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PERFORMANCE CHARACTERISTICS OF A FREE PISTON LINEAR GENERATOR (FPLG)

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Abstract

Free-piston linear generator (FPLG) engine is a novel type of engine conversion device which can generate electrical energy. It exhibits advantages of simple structure, less friction, high thermal efficiency, and operational flexibilities. This paper presents the performance characteristics of a spark ignition (SI) direct injection (DI) FPLG engine fuelled using compressed natural gas. The engine was set to run at stoichiometric ratio, 42 mm BTDC injection position and 4 mm BTDC ignition position. The data collected were processed with a macro designed with Microsoft Excel for data processing. The results of the tests revealed that the combustion and mechanical efficiencies of the FPLG engine can attain 45% and 36% respectively with the peak power output of 547 W when the engine was operated at a frequency of 20.33 Hz and air intake pressure of 8 bar. 31.64 bar and 7.61 bar are the peak in-cylinder pressure and indicated mean effective pressure (IMEP) developed respectively for the bounce to attain a pressure of 14.08 bar. Though the electrical power output is low but with further study and improvement on the linear generator assembly, this technology could be used to achieve our energy sustainable goals.

[redacted]

KEYWORDS: *Characteristics, Generator, Performanc, Piston, Linear*

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INTRODUCTION

The massive energy needs particularly in the transportation sector are growing extremely fast as the number of vehicles increases and is expected to have increased in number by 48% by the end of year 2040 [1]. Fossil fuels are the major sources of energy which serve as fuel for transportation, power generation and other applications. However, the resultant emissions from its combustion are not only posing a serious threat to the very survival of life but also increasing the carbon dioxide emission level while its price continues to rise as its reservoirs deplete. As a result of this, exhaust emission standards are instituted to impose a limit on the level of emissions to be released by internal combustion engines, and by this, alternative fuels are sought as replacement to fossil fuel. Various techniques and technologies are being researched and developed to tackle these challenges. One of the alternatives currently being researched is free piston engine (FPE) and considered a promising power generation system due to its simplicity and potential to reduce cost, emissions and perhaps high thermal efficiency [2].

FPE concept was first proposed by Pescara as an alternative to conventional engine in 1928 [3]. However, with modern applications of the free piston concept, various useful outputs such as compressed air, hot gas, hydraulic energy and electrical energy, are being produced depending on the type of load device being coupled with FPE. With the configurations of the load device-FPE arrangement, the engine can function either as a free-piston air compressor, free-piston gas generator, hydraulic free-piston engine, and free-piston linear generator (FPLG) engine. For this research study, a FPLG engine is considered. This engine structurally, consists of two main components: a free-piston engine and a linear generator. The linear generator consists of permanent magnets and windings in which the permanent magnets are coupled either to the stator or rotor [4-6]. FPLG engine is a crankless internal combustion engine with no restriction of piston motion by crankshaft thereby making the piston 'free' to move. The engine is different from those of conventional crank engines as it can operate variable compression ratio that is considered a potentially valuable feature. It is capable of generating higher mechanical and thermal

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efficiencies when compared with an equivalent and more conventional reciprocating engines [6-8]. The few moving parts of the engine makes it compact with low maintenance costs and reduced frictional losses. The engine is well suited for homogenous charge combustion ignition (HCCI) operation [9] which improves thermal efficiency and reduces temperature dependent emissions such as NOx emission [7, 10].

Owing to varying piston strokes, the FPLG engine can achieve operational flexibility through variable compression ratios which therefore allows operation optimization for all operating conditions, and multi-fuel combustion. The variable fuel injection and valve timing together with variable compression ratio enable the FPLG engine to run satisfactorily on a wide range of fuels. These potential advantages make FPLG engine be considered as a promising alternative to conventional engines [4, 6, 9] and as a result provides wide areas of application for its use. Not only can it be used as a driving system for hybrid electric vehicles or electric vehicles, but also as an auxiliary power unit for electromechanical devices. FPLG engines have been investigated by several research groups using modelling, simulation, controlling strategy as well as experimental techniques. Jia et al. developed a spark-ignited free piston engine using a numerical modeling that was validated with test results. Based on this model, the starting process and the combustion process with different throttle openings were simulated. The simulation results show good agreement with the prototype test data. The efficiency of the prototype was estimated to be 31.5% with an output power of 4 kW [2].

A 2-stroke spark ignition free-piston engine linear generator (FPLG) with engine bore of 36.5 mm and maximum stroke of 50 mm was developed at West Virginia University. With simulation models, the effect of total heat input, combustion duration, reciprocating mass and the load were studied on the operation of the linear generator. The results obtained showed significant cyclic variation in the peak in-cylinder gas pressure, the engine operation speed and the compression ratio. However with the prototype system, the output power can be increased to meet the need of hybrid vehicle propulsion [11]. The effect of operating conditions on the generated power output using a dual piston, flat-type linear generator configuration was investigated. The engine operated two

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modes – motoring and firing modes. The results of the research study showed that the maximum generating power obtained was 111.3 W when the experimental conditions set for the air gap length, electrical resistance, equivalence ratio and spark timing delay are 1.0 mm, 30 ohms, 1.0 and 1.5 ms respectively. The previous simulation study carried out under the same condition was corroborated by the experimental results obtained [5]. Sandia National Laboratory also designed a dual piston FPLG engine that can generate 30 kW power for applications such as hybrid vehicles and portable generators. The engine employed homogenous charge compression ignition (HCCI) mode of combustion while using a variety of hydrogen containing fuels. The results of the experiment indicate that the cycle thermal efficiency was improved up to 56% owing to nearly constant volume combustion at high compression ratio. The NOx emissions level was low compared with the conventional internal combustion engines [11]. A zero-dimensional model was used to simulate the operation of the FPLG, heat transfer, and frictional forces using basic empirical formulas. The earlier models developed were later built upon with more detailed thermodynamic models to compare the emission performance and efficiency of the engine based on each parameter [12].

Nanjing University of Science and Technology proposed a gasoline and spark ignition virtual opposed piston free piston linear generator prototype, modelled and, simulated to deliver 15kW average output with generating efficiency of 42.5%. The FPLG engine was coupled with a mechanical spring that served as energy storage in the power stroke and bounce for the piston in the compression stroke. The engine was designed to use natural gas as fuel of the system [13].

The German Aerospace Center (DLR) developed a compact FPLG electricity generation unit for applications such as range extender units for electric vehicles as means to provide additional electric energy to electric vehicles in case of discharged batteries, and as auxiliary power unit in both aircrafts and decentralized combined heat and power plants (CHP) [14]. The FPLG system was designed to contain two gas springs and a linear generator. The control strategies employed particularly for piston motion control motion and the controller developed were calculated to ensure stable operation of the system. In 2013, a complete autarkic FPLG system was taken into operation. Based on the experimental and simulation results, it was concluded that precise control of ignition timing is essential for the stable operation of the FPLG [15].

A team of researchers at Toyota Central R & D Labs Inc. developed a two-stroke gas spring rebounded single-cylinder FPLG prototype with a special designed structure that prevents heating of the magnets thereby allows long duration of operation of the engine [16, 17]. They studied the effect of the operating characteristics and controlling strategies [18]. The piston and the cylinder head of the engine form a combustion chamber that includes an exhaust valve, ignition plug, and fuel injector. The piston of the engine basically moves freely following the principle of simple harmonic oscillation governed by the piston mass and the air spring pressure during the remainder of the piston stroke. The linear generator also worked as a linear motor during motoring and used the electricity from battery. The effect of the electric load and the ignition timing on the engine compression ratio, based on the experimental and simulation results were presented. Both premixed charge combustion ignition (PCCI) and spark ignition modes of combustion were applied to the prototype. The results obtained such as output power, indicated thermal efficiency, and compression ratio were compared. The PCCI combustion mode was reported to have achieved 10.4 kW and 36.2% for output power and thermal efficiency respectively [16].

In view of the advantages of the free piston linear generator engine and the challenges of increasing energy demand vis-à-vis environmental pollution, the FPE technology is recently being applied for the development of a novel energy converter that harnesses energy in fuels. However, to satisfy our energy demands and to pursue the energy sustainability goal, the most available and abundant alternative fuels are seen in this light as possible candidates to consider for utilization rather than being left untapped. Natural gas being a cleaner gas with less emission when combusted is therefore used to conduct the experimental test. This research work therefore studies the performance characteristics of a direct injection FPLG engine fueled using compressed natural gas (CNG) fuel.

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Experimental Procedure

Description of FPLG engine

A spark ignition direct injection single cylinder FPLG (GX-5) engine is designed and developed using locally available resources and materials for both the components and control. It consists mainly of three subsystems which includes a free piston engine, a tubular linear generator, and gas spring. The FPE consists of a piston rod (shaft) and two pistons connected to each end of the shaft using floating joints as shown in figure 1. The pistons are then enclosed inside cylinder liners. One end of the cylinders serves as the combustion chamber to extract the energy from liquid or gaseous fuel that powers the piston; while the other end known as bounce, serves to create an adjustable gas spring. The gas spring rate of the bounce chamber is regulated by air mass in the cylinder. Positioned between the two cylinders is a tubular linear generator, which consists of a translator and a stator. Mounted on the translator shaft are series of bonded permanent magnets, while the stator housed the wound coils which are connected to a full-wave rectifier bridge.

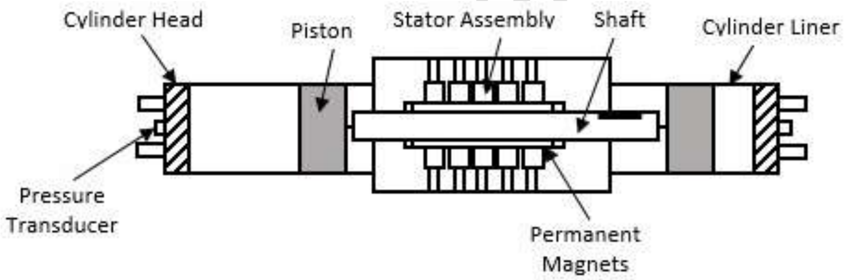

Figure 14. Structure of a free-piston linear generator engine

The detail specifications of the FPLG engine is shown in table 1. Linear encoder and magnetic strip were used to electronically measure and control the position of the translator as it moves forth and back, and to send signals to the controller. The electromagnetic valves are used to regulate fluid flow direction, flowrate. speed, and other fluid parameters. A Kistler piezoelectric pressure transducer together with a charge amplifier are used to measure the in-cylinder pressure during the expansion process, and also to provide the controller with the needed signal. Based on these signal inputs, the NI controller was able to manage and control the operation of the FPLG engine. The parameters like

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pressure, displacement, the output current and other signal outputs are logged using a National Instruments (NI) data acquisition system.

Table 3. Engine specification parameters of the FPLG engine

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)	8
Operating frequency (Hz)	10
Moving mass (kg)	7

Working Principle

Since the FPLG engine cannot be cranked over several revolutions just like conventional engines, it is essential that the FPLG engine starts its first stroke using compressed air as an aid, and thereafter keeps running with the aid of the engine control system. The working principle of the FPLG engine is similar to the two-stroke engine having intake-compression stroke (compression process) and power-expansion stroke (expansion process). Figures 2 and 3 show the prototype of the FPLG engine and the working operation of the engine with respect to the installed electromagnetic valves. B_1, B_2, C_1, and C_2 consist of 2nos. of electromagnetic valves each and are connected in parallel to each other as shown in figure 3. The operation of the FPLG begins with the electromagnetic valves B_1 and B_2 in close position while electromagnetic valves C_1 and C_2 are open to allow intake of compressed air to the combustion chamber via port PC_1 and PC_2. The duration of opening and the sequence of operation are controlled by the program written on the field programmable gate array (FPGA) module. With this process, the translator is pushed from TDC to BDC by the high-pressure air while the exhaust air at B_1 and B_2 flow through the exhaust port of the electromagnetic valves as the translator approaches BDC. After t_1 seconds, the electromagnetic valves at C_1 and C_2 are closed according to the program. On getting to BDC, the valves B_1 and B_2 are then opened to inject compressed air at 8 bar via the ports PB_1 and PB_2. At this pressure, the translator is pushed for a duration of t_2 seconds. After this duration, the translator's momentum takes over to move the translator further and to compress the working fluid. Prior to ignition, the electromagnetic valve controlling the fuel opens and closes for a short duration of t_3 seconds. From BDC point to this point defines the compression process.

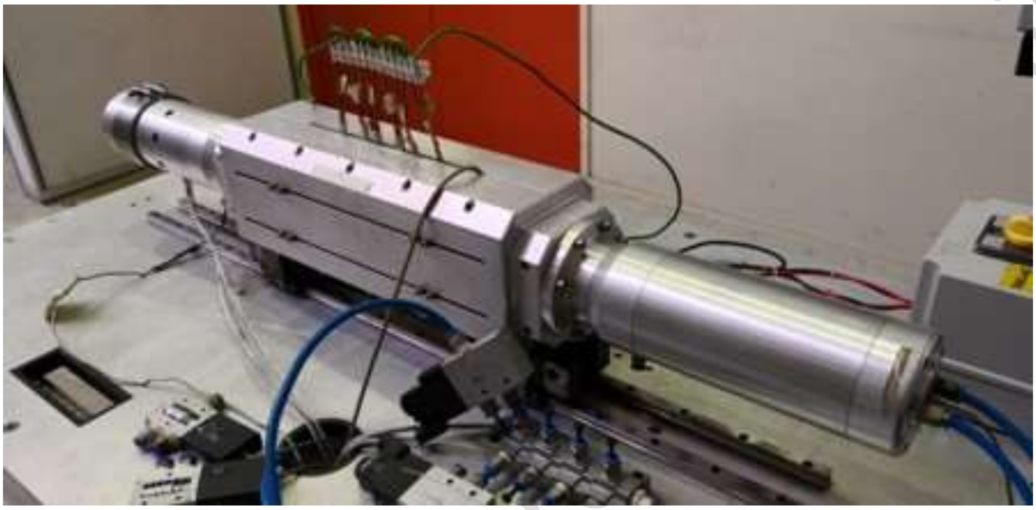

Figure 15. FPLG engine prototype

After this process, ignition occurred, and combustion is accomplished. The in-cylinder peak pressure is reached, and the high-pressure gas then expands freely until it reaches the exhaust port position as it moves down to BDC. From the ignition point to this point defines the expansion process. During this process, no mass transfer occurs, but the in-cylinder pressure continues to decrease as the translator travels down towards exhaust port position and to BDC. While the expansion continues, the data acquisition control system sends a control command which enables the opening of the electromagnetic valves C_1 and C_2 few millimeters prior to exhaust port position for purging of burnt gases out of the cylinder and intake of fresh charge. While it continues, the electromagnetic valves B_1 and B_2 remain closed. The pressure of the air mass trapped at the bounce cylinder increases and then becomes gas spring with which the translator returns to TDC for the next compression cycle and equally serves to prevent the piston from colliding with the cylinder head. The reciprocating motion of the translator forth and back cuts the magnetic flux to generate electrical energy. In other word, the translator assembly movement converts its kinetic energy into electricity that is consumed by an external load (resistor).

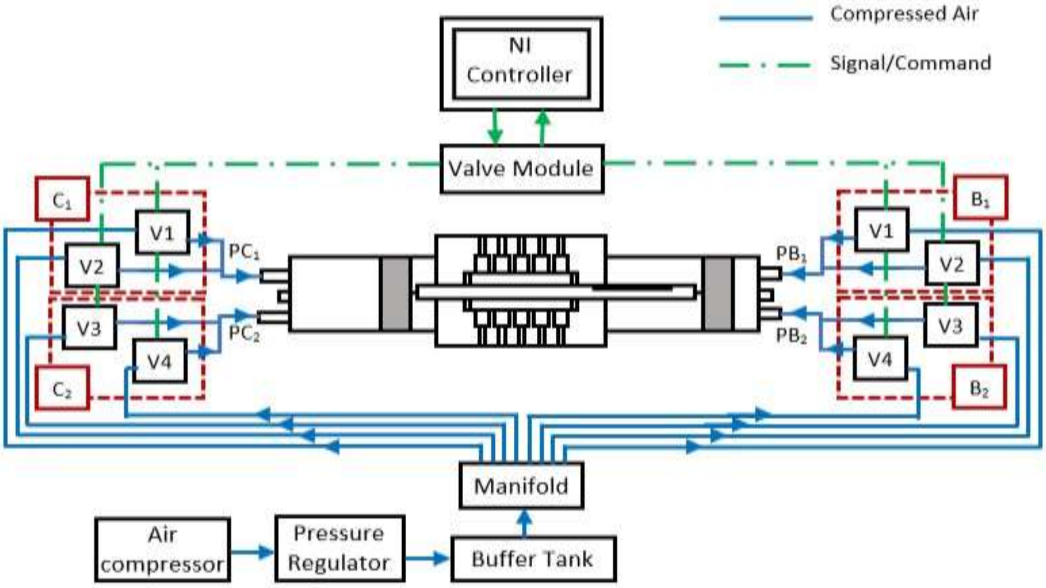

Figure 16. Working Process of the FPLG Engine

Experimental Procedure

The experimental test was carried out on a proposed spark-ignition direct-injection two stroke FPLG research engine. The schematic diagram of the experimental setup is shown in figure 4 while table 2 lists the experimental conditions used in conducting the experiment. Compressed air at 8 bar was injected into the bounce chamber via the valves to compress the mixture of air and fuel in the cylinder. CNG fuel was injected into the engine cylinder via a check valve and electromagnetic valve arrangement. Based on the ignition position set, the mixture of air and fuel was ignited for combustion to occur. The combusted gases expanded and pushed the translator to BDC. A Data Acquisition System designed using National Instruments was used to log in data. The fuel gas supply line system consists of CNG fuel cylinder, pressure regulators, fuel mass flow meter and check valves-festo valve arrangement (a form of an injector). On the fuel line, a two-stage pressure regulator was used to maintain the downstream pressure constant. The in-cylinder pressure and linear displacement data were collected via sensors connected to the data acquisition system. The in-cylinder pressure was measured using a Kistler piezoelectric pressure transducer connected to a Kistler charge amplifier while the linear displacement reading was collected using a linear displacement magnet encoder.

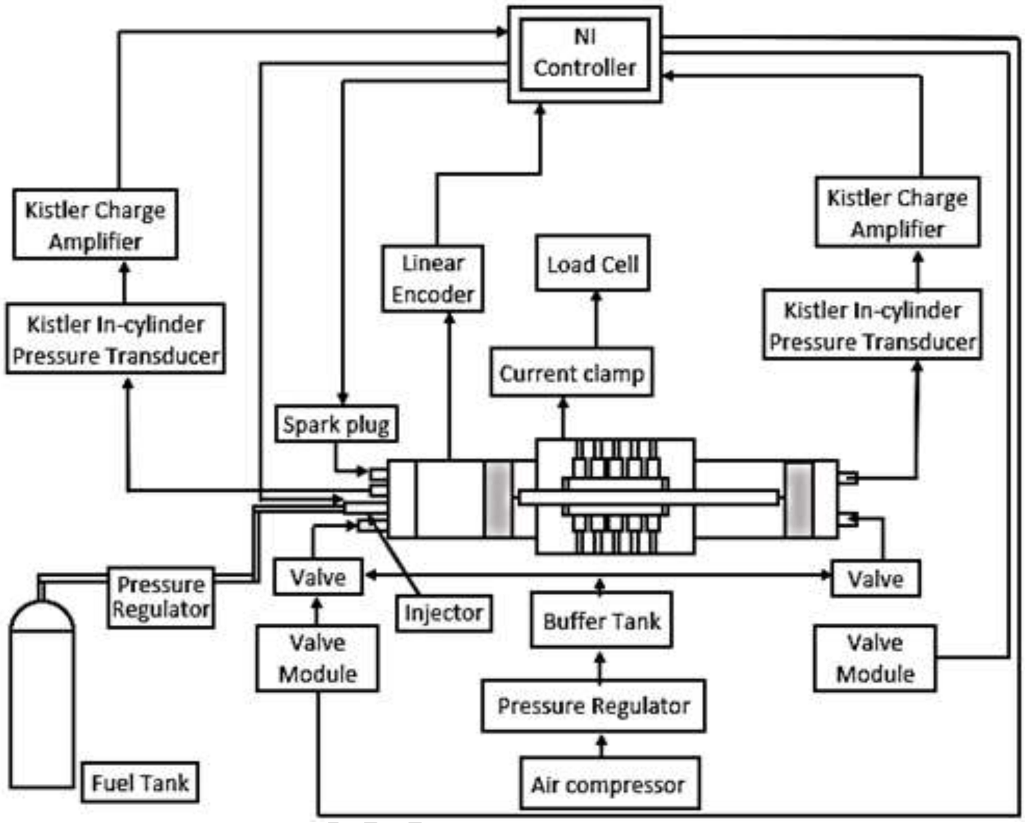

Figure 17: Schematic diagram of a FPLG engine

Table 4. Engine Experimental Conditions

Experimental conditions	Value
Air intake pressure (bar)	8
Equivalent ratio, ER	1.0
Injection position (mm)	42 mm BTDC
Ignition position (mm)	4 mm BTDC

Experimental Results and Discussions

In-Cylinder Pressure and Rate of Pressure Rise

The results of the performance characteristics of a SI DI FPLG engine fueled with CNG is presented and discussed below. The result is the representative average of the continuous combustion cycles. Figure 5

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shows the curve of the in-cylinder gas pressure as a function of time. As the compression process began, so the in-cylinder pressure started to rise gradually and continued till it reached the point where fuel was injected. In the premixed combustion stage of combustion processes, the fuel mixed with air during the ignition delay period of 6 ms to form a combustible mixture. The mixture was combusted and developed a peak pressure of 31.64 bar. After TDC, the piston continued to move downward rapidly as depicted in the graph by the sharp falling or rapid velocity of the translator. Even though the mixture continued to burn and release heat, the in-cylinder pressure declined sharply owing to the rapid increase in the gas volume.

Most of the released heat in this stage come from the mixture of fuel and air mixed by the induced gas motion resulting from the high velocity of the piston motion around TDC. This engine has an operational frequency of 20.33 Hz, which translates to 1220 cpm equivalent speed. At this speed, fast velocity and acceleration of the piston of the free piston engine induced high level of gas motion which assisted in mixing the mixture of fuel and air to completion. Moreover, the heat release rate increased rapidly at this stage as indicated in figure 6, and thus resulting to the fast expansion of the cylinder volume. However, the peak in-cylinder pressure was observed to occur later after TDC as shown in figure 5.

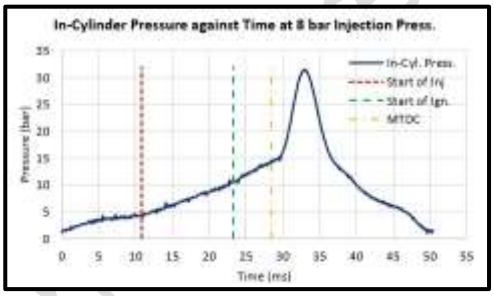

Figure 18. In-Cylinder Pressure

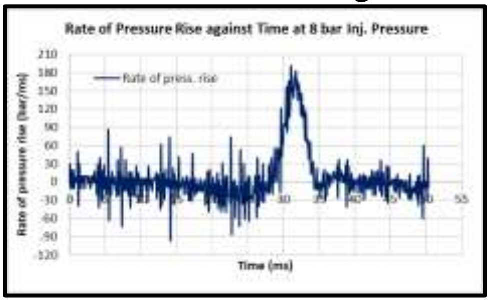

Figure 19. Rate of Pressure Rise

Bounce Chamber Pressure

The success of a continuous combustion of an FPLG engine depends on the combustion gases interaction on one side and the air bounce on the other side. Technically, there is an interplay between the in-cylinder pressure and the bounce chamber pressure. To understand this relationship, figure 7 representing the graph of the in-cylinder pressure and the bounce chamber pressure explain this. During the compression process, the bounce chamber pressure can be observed to decline quickly and later slowly due to the sudden expansion of the gas volume. Meanwhile, the in-cylinder pressure gradually increased until it reached TDC with the peak pressure achieved during the expansion process as clearly represented in the graph. After the TDC, the bounce chamber pressure was noticed to rapidly increase and later slowly as the translator moves towards the BDC where 14.08 bar peak pressure was attained. From the graph, it can be noted that the compression process started with peak bounce pressure of 18.34 bar and ended with 14.08 bar. The variation in the bounce chamber pressure may be caused by a lot of factors but not limited to piston stroke variation.

Figure 20. In-cylinder pressure and bounce chamber pressure

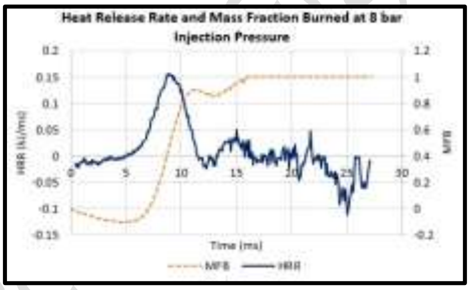

Figure 21. Heat release rate and mass fraction burned

1.1. Combustion Heat Released Process and Mass Fraction Burned

The heat release rate (HRR) and mass fraction burned (MFB) curves at 8 bar injection pressure is shown in figure 8. The heat released rate curve can be observed to have its peak of heat release occurred after combustion and during the expansion. A possible explanation for this behaviour is due to the late ignition of the mixture. After attaining the peak value, while the gas volume continued to increase, there was a rapid fall in the in-cylinder pressure and temperature thus leading to a rapid drop in the rate of heat release. 189.59 kJ/ms was the peak heat release rate recorded. Meanwhile from the curve of mass fraction burned (MFB), it is clearly shown that after a slight delay, 80% of the heat release was released to achieve the peak heat release. The duration of the heat release is however shortened due to the rapid piston motion around the TDC.

Power (rms), Peak Power and Speed

After combustion, 7.61 bar of indicated mean effective pressure (IMEP) was developed by the engine at the set engine operating conditions. The IMEP produced is then transformed to generate electrical power via the generator. At 20.33 Hz operational frequency of the engine, which is equivalent to 1220 cycle per minute (cpm) speed as presented in figure 9, the free piston engine was able to generate peak power of 547 W. For this engine, the power generation occurs during both the compression and expansion as the translator moves forth and back. During these stages, the peak power occurred at mid position of the stroke when piston velocity was at its peak. 547 W peak power was generated during expansion, while 188 W was the peak power produced during compression. The variation in the piston velocities around TDC and BDC have therefore resulted to the two peak powers produced with a higher peak power occurring during expansion owing to the higher velocity around TDC after combustion. At the same time, the root mean square power, $P_{(rms)}$ (also referred to as the average power) generated by the engine is 81 W. Obviously when this value is compared to the IMEP value produced, it is quite low. In as much as more power is expected to be generated at the speed attained by the engine, the materials used in the assembly of the linear generator could be responsible for the low average power output. Owing the novel of the FPLG engine, different materials and tests are being carried out to determine the best materials for optimum engine performance. However, for this test, an acrylic material is used as a component of the linear generator assembly, and therefore has resulted to low electrical power output. However, with the use of ferromagnetic materials, the average power output stands to improve.

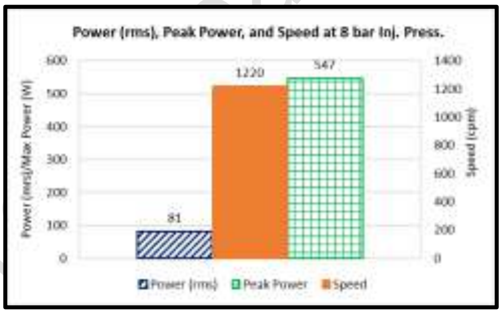

Figure 22. Peak power, power (rms) and speed

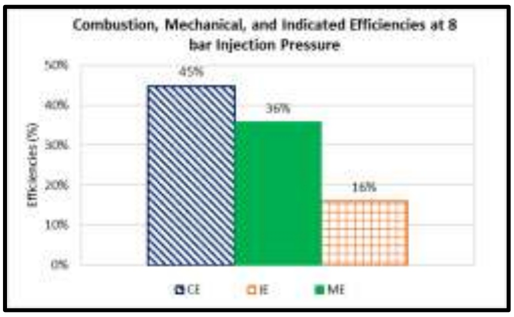

Figure 23. Combustion, mechanical and indicated efficiencies

Combustion, Mechanical, and Indicated Efficiencies

The combustion, mechanical and indicated efficiencies are the parameters used to measure the ability of an engine to convert the fuel energy into mechanical power output. The fuel conversion efficiencies to mechanical outputs is shown in figure 10. For a FPLE engine, combustion efficiency (CE) is the ratio of the heat released by the fuel to the heat input by the fuel. CE is affected by the types of fuel, equivalence ratio, combustion cycle duration etc. The faster the burning duration, the less the efficiency produced. Mechanical efficiency (ME) on the other hand is a measure of the ability of the engine to transfer the heat released to useful work. However, the ratio of the useful work to the input heat by the fuel is known as indicated efficiency (IE). Obviously from figure 10, the CE and ME are 45% and 36% respectively, while the IE is 19%.

Conclusion and Recommendations

The performance characteristics of a direct injection FPLG engine fuelled with compressed natural gas was studied. The experiment was conducted at stoichiometric ratio, 8 bar air intake pressure and 7 mm BTDC ignition position. The findings of the experiment can be summarised as follows:

1. The peak in-cylinder pressure and the peak power generated were 31.64 bar and 188 W respectively.
2. The bounce pressure attained at the bounce side of the engine is 14.08 bar, which was the air spring pressure for the subsequent cycle.
3. The fuel conversion efficiencies with respect to combustion, and mechanical for FPLG engine are 45% and 36% respectively, while indicated efficiency is 19%.

The possibility for further improvements particularly in the output power generated still exists since the stator core used in conducting the tests are made of Perspex as against metallic core. However, for further study, a design, simulation, and experimental tests will be carried out on the GU unit to improve the average power output, and equally to explore other gases for improved engine performance.

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