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A POWER GENERATION STUDY BASED ON OPERATING PARAMETERS OF THE LINEAR ENGINE USING A POWERPACK

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ABSTRACT

In this paper, we present our experimental research on a power pack based on the linear engine operating conditions and the linear generator structure for generating electric power. The power pack used in the study consisted of a two-stroke free-piston linear engine, linear generators, and air compressors. Each parameter of input caloric value, equivalence ratio, spark timing delay, electrical resistance, and air gap length were settled for identifying the combustion characteristics and for examining the linear engine performance. The linear engine was fueled with propane, and in the course of all its operations, intake air was fed under the wide open throttle condition. The air and fuel mass flow rate were varied by a mass flow controller and premixed by a pre-mixing device. The premixed gas was then directly supplied into each combustion cylinder. The experiments confirmed that power generation was induced differently for each respective operating condition. For the linear engine, piston frequency, velocity, and combustion characteristics were ultimately different for each operating condition. As a result, the piston frequency was 57.2Hz and the maximum generating power was 111.3W, where the operating conditions were as follows: 1.0 of equivalence ratio, 1.5ms of spark timing delay, 30Ω of electric resistance, and 1.0mm of air gap length.

INTRODUCTION

The crisis of global warming and shortage of fossil fuels are being a motivation for the scientists as well as the institutes to develop new energy conversion devices and environmentally friendly fuels. One of the methods to solve the crises is using a free-piston linear engine (FPLE). A free-piston linear engine is considered to be a crankless internal combustion engine with free motion of piston in cylinder. In terms of structure, the engine consists of two main components: the free-piston engine, and a linear alternator. Unlike conventional engines with a crankshaft mechanism, the combustion process of the FPLE can be optimized through the variable compression ratios [1]. Besides, the variation of compression ratios in FPLE also allows the engine to operate with various kinds of fuels as well as HCCI combustion [2]. In general, the FPLE can be classified into three types including single piston, dual piston and opposed piston [3]. Of these, the dual piston engine has a higher power/weight ratio than others [4]. However, the operation of the dual piston engine is mainly controlled by an electronic system, and the piston crown may hit the cylinder head if the piston is not controlled correctly [5]. Therefore, a damping device (e.g. metal spring) is needed to install in the engine for avoiding the collision between the piston crown and cylinder head. In a FPLE, one of the most important components is the linear alternator or linear generator, which is used to start up the engine in the beginning mode or motoring mode. Two kinds of linear alternators used in the FPLE are tubular-type and flat-type linear alternators. Therein, the flat-type linear alternator is rarely used in FPLE, although it has higher efficiency, output voltage, and current [6]. There were many previous studies for the dual piston engine using tubular-type linear alternator. Atkinson et al. [7] presented a parametric study of a spark ignition dual piston engine using the combination of two numerical models such as dynamic model and thermodynamic model. Shoukry et al. [8] established a series of dynamic and thermodynamic numerical equations to predict the behaviour of a direct injection dual piston engine over a wide operating range. In addition, there were many other simulation studies for the dual piston engine, which could be found in [9-12]. As can be seen above, most of the previous studies for the dual piston engine focused only on simulation as well as numerical analysis of this engine. Therefore, an experimental research is needed to conduct on a dual free-piston engine to find out how is the operation of the engine changed under real operating conditions.

This paper presents an experimental research for a power pack using the dual piston free-piston engine combined with the flat-type linear generators. Therein, the effects of the main parameters such as input caloric value, spark timing delay, equivalence ratio and air gap length on the electric power output and in-cylinder pressure of the linear engine are investigated. The linear engine uses propane as a fuel, because propane has a high octane number and can be easily mixed with air.

EXPERIMENTAL APPARATUS

The experimental apparatus consists of the free-piston engine with kind of dual piston, flat-type linear generators, ignition device, sensor parts, engine control parts and data acquisition parts.

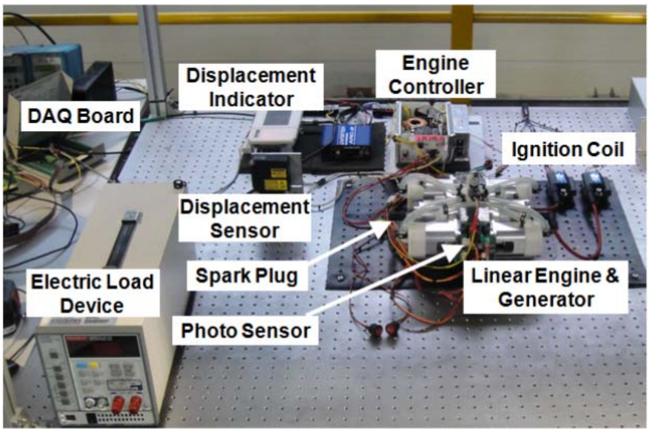

Figure 1 A picture of the experimental system

Figure 1 and Figure **2** show the photography and schematic diagram of experimental system, respectively. The specification of linear engine is shown in Table 1. Figure 3 shows a schematic of the free-piston linear engine. Therein, a spark plug is placed in the cylinder head to ignite the air/fuel mixture. A full stroke of the piston is 31mm and an effective stroke length is 18mm. The piston of the linear engine is combined with the translator of linear generator and is controlled by ECU through the linear generator. The schematic of the linear generator is shown in Figure 4. The linear generator consists of two main components, a stator and a translator. In the stator of linear generator, the copper windings are wrapped around the back iron made of silicon steel. The permanent magnets are mounted on the translator as a moving part.

In order to start the free-piston linear engine, the linear generator will operate to drive the free-piston engine through the connecting rod system. This stage is called the motoring mode. After certain frequencies, the spark plugs are activated, and the combustion process will occur alternatively at each cylinder, forcing the connecting rod to move back and forth. The movement of the connecting rod will generate current in the wires due to the changing magnetic flux linked with the wire in the stator. This stage is called the firing mode or electric power generation.

Table 1 The specification of the linear engine

Bore [mm]	30
Maximum stroke [mm]	31
Effective stroke length [mm]	18
Mass of translator [kg]	0.8
Scavenging type	Cross-scavenged type
Compression ratio	Variable
Maximum compression ratio	27.23

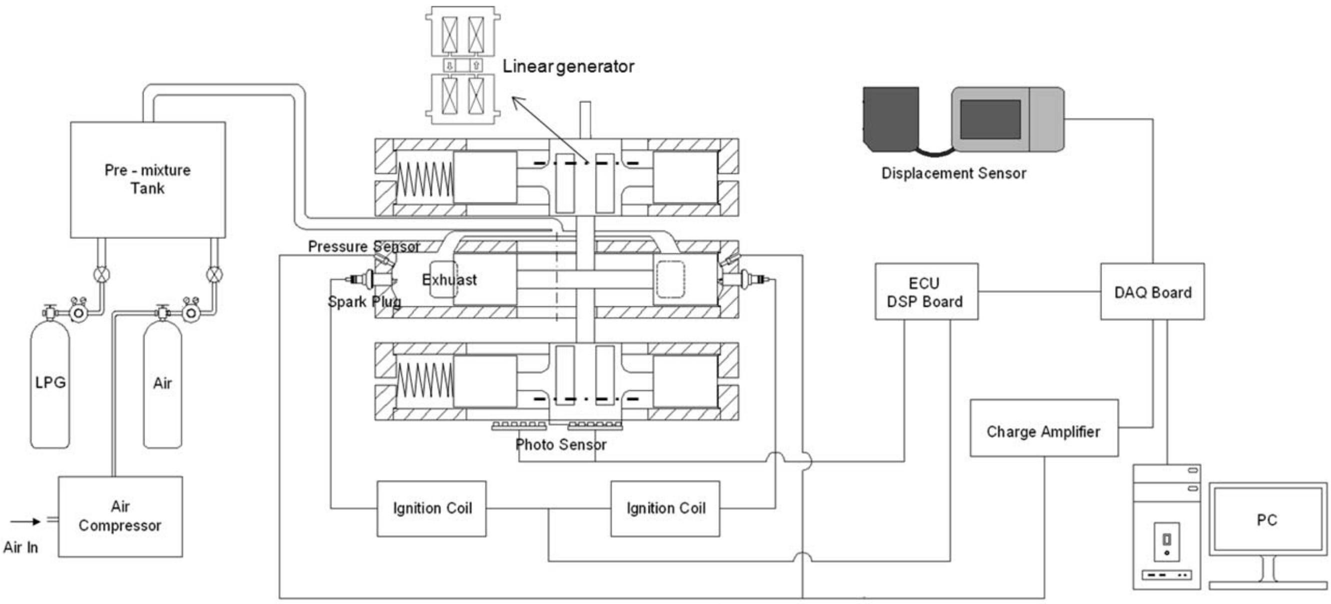

Figure 2 A schematic diagram of the experimental system

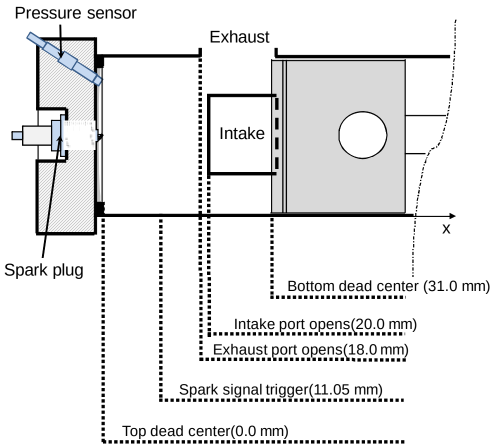

Figure 3 Schematic of the free-piston linear engine

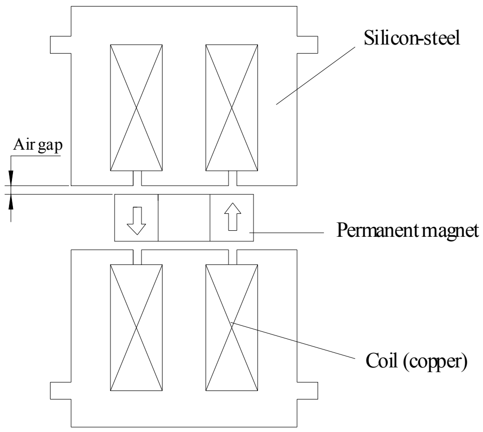

Figure 4 Schematic of the linear generator

EXPERIMENTAL METHODS

Firstly, for investigating the generating power according to the input caloric value and electrical resistance, the air-propane mixture was put into combustion chamber directly with the following conditions: 4.56, 5.21, 5.88 and 6.53kJ/s. The intake air flow rate was varied at 70, 80, 90, 100 liter per minute (lpm), while the equivalence ratio is fixed at 1.0. Concurrently, electrical resistance was applied from 5Ω to 40Ω. The other parameters such as spark timing delay and air gap length (Lair_gap) were fixed at 1.0ms and 2.0mm, respectively. Afterwards, the linear engine performance test was conducted.

Secondly, to investigate the effects of the spark timing delay on the generating power of the linear engine, the spark timing was varied at 0.5, 1.0, 1.5 and 2.0ms by using the Matlab/Simulink, which was installed at ECU (DSP board). According to the first experiments, the maximum electric power was induced when the equivalence ratio and electrical resistance were 1.0 and 20Ω, respectively. Besides, the air gap length and input caloric value were fixed at 2.0mm and 5.88kJ/s, respectively.

Thirdly, the experiment was performed to confirm generating power of the linear engine according to the equivalence ratio. The air flow rate was fixed as 90.0lpm before mixing with propane and input caloric value was varied at 4.70, 5.29, 5.88, 6.46, and 7.05kJ/s respectively. The equivalence ratio was varied from 0.8 to 1.2 with the increment of 0.1.

Finally, to investigate the effects of the air gap length on the generating power of the linear engine, experiment was performed. The air gap length was varied at 1.0mm and 2.0mm, while the electrical resistance was varied at 5, 10, 15, 20, 30 and 40Ω, respectively. The equivalence ratio was fixed at 1.0 by fixing the air flow rate and input caloric value at 90.0lpm and 5.88kJ/s, respectively. The spark timing delay was fixed at 1.5ms. To change the air gap length, a thin plate of 1.0mm was added between stator and engine body.

EXPERIMENTAL RESULTS

The effects of input caloric value

The input caloric value is varied at 4.56, 5.21, 5.88, 6.53kJ/s, while the equivalence ratio, spark timing delay and air gap length are fixed at 1.0, 1.5ms and 2.0mm, respectively. In order to provide more information for this study, the electrical resistance is varied from 5Ω to 40Ω with increment of 5Ω. The results are shown in Figure 5 and Figure 6.

As can be seen in Figure 5, the generating power at input caloric value of 5.88kJ/s is higher than others. This is because the velocity of translator is increased due to the increased in-cylinder pressure, which can be observed in Figure 6. The highest generating power is found at the input caloric value of 5.88kJ/s and electrical resistance of 20Ω, with the value of 90.48W, as shown in Figure 5. By increasing the electrical resistance from 20Ω to 40Ω, the generating power has a reduced tendency. To explain this, at first, it is needed to know that the electrical power output is considered a multiplication of electromagnetic force with velocity of translator [13], in which the electromagnetic force is considered a resistance force for the motion of translator. By increasing the electrical resistance from 20Ω to 40Ω, the electromagnetic force is decreased [14], and the decrement of the electromagnetic force is so much faster than the increment of velocity. As the result, the generating power has a reduced tendency.

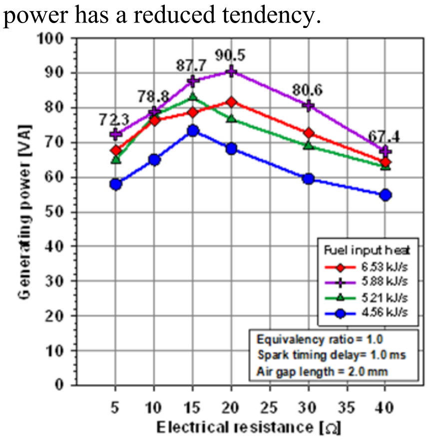

Figure 5 The effects of input caloric value on generating power

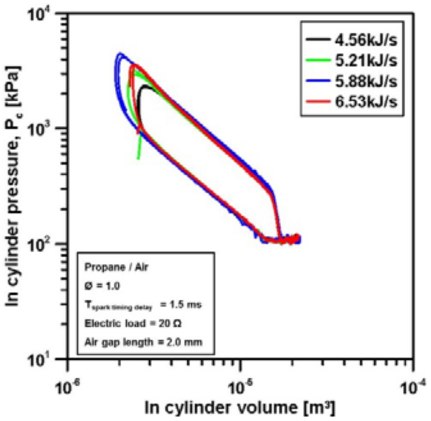

Figure 6 The effects of input caloric value on in-cylinder pressure

The effects of spark timing delay

In this experiment, the definition of the spark timing delay is as follows. When the translator combined with piston is reciprocated, a 5V signal is generated immediately after a thin plate stuck on the translator is detected by the photo sensors. This signal is sent to ECU to define the spark timing delay. The spark timing is delayed from 0.5 to 2.0ms with the increment of 0.5ms by using Matlab/Simulink.

The results for the generating power and in-cylinder pressure according to the spark timing delay can be seen in Figure 7 and Figure 8. Except the spark timing delay, the other conditions mentioned in the previous section such as electrical resistance, input caloric value, et al are retained same when the generating power is the peak value.

In the Figure 7, the highest generating power is 93.9W when the spark timing delay is 1.5ms. The highest generating power is a result of the highest in-cylinder pressure at the spark timing delay of 1.5ms, as shown in Figure 8. As can be seen in Figure 8, the in-cylinder pressure as well as the maximum stroke of the piston has an increased tendency as the spark timing is delayed from 0.5ms to 1.5ms. However, the maximum in-cylinder pressure and piston stroke are reduced as the spark timing is delayed to 2.0ms. This is because the combustion of air/fuel mixture at spark timing delay 2.0ms is more taken place in expansion process. As the result, the maximum in-cylinder pressure and piston stroke at spark timing delay 2.0ms are decreased, as shown in Figure 8.

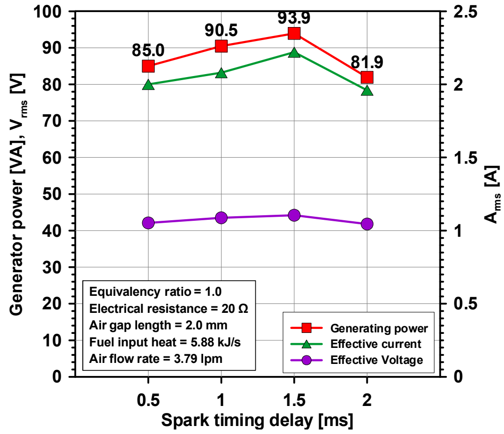

Figure 7 The effects of spark timing delay on generating power

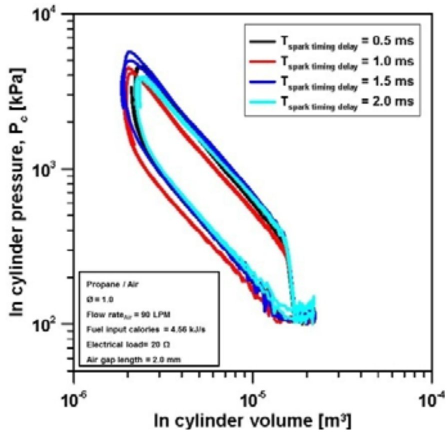

Figure 8 The effects of spark timing delay on in-cylinder pressure

The effects of equivalence ratio

The results for the generating power and in-cylinder pressure according to the equivalence ratio are shown in Figure 9 and Figure 10. In order to vary the equivalence ratio, the air flow rate is fixed at 90.0lpm, while the input caloric value is varied at 4.70, 5.29, 5.88, 6.46, 7.05kJ/s, respectively. Therefore, the equivalence ratio is varied from 0.8 to 1.2 with the increment of 0.1. The electrical resistance, air gap length and the spark timing delay are fixed at 30Ω, 1.0mm and 1.5ms, respectively.

As can be seen in Figure 9, the generating power is increased as the equivalence ratio is adjusted from 0.8 to 1.0. As the result, the generating voltage and current are increased. However, the generating power, voltage and current are decreased when the equivalence ratio is higher than 1.0. This is occurred as a result of decreasing in-cylinder pressure and piston stroke as the equivalence ratio is increased from 1.0 to 1.2, as shown in Figure 10. Figure 10 also shows that the combustion process is good at ideal air/fuel ratio.

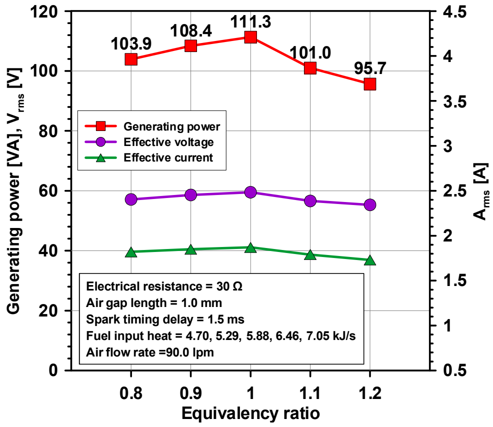

Figure 9 The effects of equivalence ratio on generating power

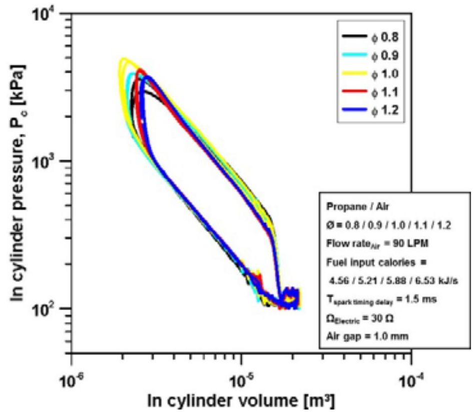

Figure 10 The effects of equivalence ratio on in-cylinder pressure

The effects of air gap length

The experiment is performed to investigate the generating power of the linear engine under the effects of air gap length, which is varied at 1.0mm and 2.0mm.

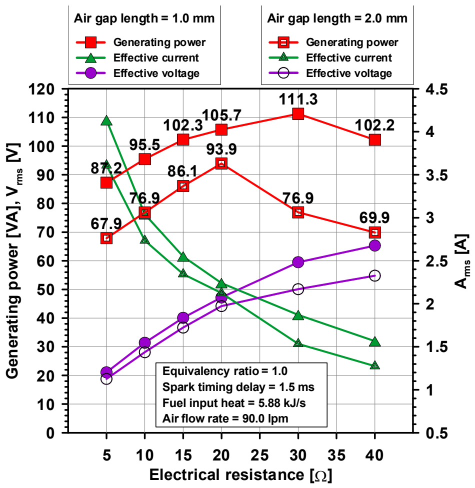

Figure 11 The effects of air gap length on generating power

In order to provide more information for this study, the electrical resistance is varied at 5, 10, 15, 20, 30 and 40Ω. The equivalence ratio is fixed at 1.0 by fixing the air flow rate and input caloric value at 90.0lpm and 5.88kJ/s, respectively, while the ignition timing delay is fixed at 1.5ms. The generating voltage and current were measured by varying the electrical resistance from 5Ω to 40Ω at each condition of the air gap length. The generating power was calculated through multiplication between the voltage and current.

As can be seen in Figure 11, the generating power is increased as the air gap length is decreased from 2.0mm to 1.0mm at each condition of electrical resistance. This is also appropriate with results obtained in previous study [6]. The highest generating power is obtained at the air gap length of 1.0mm and the electrical resistance of 30Ω.

In summary, the maximum generating power is 111.3 W when the experimental conditions are that the air gap length, electrical resistance, equivalence ratio and spark timing delay are 1.0 mm, 30 Ω, 1.0 and 1.5 ms, respectively.

CONCLUSION

The linear engine performance test was conducted by changing the parameters such as input caloric value, equivalence ratio, and electrical resistance, spark timing delay and air gap length. The results indicated that the electrical resistance has a negative effect on displacement and frequency of the translator if it exceeds a certain value. Besides, the experimental results also showed that the input caloric value, spark timing delay, equivalence ratio and air gap length had a considerable influence on the in-cylinder pressure as well as electrical power generation of the linear engine. The maximum generating power was found with the value of 111.3W at the input caloric value, spark timing delay, equivalence ratio, electrical resistance and air gap length were 5.88kJ/s, 1.5ms, 1.0, 30Ω and 1.0mm, respectively. Current work just focused on the generating power and finding the suitable conditions to optimize the generating power of the free-piston linear engine. The next stage of testing is to investigate dynamic behaviours and combustion characteristics of the linear engine. At the final stage, the test will be performed for exhaust emission and fuel efficiency of the linear engine. Furthermore, the various fuels will be used in the linear engine such as diesel, DME and hydrogen et al.

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