsik & Heron, 2013). The few moving parts of the engine make it compact with low maintenance costs and reduced frictional losses. The engine is well suited for homogenous charge combustion ignition (HCCI) operation (Mikalsen & Roskilly, 2007) which improves thermal efficiency and reduces temperature-dependent emissions such as NOx emission (Graef et al., 2007; Sherazi & Yun, 2011). Despite the gains and benefits that are associated with the FPLG, there are drawbacks such as the piston motion control, starting problem, misfire, balancing, and unstable operation (Hung & Lim, 2016; Rathore et al., 2019). Nevertheless, several researchers and research institutes have investigated FPLG engines using different approaches such as modelling, simulation, controlling strategy as well as experimental.

Zhang and Sun developed and studied an advanced combustion control (trajectory-based combustion control) to optimize both an FPE efficiency and emissions. Previous studies conducted utilized fossil fuels but later extended to varieties of renewable fuels such as hydrogen, biogas, syngas, ethanol, dimethyl ether (DME), biodiesel, and Fisher-Tropsch fuel. The effects of compression ratio and piston motion pattern on the combustion process were studied. The result of the study for the various fuel showed that emission production was reduced by the effect of the combustion control, while thermal efficiency improved in some cases and others decreased. Above all, the result established that FPE has ultimate fuel flexibility (Zhang & Sun, 2017). Ahmed and Lim utilized artificial neural networks (ANNs) to assess the performance and exhaust emissions of a two-stroke dual-piston FPLG to predict the best engine operating condition. Simulation models were developed and validated with experimental tests. At various equivalence ratios, ranging from the lean to the rich mixture, experimental tests were conducted on a free-piston engine fueled with propane. The results of the tests revealed strong agreement between the predicted and experimental values. At an equivalent ratio of 0.7, 26.63% and 118.8 W were the maximum thermal efficiency and power generated obtained, respectively, while a maximum IMEP was found to be 4.39 bar at stoichiometric. The likelihood of exhaust gas temperature and exhaust emissions to increase with increasing equivalence ratio was also reported (Ahmed & Lim, 2016). A two-stroke, two-cylinder spark-ignited FPLG prototype was developed by the Beijing Institute of Technology and effectively tested for cold start-up, combustion when fueled with gasoline, and a generating process during operation (Mikalsen & Roskilly, 2010a, 2010b). Successful combustion also was reported for a compressed ignition two-cylinder FPLG prototype built at the same time (Jia et al., 2016; Zhang et al., 2015). The authors in their previous work investigated the effect of premixed compressed natural gas and carbon dioxide on the performance and combustion characteristics of a spark ignition direct injection free-piston linear generator engine. The outcome of their studies showed that the engine displayed better stability with lower cycle-to-cycle variation (Ayandotun et al., 2021). Zhang and Sun (Zhang & Sun, 2017) in their published work investigated using a simulation method to study the effects of advanced control on the combustion process of different renewable fuels. They found that two varieties of syngas with certain compositions were considered noncombustible for internal combustion engine (ICE) and therefore produced a relatively low work output when combusted though at a higher compression ratio (CR).

Many researchers have dedicated lots of time to studying FPLG engines using both simulation and experimental methods. Reports from published works indicate that more works are still to be done to overcome the technical challenges such as starting difficulty, piston motion control, misfire, scavenging, etc. standing as a barrier to achieving stable engine operation and high efficiency. Moreover, different renewable fuels have been utilized; however, syngas with a particular composition was reported to barely combust even when used in a conventional engine. Since no one has utilized this composition in an FPLG engine experimentally, the present study, therefore, considered utilizing the very syngas in an FPLG engine to investigate the engine performance characteristics. Besides, the simulation study alone is enough to understand an FPLG engine, so, more experimental studies are required for better understanding and to complement the limited available experimental data needed to validate numerous simulation models whose results proved high efficiency and power output.

EXPERIMENTAL PROCEDURE

Description of FPLG Engine

The spark ignition direct injection FPLG engine is comprised of three main subsystems: (1) a free-piston engine, (2) a tubular linear generator, and (3) a gas-spring bounce. Their major components include translator shaft, pistons, stator assembly, permanent magnet, and liners. The schematic of the FPLG engine can be found in the previous publication of the authors (Ayandotun et al., 2021). The ends of the translator shaft are coupled to two pistons enclosed by two cylinders (liners) designated as combustion and bounce cylinders. The combustion cylinder serves to extract the energy from liquid or gaseous fuel that powers the piston. Its cylinder head has a pressure sensor, a spark plug, and an injection valve attached to this side of the cylinder. Whereas the bounce chamber creates a gas spring that provides the compression work to sustain combustion operation. Its (bounce chamber) cylinder head is equipped with a pressure sensor to monitor the bounce cylinder pressure. The tubular linear generator is located between the two cylinders and consists of permanent magnets, stator core, coils, and partition plates as its components. A series of bonded permanent magnets are mounted on the translator shaft while the stator core housed the coil connected to external loads that consume the generated electric current. Table 1 shows the detailed specifications of the FPLG engine and Table 2 presents the

properties of the fuel (syngas) used for the current study. The in-cylinder pressure during the expansion process was measured using a Kistler piezoelectric pressure transducer coupled with a charge amplifier, which simultaneously provided the controller with the required signal. The operation of the FPLG engine was managed and controlled by the NI controller based on these signals' inputs. The position of the translator as it travels back and forth was measured using a linear encoder and magnetic strip that provides feedback to the controller. In-cylinder pressure, piston displacement, and output current to mention but a few are the parameters logged using a
National Instruments (NI) data acquisition system via their various sensors. The detailed working principle of the FPLG engine can be found in the authors' previous work (Ayandotun et al., 2021).

Table 1: Engine specification parameters of Table 2: Some of the properties of syngas the FPLG

Engine Specifications	Value
Hydrogen (%)	17.92
Carbon monoxide (%)	23.08
Carbon dioxide (%)	11.98
Methane (%)	1.4
Nitrogen (%)	46.625
Density [kg/m^3]	0.95
LHV [MJ/m^3]	7
Stoichiometric A/F ratio	1.23

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Engine Specifications	Value
Cylinder bore [mm]	56
Maximum stroke [mm]	96
Effective stroke [mm]	84
Cylinder displacement [cc]	221
Number of cylinder liner [-]	2
Working pressure [bar]	5
Moving mass [kg]	7
Intake valve opening time [ms]	5 -100

Experimental Setup and Procedure

The schematic diagram of the experimental setup is shown in Fig. 1. Both the air pressure and the fuel line systems were checked and maintained at 5 bar. The fuel line consisted of a syngas fuel cylinder, pressure regulators, fuel mass flow meter, and pressure gauges. Before conducting the experiments, the preliminary checks of the equipment were done and standard safety procedures for operating the engine were followed to ensure that the engine run safely. After that, the engine was warmed up until the cooling water temperature reached 60°C. As soon as the temperature was attained, the engine was operated at an ignition velocity of 0.3, injection position of -25 mm, and lambda value of 1.3 representing the optimum condition for the engine operation. The air supply system was comprised of an air compressor, air receiver tank, pressure gauge, pressure regulator, and electronic valves. The air delivery was electronically operated to control the timing of the air intake valves at both chambers. At the stated operating conditions, the engine was run; the in-cylinder pressure, electric current and linear piston displacement data were via their respective sensors measured and logged to the data acquisition system connected to it. Afterwards, the logged data were computed to analyze the rate of heat release (ROHR), mass fraction burned (MFB), and other related in-cylinder parameters.

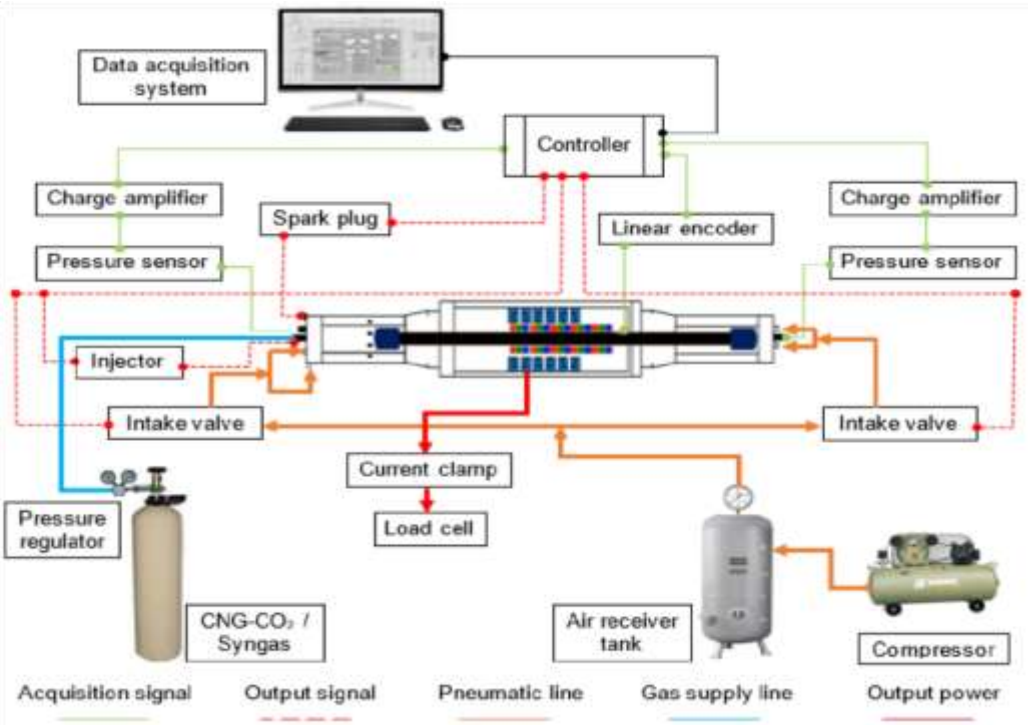

Fig. 1: The schematic of the experimental setup of the FPLG engine

RESULTS AND DISCUSSION

The experimental test was conducted on the SI DI FPLG engine fuelled with syngas at 5 bar operating pressure. After several attempts to get the engine running at different experimental conditions based on the experimental matrix, a continuous operation of the engine could not be achieved as the engine could only produce a single cycle operation at the stated engine operating condition (i.e., at ignition velocity of 0.3, injection position of -25 mm, and lambda value 1.3). So, having it combusted indicates an improvement as the fuel with this composition barely combusts even in a conventional engine. Nevertheless, the available data collected were processed and the results obtained are presented as follows.

Effect on the in-cylinder pressure

Fig. 2 presents the in-cylinder pressure curves for the FPLG engine powered using syngas and plotted as a function of the piston position. The gradual rise in pressure can be observed as the translator travels from BDC to TDC. During the compression process, fuel was injected, and the mixture of fuel and air is ignited and combusted to develop a peak pressure of 14.34 bar. After TDC, the translator continued to move downward rapidly as indicated by the sharp falling curve. This, however, was terminated when the in-cylinder pressure is below 5 bar. This is an indication that the two chambers have the same pressure, which of course could not sustain the engine operation further, thus causing the engine to stop. As the piston approaches BDC, the developed combustion pressure decreases continuously and becomes too low to overcome the bounce pressure talking less of the energy required to return the translator to TDC for the next operation. This finding suggests that the continuous engine operation of the FPLG engine cannot be sustained if the FPLG engine is powered with syngas fuel at 5 bar operating conditions. The low pressure achieved by the engine fuelled with syngas may not be unconnected with the fuel composition, low compression ratio, and probably mixing formation pressure as a function of time

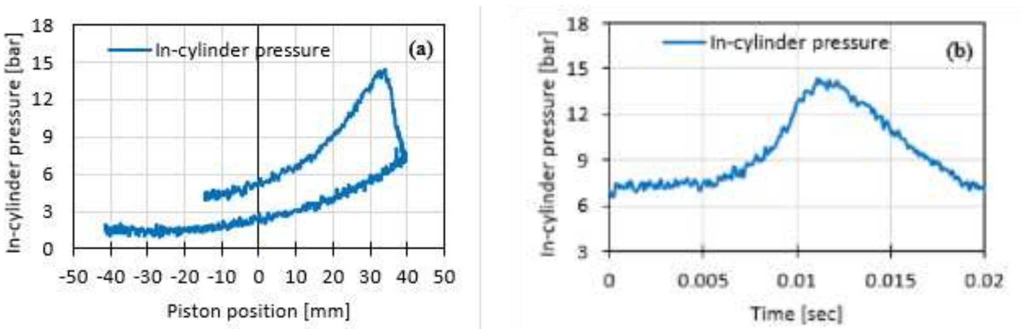

Fig. 2: Effect of syngas on FPLG performance: (a) in-cylinder pressure (b) in-cylinder

Effect on the rate of heat release (ROHR) and mass fraction burned (MFB)

A high rate of heat release can be attributed to high flame propagation and high fuel energy content. Fig. 3(a) offers the ROHR of the syngas fuel having plotted the curve of the graph at a moving average of 5. It clearly shows that the maximum ROHR obtained is 111.37 kJ/s indicating slow flame propagation speed which of course slower the combustion reaction and elongates the heat release duration. Having higher ROHR implies better combustion efficiency and vice versa. From Fig. 3(a), syngas displays a low ROHR that necessitates the low in-cylinder pressure and when compared with CNG-CO_2 (50-50%), the ROHR is 32.4% less thus indicating that the mixture composition (containing highly non-combustible gas in the charge) inhibits the combustion reaction and reduces the ROHR.

Fig. 3(b) shows the mass fraction burned curves for the syngas fuel. Obviously, the burning duration of syngas during the rapid combustion stage is 18.6 ms and longer than that of the CNG-CO_2 (50-50%) due to the fuel composition, lower flame propagation speed, reduced oxygen concentration, and reduced temperature and pressure during ignition initiation (Li et al., 2018). The reason for this is that when the engine runs with syngas, the flame propagation speed is inhibited by the non-combustible components of the charge thereby diminishing the flame front surface. The initial combustion duration demonstrates a longer ignition delay of 7.3 ms and of course resulted in the lower in-cylinder pressure obtained burned

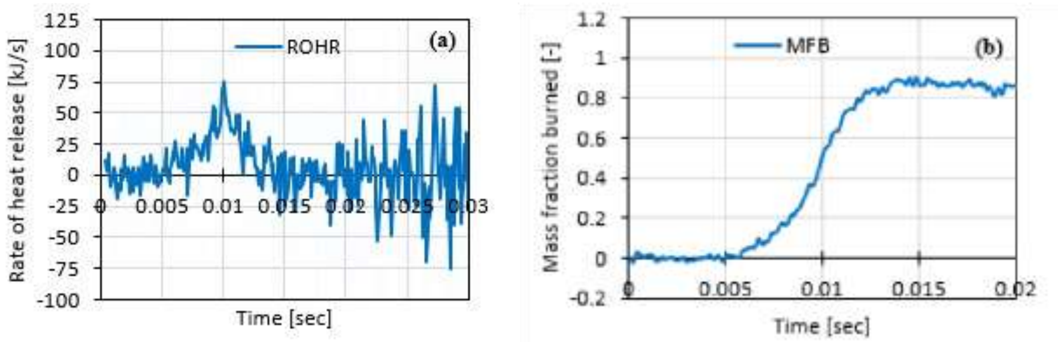

Fig. 3: Effect of syngas on FPLG performance: (a) rate of heat release and (b) mass fraction

Effect on the peak output power

The electrical power output of the FPLG engine as a function of the displacement is presented in Fig. 4(a) when the engine is fuelled using syngas. Fig. 4(b) illustrates the piston velocity profile of the engine as a function of the displacement. The curves in the graph were plotted at a moving average of 5. There seems to be a correlation between the power output and the piston velocity as the piston travels back and forth between TDC and BDC to produce electric power. The piston velocity is maximum during the expansion stroke when the gas pressure developed after combustion exerts pressure force on the piston as it translates to BDC. During this stroke, the translator attains a peak power output when the piston velocity reaches the maximum at the mid piston position. Similarly, during the compression stroke, the lower piston velocity is obtained to produce the lower peak output power. Apparently from the figure, the peak piston velocity of 3.75 m/s recorded by the translator when the engine is fuelled with syngas accordingly produces the peak output power of 518 .6 W generated during the expansion stroke and 236.73 W during the compression stroke when the peak piston velocity is 3.25 m/s. It is obvious that syngas has a lower energy content available to drive the translator to lower velocity and, in turn, generate lower output power.

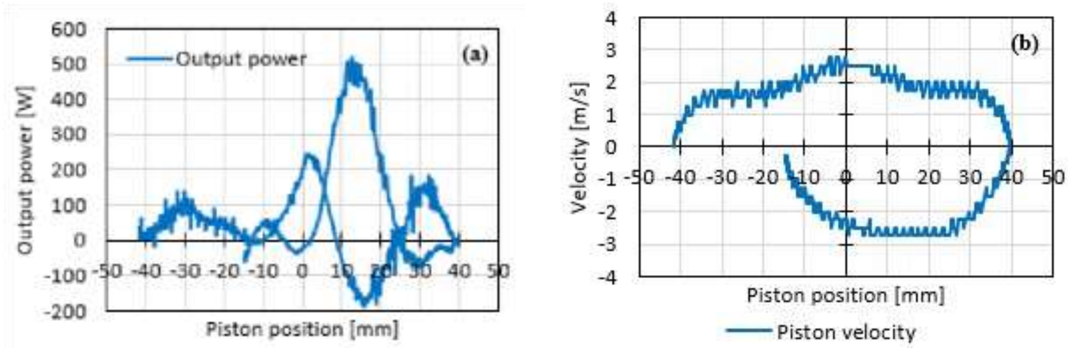

Fig. 4: Effect of syngas on FPLG performance: (a) output power and (b) piston velocity

Effect on the indicated mean effective pressure (IMEP)

To better understand the power produced by the engine per cycle, the indicated mean effective pressure (IMEP) was used and calculated. The fuel properties and the mixing quality significantly impact the in-cylinder pressure and subsequently the engine IMEP. After combustion of the charge (fuel and air), the in-cylinder pressure rose to build a peak pressure as shown in Fig. 2(a). Thereafter, the piston expanded sharply as it moves towards the BDC position owing to high in-cylinder pressure and velocity around the TDC and above all, lack of crankshaft. The burning of the mixture continues to release heat despite the decline in the in-cylinder pressure caused by the sudden expansion in the gas volume. The IMEP and the indicated work developed when the engine is powered using syngas are offered in Fig. 5, showing the pressure-volume (P-V) diagram. The indicated work done by the piston on the combusted gases was computed using the area bounded by the curve. For the syngas fuel under the stated condition, IMEP of 4.16 bar is realized to develop the indicated work of 104.47 kJ.

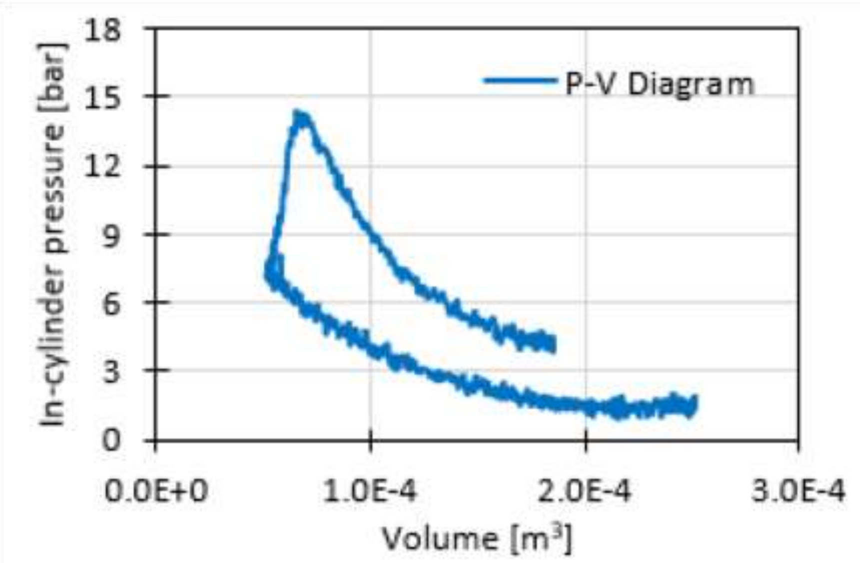

Fig. 5: Effect of syngas on FPLG performance: pressure-volume (p-v) diagram

Effect on the combustion and indicated thermal efficiencies

Combustion efficiency (CE) is used to measure the fraction of fuel an engine can convert to energy. It is expressed as the proportion of the heat released after combustion by the fuel to the input energy by the fuel. Because the system is still in its prototype stage, the CE for the syngas fuel is determined as 22.56% signifying low efficiency compared with conventional engines that utilized other types of syngas while the indicated thermal efficiency recorded is 10%. The leakage caused by the drop in the in-cylinder pressure, losses due to friction, cooling system and lubrication are the likely factors that contribute to the low efficiency recorded as well.

CONCLUSION

In this paper, the experimental results obtained from the performance of an FPLG engine prototype fuelled using syngas are presented. The study was conducted under a steady-state condition. The best engine operating performance (i.e., at ignition velocity of 0.3, injection position of -25 mm, and lambda value 1.3) was analyzed in detail. The findings of the experiment are summarized as follows:

- The lower rate of heat release affects the in-cylinder pressure developed owing to its low heating value and its attendant lower piston velocity that results in the slower translator's speed and in turn, generates lower output.
- At the optimal engine operating conditions, the peak power output and indicated work of the FPLG engine are calculated and found to be 104.47 kJ and 518.6 W. Similarly, it is found that the engine displays relatively low combustion and indicated thermal efficiencies of 22.% and 10%, respectively when compared to a conventional engine.

The findings in this paper are expected to offer directions on improving the performance characteristics of the FPLG engine. Besides, there is a possibility for further improvements, particularly in the in-cylinder pressure and the optimization of the engine control parameters. However, the next study will focus more on optimizing the operating parameters to achieve continuous cycles.

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