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A Preliminary Study of Spark-Ignition System for Free-Piston Linear Engine

Van-Trang Nguyen[1*], Huynh-Thi Nguyen[1], Thanh-Cong Huynh[2], Huu-Huy Dao[1]

[1]*Faculty of Vehicle and Energy Engineering, Ho Chi Minh City University of Technology and Education, Ho Chi Minh City, Vietnam*
[2] *Vietnam National University-Ho Chi Minh City Ho Chi Minh City, Vietnam*

[*] Corresponding author. *Email:* trangnv@hcmute.edu.vn

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ABSTRACT

In recent years, the free-piston linear engine (FPLE) has attracted increasing interest from researchers worldwide. With the development of computer control technology, internal combustion engine technology, and material science, there have been significant advances in the aspects of FPLE simulation, experimental techniques, as well as systems FPLE control. This paper presents a model of a two-stroke, spark-ignition free-piston engine converted from two small two-stroke engines. It has a bore size of 34 mm and a maximum stroke of 28 mm. The linear engine uses gasoline fuel that is available on the market. The purposes of the research show a model of the starting system, investigation the effects of spark timing, and effective pressure. A premixed air-fuel charge is conducted by a carburetor then it is directly supplied into each cylinder. The spark timing was varied at 1 mm and 2 mm away from the maximum top dead center with the speed starting at 10 Hz. The model successfully ignited with a maximum pressure of 7.5 kg/cm^2 at the ignition of 1 mm before top dead center (TDC) and 9.5 kg/cm^2 at the ignition of 2 mm before TDC. The research has completed the initial intentions such as a theoretical investigation, calculation, determination of the engine model, and starting mechanism. Preliminary results have confirmed the feasibility of proposing the FPLE model.

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1. Introduction

Linear engines aren't a new idea, it is first proposed in the early 1920s [1]. However, compared to conventional internal combustion engines; it is unnoticed because of some issues such as control, application... In recent years, due to environmental pollution and energy issues, research on alternative high-efficiency internal combustion engines is considered to be one of the most attractive research topics. Outstanding among them is a linear engine because the linear engine removed the crankshaft mechanism, which allows the piston to move freely inside the cylinder liner. This helps the engine reduce mechanical friction losses and variegates compression ratios under different load conditions, and fuel types [2]-[3]. Besides, researchers have started investigating it as a generator using a linear alternator used as an auxiliary power source in a hybrid.

Unlike traditional internal combustion engines, the lack of a crankshaft and a flywheel mechanism makes a linear engine not have a fixed rotation angle. Therefore, the control of top dead center (TDC) becomes complicated with a small deviation leading to the dynamics of the piston instability. The dynamics of the piston are determined by the resultant forces applied, such as the in-cylinder peak pressure, the electric load force, and the friction. In dual-piston linear 2 engines, TDC is considered the piston point of reverse movement. Thus, TDC in the current cycle depends on the previous cycle. In this model, the electric load force is removed. Therefore, the in-cylinder peak pressure is an important parameter to control the engine. The in-cylinder peak pressure is too high or low in this cycle will affect the load, and speed of piston movement in the cycle opposite. Similarly in engine 2, spark ignition, spark timing is an important factor affecting the formation of peak pressure in a cylinder [4]-[7]. Besides, a parameter considered is the initial compression pressure, high compression pressure and high density of air in the combustion chamber leading to short burning time, the peak pressure is formed earlier than expected. At present, the optimal controller for two-piston configuration linear motors is still the large challenge, although there are many research groups in this field through simulation or experimentation [8]-[11]. Some simulations focus on finding connections between kinetic influencing factors but still encounter difficulties in certain issues. Several studies have shown that a variety of factors affecting combustion and dynamics are needed to increase the stability of linear engines based experiments conducted [12]-[14].

In this paper, the ignition timing affects the FPLE combustion mentioned with the speed slow of the piston at a linear frequency 10Hz. A dual linear design was introduced, to simplify the dynamic factors so the generator was removed, instead of a mechanical starter system. The carburetor with high pressure is entered into the cylinder via a compressor. The effect of spark time, piston startup speed, pressure at ignition time, and ignition time are studied based on simulation. The simulation was performed with commercial software, MATLAB / SIMULINK, a designed model based on a Wiebe function used to simulate the combustion process. The resulting simulation will be the basis for the experiment conducted to consider the starting ability.

2. Development of Engine Model

The model is shown in figure 1, two engines and two-stroke forced ignition are placed at both ends. Friction between parts has minimum friction due to lubrication. A carburetor is used to distribute it before putting it into the cylinder. Varying the velocity of the airflow helps the pressure difference enter the carburetor and the nozzle of the nozzle. When opening the air inlet, it is put into the compressed air chamber and then compressed into the combustion chamber through the transfer port. A locking mechanism that locks the piston does not exceed the desired point - the top dead center.

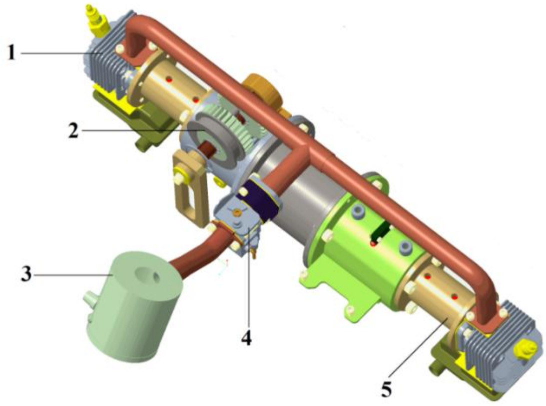

Figure 1. *A 3D model of two-stroke free piston engine*

1- Cylinder; 2- Starter mechanism; 3- Compressor; 4-Carburetor, 5- Compressed air chamber

Principle of operation, Stages first: the intake air is brought into the intake port by the compressor, and the air stream passes through the carburetor where the gas is mixed with the fuel. Then the mixture enters the compressed air chamber and the combustion chamber via the transfer port, and the compression stroke begins when the exhaust port and the transfer port close. Stages second: When the piston is on the TDC, the spark plug creates a high pressure that pushes the piston in the opposite direction and opens the valve, bringing the gas out of the cylinder.

A separate mechanical start-up system is presented, the failure to integrate the starter and separate it from the transmitter will help reduce the cross-section, and the weight of the transmitter, and reduce the complexity of control. However, it increases the shaft length and the mass of the shaft. Like a conventional engine at start-up, the linear engine must be set to a certain frequency to produce the necessary compression pressure by mechanical resonance [15]. The goal of the starter system in this design is to convert from rotary motion to linear motion. The conversion is made by a gear structure, which is shown in figure 2. The speed sensors located in the sensor chamber will check the motor speed, piston movement speed, and ignition position. When the engine starts successfully, the mechatronic mechanism will remove the gear from the gear bar when the piston moves freely in the cylinder.

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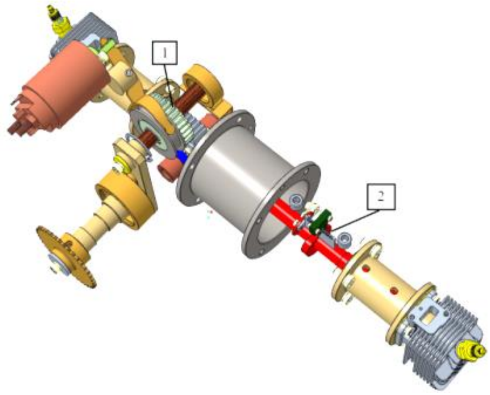

Figure 2. *Mechanical start-up of FPLE*

1- The starter mechanism; 2- The sensor chamber

3. Conceptual Design of the Ignition System

3.1. Design of Ignition System

In this model, the ignition system is no different from a conventional engine. The spark of ignition system is created from the 12V battery, ignition coil, control system, and spark plug. The model uses a transistorized ignition system (TI), with simple control advantages. Ignition signals are generated by a control program with signals based on position sensor, ignition time before TDC. The structure of the position sensor consists of an optical sensor and a gear bar with 1mm spacing that determine the position and movement. Based on, the signal from the position sensor, the ignition time before 1mm, 2mm before TDC, was chosen as the early ignition time for experimental simulation. The 5v signal generated using the primary control coil of the ignition coil will trigger a voltage of more than 30 kV in the secondary coil of the ignition coil. High voltage is transmitted to the spark plug electrode to ignite and ignite the charge in the cylinder. The ignition strategy is shown in Figure 3 and Control system diagram shows in Figure 4.

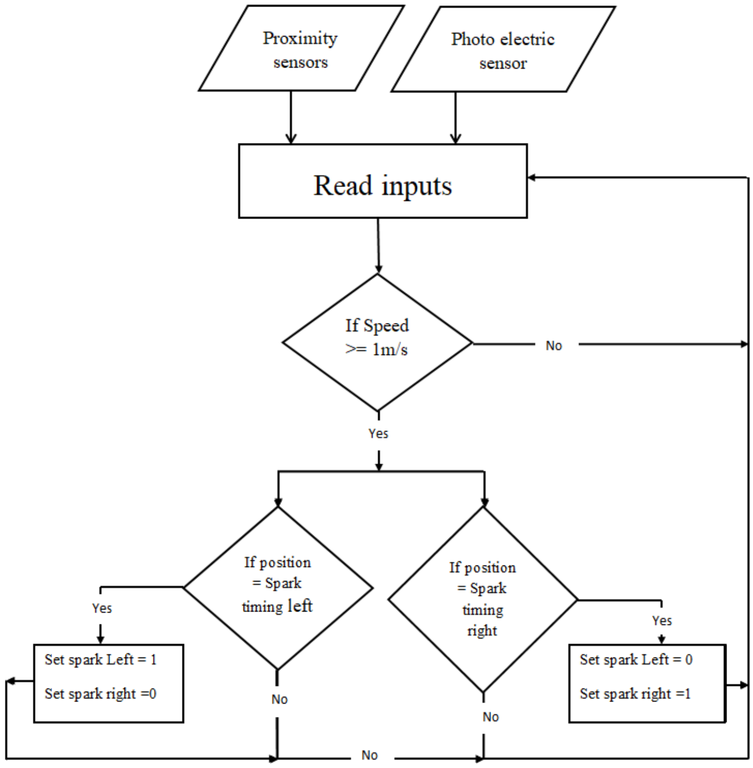

Figure 3. *The ignition control strategy*

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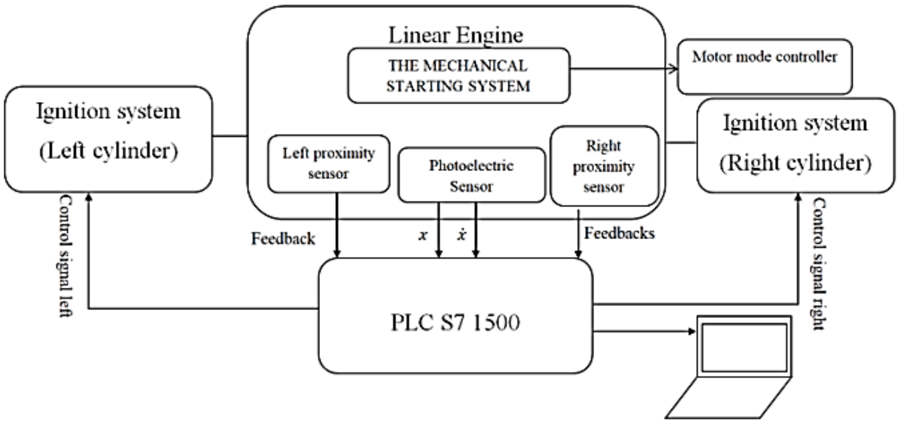

Figure 4. *Control system diagram*

3.2. Simulation

The simulation parameters of the model are shown in Table 1.

Table 1. *Free-piston engine specifications*

Description	Specification
Number of cylinder	2
Engine type	2 stroke
Bore	34 mm
Stroke	28 mm
Moving mass	0.58 kg
Nominal compression ratio	7.5:1
Fuel type	gasoline

The free-piston engine model is separated into a combustion chamber model to set initial parameter conditions such as piston displacement speed, ignition time, and compression pressure. Initial piston speed determined by the pull of the starter system, the previous combustion takes place after successful ignition.

Application in cylinders can be assessed by the derivative form of the first law of thermodynamics. The simulation will be based on Matlab/Simulinks software.

$$\frac{dy}{dx} = -\gamma.\frac{p}{V}.\frac{dV}{dt} + (\gamma - 1)\frac{Q_{in}}{V}\frac{dx_b}{dt} \quad (1)$$

P is in-cylinder pressure (MPa); γ is the specific heat ratio; V is in-cylinder volume (m^3); Q_{in} is the input heat energy; x_b is mass fraction burned (MFB). The combustion process, which simulates the mass fraction burned, is performed by the Wiebe function [16], [17].

$$x_b = 1 - \exp\left[-a\,.\,\left(\frac{t - t_s}{C_d}\right)^{b+1}\right] \quad (2)$$

C_d: is the combustion duration; t_s: is time to start ignition. The constants of a = 5 and b = 2 are used. These constants are widely used for general ignition engines and it has been shown that they correlate well with experimental data [18].

Initial experiments shown that the pressure at the start of the ignition is about 4.5 MPa at 1 mm and 2 mm BTDC with an engine speed of 10 Hz, this is the goal to be achieved for the ignition process to succeed. Simulated burning time (t-t_s) 5 ms, 10 ms, 15 ms, and 20 ms with 100% mass fraction burned.

It is assumed that the peak pressure is the pressure value that pushes the piston in the opposite direction. Therefore, the peak pressure must be released before the piston impacts with the top of the cylinder. In this simulation, TDC is the limit of displacement between the rack and pinion gears. The simulation in Figure 5 and Figure 6 shows a start speed of 10 Hz and successful ignition at 1 mm and 2 mm BTDC. At 2 mm BTDC is the best ignition timing because peak pressure is almost located at TDC. The peak pressure decreases when the burning time is long because most of the fuel burns when the starting device brings down the piston.

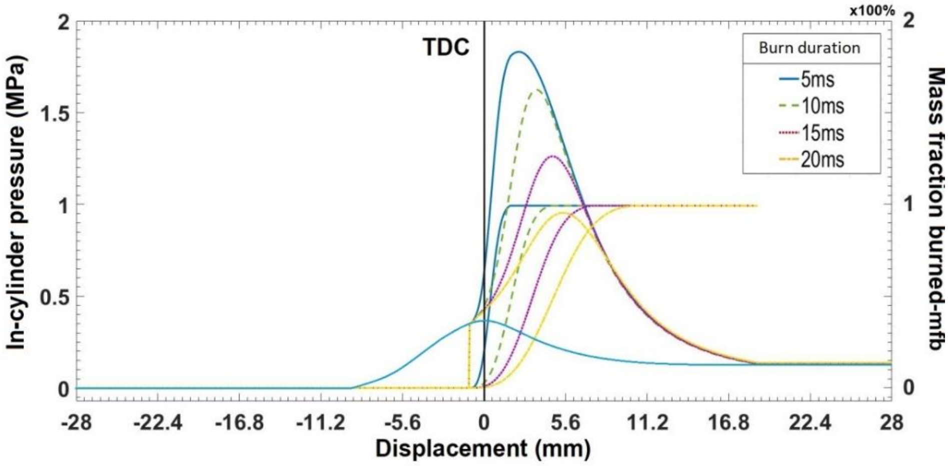

Figure 5. *The peak pressure at piston position of 1 mm BTDC*

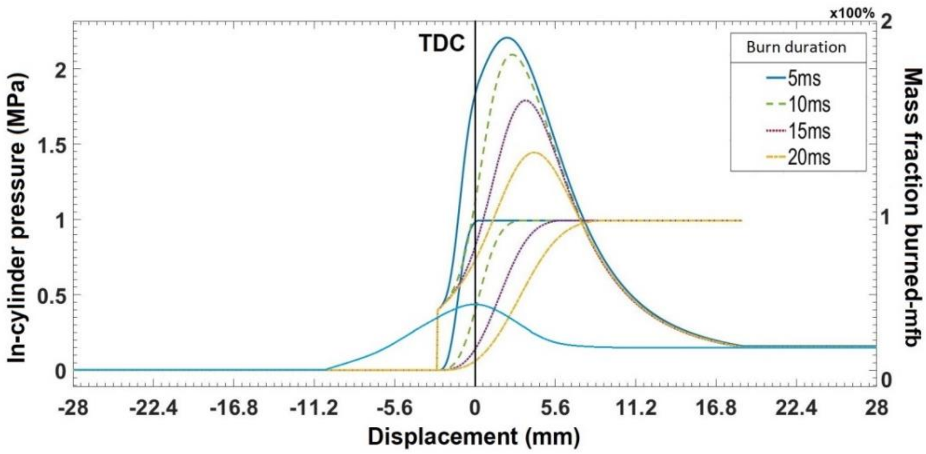

Figure 6. *The peak pressure at piston position of 2 mm BTDC*

In FPLE, the successful ignition of the first cylinder has influence on the opposite one, the raise of in-cylinder pressure resulted the increase of piston acceleration. If the ignition timing of the opposite cylinder is not changed, the engine will become unstable and collide with the peak cylinder. The impact of the piston on the blocking mechanism will suppress the inertial force so that the compression ratio is stable, reducing the possibility of fire loss, but the engine will not operate smoothly. In fact, FPLE does not need to form the maximum pressure, just a force greater than the pressure from the ignition pressure of the opposite cylinder, the piston can move backwards. Therefore, the appropriateness of the ignition timing is the decisive factor for the stable operation of the FPLE.

4. Results and Discussion

The experimental model of the mechanical starting system is shown in Figure 7. The data of piston displacement and piston velocity is measured through a photoelectric sensor Omron EE-SX670A and position sensor plate, the resolution of sensors 1 mm as show in Figure 4. The displacement direction uses 2 proximity sensors Hanyoung UP08RD-2PA for two-way displacement left and right. In-cylinder

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gas pressure is measured by the Sensys M5256 pressure sensor, the sensor is able to measure from 0 MPa to 3 MPa and it corresponds to the voltage range 0V to 5V. The data generated from the sensors is acquired by a PLC s7 1500 and synchronized with the real time.

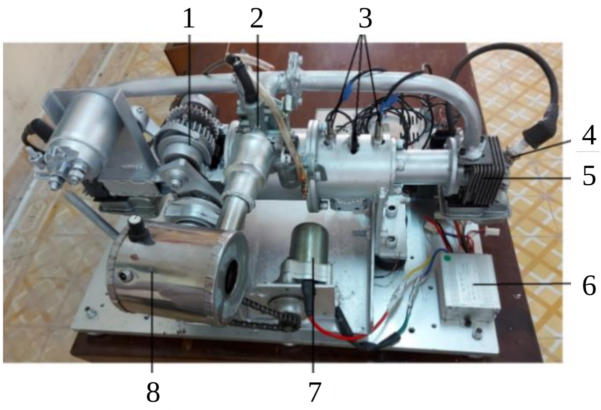

Figure 7. *Experimental model of PFLE*
1- Activation mechanism; 2-Carburetor; 3- Sensors; 4- Ignition system 5- Cylinder; 6-Motor mode controller; 7- Motor ; 8- Compressor

Figure 8 shows the maximum speed that can achieve 1 m/s equivalent to a frequency of about 10 Hz. The speed can be changed by changing the mode motor controller, however too high engine speed increases the force of inertia, affecting the airflow into the cylinder.

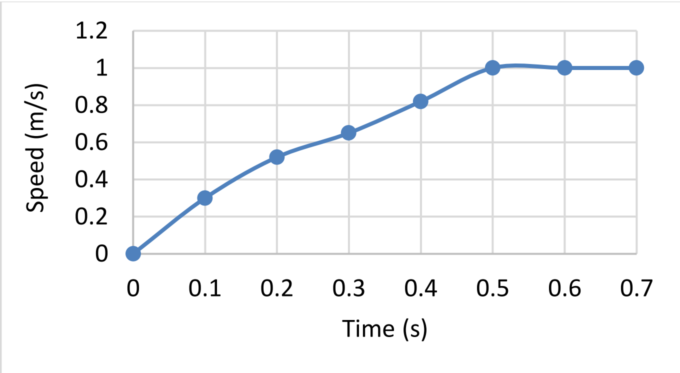

Figure 8. *Piston speed versus starting time*

In about 2 seconds, the maximum pressure reached 4.5 kg/cm^2 shown in Figure 9. Similar to other studies [19]-[21], the pressure in the cylinder to reach the maximum must have a certain number of oscillations. The maximum pressure between cylinder 1 and cylinder 2 is approximately the same, the maximum pressure in cylinder 1 reached 4.5 kg/cm^2 faster than in cylinder 2.

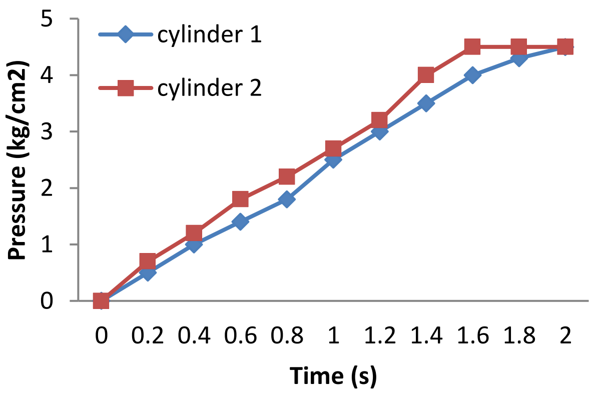

Figure 9. *Compression pressure in the cylinder and starting time*

Figure 10, and Figure 11 show the engine model has successfully started up. With the speed engine of 10 Hz, the maximum pressure when successful ignition reaches over 7.5 kg/cm^2 at the ignition of 1 mm BTDC and 9.5 kg/cm^2 at the ignition of 2 mm BTDC when the starting system is still working.

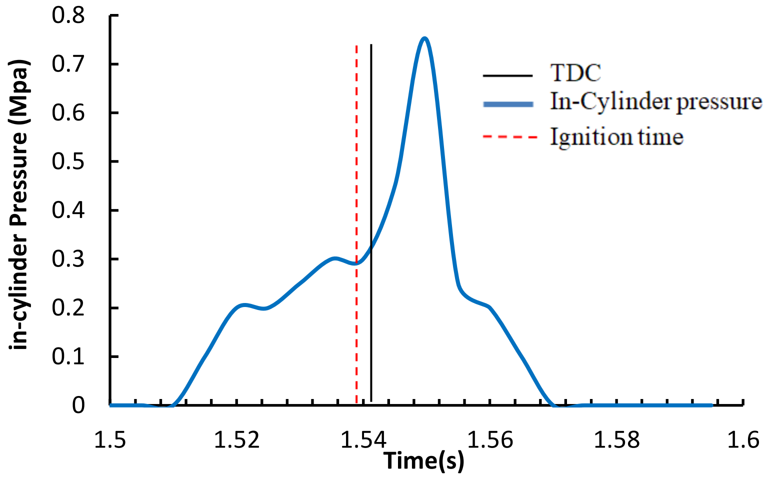

Figure 10. *Peak pressure for successful startup at 1 mm BTDC*

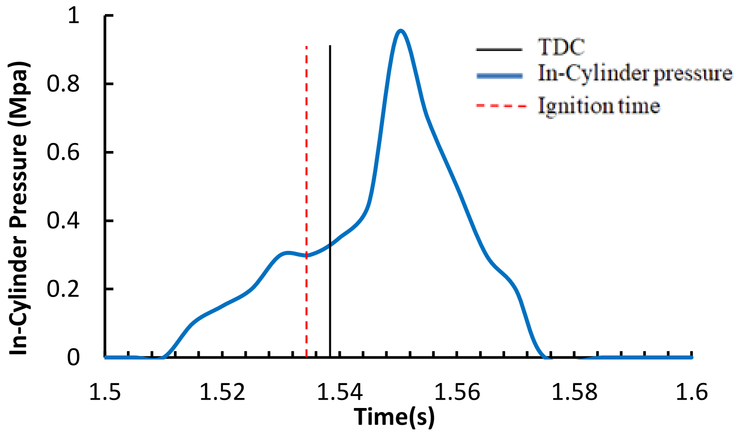

Figure.11. *Peak pressure for successful startup at 2 mm BTDC*

There is a no larger difference between the time of peak pressure formation. The engine misfire problem occurred quite a lot in the next ignition. There are many parameters affecting the ignition success such as the friction, injection time, and airflow into the cylinder. This study focused on the influence of ignition time on combustion, it can be seen that 2 mm pre-ignition timing before TDC will give higher peak pressure.

5. Conclusions

This paper presented a model of a two-stroke, spark-ignition free-piston engine converted from two small two-stroke engines. It has a piston with a 34 mm diameter and a maximum stroke of 28 mm. The spark timing was varied at 1 mm and 2 mm away from top dead center while the speed starting was varied at 10 Hz. The research showed that FPLE ignition was successful and reached over 7.5 kg/cm^2 and 9.5 kg/cm^2. The FPLE model has not yet reached a steady state caused by problems with ignition control, pressure and effect of the opposite cylinder. However, the results of this study may help the additional work for making the FPLE.

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Van-Trang Nguyen received his B.S. in Mechanical Engineering from Vietnam National University, Ho Chi Minh City University of Technology in 2002 and M.S. degrees from Ho Chi Minh City University of Technical Education (HCM UTE) in 2004 respectively. He then received his Ph.D degree from Yeungnam University, Republic of Korea, in 2014. He is currently a lecturer at the Ho Chi Minh City University of Technology and Education, Vietnam. His research interests focus on internal combustion engine, electric vehicle, and mechanical vibration.

Huynh-Thi Nguyen received the B.Eng and Master of Engineering in Faculty of Vehicle and Energy Engineering, in 2001 and 2006 respectively. He is a Ph.D student at Faculty of Vehicle and Energy Engineering in Ho Chi Minh City University of Technology and Education, Viet Nam.
Currently, his research interests include the Magnet Linear Generator and free-piston internal combustion engine.

Thanh-Cong Huynh received his B.S. degrees in Mechanical Engineering from Ho Chi Minh City University of Technology, Vietnam, in 2000. He received M.S degree in Thermal and Energy Engineering in L’Ecole Centrale de Lyon, France, in 2004. He received his Ph.D. degree in Thermal and Fluid Engineering in School of Mechanical Engineering (special in internal combustion engine), Sungkyunkwan University, Republic of Korea, in 2009. He has currently served as a Deputy Director of Department of Science and Technology, Vietnam National University – Ho Chi Minh City. Dr. Cong’s research interests include: next generation of internal combustion engines with higher thermal efficiency (free-piston, gas engines,...), electric vehicles...

Huu-Huy Dao received B.Eng and M.Eng in Faculty of Vehicle and Energy Engineering at Ho Chi Minh City University of Technology and Education, Viet Nam.
His research interests include the Magnet Linear Generator and free-piston internal combustion engine.