Combustion Characteristics of a Free Piston Engine Linear Generator using Various Fuel Injection Durations

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Abstract: A free piston engine linear generator (FPELG) is considered a type of contemporary technology for energy conversion. The main features of FPELG are less emission, few parts i.e., less friction, and high efficiency. However, because the FPELG does not have a crankshaft, critical issues e.g., combustion efficiency, and performance were reported. This study examines the influence of various fuel injection durations (FID) on combustion behaviors. According to the results of the experiments, as the time increased of the fuel injection, the in-cylinder pressure and translator velocity both slightly grew. The highest work output and combustion efficiency were at FID17 and FID 14 ms, respectively. Thus, FID plays a significant role to improve FPELG performance and optimal fuel duration is required.

Keywords: Free piston engine; Hybrid engine; combustion efficiency; performance

1. Introduction

The technology of internal combustion engines is widely used in a variety of applications, including power plants, generators, and vehicles. However, exhaust gas emissions, energy output, and fuel consumption are the main challenges for conventional engines. Thus, the researchers start to develop alternatives to conventional engines using the latest technologies. The renewable energy system was considered as one of these technologies[1,2,3)]. The FPELG has some characteristics (advantages) over a traditional engine, including low frictional losses, few parts, high efficiency, assembly simplicity, multi-fuel engine, and low emissions[4,5,6,7)]. Thus, the FPELG is a novel energy conversion device that can also consider as an alternative of a conventional engine[8)]. There are two-stage for FPE history: the first stage in 1928, the single-piston free-piston engine (FPE) prototype was constructed by Pescara for use in air compressor applications, followed by the second stage after the 1960s[9,10)]. Researchers developed other designs for utilization in many new applications, including hydraulic engines, and small and big size of generator engines[11,12,13,14)]. Furthermore, some challenges of FPE were solved by researchers, that summarized in[4)]. In this work, a linear electric machine (LEM) and a direct injection FPE were combined for the FPELG investigation. This research provides a thorough explanation of an assembly as well as the working mechanism of the FPELG. However, there are some problems related to FPELG. The main problems can be concluded as performance, stability, and piston motion control[4,11,12,13,14)]. Thus, this type of FPELG requires controlling some parameters, and a highly accurate control strategy requires too[6,7,15)]. The researchers in previous studies focused on some parameters such as ignition timing and piston motion control of FPELG[12,16,17,18,19)]. The forces generated by FPELG were classified into the forces that come from in-cylinder pressure for each side of FPE. These forces cause the piston to move toward the bottom dead center (BDC) from the top dead center (TDC) and vice versa. The current is generated during this movement[20,21)]. On the other hand, the piston moves freely because the crankshaft is absent in FPE. Thus, by adjusting and controlling some parameters such as load, amount of injection fuel, and timing of injection the characteristics of piston motion for the FPELG can be controlled. Furthermore, the injection fuel value affecting on the released energy from the cylinder[17,22].

In other studies[12,18,22,23,24], they observed that the timing of the injection had an impact on the gas pressure generated inside the cylinder and combustion behaviors during combustion. Most injection systems work with the same concept i.e., when the piston moves to a certain position, the fuel is fed into the chamber. However, the piston motion of FPELG has different characteristics compared to the conventional engine. Because there is no crankshaft for FPELG the differences can be described by the association between the engine performance and the injection position, ignition timing, and injection timing[19]. Moreover, the crank angle value in conventional engines was used as an injection timing signal value. While crank angle value cannot use as a suitable method for FPELG because there is no crankshaft. Therefore, the variation in the piston velocity and piston position of conventional engines is less than FPELG[25]. Some studies investigated and worked on the hydraulic FPE[26]. On the other hand, studies were conducted on the efficiency of the four-stroke engine type (CNGDI) for traditional internal combustion engines. The various positions of injection timing were examined. The findings demonstrated that the time of the start injection has an impact on the thermal efficiency, torque, and volumetric efficiency. Moreover, the pressure was increased[27]. In another study, based on the organic Rankine cycle concept the power generator has been created using the modified cooling cars compressor into an expander. The findings revealed that the thermodynamic efficiency was between 2.5-4.45% and expander rotation was between 1650-2750 rpm[28]. Moreover, the optimization of a spark-ignition engine was studied. Different octane numbers with specific volume % of bioethanol were used for gasoline fuel. Advanced ignition timing with reduction by 10% of injection duration was set to collect data for optimization. The results with different engine speeds were analyzed. The outcomes demonstrated that the torque, engine performance, and effective fuel consumption were improved using this control strategy of optimization[29]. In order to decrease exhaust gas emissions, The motorbike linked with an electric engine has been proposed and explored as an alternative of a conventional engine[30]. In conclusion, both simulation and experiments on FPLG performed focused on many issues such as piston motion control, power output, and efficiency. In addition, one of the most significant factors that influence FPELG efficiency is FID. However few studies focused on the fuel injection strategy for both initial and stable operating of FPELG. Therefore, in this paper, different fuel injection duration on FPELG performance was studied. Single-piston FPELG prototype was used to collect data. Three different values of FID i.e., 14, 15, and 17 ms were utilized in this experiment in order to examine the impact of FID on combustion behaviors. The influence of various FID on piston velocity, in-cylinder pressure, and efficiency was also investigated. According to the experimental findings, the FID seriously influences the FPELG performance. Thus, further study to find the optimal FID is required.

2. Experiment setup

As shown in Figure 1, the CAREM center at Universiti Teknologi PETRONAS is where the single-piston FPELG was developed. The following is a simple description of the FPELG: a two stroke internal combustion engine has only two cylinders, first one for the combustion and the second one for the bounce device. LEM is positioned in the middle distance (between) of these two cylinders.

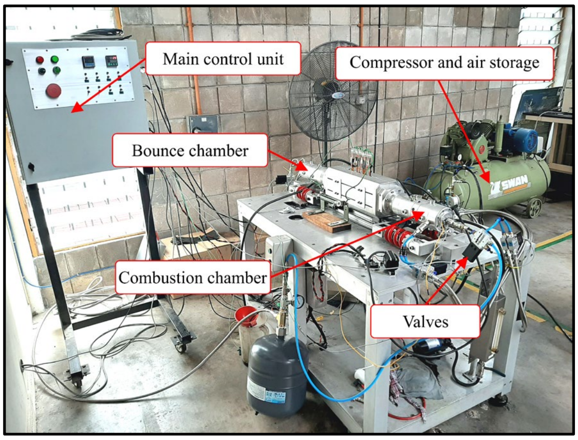

Fig. 1: The physical FPELG prototype and test bench

Table 1. Operating conditions and engine parameters

Parameter	Value
Combustion chamber's bore	56 mm
Bounce chamber's bore	56 mm
Maximum stroke	96 mm
Effective stroke	84 mm
Combined mass of the drive shaft and the piston	7 kg
Exterior load (Resistance)	4.8 ohm
No. of cylinders	2
Pressure of feeding	8 bar
Chamber bore volume	221 cc
Frequency	13
Fuel injection duration	14, 15, and 17 ms
Position of Injection before TDC	59 mm
Position of Ignition before TDC	7 mm

A spark plug is used to produce ignition and hydrogen is used as a fuel for combustion process. In addition, the check valve-electromagnetic valve is used as an alternative to the injection system. It can be clearly seen that the FPELG mainly involves the other parts such as the control system, air storage tank, compressor and all types of sensors. In this study, Table 1 displays the conditions used in operating the engine as well as the specifications of the single-piston FPELG. The specifications of the prototype such as connecting rod and piston mass and geometric dimensions are listed in table1. In addition, the input operating parameters such as ambient conditions, LEM parameters, ignition position, and injection duration are also listed in table1. The signals of both input and output are controlled using the main control unit (MCU). In a separate part (section) of this study, the MCU and the instruments that utilized will be described in greater detail.

3. Operation principle

The FPELG running principle is similar to any engine working with two-stroke[17)]. The power stroke is produced by each cylinder, however, not both cylinders at the same time but alternatively. The current will be generated through the resonance mechanism after the LEM is switched into generator mode.

The compression stroke is considered the first stage of the two-strokes operation. This stage begins once both intake and exhaust valves have been locked by a control system. At that time, the piston reaches TDC. After the piston reaches TDC, the air-fuel combination inside the cylinder is mixed as well as compressed. Thus, the system achieves a required compression ratio (CR). At this moment the second stage takes place, it is a power stroke stage. The power stroke stage begins by providing a signal to the spark system to generate a spark. The mixture is burned in this stage and the combustion stroke followed by the expansion will have occurred. During this process, the piston assembly is driven propelled forward to BDC by the in-cylinder pressure produced from combustion. The control system then opens each of the exhaust valves as well as the feed valve. Subsequently, the new supply of air-fuel combination is charged, and at the same time the residual gas is discharged and drawn out of the cylinder.

In general terms, there are two modes for the FPELG: motoring mode and generator mode. In the first mode, the LEM functions as a motor to drive the pistons from TDC into BDC and back to TDC (combustion cycle) in order to create a resonance mechanism and prepare the cylinders for combustion requirements. In the second mode, the LEM is switched to generator mode and current is produced during the combustion process. These two modes are managed by utilizing a control system[6,31)]. The prototype utilized in this study is considered a single-piston FPELG. Thus, the rebound system is used to drive-back the piston towards TDC, therefore, the LEM function is used only to generate current.

4. Free-piston engine configurations

In general, types of the linear FPEs were classified into: single-piston, two-piston (i.e., opposed-piston or dual-piston), and four-piston (i.e., complicated piston configuration, opposed-piston combined with dual-piston) as illustrated in Figure 2,[4,31,32,33)].

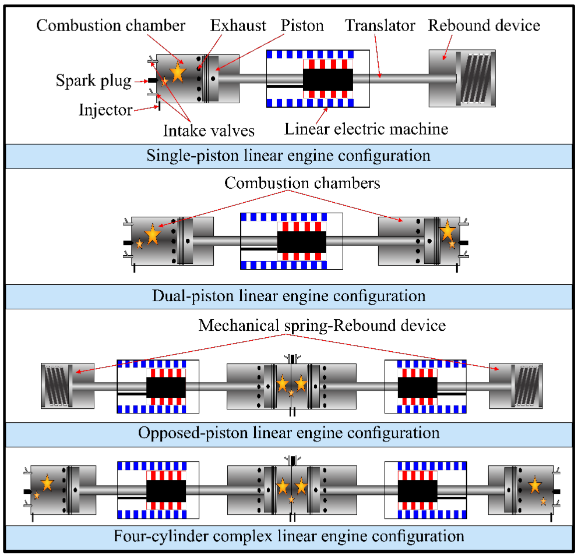

Fig. 2: FPE configuration types

The single-piston engine has some characteristics such as a simpler structure with lower fuel consumption as well as used in a variety of applications, including hydraulic FPE, generator, and compressor compared to other types of FPELG. However, it has difficulties in adjusting the dynamic balance because it has only one combustion cylinder side. In[34)], Mikalsen and Roskilly proposed a single-piston prototype of FPE for electric power generation. The engine consists of two cylinders: one for combustion other for the bounce chamber and between these two cylinders the LEM was connected, as shown in Figure 3. During the engine running the translator moves between TDC and BDC to produce the resonance movement, and the current was generated from LEM during this movement.

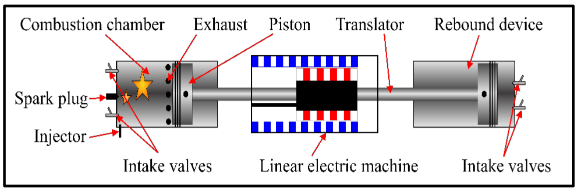

Fig. 3: FPELG with a bounce chamber

In other research, as illustrated in Figure 4, the bounce cylinder is replaced with such a rebound spring[35)]. This resulted in a simple construction than Mikalsen and Roskilly's design for FPE[34)]. Due to its simpler structure, the FPE-type single-piston engine is currently on the brink of becoming a commercial engine. In general, the FPELG consist of LEM between two cylinders, MCU and some accessories such as sensors, compressor, compressed air tank, and high-pressure pipes. through valves, the air-fuel amount is provided for the combustion cylinder and compressed air is provided for the bounce chamber side. In addition, PC and LabVIEW software is used to collect data and provide the input signals to the engine based on the input parameters value.

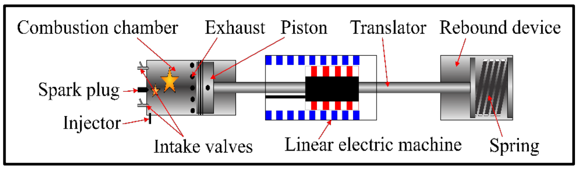

Fig. 4: FPELG with mechanical spring

5. Methodology

5.1 Mathematical model

LEM, in-cylinder pressure, friction, and moving mass are considered as the main parameters to produce the forces acting on pistons[36]. As illustrated in Figure 5, the FBD (free body diagram) of FPELG demonstrates the system's forces in great detail. The second law of Newton can be utilized to derive the FPE dynamic formula.

$$F_l - F_r - F_e - F_f = m\frac{d_x^2}{dt^2}\,, \qquad (1)$$

where F_e represents the force generated by LEM (N), F_f represents the frictional force between the piston components (N), F_l and F_r represent the forces generated by in-cylinder pressure (from left and right cylinder) (N), m represents the weight of piston including accessories (kg), and x represents the displacement of piston (m).

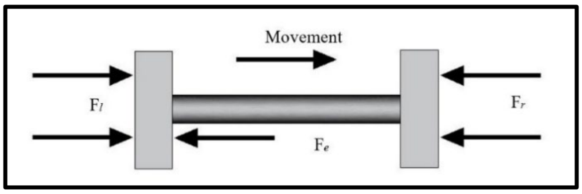

Fig. 5: FBD of FPELG

5.2 Instrumentations and control system of the FPELG

The instruments e.g., air compressor, MCU, sensors, and PC are used to run FPELG. In addition, LabVIEW software is utilized to regulate both input signals as well as output signals or can be described as a control system that can set engine parameters and collect data. Thus, PC including a program developed using LabVIEW is used for the data acquisition systems (DAS) and control system. Once the input settings have been configured using the interface tool installed on the PC, the signal will be delivered to MCU, and then the FPE will begin to operate. The MCU consist of sub-controllers such as the injection timing controllers, ignition timing controller, cooling system controller, and LEM controller. In this study, the National Instrument PXI-type integrated controller is the MCU model that utilized in FPELG prototype. For more details about the MCU specifications that can be described as follows: 2.2 GHz, Pentium 4-based, 32-channel amp unit (model SCXI-1102C) for analog signal readings of current as well as pressure, integrated controller for commercial Desktop computer platform (model PXI-8186), in addition, 8-channel counter/timer control unit (model PXI-6602) for linear encoder input, ambient sensor input, as well as gate-drive signal outcome. All signals that come from engine sensors and from PC (input parameters) are processed through MCU, so it is considered the important part and the engine can not work without MCU. After these signals are processed using MCU will be sent back to the sub-controller. While the sub-controllers can be classified into piston velocity control, throttle control, output electric current control, FID control, piston displacement control, intake pressure control, ignition timing control and exhaust valve control. Figure 6 shows the control system diagram including the main controller and sub-controllers connected to the FPELG prototype and other instruments such as compressor, air tank, valves and sensors.

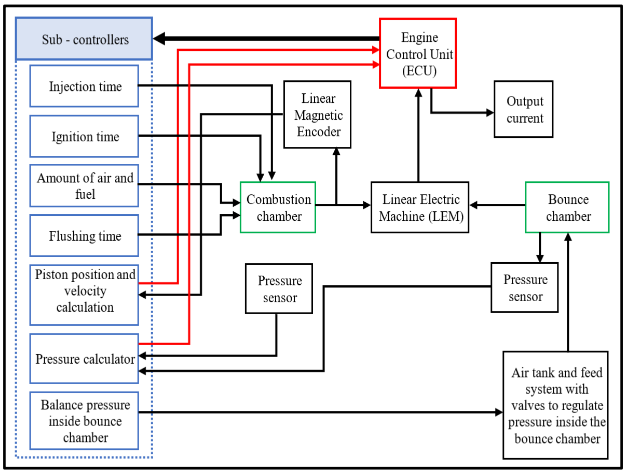

Fig. 6: Instrumentations and control system diagram of FPELG

5.3 Injection

The fuel injection system and valve system have the same goal which is to provide fuel into the cylinder. In this study, a check valve-electromagnetic valve arrangement is used as a form of injector for the experiment. Through the valve, the 8-bar pressure of fuel is transferred from the fuel tank to the cylinder of the engine via a high-pressure fuel line. Based on the duration is set, the engine control activates the valve to inject the fuel for the duration set. Finally, the Fuel Injection Durations (FID) that is used in this study are as follows: FID14 ms, FID 15 ms, and FID 17 ms.

6. Results and discussion

Experimental data analysis is conducted in this research.

Figure 7 shows that the test result of piston velocity against piston position. It is apparent that the piston velocity increases slightly as the period time of fuel injection increases. Moreover, the duration of the fuel injection has an influence on the cylinder pressure resulting from the combustion process. In addition, there is some delay for the peak pressure when the less injection duration is supplied. But not that means the maximum pressure can produce by providing maximum fuel injection duration because the combustion characteristics and emission will be affected. Thus, the optimal value can be considered when the maximum pressure is produced at a minimum amount of fuel. Figure 8 illustrates a direct correlation in between the increase in pressure generated by the combustion process and the amount of fuel. It can be observed that FID 15 ms shows delay in the combustion which subsequently affects the next combustion cycles. As a result, the delay of combustion can affect the combustion characteristics such as the in-cylinder peak pressure is decreased because of this delay.

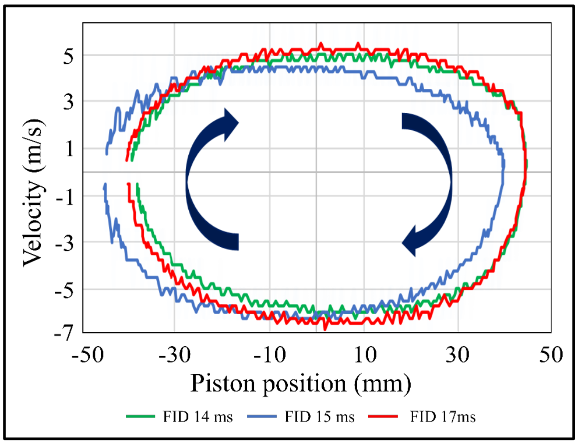

Fig. 7: Piston velocity vs position for various FID

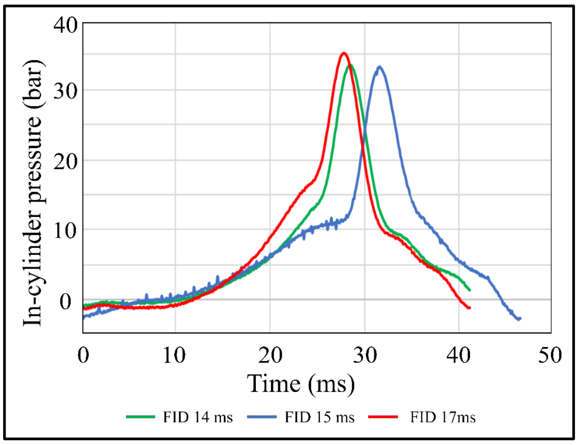

Fig. 8: In-Cylinder pressure vs time for various FID

Figures 9 and 10 illustrate the analysis results for the work output curve and the combustion efficiency curve, respectively. The real experimental data shows that the work value and combustion efficiency are not proportional to increases in fuel injection duration. The lowest work output and combustion efficiency are recorded at 15 ms fuel injection duration. While the highest work output and combustion efficiency occurred at 17 ms and 14 ms respectively. The highest value of work is observed at the FID was 17. Moreover, the highest combustion efficiency is recorded at 14 ms fuel injection duration. Thus, a high percentage of fuel is burned at this value compared to other values of the fuel injection duration.

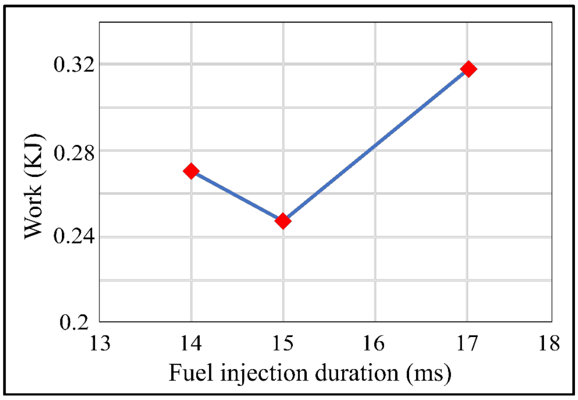

Fig. 9: Work (out) against fuel injection duration (ms)

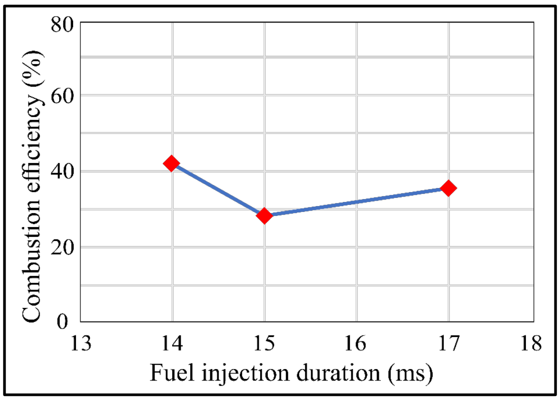

Fig. 10: Combustion Efficiency against fuel injection duration (ms)

The reason for the highest efficiency of combustion at the FID value of 14 ms can be described as follows: the high efficiency is produced when there is sufficient time to burn the most mixture. While there are no benefits to injecting more fuel but not enough time (only a short time) to burn. Thus, the efficiency is reduced when the fuel burning time used for each of the FID values of 15 ms and 17 ms is similar to the fuel burning time used for the FID value of 14 ms. Moreover, the expected results indicate that the exhaust emissions for FID values of 15 ms and 17 ms are higher compared to this for FID value of 14 ms because the residual gas contains the most unburned fuel. However, there is a probability to increase the efficiency of the FID value of 17 ms more than the FID value of 14 ms by using advanced injection or earlier injection, in order to increase the burning time and then get the chance to burn most fuel, thus also reducing emissions. In addition, if the same scenario is utilized for the FID value of 15 ms as for the FID value of 17 ms, the probability findings could be comparable. Hence, different outputs were produced at different durations. Therefore, there is an optimal value for the fuel injection duration. This value changing depends on some parameters such as external load, fuel type, injection position (retard or advanced), and engine design. In summarizing, in order to achieve optimal fuel duration that enhances engine performance, further investigation of the optimal fuel duration is required, that, which will be the focus of our study.

7. Conclusion

FPELG is one of the newest energy conversion technologies. Stability and performance are the main challenges for the FPELG. In this work, the FPELG prototype's corresponding experimental data were gathered and examined. Three different fuel injection durations were used to conduct the experiments. Combustion characteristics including the velocity of piston, pressure resulting combustion process, workout, and combustion efficiency were studied. The findings of the experiment indicate that when the period time of fuel injection was expanded, the piston velocity and in-cylinder pressure rose. In addition, it was observed that the combustion efficiency and work output were not directly proportional to the fuel injection duration. The lowest work output and efficiency were recorded at 15 ms fuel injection duration. While the highest work output was recorded at the FID of values 17 ms and 14 ms respectively. On the other side, the FID value of 14 ms exhibited the maximum combustion efficiency. Thus, FID plays a significant role to improve FPELG performance. Obviously, further study is necessary onto the optimization of the fuel injection duration utilizing simulation and experimental data for validation in order to enhance the engine performance of the FPELG.

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References

1) S.A. Solarin, "An environmental impact assessment of fossil fuel subsidies in emerging and developing economies," *Environ. Impact Assess. Rev.*, **85** 106443 (2020).
2) Z. Chen, L. Wang, X. Yuan, Q. Duan, B. Yang, and K. Zeng, "Experimental investigation on performance and combustion characteristics of spark-ignition dual-fuel engine fueled with methanol/natural gas," *Appl. Therm. Eng.*, **150** 164–174 (2019).
3) A. Smallbone, M.R. Hanipah, B. Jia, T. Scott, J. Heslop, B. Towell, C. Lawrence, S. Roy, K. V Shivaprasad, and A.P. Roskilly, "Realization of a novel free-piston engine generator for hybrid-electric vehicle applications," *Energy & Fuels*, **34** (*10*) 12926–12939 (2020).
4) R. Mikalsen, and A.P. Roskilly, "A review of free-piston engine history and applications," *Appl. Therm. Eng.*, **27** (*14–15*) 2339–2352 (2007). doi:10.1016/j.applthermaleng.2007.03.015.
5) R. Mikalsen, and A.P. Roskilly, "Performance simulation of a spark ignited free-piston engine generator," *Appl. Therm. Eng.*, **28** (*14–15*) 1726–1733 (2008).
6) R. Mikalsen, E. Jones, and A.P. Roskilly, "Predictive piston motion control in a free-piston internal combustion engine," *Appl. Energy*, **87** (*5*) 1722–1728 (2010).
7) R. Mikalsen, and A.P. Roskilly, "The control of a free-piston engine generator. part 1: fundamental analyses," *Appl. Energy*, **87** (*4*) 1273–1280 (2010).
8) C. Guo, Z. Zuo, H. Feng, B. Jia, and T. Roskilly, "Review of recent advances of free-piston internal combustion engine linear generator," *Appl. Energy*, **269** 115084 (2020).
9) R.P. Pescara, "Motor compressor of the free piston type," *United States Pat. Off.*, (1941).
10) P.R. Pateras, "Motor-compressor apparatus," *United States Am. Pat.*, **1** 31 (1928).
11) N.B. Hung, and O.T. Lim, "A study of a two-stroke free piston linear engine using numerical analysis," *J. Mech. Sci. Technol.*, **28** (*4*) 1545–1557 (2014).
12) Z. Zhao, D. Wu, Z. Zhang, F. Zhang, and C. Zhao, "Experimental investigation of the cycle-to-cycle variations in combustion process of a hydraulic free-piston engine," *Energy*, **78** 257–265 (2014).
13) M.R. Hanipah, R. Mikalsen, and A.P. Roskilly, "Recent commercial free-piston engine developments for automotive applications," *Appl. Therm. Eng.*, **75** 493–503 (2015).
14) J. Kim, C. Bae, and G. Kim, "Simulation on the effect of the combustion parameters on the piston dynamics and engine performance using the wiebe function in a free piston engine," *Appl. Energy*, **107** 446–455 (2013).
15) R. Mikalsen, and A.P. Roskilly, "The control of a free-piston engine generator. part 2: engine dynamics and piston motion control," *Appl. Energy*, **87** (*4*) 1281–1287 (2010).
16) B. Jia, G. Tian, H. Feng, Z. Zuo, and A.P. Roskilly, "An experimental investigation into the starting process of free-piston engine generator," *Appl. Energy*, **157** 798–804 (2015).

17) B. Jia, A. Smallbone, H. Feng, G. Tian, Z. Zuo, and A.P. Roskilly, "A fast response free-piston engine generator numerical model for control applications," *Appl. Energy*, **162** 321–329 (2016).
18) H. Feng, Y. Song, Z. Zuo, J. Shang, Y. Wang, and A.P. Roskilly, "Stable operation and electricity generating characteristics of a single-cylinder free piston engine linear generator: simulation and experiments," *Energies*, **8** (*2*) 765–785 (2015).
19) A.T. Raheem, A.R.A. Aziz, S.A. Zulkifli, W.B. Ayandotun, E.Z. Zainal, and S.M. Elfakki, "Experimental Analysis for the Influence of Ignition Time on Combustion Characteristics of a Free Piston Engine Linear Generator," in: J. Phys. Conf. Ser., IOP Publishing, 2021: p. 12051.
20) B. Jia, Z. Zuo, H. Feng, G. Tian, A. Smallbone, and A.P. Roskilly, "Effect of closed-loop controlled resonance based mechanism to start free piston engine generator: simulation and test results," *Appl. Energy*, **164** 532–539 (2016).
21) H. Feng, C. Guo, C. Yuan, Y. Guo, Z. Zuo, A.P. Roskilly, and B. Jia, "Research on combustion process of a free piston diesel linear generator," *Appl. Energy*, **161** 395–403 (2016).
22) H. Yu, Z. Xu, Q. Zhang, L. Liu, and R. Hua, "Two-stroke thermodynamic cycle optimization of a single-cylinder free-piston engine generator," *Adv. Mater. Sci. Eng.*, **2019** 1–11 (2019). doi:10.1155/2019/9783246.
23) H. Kosaka, T. Akita, K. Moriya, S. Goto, Y. Hotta, T. Umeno, and K. Nakakita, "Development of free piston engine linear generator system part 1-investigation of fundamental characteristics," SAE Technical Paper, 2014.
24) S. Goto, K. Moriya, H. Kosaka, T. Akita, Y. Hotta, T. Umeno, and K. Nakakita, "Development of free piston engine linear generator system part 2-investigation of control system for generator," SAE Technical Paper, 2014.
25) Y. Miao, Z. Zuo, H. Feng, C. Guo, Y. Song, B. Jia, and Y. Guo, "Research on the combustion characteristics of a free-piston gasoline engine linear generator during the stable generating process," *Energies*, **9** (*8*) 655 (2016).
26) L. Wang, Z. Zhao, C. Yu, F. Zhang, and C. Zhao, "Energy and exergy analysis of hydraulic free-piston engines," *Proc. Inst. Mech. Eng. Part D J. Automob. Eng.*, **233** (*12*) 3074–3087 (2019).
27) H. Amiruddin, W.M.F.W. Mahmood, S. Abdullah, and M.R.A. Mansor, "CNGDI engine performance using a vaned diffuser turbocharger compressor with varying injection timings," *Evergreen*, **8** (*2*) 414–420 (2021). doi:10.5109/4480723.
28) M. Muslimm, M.I. Alhamid, and B. Ismoyo, "Analysis of the scroll compressor changing into an expander for small scale power plants using an organic rankine cycle system," *Evergreen*, **7** (*4*) 615–620 (2020).
29) F. Adian, and B. Sugiarto, "The optimization of the relationship between octane number of gasoline-ethanol blend fuels in various settings of the engine control module," *Evergreen*, **7** (*4*) 587–592 (2020). doi:10.5109/4150510.
30) A. Habibie, M. Hisjam, W. Sutopo, and M. Nizam, "Sustainability evaluation of internal combustion engine motorcycle to electric motorcycle conversion," *Evergreen*, **8** (*2*) 469–476 (2021). doi:10.5109/4480731.
31) N.B. Hung, and O. Lim, "A review of free-piston linear engines," *Appl. Energy*, **178** 78–97 (2016).
32) Q. Li, J. Xiao, and Z. Huang, "Simulation of a two-stroke free-piston engine for electrical power generation," *Energy & Fuels*, **22** (*5*) 3443–3449 (2008).
33) W.B. Ayandotun, A.R.A. Aziz, Z.A.B.A. Karim, S.E. Mohammed, A.T. Raheem, and M.A. Ismael, "Investigation on the combustion and performance characteristics of a di free piston linear generator engine fuelled with cng-co2 blend," *Appl. Therm. Eng.*, 117441 (2021).
34) R. Mikalsen, and A.P. Roskilly, "The design and simulation of a two-stroke free-piston compression ignition engine for electrical power generation," *Appl. Therm. Eng.*, **28** (*5–6*) 589–600 (2008).
35) C.L. Tian, H.H. Feng, and Z.X. Zuo, "Oscillation characteristic of single free piston engine generator," in: Adv. Mater. Res., Trans Tech Publ, 2012: pp. 1873–1878.
36) T. Zhao, H. Zhang, X. Hou, Y. Xu, J. Li, X. Shi, and Y. Wu, "Modelling and validation of a free piston expander-linear generator for waste heat recovery system," *Appl. Therm. Eng.*, **163** 114377 (2019).