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Experimental Analysis for the Influence of Ignition Time on Combustion Characteristics of a Free Piston Engine Linear Generator

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Abstract. Free Piston Engine Linear Generator (FPELG) is a modern engine and promising power generation engine. It has many advantages compared to conventional engines such as less friction, few numbers of parts, and high thermal efficiency. The cycle-to-cycle variation one of the big challenges of the FPELG because it is influence on the stability and output power of the engine. Therefore, in this study, the effect of ignition time on combustion characteristics is investigated. The single-cylinder FPELG with spark ignition (SI) combustion type by using compressed natural gas (CNG) fuel type was set to run. LabVIEW is used to run the engine and control of input parameters. All experimental data have been collected and processed based on LabVIEW and Macro tool. The analysis results of the experimental based on ignition time show that the in-cylinder pressure with double peak shape was produced when the ignition delay after Top Dead Centre (TDC). On the other hand, the in-cylinder pressure and output power with ignition before TDC is higher in approximately (33.8%, and 17.8% respectively) compared to the in-cylinder pressure with ignition after TDC. Though investigate the influence of ignition time on the combustion characteristics but with further study and investigation for such as the combustion during expansion, exhaust gas temperature, and emission under various ignition time could be achieved in our future work.

1. Introduction

Technologies have been widely used to decrease engine size, especially automotive engines. As well as to improve automotive engine efficiency. Therefore, when the few parts in engine assembly is produced, the thermal loss, friction loss, and emissions are decreased. All these advantages can find in the Free Piston Engine (FPE) [1-4]. The first FPE prototype made by Pescara in 1928 as a single piston air compressor [5]. The engine was developed by other researchers to use in advanced applications, such as free-piston linear generator engines and hydraulic engines [6-9]. Moreover, they solved some of the limitations that summarized in [1]. The detailed illustration of a structure and the operating principle of this type of free piston engine can be found in [1]. However, there are some challenges of the FPELG such as piston motion control, combustion characteristics, and generator performance [1, 6-9]. During the engine running, there are two forces generated, and each force for each side of the cylinders working alternately to push the translator left and right caused resonance movement and finally, the current is generated [10, 11]. Because of the engine working without crankshaft and piston move freely, that means there are some parameters to control of the piston motion characteristics such as load, injection fuel amount, and injection timing by adjusted and controlled in advance. Moreover, the energy which is released from the cylinder depends on the injection fuel value [12, 13].

In [14] Laura Manofsky et al. studied the effect of spark timing on temperature, in-cylinder pressure, and heat release rate. The spark position was used from 28 to 35 degree Before Top Dead Centre (BTDC). They found the in-cylinder pressure changed as the spark was advanced. Earlier spark timing resulted in higher in-cylinder pressures, going early combustion, and higher in-cylinder temperatures. Moreover, the heat release was more rapid with earlier spark timing. These results similar to that results in [15], who showed that Earlier spark timing can be used to phase combustion even when the majority of the heat release comes from auto-ignition. In [16] Cenk Sayin studied the effects of Spark Timing (ST) on emissions and performance for the SI engine using different RON gasoline was investigated experimentally. The experimental results showed that emissions and performance can be clearly improved by changing the spark timing depending on octane number in a gasoline engine. Moreover, by using different octane numbers with the same spark time, the result shows that the type of octane number effects on the peak pressure. In [17] Lukas Tunka and Adam Polcar analyzed the combustion process under various ignition timing of the air-fuel mixture in a spark-ignition engine. The results showed that the engine torque and power increased when the ignition timing increases. The increase in these parameters produces higher in-cylinder pressure. Furthermore, the maximum value of pressure can be achieved at higher ignition timing near the TDC in the expansion stroke. Also, they used different spark time BTDC [°CA] (18, 20, 22, 24, 26, 28, 30, and 32) with in-cylinder pressure. In [18] A.H.Kakaee et al. analyzed the performance of the SI engine with different ignition timing conditions. In order to assume the ignition timing for higher engine performance including the thermal efficiency, torque, power, and so forth. They found when the ignition advance is increased the pressure in-cylinder and temperature was increased. However, thermal efficiency and power were reduced, and higher losses were produced such as friction losses and other losses.

However, few experimental data in previous literature found to investigate the effect of ignition time on combustion characteristics for the FPE. Therefore, in this paper, the effect of various ignition time on the combustion characteristics was studied experimentally. The spark ignition (SI) of the free-piston engine coupled with a linear generator (FPELG) type was used. Based on the LabVIEW interface to run the engine, the ignition time, and other parameters such as injection time, and the duration of injection was set. the experimental data were analyzed, and the results showed the peak of in-cylinder pressure is influenced when ignition time changed which leads to a decrease in output power and engine efficiency.

2. FPELG operation principle and methodology

2.1. Experiment setup

Figure 1 is the diagram of the free piston engine. The engine parts and connection can be clearly seen in this figure. The single-cylinder two-stroke FPELG (GX-5) was designed and developed by the Centre for Automotive Research and Electrical Mobility (CAREM) in Universiti Teknologi PETRONAS (UTP) using locally available resources. The engine description simply is a linear generator (LG) connected to two cylinders, the right cylinder for the combustion side and the left cylinder for rebound device. These two cylinders connected into high pressure pipeline which comes from the air tank which charge by the compressor. Moreover, there are sensors to measure such as the pressure, temperature, airflow, and pistons position. Based on the Data Acquisition System (DAS) the data is collected. Finally, by using LabVIEW interface the engine is running.

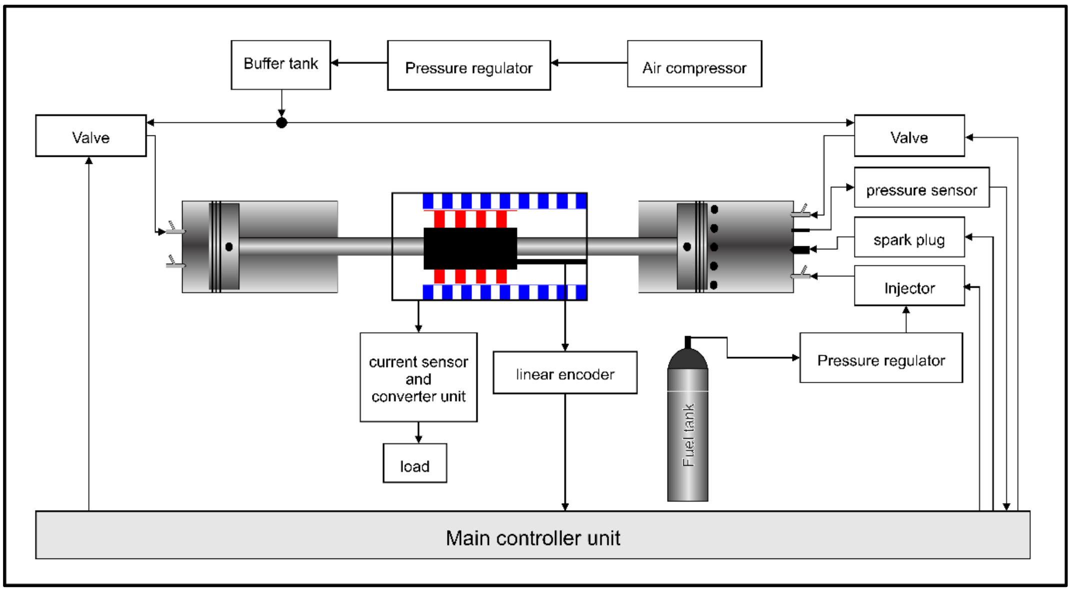

Figure 1 Schematic diagram of the FPELG

The FPELG prototype specifications and operating conditions including input parameters such as connecting rod and Piston mass, Engine parameters, Ambient conditions, LEM parameters, and geometric dimensions have been listed in Table 1. The Engine Control Unit (ECU) was used to control the input and output signals of the engine which is explained in detail in the methodology section. Moreover, the instruments that were used and the methodology which was used to run this prototype are explained.

Table 1 Engine parameters and operating conditions

Parameter	Value	Unit
Combustion chamber bore	56	(mm)
Bounce chamber bore	56	(mm)
Maximum stroke	96	(mm)
Effective stroke	84	(mm)
Piston and connecting rod mass	7	(kg)
External load resistance	4.7	(ohm)
Number of cylinders	2	-
Intake pressure	8	(bar)
Intake valve opening time	5-100	(ms)
Cylinder displacement volume	221	(cc)
Engine frequency	30	(Hz)
Fuel injection duration	16.79	(ms)
Injection position BTDC	59	(mm)
Ignition position BTDC	7	(mm)

2.2. Operation principle
The experiment setup of FPELG (GX-5) is shown in Figure 2. The operation principle of FPELG (GX-5) is similar to the two-stroke engine. Generally, during the engine running, there are two forces generated, and each force for each side of the cylinders working alternately to push the translator left and right caused resonance movement and finally, the current is generated. at the start, the left cylinder

feeding with a high intake pressure to push rod assembly to the right side during this time the fuel valve and air valve will be opened, and the air-fuel mixture will be provided to the right cylinder. After the piston reach to top dead centre the ignition signal come from Engine Control Unit (ECU) the spark will be ignited and the combustion will be done. The high pressure which is generated by heat release from combustion will push back rod assembly to Bottom Dead Centre (BDC). After the piston reach BDC the exhaust will be opened, and the residual gas will be exhausted. The gas inside the rebound device (left cylinder) will be compressed after piston reach BDC to push back again rod assembly to TDC because it is working as a gas spring. During this resonance movement, the current will be generated by LG. The DAS will be used to collect experimental data.

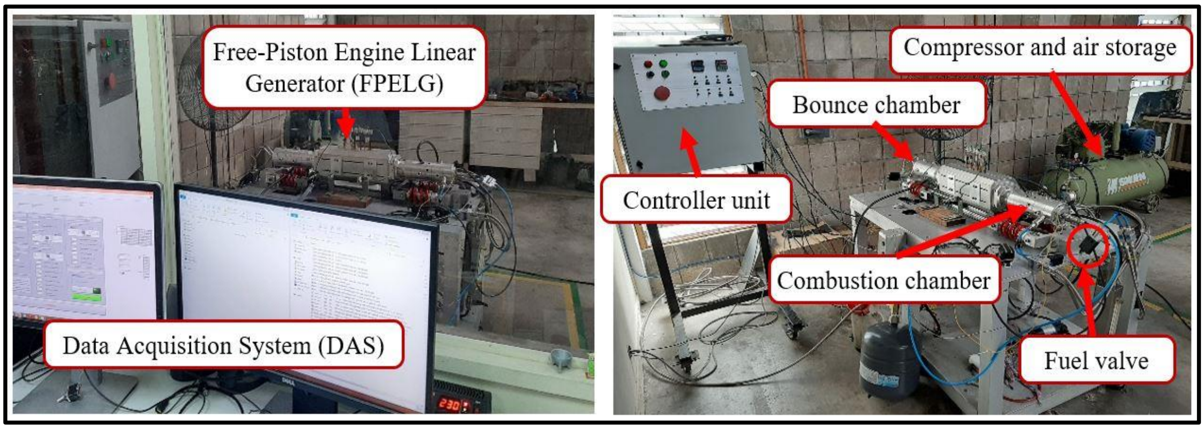

Figure 2 FPELG prototype developed by CAREM in Universiti Teknologi PETRONAS

2.3. Methodology

2.3.1. Mathematical model

The main parameters such as LEM, friction, intake pressure, and moving mass are used to determine the forces acting on pistons [19]. Figure 3 illustrates the free body diagram of FPELG and the details of forces on the system. The dynamic equation of FPE was expressed by using Newton's second law.

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

Where Fe is the electrical force by generator, Fl and Fr is the pressure force of the left and right cylinder respectively, Ff is the frictional force between the piston components, and M is the mass of the piston assembly, X is the displacement between the piston and cylinder.

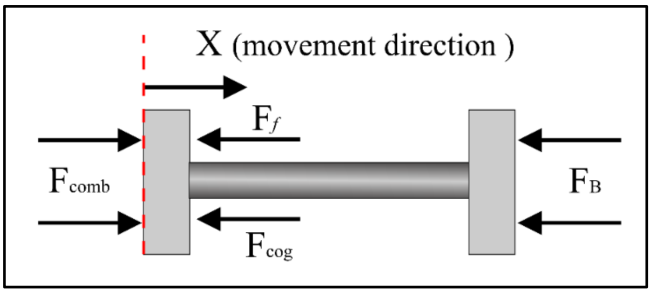

Figure 3 Free body diagram of FPELG

2.3.2. Control system and instrumentation details of the FPELG

FPELG is running by using some instruments such as PC, sensors, air compressor, and controllers. Moreover, the LabVIEW program working in Real-Time was developed for the control system and data acquisition systems (DAS). The engine starting when the signal produces by using the interface software in PC (it is developed by LabVIEW) then send this signal into the Engine Control Unit (ECU). The ECU is considered the main controller, it was developed by using a National Instrument (NI) PXI embedded controller. The purpose of ECU is to receive any signal from engine sensors, also from the sub-controller as a feedback signal and processing it. After the signal is processed send it again into the sub-controller. The specification of the ECU is Pentium 4-based, 2.2 GHz, industrial PC platform PXI-8186 embedded controller. The modules are (SCXI-1102C) 32-channel amplifier module for analog input measurements of pressure and current, and (PXI-6602) 8-channel counter/timer module for home sensor input, linear encoder input, and gate-drive signal output. The starting control, current control, throttle control, speed control, fuel amount control, position control, injection time control, bounce pressure control, ignition time control, Pressure calculator, and flushing time control all these are considered as a sub-controllers as illustrated in figure 4. Some other instrumentations as shown in figure 4 were used in the FPELG and considered the main parts of the prototype such as pressure sensors, air tank, compressors, and valves.

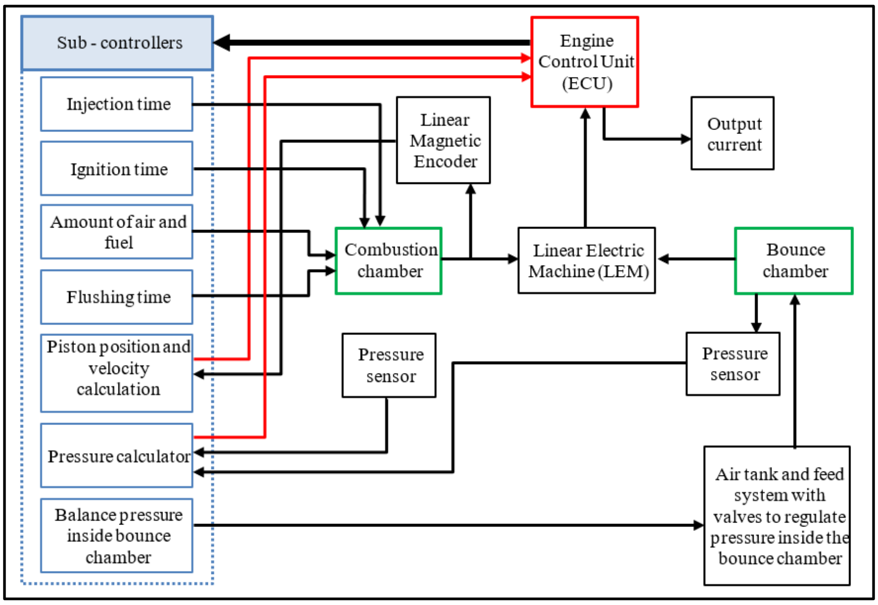

Figure 4 FPELG control system block diagram and instrumentation details

3. Results and Discussion

The goal of the ignition system is to provide a high voltage for the spark plug to ignite the mixture of air-fuel inside the cylinder with a specific time. However, the cycle-to-cycle variation is produced, not only because of ignition time variation but there are many parameters difficult to control in this system because there is no crankshaft. Therefore, in this study, the effect of ignition time on combustion characteristics was investigated. Finally, based on the piston position can be determined the ignition time for this experiment.

Based on experiment operation parameters the TDC position is +42mm and the BDC position is -42mm. Figure 5 shows the experimental results for the in-cylinder pressure and piston velocity with the TDC position and ignition position for each cycle. 16 cycles were analyzed from the FPELG running cycles by using CNG fuel. According to the real experiment data, the ignition delay is observed for some cycles, therefore, the in-cylinder pressure with double Peake was produced. Cycles number 1, 2, 3, 4, 6, 13, and 14 have one peak of in-cylinder pressure. all these cycles have similar behaviours of ignition position which is the position of the ignition before the TDC position. Moreover, the experiment results show when the ignition was produced after the TDC position the double peak of in-cylinder pressure was produced as in cycles number 5, 7, 8, 9, 10, 11, 12, 15, and 16.

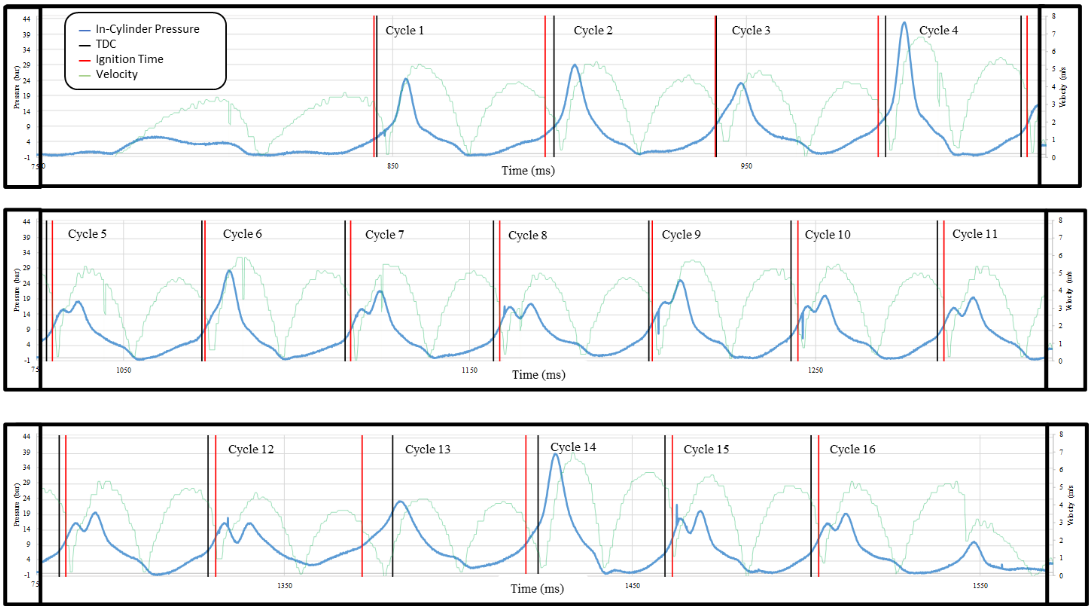

Figure 5 Influence of the ignition time for both before and after TDC on in-cylinder pressure.

Moreover, table 2 shows the 16 cycles and how ignition time influence on the peak shape of in-cylinder pressure when the ignition was produced before or after TDC.

Table 2 The number of peaks for in-cylinder pressure under ignition position before and after TDC.

No. of cycle	No. of peak	Linear position of ignition	No. of cycle	No. of peak	Linear position of ignition
1	One	BTDC	9	Two	ATDC
2	One	BTDC	10	Two	ATDC
3	One	BTDC	11	Two	ATDC
4	One	BTDC	12	Two	ATDC
5	Two	ATDC	13	One	BTDC
6	One	BTDC	14	One	BTDC
7	Two	ATDC	15	Two	ATDC
8	Two	ATDC	16	Two	ATDC

In this study, two cycles with different ignition time are analyzed, to study the combustion characteristics and cycle-to-cycle variation of the FPELG. The experiment results as in Figure 6 illustrate in-cylinder pressure and piston velocity against the time for cycle number 2 with TDC position, ignition time, and end of injection time. The in-cylinder pressure almost reached 30 bar for cycle number 2 and it has clearly one peak. The ignition time in this cycle was before TDC at the same time close to the TDC position.

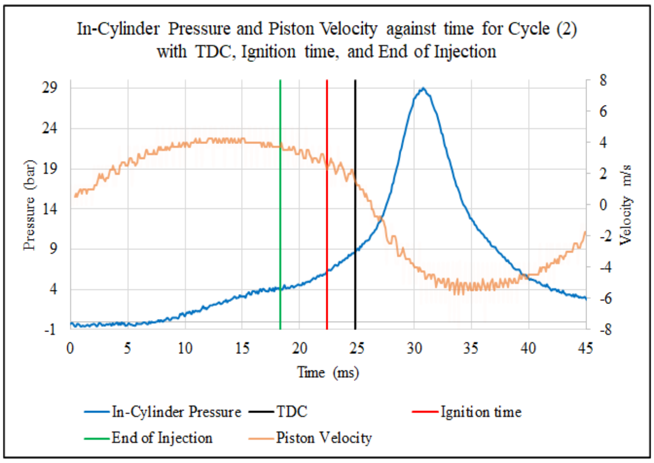

Figure 6 In-cylinder pressure and piston velocity against time for cycle (2) with TDC position, ignition time, and end of injection

However, for cycle number 8 as in Figure 7 that shows the in-cylinder pressure decreased to around 18 bar with double peak shape compared to cycle number 2 because the ignition was produced after TDC. In general, the in-cylinder pressure with ignition before TDC is higher in approximately 33.8% compared to the in-cylinder pressure with ignition after TDC.

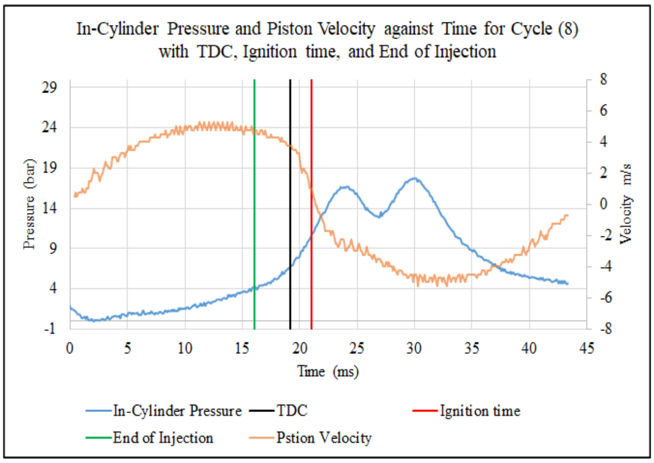

Figure 7 In-cylinder pressure and piston velocity against time for cycle (8) with TDC position, ignition time, and end of injection

According to our previous analysis in this study. In addition, the observation of engine behaviour that shows in the figure 8 related to the output power for the cycle number 2 and 8. We found that the ignition delay influence on the in-cylinder pressure was reflected in the output power. The output power with ignition before TDC is higher in approximately 17.8% compared to the output power with ignition after TDC.

In summary, there are many parameters affecting the combustion characteristics such as the injection time, friction, design, rod and piston mass, amount of fuel, and external load… etc. This study focused on the influence of ignition time or the ignition delay on the combustion characteristics based on the real experimental data. Can be concluded that could occur the combustion during expansion, high exhaust gas temperature, and more emission, besides the losses in output power, and the decrease in the peak of pressure when the ignition delay has been produced.

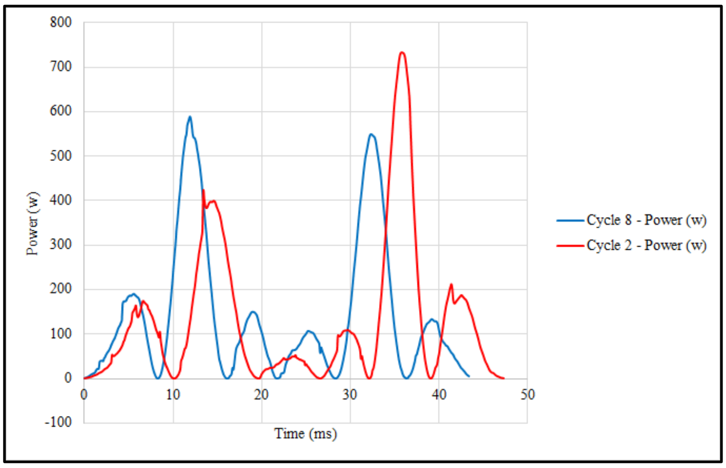

Figure 8 Output power comparison between cycle number 2 with ignition position before TDC and cycle number 8 with ignition position after TDC

4. Conclusion

Cycle-to-cycle variation one of the big challenges of the FPELG because it is influence on the stability and output power of the engine. Therefore, in this study, the influence of ignition time on combustion characteristics was investigated. The experiment setup was done for the single-cylinder FPELG with SI combustion type by using CNG fuel type. LabVIEW was used to run the engine and control of input parameters. The ECU was used to transfer the input values into signals and send them to the engine. The real experimental data of the FPELG prototype has been collected and analyzed based on ignition time. The results of the experiment showed that ignition time influence on combustion characteristics. The following conclusions have been drawn.

1- Double-peak shape was produced when the ignition delay after TDC.
2- The in-cylinder pressure with ignition before TDC was higher in approximately 33.8% compared to the in-cylinder pressure with ignition after TDC.
3- The output power with ignition before TDC was higher in approximately 17.8% compared to the output power with ignition after TDC.
4- If ignition timing does not become advance enough, the combustion during expansion, high exhaust gas temperature, emission, and some other parameters could affect combustion characteristics. These needs to more investigate in future work.

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