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EFFECTS OF INJECTION POSITION ON THE PERFORMANCE OF A FREE PISTON LINEAR GENERATOR POWERED WITH LOW-GRADE FUEL

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Abstract

A free-piston linear generator (FPLG) is an energy conversion device that can generate electrical energy using different types of fuel. This paper focused on the performance and combustion characteristics of a direct injection spark ignition FPLG fuelled with a mixture of compressed natural gas and carbon dioxide ($CNGCO_2$). An experimental test was conducted under a steady state condition on the engine prototype to study the engine performance at various injection positions (-20, -15, -10, -5, 0 mm) while the ignition velocity and lambda were fixed at 0.6 m/s and 0.6, respectively. Experimental results from the tests reveal that the engine performance and combustion are improved when the injection position is set to -10 mm. Based on this condition, the engine shows a fast combustion reaction when fuelled with the mixture and attains the peak ROHR of 164.83 kJ/s that resulted to the rapid expansion of the gas after combustion. At a high engine speed and operating frequency, the peak power output generated is 1316.1 W as the translator cut the magnetic flux.

KEYWORDS: *free-piston engine, CNG-CO_2, compressed natural gas, linear generator, engine performance.*

Introduction

The increasing energy needs particularly in the transportation sector has necessitated the high demand place on the fossil fuels. Undoubtedly, fossil fuel is a main source of energy for transportation, power generation, and

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other applications [1], [2]. However, the fossil fuel combustion releases emissions that deteriorate environment and become a great concern to deal with [3]. Other concerns are increasing fossil fuel price, reservoir depletion, and stringent emission standards. With the development of advanced technologies, alternative fuels such as natural gas, biogas, syngas etc., are sought as a replacement for fossil fuel [4], [5]. Recently, various technologies are being researched and developed to tackle these challenges including fuel cells, micro-gas turbine, Otto/Wankel system, and free-piston engine (FPE). FPE is a new device that has received a lot of attentions of researchers all over the world because of its unique features of simplicity, potential to reduce cost, high power density, and perhaps high thermal efficiency [6], [7]. FPE is a 'crankless' internal combustion engine with no restriction of piston motion by crankshaft thereby making the piston 'free' to move. Different load device such as air compressor, linear generator, etc. can be coupled to an FPE to become a free-piston linear generator (FPLG) in the case of a linear generator [8]. 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 efficiencies when compared with equivalent and more conventional reciprocating engines [9], [10]. 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 [8] which improves thermal efficiency and reduces temperature-dependent emissions such as NOx emission [11], [12].

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 the variable compression ratio enables the FPLG engine to run satisfactorily on a wide range of fuels. These potential advantages make the FPLG engine be considered as a promising alternative to conventional engines [9], [13] and as a result, its use for power generation and other applications has been explored as reported in the literature in many ways ranging from small to large scale systems [14]–[16]. In spite of 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 [9], [17]. Still, FPLG engines have been investigated by several research groups using modelling, simulation, controlling strategy as well as experimental techniques. Jia et al. developed a sparkignited

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 [18]. Ahmed and Lim evaluated the performance and exhaust emissions of a two-stroke dual-piston FPLG using artificial neural networks (ANNs) to predict the best engine operating condition. The experiment was conducted using propane as fuel at various equivalence ratio ranging from the lean to the rich mixture to validate the model developed. The results show strong agreement between the predicted and experimental values. At an equivalent ratio of 0.7, the maximum thermal efficiency and power generated were recorded as 26.63% and 118.8 W respectively. While a maximum IMEP value of 4.39 was obtained at stoichiometric. The likelihood of exhaust gas temperature and exhaust emissions to increase with increasing equivalence ratio was also reported [19].

It is obvious that many researchers have dedicated lots of time to study FPLG engines using both simulation and experimental methods. Reports from published works indicate that more work 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 achieve stable engine operation and high efficiency. Besides, the available experimental data are limited to validate numerous simulation models whose results proved high efficiency and power output. Hence, the need for more experimental study to be conducted. Moreover, as a way of harnessing low-grade fuel for possible utilization, a mixture of compressed natural gas and carbon dioxide (CNG-CO_2) is used in this study as a way of simulating the abandoned natural gas fields with high CO_2 content. To this end, the performance characteristics of an FPLG fuelled with CNG-CO_2 was, therefore, investigated under variable injection positions.

EXPERIMENTAL PROCEDURE

Description of FPLG Engine

A spark ignition direct injection FPLG engine is designed and assembled with three main parts including a freepiston engine, a tubular linear generator, and a gas-spring chamber. The components of the FPLG engine are the translator shaft, pistons, stator assembly, permanent magnet, and liners. The engine has two pistons enclosed by the cylinder liners and coupled to the end of the translator

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shaft. The cylinders of the engine are 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. While the bounce creates a gas spring that provides the compression work to sustain a combustion cycle. Its cylinder head is equipped with a pressure sensor to monitor the bounce cylinder pressure. The tubular linear generator is positioned between the two cylinders and consists of permanent magnets, stator iron core, coils, and partition plates. On the translator shaft, series of bonded permanent magnets are mounted on it while the stator is designed to house the coils, which are coupled to external loads. The detailed specifications of the FPLG engine are shown in Table 1.

Table 1: Engine specification parameters of the FPLG

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**

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 fluid flow direction, flow-rate, speed, and other fluid parameters are regulated using valves. A Kistler piezoelectric pressure transducer together with a charge amplifier was 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 pressure, displacement, the output current to mention but a few are logged using a National Instruments (NI) data acquisition system via their various sensor.

Experimental Setup and Procedure

The schematic diagram of the experimental setup is shown in Fig. 1. Prior to conducting the experiments, the preliminary checks of the equipment were done and standard safety procedures of operating the engine were followed to ensure that no fault arises during operation. Both the air pressure and the fuel line system consisting of a CNG-CO_2 fuel cylinder, pressure regulators, fuel mass flow meter, and pressure gauges, were checked and kept constant at 5 bar. Afterward 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 different conditions by varying the engine injection positions. On the fuel line, a two-stage pressure regulator was used to keep the downstream pressure constant. Compressed air at 5 bar was injected into the bounce chamber via the valves. The fuel (CNG-CO_2) was injected into the engine cylinder at a 5-bar. Based on the ignition velocity set at 0.6 m/s while the lambda is kept at 0.6, the mixture of air and fuel was ignited for combustion to occur. The in-cylinder pressure and linear displacement data were collected via sensors connected to the data acquisition system and afterwards analyzed.

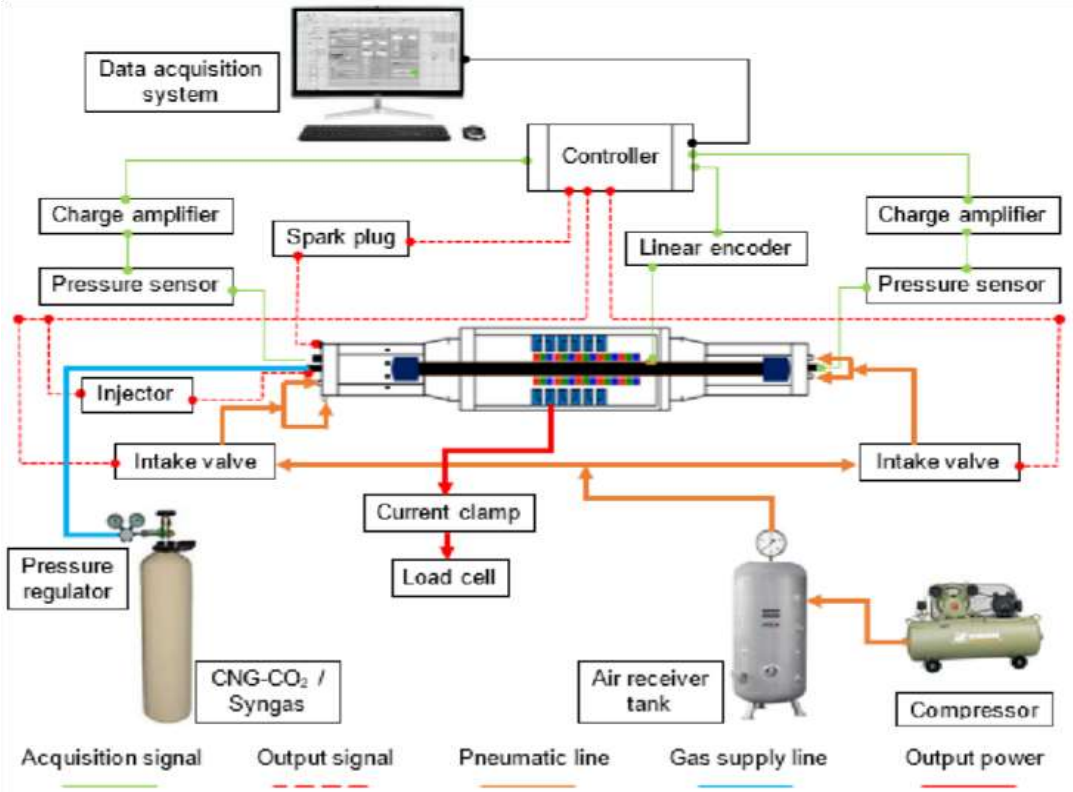


Fig. 1: The schematic of the experimental setup of the FPLG engine

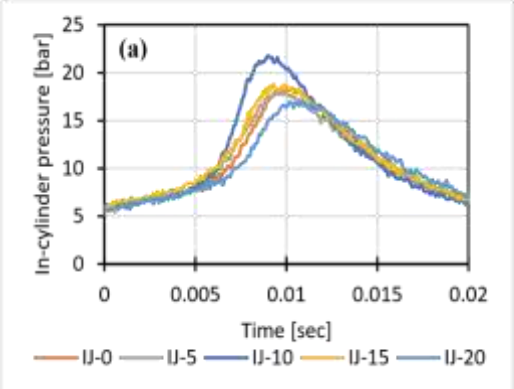
RESULTS AND DISCUSSION

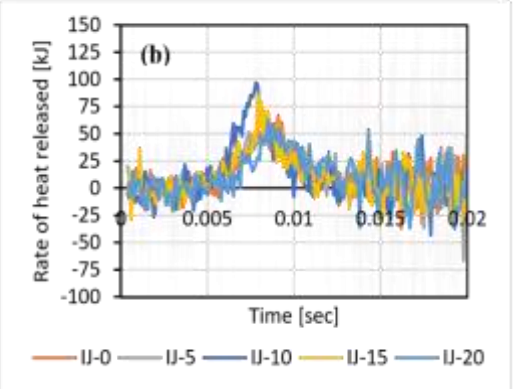
The results of the performance characteristics of a DI SI FPLG powered by a mixture of compressed natural gas and carbon dioxide (CNG-CO_2) at 50-50% proportion by volume are presented in the following sections. The test was conducted at various injection positions ranging from -20 mm to 0 mm at interval of 5 mm while the ignition velocity and lambda value were kept constant at 0.6 m/s and 0.6, respectively.

Effect on the in-cylinder pressure

The effect of CNG-CO_2 mixture and injection position variation on the in-cylinder pressure of the FPLG engine is shown in Fig. 2(a). It is worthy of note that the ignition velocity used in running the tests is an optimized ignition velocity of 0.6 m/s while other parameters are varied. It should also be noted that 0 mm position stands for the middle of the stroke. Later in the section, the terminology 'retarded' injection position is used when the injection starts near to TDC. Equally, the 'advanced' injection position indicates when the injection starts rather earlier before the TDC. As presented in Fig. 5, advancing of the injection position from 0 mm to -10 mm increases the in-cylinder peak pressure from 17.05 bar to 21.78 bar. However, when the injection position is further advanced to -15 mm and -20 mm, the in-cylinder peak pressure decreases by 17.7% and 16%, respectively. This shows that the flame propagation continues to improve as injection position is advanced from 0 mm up to -10 mm and later reduces with further advanced injection position thus, suggesting -10 mm as the injection position where the peak pressure is maximum. From the figure, the maximum peak pressure occurred 0.009 sec (9 ms) after the start of ignition and found to be the shortest duration compared to other peak pressures at other injection positions [see Fig. 3(a)]. The reason for this is because the air-fuel mixture uniformity at the -10 mm injection position results in the faster flame

propagation speed that produced the highest in-cylinder pressure.





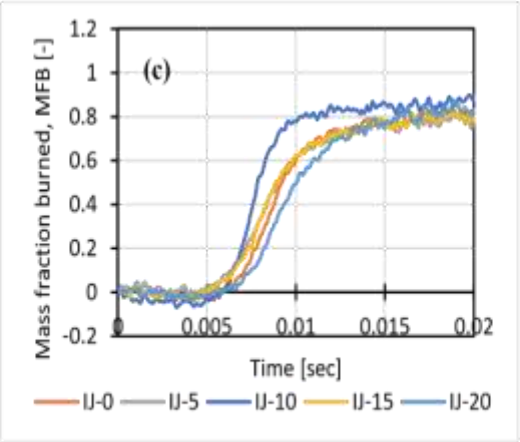


Fig. 2: Effect of injection position variation on (a) in-cylinder pressure (b) rate of heat release (c) mass fraction Burned

Effects on the rate of heat release

To better understand the process of combustion, the rate of heat release (ROHR) profile is used for the analysis. Higher ROHR is an indication of better combustion efficiency and higher generation of nitrogen oxides (NOx) emission. Similarly, lower ROHR implies a poor combustion process and longer burning duration. Fig. 2(b) illustrates the ROHR profile of the engine when fuelled with CNG-CO_2 at different injection positions. Following the same trend as the in-cylinder pressure, when the injection position is advanced from 0 mm to -10mm, the ROHR increases and then decreases as the injection position is further advanced to -15, and -20 mm. Their peak ROHRs for the injection positions 0, -5, -10, -15, and -20 mm occurred at 5.5, 8.9, 7.8, 7.9, and 8.5 ms after ignition, respectively. The highest peak of the ROHR is 164.83 kJ/s and found at -10 mm injection position while ROHR at 0 and -20 mm injection positions are 39.5% and 57.7% lower, respectively. This shows that -10 mm injection position enhances the combustion reaction that results in the faster combustion speed and shorter combustion time. The ROHR values recorded at -15 and -20 mm suggest that the injection positions are too advanced while 0 and -5 mm are considered late for a better combustion process to take place. From the figure, -10 mm injection position exhibits the highest ROHR that warrants the highest in-cylinder pressure recorded (see Fig. 2(a)) compared to other injection positions. So, this high pressure recorded, in turn, occasioned the faster expansion of the gas volume as demonstrated by the steeply pressure curve (see Fig. 2(a)) and the attendant quick drop in the ROHR, in-cylinder pressure and combustion temperature.

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Effects on the mass fraction burned

Mass fraction burned (MFB) is another parameter considered when analyzing the combustion process and it considerably affects the total combustion efficiency. For the various injection positions used for this study, Fig. 2(c) displays the mass fraction burned as a function of time. At the -10 mm injection position, the burning duration is the shortest compared to other injection positions and calculated as 13 ms during the rapid combustion period as illustrated in Fig. 3(a). For the 0, -5, -15-, and -20-mm injection positions, the elongation of their burning duration compared to the duration at -10 mm injection position is calculated to be 26.9%, 49.2%, 59.2%, and 60%, respectively. This shows that the mixture uniformity enhances and enlarges the flame front surface so causing the flame propagation speed to be fast and burning duration to reduce. From Figure 3(a), the initial combustion stage (ignition delay) for CNG-CO_2 at all the injection positions is computed and found to be almost the same, indicating that the delay in the start of combustion is not influenced by compression ratio even though the slight difference may be due to other factors such as residual concentration, reduced temperature and pressure during ignition initiation, and reduced oxygen concentration. Similarly, the final stage of the combustion process for all the injection positions appears to be shorter than the rapid combustion stage The reason for this is because the low energy content of the fuel inhibits the flame propagation speed thereby causing the low ROHR that extends into the expansion stroke as demonstrated in Fig. 2(c). According to the results obtained in Fig. 2, the variation of injection positions evidently proves to positive effect on the engine performance and moreover, shows that -10 mm is the optimal position to improve the combustion reaction, ROHR, in- cylinder pressure, while shortening the combustion time.

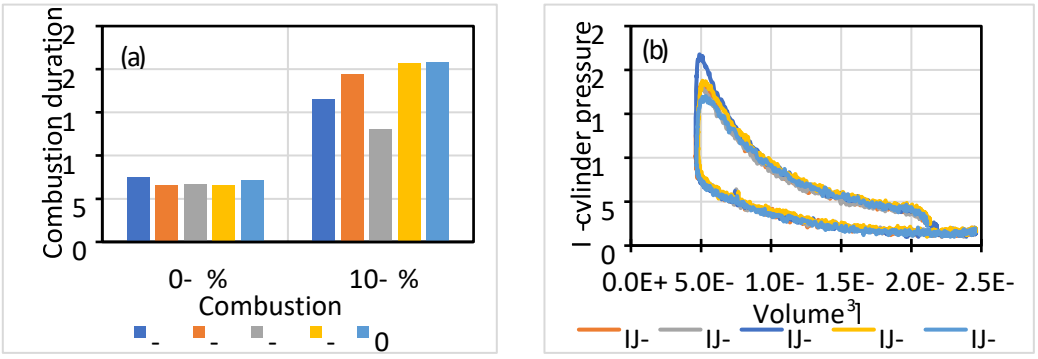

Fig.3: Effect of injection position variation on (a) duration of combustion and (b) PV diagrams

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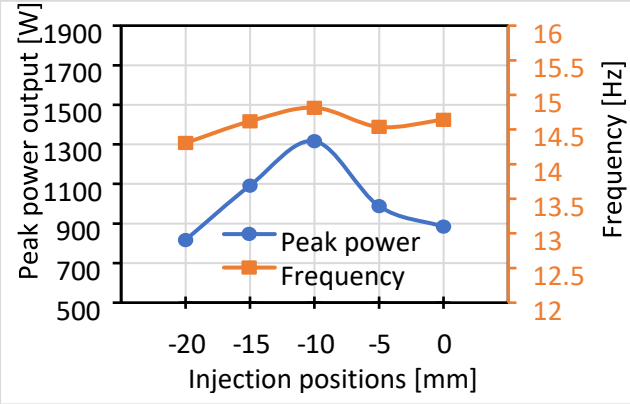

Fig. 4: Effect of injection position variation on peak power output and operating frequency

Effects on the indicated mean effective pressure (IMEP)

Fig. 3(b) illustrates the graph of the in-cylinder pressure against the displaced volume (i.e., P-V) diagram. The area covered by the curve is expressed as indicated work and denotes the work done by the combustion gases on the piston. From the figure, the engine shows the highest indicated work of 127.4 J at -10 mm injection position followed by at -15, -20, 0, and -5 mm having produced indicated works of 5.78%, 5.46%, 9.87%, and 7.49% lower than the value obtained at -10 mm, respectively. From the indicated work, the indicated mean effective pressure (IMEP) was calculated and that equally reveals that -10 mm injection position has the highest IMEP of 5.18 bar compared to other injection positions with 5.78%, 5.46%, 9.87%, and 7.49% corresponding to the injection position of -20, -15, -5, and 0 mm, respectively. The explanation to the -10 mm injection position producing the highest work is because the high flame propagation speed exhibited by the mixture resulted in the higher in-cylinder pressure and higher mean effective pressure compared with the engine performance at the other injection positions.

Effects on the peak power output and operating frequency

The effect of injection position variation on the peak power output of the FPLG engine fuelled with CNG-CO_2 is illustrated in Fig. 4. Expectedly, the highest peak power output produced is 1316.1 W and occurred at -10 mm injection position. At advanced injection positions (-15 and -20 mm), the peak power output drops by 17.0% and 37.9%, respectively. While at retarded injection positions (-5 and 0 mm), the peak power output decreases by 24.9% and 32.8%, respectively. Besides, the operating frequency follows the same trend as the in-cylinder pressure. So, advancing of the injection position from -10 mm position directly and affects the average power output generated significantly and negatively as displayed in the figure. Similarly, when the injection position is retarded, the power output

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declines. It is evidently shown that at -10 mm injection position; the engine shows a higher speed and operating frequency that result in a higher peak power output as the translator cuts more magnetic flux. In the current study, it is obvious that a direct relationship exists between the power output, velocity, and in-cylinder pressure.

CONCLUSION

In this paper, the experimental results obtained from the performance of an FPLG engine prototype fuelled using CNG-CO_2 mixture are presented. The study was conducted under a steady state condition. The best engine operating performance (i.e., ignition velocity of 0.6 m/s and λ = 0.6) at varying injection positions were analyzed in detailed. The findings of the experiment are summarized as follow:

- The peak in-cylinder and peak power output are affected by the injection position variation. The engine is found to achieve the best engine performance at the optimal operating conditions of 0.6 m/s, 0.6, and -10 mm for ignition velocity, lambda, and injection position, respectively.
- The FPLG engine shows a better fuel-air mixing at -10 mm fuel injection than at other injection positions. Thus, the flame propagation speed and combustion duration at -10 mm are found to be the fastest and shortest, respectively. Based on the selected injection position range, the ROHR is found to be 57.7% and 39.5% higher when it is advanced and retarded about -10 mm.
- At the best engine performance, the indicated work and peak power output of the FPLG engine are evaluated and found to be 127.4 J and 1316.1 W.

The findings in this paper are expected to establish that the FPLG engine can utilized low grade fuels for power generation with minimal engine performance deterioration in remote areas; and to offer directions on improving the performance characteristics.

References

N. S. Caetano, T. M. Mata, A. A. Martins, and M. C. Felgueiras, New Trends in Energy Production and Utilization, *Energy Procedia*, vol. 107, no. September 2016, 7–14, (2017), doi: 10.1016/j.egypro.2016.12.122.

Y. Sugiawan and S. Managi, New evidence of energy-growth nexus from inclusive wealth, *Renew. Sustain. Energy Rev.*, vol. 103, no. November 2017, 40–48, (2019), doi: 10.1016/j.rser.2018.12.044.

EDITOR-IN-CHIEF
Prof. Saeid Eslamian [IRAN]

F. Perera, Pollution from fossil-fuel combustion is the leading environmental threat to global pediatric health and equity: Solutions exist, *Int. J. Environ. Res. Public Health*, vol. 15, no. 1, (2018), doi:
10.3390/ijerph15010016.
C. Bae and J. Kim, Alternative fuels for internal combustion engines, *Proc. Combust. Inst.*, vol. 36, no. 3, 3389–3413, (2017), doi: https://doi.org/10.1016/j.proci.2016.09.009.
A. Kowalewicz and M. Wojtyniak, Alternative fuels and their application to combustion engines, *Proc.*
Inst. Mech. Eng. Part D J. Automob. Eng., vol. 219, no. 1, 103–125, (2005), doi:
10.1243/095440705X6399.
P. A. J. Achten, A review of free piston engine concepts, *SAE Tech. Pap.*, no. 412, (1994), doi:
10.4271/941776.
Y. Woo and Y. J. Lee, FREE PISTON ENGINE GENERATOR : TECHNOLOGY REVIEW AND AN EXPERIMENTAL EVALUATION WITH HYDROGEN FUEL, *Int. J. Automot. Technol.*, vol. 15, no. 2, 229–235, (2014), doi: 10.1007/s12239.
R. Mikalsen and A. P. Roskilly, A review of free-piston engine history and applications, *Appl. Therm. Eng.*, vol. 27, no. 14, 2339–2352, (2007), doi: https://doi.org/10.1016/j.applthermaleng.2007.03.015.
N. B. Hung and O. Lim, A review of free-piston linear engines, *Appl. Energy*, vol. 178, 78–97, (2016), doi: https://doi.org/10.1016/j.apenergy.2016.06.038.
R. Virsik and A. Heron, Free piston linear generator in comparison to other range-extender technologies, in *2013 World Electric Vehicle Symposium and Exhibition (EVS27)*, 2013, 1–7. doi:
10.1109/EVS.2013.6914925.
M. Graef, P. Treffinger, S.-E. Pohl, and F. Rinderknecht, Investigation of a high efficient Free Piston Linear Generator with variable Stroke and variable Compression Ratio A new Approach for Free Piston Engines, *World Electr. Veh. J.*, vol. 1, no. 1, (2007), doi: 10.3390/wevj1010116.
H. I. Sherazi and L. Yun, Homogeneous Charge Compression Ignition engine: A technical review, in *The 17th International Conference on Automation and Computing*, 2011, 315–320.
I. Abdulwehab A, A. Ezrann Zharif B. Zainal, A. Rashid A, and Z. Saiful A, Effect of Injection Timing on the Operation of Hydrogen-Fuelled Free-Piston Linear Generator Engine during Starting, *Int. J. Automot. Eng.*, vol. 4, no. 2, 47–53, (2013), doi: 10.20485/jsaeijae.4.2_47.
Y. Tian, H. Zhang, G. Li, X. Hou, F. Yu, F. Yang, Y. Yang, and Y. Liu, Experimental study on free piston linear generator (FPLG) used for waste heat recovery of vehicle engine, *Appl. Therm. Eng.*, vol. 127, 184– 193, (2017), doi: https://doi.org/10.1016/j.applthermaleng.2017.08.031.
G. Li, H. Zhang, F. Yang, S. Song, Y. Chang, F. Yu, J.-F. Wang, and B. Yao, Preliminary Development of a Free Piston Expander–Linear Generator for Small-Scale Organic Rankine Cycle (ORC) Waste Heat Recovery System, *Energies*, vol. 9, 300, (2016), doi: 10.3390/en9040300.
M. A. Ismael *et al.*, Investigation on free-piston motion and power generation of a dual-piston air-driven expander linear generator, *Energy Reports*, vol. 7, 2388–2397, (2021), doi: 10.1016/j.egyr.2021.04.035.
S. S. Rathore, S. Mishra, M. K. Paswan, and Sanjay, A Review on Design and Development of Free Piston Linear Generators in Hybrid Vehicles, *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 691, no. 1, (2019), doi:

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Prof. Saeid Eslamian [IRAN]

10.1088/1757-899X/691/1/012053.
B. Jia, Z. Zuo, G. Tian, H. Feng, and A. P. Roskilly, Development and validation of a free-piston engine generator numerical model, *Energy Convers. Manag.*, vol. 91, 333–341, (2015), doi: https://doi.org/10.1016/j.enconman.2014.11.054.
T. Ahmed and O. Lim, A two stroke free piston engine's performance and exhaust emission using artificial neural networks, *J. Mech. Sci. Technol.*, vol. 30, no. 10, 4747–4755, (2016), doi: 10.1007/s12206-0160946-3.

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