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DISSERTATION TITLE
RESEARCH AND EXPERIMENTAL MANUFACTURING OF FREE PISTON ENGINES

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SUMMARY
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INTRODUCTION

1. Reasons for Choosing the Topic

Under the impact of industrialization and modernization, the transportation system in Vietnam plays a crucial role in economic growth while also posing significant environmental and public health challenges. The search for solutions to improve energy efficiency and reduce pollution has become increasingly urgent. Environmentally friendly vehicles, such as electric and hybrid cars, are considered potential solutions but still face limitations, including large battery weight, long charging times, and limited operating range. In this context, the Free Piston Engine Generator (FPEG) emerges as a promising solution, offering high thermal efficiency, low friction, and a compact structure, making it suitable for charging electric vehicles. However, challenges related to the performance and stability of FPEG still require further research. Therefore, the study "Research and Experimental Fabrication of a Free Piston Internal Combustion Engine" is conducted to address these challenges, paving the way for widespread future applications.

2. Research Objectives

This dissertation provides a comprehensive analysis of the research gaps in previous studies to establish research hypotheses, set a central objective, and define specific goals as follows:

Research Gap:

The existing mechanisms for piston reversal and linear generators are overly complex. A simpler free piston engine structure is needed to reduce system complexity, facilitating the further development and optimization of free piston engines.

Research Hypotheses:

A mechanical starting mechanism can be designed to regulate the starting speed and ensure stable piston oscillation amplitude.

The opposing cylinder pressure can reliably reverse the piston motion without requiring a complex piston reversal assistance mechanism or a controlled linear generator.

Central Research Objective:

Based on the identified research gap and hypotheses, the dissertation aims to investigate the conditions under which the piston can autonomously reverse using the opposing cylinder pressure in a dual-cylinder free piston engine.

Specific Objectives:

Design and fabricate a prototype of a dual-piston, two-stroke, spark-ignition free piston engine capable of operating without a complex piston reversal assistance mechanism.

Develop a suitable starting mechanism and electronic control system to enable engine startup and operation under conditions that allow for reliable piston self-reversal.

Conduct experimental studies to evaluate the starting capability and operational stability of the prototype under no-load conditions, verifying the validity of the proposed piston self-reversal mechanism.

3. Research Subject and Scope

The study focuses on a small-scale (30 cm^3) dual-piston, two-stroke, free piston engine with forced ignition, operating on conventional gasoline fuel.

4. Scope of Research

Investigate and analyze the kinematic and dynamic characteristics of a small-scale, two-stroke, crankshaft-free engine (approximately 30 cm^3) with forced ignition.

Design and fabricate an FPE model and propose a mechanical starting mechanism.

Model and simulate the combustion pressure during the starting process and experimentally examine some key parameters of the starting process and no-load operation based on the designed model.

This study does not delve deeply into lubrication, cooling, or the theoretical foundations of combustion and heat transfer processes occurring inside the engine.

5. Research Methodology

This dissertation employs theoretical research, design, simulation, and experimental modeling, specifically as follows:

Theoretical Research: Study the dynamics of free piston engine engines, ignition theory, starting theory, and the combustion process theory of the engine.

Computational and Design Research: Calculate the fundamental engine parameters, the mechanical starting principle for the free-piston engine, and the parameters of the starting system and engine control.

Simulation Research: Utilize Matlab Simulink to simulate and evaluate the combustion process based on the design framework.

Experimental Research: Based on theoretical and simulation studies, fabricate an experimental model to validate the simulated parameters.

6. Scientific and Practical Significance of the Dissertation

Scientific Significance: Contributes to the methodological foundation for determining the conditions required for the piston to reverse direction in a dual-cylinder, crankshaft-free engine.

Practical Significance: The study's results provide a basis for the calculation, design, and control of a dual-cylinder, crankshaft-free engine without a piston reversing mechanism. This contributes to the development and optimization of the potential of dual-piston, two-stroke, crankshaft-free engines with forced ignition using a directed spark ignition system for power generation.

7. Structure

Introduction
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Chapter 1: Overview
Chapter 2: Theoretical Basis
Chapter 3: Research on Modeling and Simulation of Crankshaft-Free Internal Combustion Engine (FPE)
Chapter 4: Experimental Research
Conclusion and Future Directions

Chapter 1: Overview

This chapter provides an overview of the fundamental information related to free piston engines, along with recent research advancements in this field. Published studies on modeling, design, and prototype testing, as well as control strategies for free piston engines, are summarized and analyzed. The objective of this review is to present a comprehensive overview of the current state of research while identifying key challenges to serve as a foundation for proposing appropriate future research models.

1.1. The History of the Free Piston Engine Development

The Free Piston Engine - FPE is an internal combustion engine that operates based on the linear motion of the piston assembly without the use of a crankshaft. First proposed in the 1930s, the FPE was initially employed in air compressors and gas generators. This engine type offers superior thermal efficiency compared to conventional internal combustion engines, achieving approximately 40%–50% efficiency, whereas traditional engines typically range from 30%–40%. Recent advancements in control technology and real-time drive systems have enabled the further development of FPE as a viable alternative to traditional powertrains. Currently, FPE is being researched and applied in power generation and hydraulic systems, particularly in hybrid electric vehicles, due to its potential for reducing energy consumption and minimizing environmental impact.

1.2. Evaluation of Advantages and Disadvantages of the Free piston engine

The Free piston engine (FPE) offers several outstanding advantages due to its design, which eliminates the crankshaft mechanism. This reduction leads to lower frictional losses, minimized heat transfer losses, and optimized compression ratio. Additionally, the engine features a compact structure, reduced maintenance costs, improved reliability, and the capability to operate with multiple fuel types. However, FPE also presents significant technical challenges, particularly in ignition and fuel injection control, as it lacks a crankshaft reference. Issues such as engine startup, piston motion control, piston reversal assistance, and operational stability must be addressed. The development of advanced control systems and sensor technologies is crucial to overcoming these limitations, paving the way for broader applications in the future.

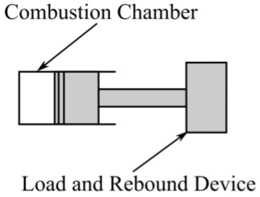
1.3. Free Piston Linear Generator (FPEG)

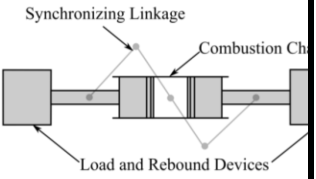
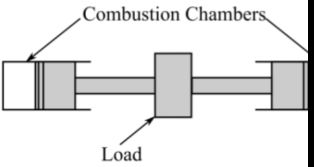
1.4. Research Status Related to the Topic

1.4.1. Evaluation of Piston Configurations

According to research findings, Free Piston Engines (FPEs) can be classified into three types based on piston configuration: single-piston, dual-piston, and opposed-piston designs. The structural diagrams and a comparative evaluation of the advantages and disadvantages of each type are illustrated in Table 1.1. The dual-piston configuration eliminates the need for a reversal mechanism, as the power stroke of one piston drives the compression process in the opposite cylinder. This design enables a simpler and more compact system with higher efficiency. Therefore, this configuration is chosen for further development.

Table 1.1: Types of Free Piston Engines - FPEs

Type	Representation	Comments
Single piston		• Simple and easy to control • Unbalanced operation • Possible use of counterweights • Requires a recovery mechanism to assist piston reversal for continuous operation

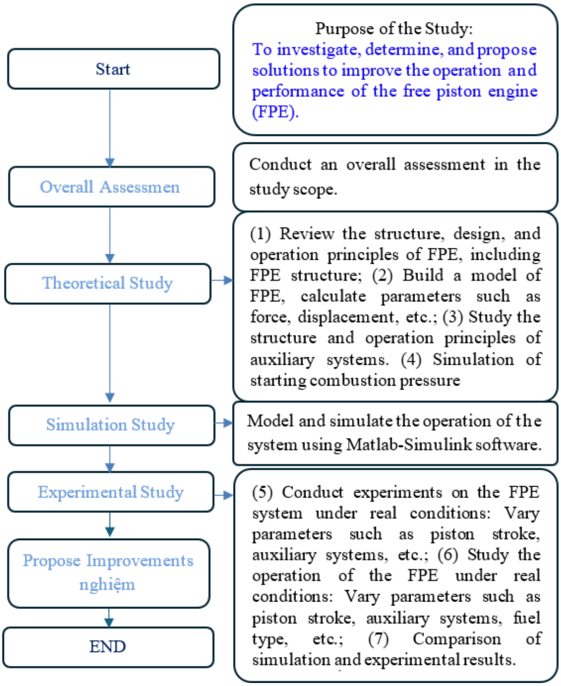
Opposed piston		• Balanced center of mass • No oscillation with equal piston masses • Requires piston synchronization • Needs a recovery mechanism to assist piston reversal for continuous operation
Dual pistons		• Higher power density • Potentially higher efficiency; unbalanced operation • Self-sustaining without the need for a piston reversal mechanism • Relatively difficult to control

1.4.2.Selection of the Starting Principle

This study focuses on the dual-piston free piston engine (FPE) with forced ignition. A mechanical starting mechanism is proposed, incorporating both strategies mentioned above. This mechanism is designed to ensure the piston completes its full stroke and achieves stable linear oscillation.

1.5. Establishing the Research Direction

This research direction not only focuses on the development and improvement of the dual-piston FPE model but also emphasizes finding a reliable starting method. Figure 1.1 illustrates the research orientation and approach of this study.



Purpose of the Study: To investigate, determine, and propose solutions to improve the operation and performance of the free piston engine (FPE).

Conduct an overall assessment in the study scope.

(1) Review the structure, design, and operation principles of FPE, including FPE structure; (2) Build a model of FPE, calculate parameters such as force, displacement, etc.; (3) Study the structure and operation principles of auxiliary systems. (4) Simulation of starting combustion pressure

Model and simulate the operation of the system using Matlab-Simulink software.

(5) Conduct experiments on the FPE system under real conditions: Vary parameters such as piston stroke, auxiliary systems, etc.; (6) Study the operation of the FPE under real conditions: Vary parameters such as piston stroke, auxiliary systems, fuel type, etc.; (7) Comparison of simulation and experimental results.

Figure 1.1 Research Orientation of the Dissertation

1.6. Chapter 1 Conclusion

Chapter 2: Theoretical Basis

This chapter presents fundamental theoretical background on the free piston engine, analyzes and evaluates previous studies, and provides a comprehensive overview of the potential and challenges of FPE technology. These insights lay the foundation for proposing and developing the FPE design model in this research.

2.1. Động lực học động cơ không trục khuỷu

The forces acting on the Free Piston Linear Engine (FPLE) include:

- Force exerted by the gas in Cylinder 1 F_{p1} và Cylinder 2 F_{p2}
- Friction force: F_f, caused by the contact between moving surfaces
- Electromagnetic force: F_{cog}, generated by the linear generator coil
- **Inertial force**: $m\ddot{x}$, due to the reciprocating motion of the moving mass

Newton’s Second Law Applied to the Moving Mass:

$$m\overrightarrow{\ddot{x}} = \overrightarrow{F_{p1}} + \overrightarrow{F_{p2}} + \overrightarrow{F_f} + \overrightarrow{F_{cog}} \quad (2.1)$$

2.2. Theory of Combustion Process in Spark-Ignition Engines

2.2.1. Thermodynamic System of Internal Combustion Engines

2.2.2. Thermodynamic Cycle of Spark-Ignition Engines

2.3. Simulation Objectives

2.4. Dynamics of the FPE Model

The piston is controlled to oscillate from the top dead center (TDC) to the bottom dead center (BDC) or vice versa with a fixed displacement. The motion of the piston can be approximated as simple harmonic motion (sinusoidal form) and is expressed as:

$$x_s = A\times(1-\frac{1}{\varepsilon})\sin(2\pi f\times t) \tag{2.2}$$

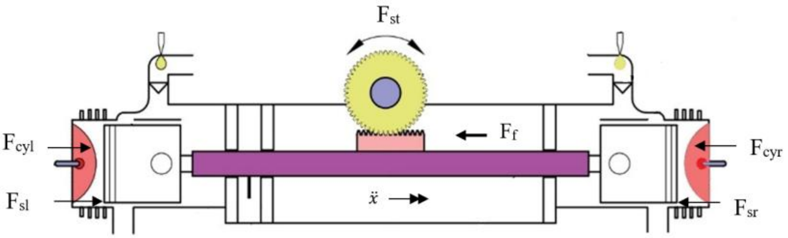


Figure 2.1: FPE Dynamics Diagram

The dynamics of a piston can be determined using Newton's second law.

$$F_{st} - F_{sl} - F_{sr} - F_f = m\frac{d^2x}{dt^2} \text{ (starting process)} \tag{2.3}$$

$$F_{cyl} - F_{cyr} - F_f = m\frac{d^2x}{dt^2} \text{ (operating process)} \tag{2.4}$$

$$F_{cyl} = P_{cyl} \times S \tag{2.5}$$

$$F_{cyr} = P_{cyr} \times S \tag{2.6}$$

$$P_{cyl} = P_{lcp} + P_{lh} \times \sigma_l \tag{2.7}$$

$$P_{cyr} = P_{rcp} + P_{rh} \times \sigma_r \tag{2.8}$$

$$\sigma_l = \begin{cases} 1, & \frac{dx}{dt} \geq 0 \\ 0, & \frac{dx}{dt} < 0 \end{cases}$$

$$\sigma_r = \begin{cases} 1, & \frac{dx}{dt} \geq 0 \\ 0, & \frac{dx}{dt} < 0 \end{cases}$$

$$F_{cyr}\,(\sigma_r = 0) \le m\,\frac{d^2x}{dt^2} \le F_{cyr}\,(\sigma_r = 1) \qquad (2.9)$$

2.5. Cylinder Combustion Pressure Model

The pressure change in the cylinder due to the combustion of FPE can be obtained as a derivative of the first thermodynamic equation:

$$\frac{dp}{dt} = -\gamma\,\frac{p}{V}\,\frac{dV}{dt} + (\gamma - 1)\,\frac{Q_{in}}{V}\,\frac{dx_b}{dt} \qquad (2.47)$$

Trong đó:

p: In cylinder pressure (bar)
$\gamma = 1,4$: heat capacity ratio
V: cylinder volume (m^3)
Q_{in}: heat input
x_b: mass fraction burned – mfb

In the combustion process, the simulation of the burned mass fraction is performed using the Wiebe function:

$$x_b = 1 - \exp\left[-a\left(\frac{t - t_s}{C_d}\right)^{b+1}\right] \qquad (2.10)$$

Trong đó:

C_d: % Combustion duration
t_s: Start of ignition

The constants of a = -5 and b = 2 are used. These constants are widely used for spark-ignition engines in general, and it has been proven that they correlate well with experimental data. The simulation flowchart and the Matlab Simulink simulation model.

2.6. Chapter 1 Conclusion

This chapter introduces the dynamic models of a free-piston engine (FPE), providing an important theoretical foundation for simulating and analyzing FPE in research. The combustion simulation model of the FPE during the startup phase is developed based on the first law of thermodynamics combined with the Wiebe function, and the entire simulation system is implemented on the Matlab Simulink platform.

Chapter 3. RESEARCH ON MODELING AND SIMULATION OF FREE-PISTON ENGINE (FPE)

In this section, the parameters of the mechanical starting mechanism are calculated and designed in detail. After completing the design, the FPE model was fabricated and underwent initial testing to determine key parameters such as compression pressure and initial startup speed—factors that play a crucial role in the engine's operational efficiency.

A control method for the startup and operation of the FPE is also proposed to ensure the engine maintains stability throughout its operation. The initial technical parameters, once calculated and verified through experimentation, will serve as a critical foundation for pressure simulations during combustion, as well as further investigations into the startup and operation processes, which are presented in Chapter 4.

3.1. Các thông số cơ bản của động cơ

The FPE model is shown in Figure 3.1, utilizing two-stroke engines with a spark ignition system.

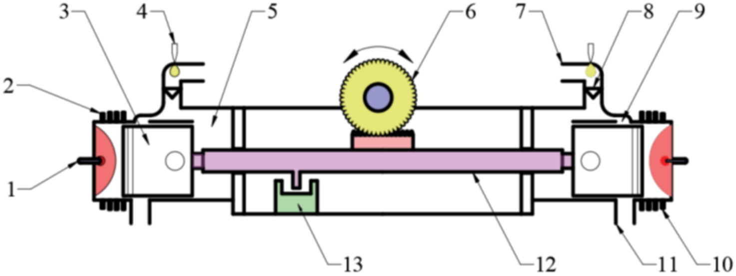


Figure 3.1: Schematic diagram of the FPE
1. Spark plug; 2. Cylinder; 3. Piston; 4,8. Fuel injection; 5. Scavenging chamber; 6. Mechanic starting; 7. Air-intake port; 9. One-way valve; 10. Scavenging port; 11. Exhaust port; 12. Main connection shaft; 13. Piston displacement fixed mechanism.

Table 3.1: Engine specifications

Number of cylinders	2
Type of engine	2 stroke
Bore	34 mm
Motoring Stroke	22mm
Maximum Stroke	30 mm
Moving mass	0.5 kg
Maximun compression ratio	9.5:1
Fuel	gasoline

3.2. Mechanical Starting Principle for the FPE Model

The mechanical starting principle for the free-piston engine (FPE) model is as follows: Fundamentally, the mechanical starting system for the FPE is a Culit mechanism, designed to ensure a displacement amplitude of 22 mm, as illustrated in Figure 3.2.

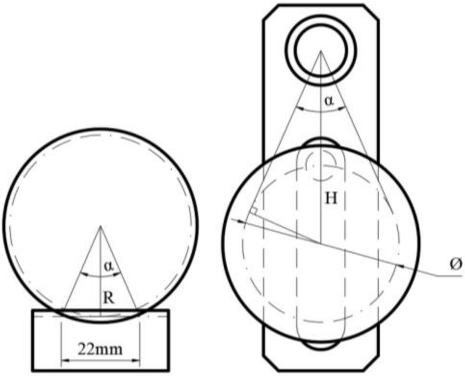


Figure 3.2: Coulisse mechanism

3.3. Main Components of the Model

3.3.1. Piston-Cylinder Assembly

3.3.2. Intake Chamber

3.3.3. Anti-Rotation Mechanism

3.3.4. Main Shaft

3.3.5. Stroke Limiting Mechanism

3.4. Design of the Mechanical Starting System for the FPE Model

3.4.1. Calculation of the Final Compression Pressure in the Startup Process

3.4.2. Eccentric Shaft Assembly and Culit Mechanism

3.4.3. Selection of the Starter Electric Motor

3.5. Control of the FPE Model

3.5.1. Control System

Stage One: The starting mechanism follows the resonance startup principle, where the piston is driven at a maximum linear speed of approximately 0.7 m/s, maintaining a constant starting force of 435 N. The piston is driven by an electric motor combined with a chain transmission system, enabling a constant displacement amplitude of 22 mm (with the piston 9 mm from the upper limit), achieving a low compression ratio of $\varepsilon = 3$.

Stage Two: Fuel is injected into the intake pipe to form an air-fuel mixture. Due to the pressure difference in the intake chamber, the mixture is drawn into the intake chamber and retained by a one-way valve. During this phase, the piston continues its linear motion, pushing the air-fuel mixture into the combustion chamber through the scavenging port.

Stage Three: The electromagnetic clutch in the mechanical starting mechanism disengages from the main shaft, and ignition occurs immediately, transitioning the engine into its free-piston operation mode. These stages are illustrated in Figure 3.3..

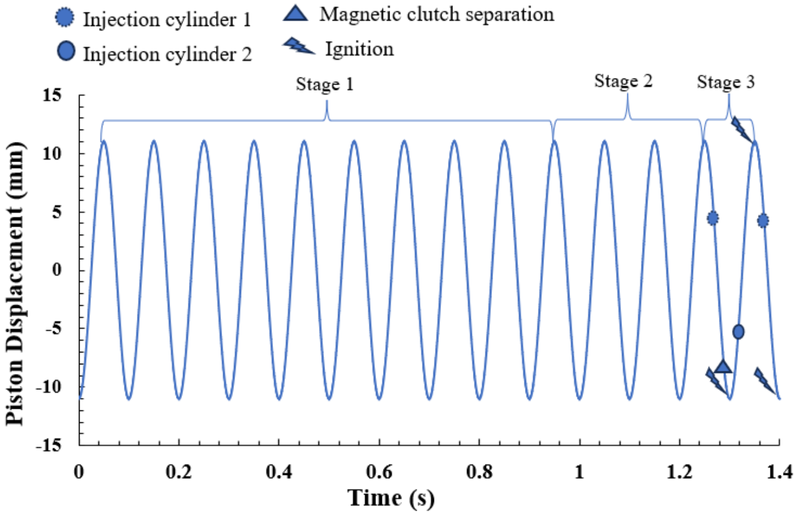


Figure 3.3: Control Strategy for the FPE Model

3.5.2. Control of the Fuel Injection and Electronic Ignition System

3.5.3. Control of the Fuel Injection System

3.6. Simulation of the Combustion Process During FPE Startup

3.6.1. Objectives and Scope of the Simulation

The simulation serves as the initial basis for evaluating whether the proposed mechanical startup method is suitable for the FPE model. The simulation parameters are presented in the following table:

Table 3.2: Simulation Parameters of the Initial Combustion Process

Technical Parameter	Symbol	Value
Startup Frequency (Hz)	f	10
Startup Compression Ratio	ε	≈ 3
Final Compression Pressure (bar)	pc	4
Combustion Duration (ms)	t	2 – 5
Fuel Input Mass (mg)	mf	2 – 4
Specific Heat Ratio	γ	1.4

Lower Heating Value of Gasoline (MJ/kg)	LHV	43.96

3.6.2. Experiment on the Final Compression Pressure in the Startup Process

Experiments were conducted at four linear frequencies: 5 Hz, 8 Hz, 10 Hz, and 12 Hz. The frequency was adjusted by changing the gear ratio between the electric motor and the starting mechanism, as illustrated in Figure 3.4.

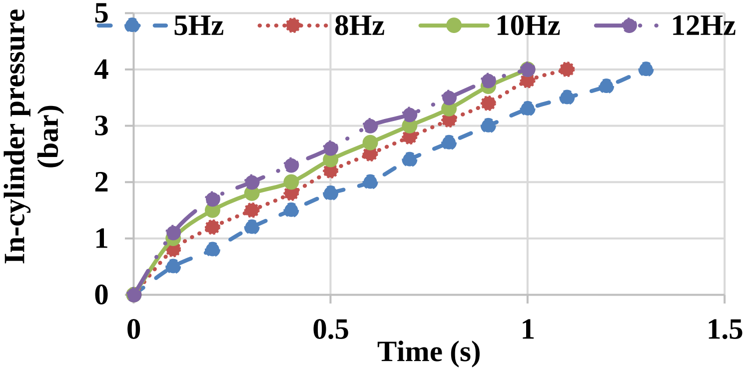


Figure 3.4: Graph of Startup Pressure Attainment Time at Different Frequencies

3.6.3. Simulation Results

The ignition timing is determined when the piston reaches 22 mm (9 mm from TDC), corresponding to a piston displacement time of over 50 ms, as shown in Figure 3.5. The startup speed at 10 Hz (with a piston velocity of approximately 0.7 m/s) is also illustrated in Figure 3.6.

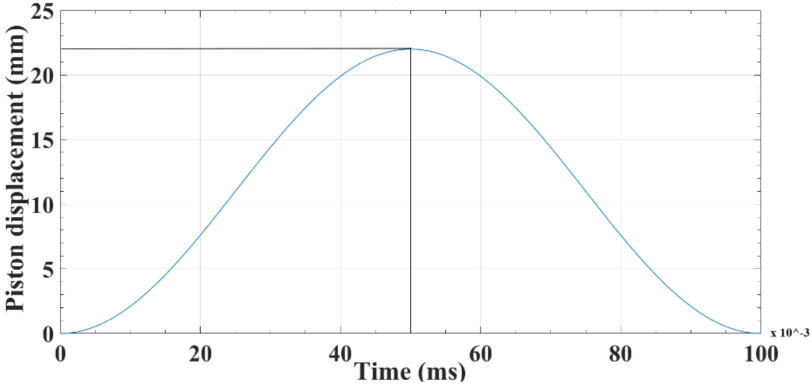


Figure 3.5: Piston Displacement Time During the Startup Process

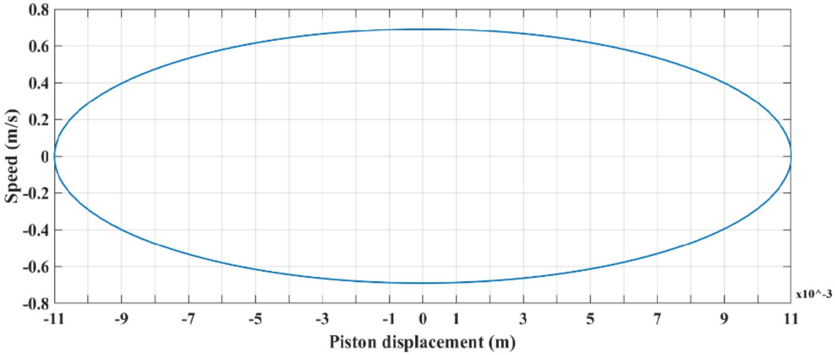


Figure 3.6: Piston Velocity and Displacement During the Startup Process

Điều kiện để FPE duy trì hoạt động sau lần đánh lửa đầu tiên:

$$F_{cyr} > m\frac{d^2x}{dt^2} + F_{sl}$$

$$F_{cyl} > m\frac{d^2x}{dt^2} + F_{sr}$$

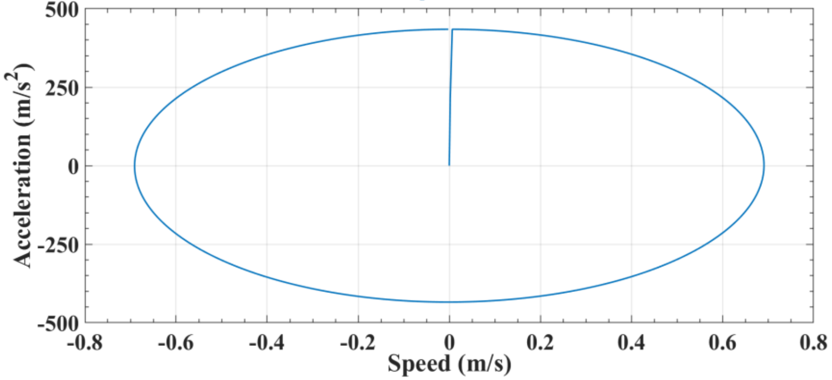


Figure 3.7: Piston Velocity and Acceleration During the Startup Process

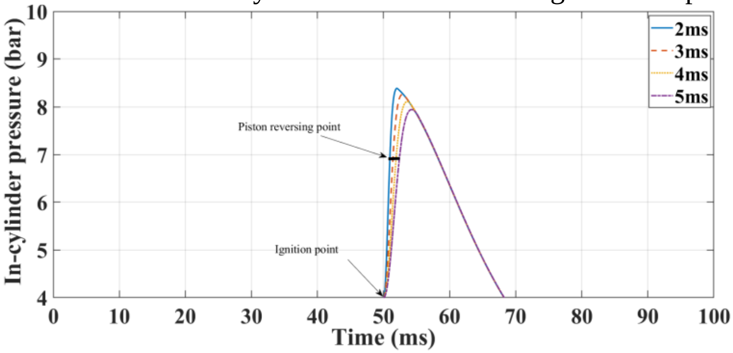


Figure 3.8: Simulation Results of Cylinder Pressure with a Fuel Injection Quantity of 2 mg, Combustion Duration of 2 ms – 5 ms, Initial Pressure of 4 bar, and Startup Frequency of 10 Hz

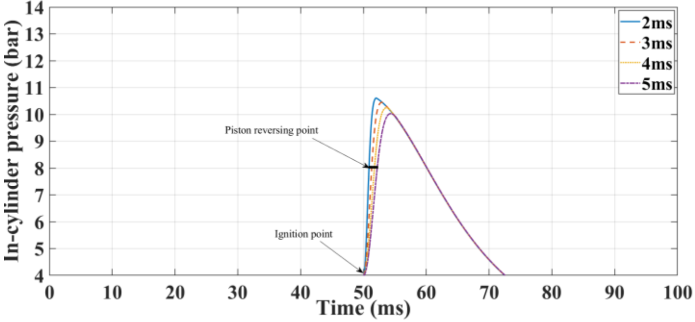


Figure 3.9: Simulation Results of Cylinder Pressure with a Fuel Injection Quantity of 3 mg, Combustion Duration of 2 ms – 5 ms, Initial Pressure of 4 bar, and Startup Frequency of 10 Hz

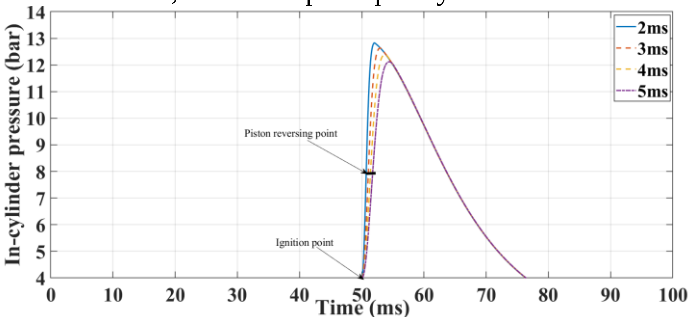


Figure 3.10: Simulation Results of Cylinder Pressure with a Fuel Injection Quantity of 4 mg, Combustion Duration of 2 ms – 5 ms, Initial Pressure of 4 bar, and Startup Frequency of 10 Hz

3.7 Chapter 3 Conclusion

This chapter presents the design and fabrication process of a free-piston engine (FPE) model with a unique configuration. The model features a dual-piston, two-stroke engine with spark ignition, utilizing a self-developed mechanical starting mechanism.

To study the engine’s operation, kinematic and thermodynamic simulations were conducted using the Wiebe combustion model in the Matlab Simulink environment. The simulation results indicate that the engine can achieve stable startup when the mechanical starting mechanism operates at a frequency of 10 Hz. Furthermore, when the injected fuel quantity per cycle ranges from 2 mg to 4 mg, the engine can sustain continuous operation, ensuring high efficiency during its performance.

Chapter 3. EXPERIMENTAL STUDY

In this chapter, a series of experiments were conducted to examine key factors such as pressure, engine speed, fuel injection quantity, ignition timing, and more. These experiments were carried out under two different operating modes: startup mode and engine running mode.

Controlling these parameters in both modes is crucial for evaluating engine performance. In startup mode, specific adjustments are required to ensure that the engine can start easily and stably, even under varying environmental conditions. Meanwhile, in engine running mode, parameters such as pressure and ignition timing must be fine-tuned to maintain optimal engine operation.

4.1. Objectives and Scope of the Experiment

The experiment was conducted to investigate key parameters in two phases: the startup phase and the operating phase. In the startup phase, the first ignition after clutch disengagement is critical. High precision is required in this phase because if the clutch does not fully disengage, the piston may fail to reverse direction or only reverse with insufficient inertial force, preventing the engine from starting.

4.2. Experimental Model Setup

The FPE experimental model is presented in Figures 4.1 and 4.2.

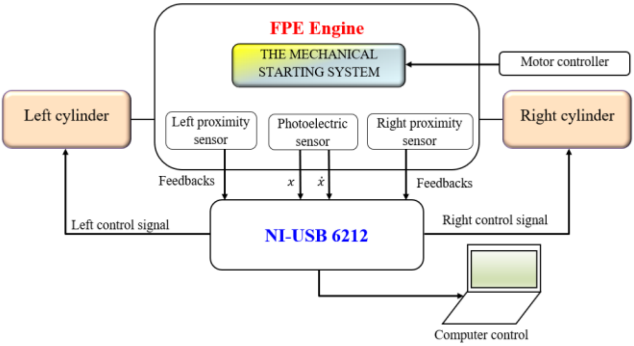


Figure 4.1: FPE model control structure

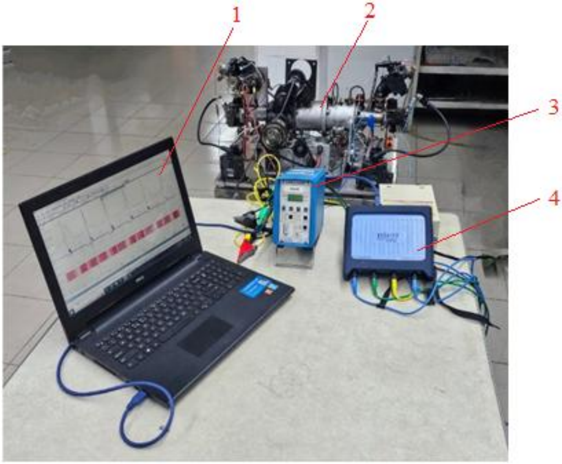


Figure 4.2: Experimental model of FPE
1. Computer, 2. FPE Model, 3. Kistler 5010 Amplifier, 4. PicoScope 4425 Pulse Measurement Unit

In the experiments, ignition timing was determined by detecting the first spark occurrence. The FPE data acquisition system, developed using LabView software, is integrated with the PicoScope 4425 data acquisition device. To measure cylinder combustion pressure, the AVL-ZF43 pressure sensor (shown in Figure 4.3 and detailed in Table 4.1) was used in combination with the Kistler 5010 amplifier. A high-resolution encoder (0.2 mm/pulse) was installed on the engine to provide position and velocity data. Control signals and sensor data were transmitted to the computer via the NI-USB 6212 device.

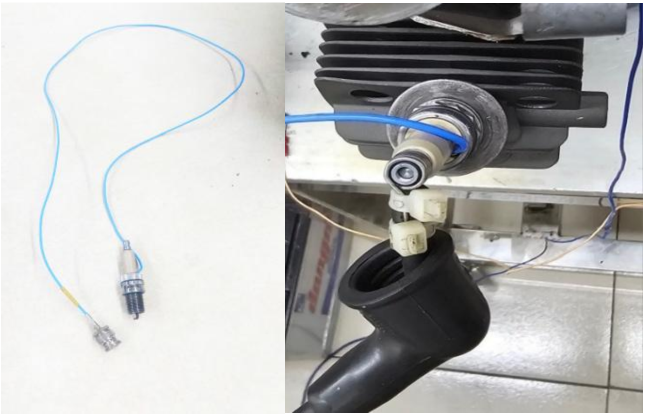


Figure 4.3: AVL-ZF43 sensor

Table 4.1: Technical Specifications of the AVL-ZF43 Sensor

Specification	Value
Measurement Range	0…250 bar
Sensitivity	16 pC/bar
Accuracy	±0.3%
Frequency Response	115 kHz
Operating Temperature	-40°C…400°C

4.3. Fuel Injection Determination

4.3.1.Fuel Injection Experiment

When the control signal is sent to the actuator (injector), a response time is required, resulting in a discrepancy between the commanded injection duration and the actual injection duration. Therefore, an experiment is necessary to accurately determine the actual fuel injection quantity corresponding to the injection time.

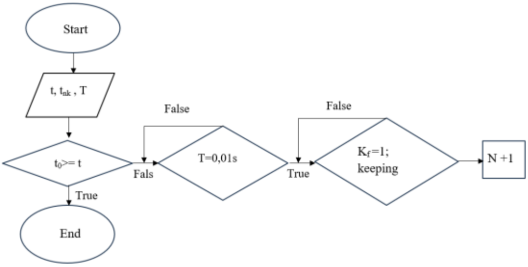


Figure 4.4: Fuel Injection Measurement Experimental Setup Diagram

The experiment was conducted with various injection durations to collect comparative results, which are presented in Figure 4.5.

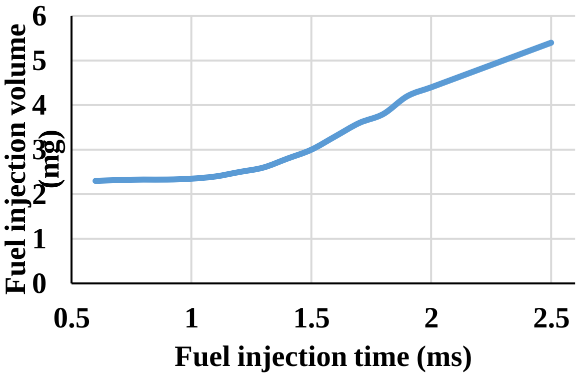


Figure 4.5: Fuel Injection Quantity Over Time

4.3.2.Air-Fuel Ratio (A/F) Experiment

In this experimental model, the air-fuel ratio (A/F) during the startup process was measured using an A/F sensor with a measurement range of 10:1 to 20:1. The A/F ratio determination was conducted before the engine started running to measure the air-to-fuel ratio in the combustion chamber through the exhaust port. Therefore, the sensor was placed in the exhaust pipe. Experimental results indicate that the average air-fuel ratio during startup was 11.6:1 when the fuel injection quantity was 3 mg, ensuring the engine quickly reaches stable operating conditions (Figure 4.6).

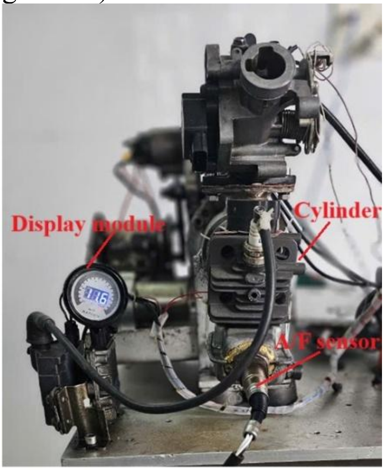


Figure 4.6: A/F Experiment

During engine operation, the air-fuel ratio (A/F) was maintained at approximately 19.7:1 with a fuel injection quantity of 3 mg.

4.4. Experimental Results

4.4.1. Startup Process

At the start of the ignition process, signals are sent to the controller, causing the piston to oscillate with a constant amplitude of 22 mm at a fixed frequency of 10 Hz. The initial compression pressure is 4 bar, which is sufficient for ignition to occur and sustain combustion. This process is illustrated in Figure 4.7

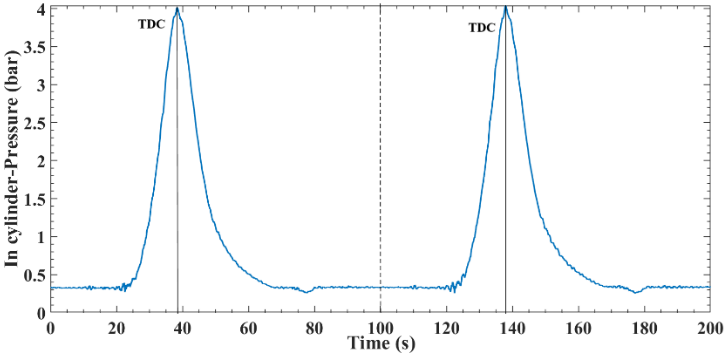


Figure 4.7: Startup Pressure

The transition process between startup and operation is illustrated in Figure 4.8. During the first 1.4 seconds, the piston undergoes linear displacement with an amplitude of 22 mm due to the mechanical startup mechanism, maintaining a stable displacement position. In the following 0.5 seconds, the engine transitions to free operation mode, causing the piston position to become unstable, with a peak position reaching 30 mm. The engine's maximum velocity changes from 0.7 m/s during the startup phase to 5 m/s in free operation.

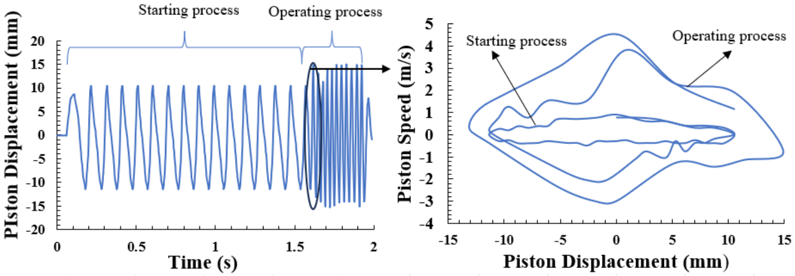


Figure 4.8: The transition process between startup and operation modes

When the mechanical startup mechanism disengages from the main shaft, the piston continues to move due to inertia, causing the compression pressure and compression force to gradually increase. When the compression force balances with the inertial force, the piston comes to a stop, and the pressure from the combustion process after ignition pushes the piston in the opposite direction. During this process, the peak pressure occurs immediately after the reversal point. Figure 4.9 illustrates that the reversal point represents the phase transition between CH A and CH B; pulse 2 indicates the peak pressure, with 1V corresponding to 4 bar.

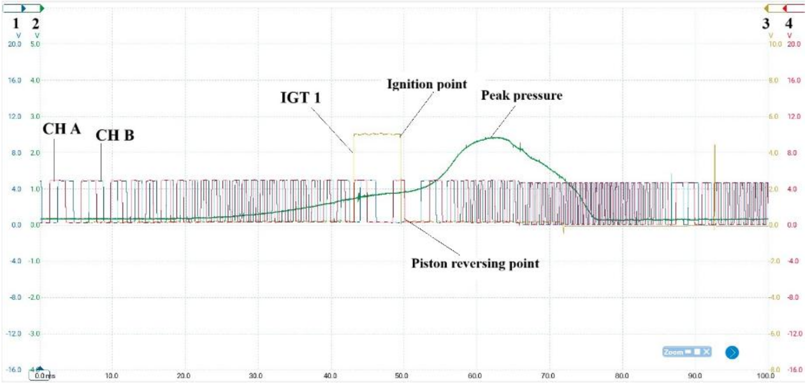


Figure 4.9: The relationship between peak pressure, ignition timing, and the piston reversal point in the first combustion process

4.4.2. Operation Process

During the first combustion process, the cylinder pressure fluctuates between 8 bar and 14 bar, with a fuel injection quantity of 3 mg per cycle and an air-to-fuel ratio (A/R) of 11.6:1. The time from spark initiation to peak pressure ranges from 6 to 8 ms, which also represents the experimental combustion duration.

Figure 4.10a illustrates that the engine operates in two distinct regions. Region 1: The efficient operating region, where combustion pressure exceeds compression pressure, similar to conventional internal combustion engines.

Region 2: The power loss region ("negative work"), where combustion pressure is lower than compression pressure. The cause of "negative work" is the high inertial force of the opposing piston; when the opposing piston reverses direction, a portion of the combustion energy is dissipated (due to the absence of a crankshaft for power transmission). These regions may vary depending on the inertial and compression forces of the two cylinders.

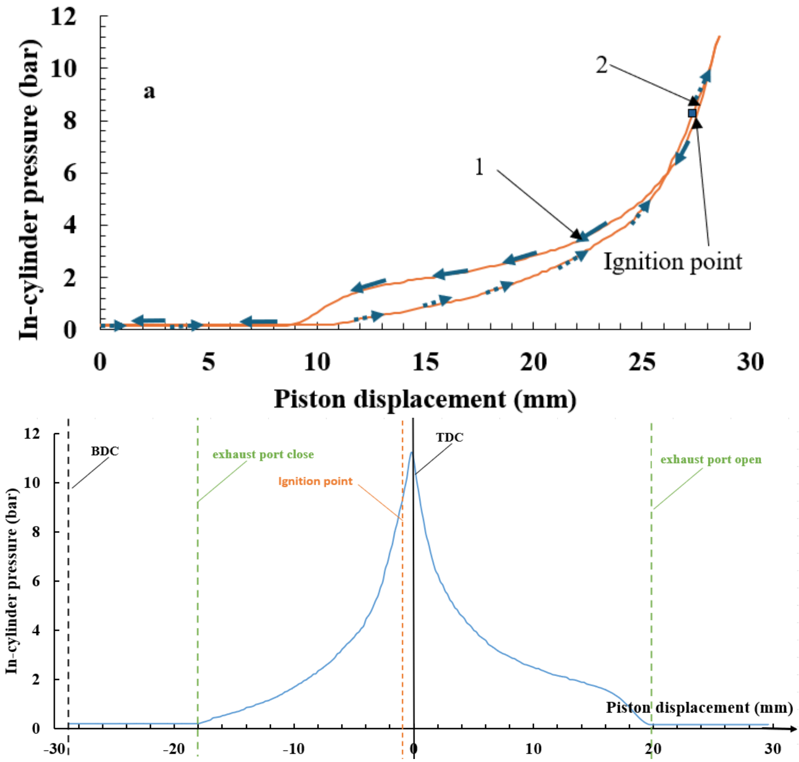


Figure 4.10 (a,b): Cylinder Pressure and Piston Position

The time from ignition to peak pressure formation is unstable, ranging from 1 ms to 2 ms. At the moment of ignition, the compression pressure varies between 6 bar and 8 bar. Due to the rapid increase in piston speed during operation mode, the energy accumulation time remains unchanged at 5 ms and continues until the spark occurs. The increase in compression pressure is partly influenced by residual gases from the expansion phase of the previous combustion cycle. Since the energy accumulation time is constant at 5 ms, a higher piston speed results in a delayed spark timing, and vice versa. This variation leads to differences in ignition timing and peak pressure in each cycle, causing displacement fluctuations between cycles, as shown in Figure 4.11. The peak pressure is formed before the reversal point when the piston changes direction due to gas forces. This occurs when the gas force becomes large enough to overcome the inertia from the opposing side, as illustrated in Figure 4.12.

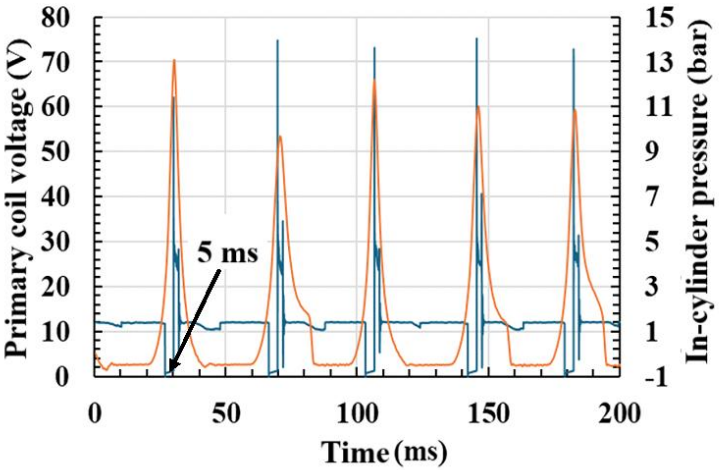


Figure 4.11: Primary Coil Voltage and Cylinder Pressure

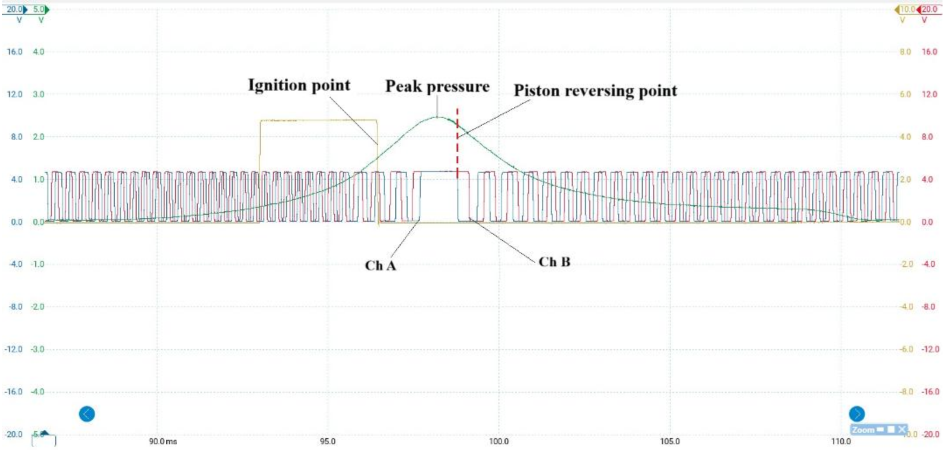


Figure 4.12: Relationship Between Peak Pressure, Ignition Timing, and Piston Reversal Point in Operation

The fuel injection timing, ignition timing, motion reversal point, and pressure during the combustion process in the cylinder are shown in Figure 4.13. The peak pressure fluctuates between 10 bar and 15 bar over five consecutive cycles, with the piston's linear oscillation frequency of approximately 25 Hz.

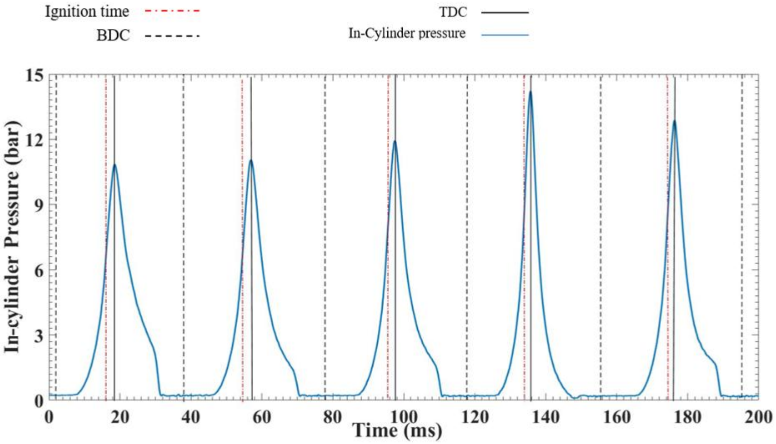


Figure 4.13: The cylinder pressure over five consecutive cycles

The fuel quantity is adjusted to examine the engine's starting capability and maximum speed, as illustrated in Figure 4.14. The maximum speed reaches approximately 35 Hz when the injected fuel per cycle is 4-4.5 mg, while the lowest speed is 25 Hz with an injection quantity of 3 mg.

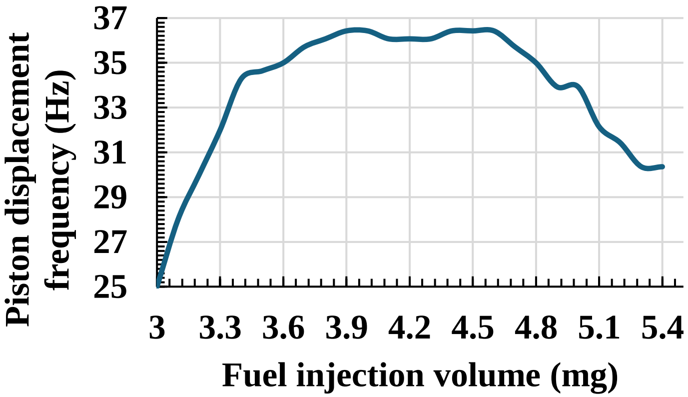


Figure 4.14: Fuel Injection Mass and Operating Frequency

Currently, the engine lacks a complete lubrication and cooling system. Therefore, to prevent damage, the engine's operating test duration is limited to approximately 10 seconds, as shown in Figure 4.15. The piston's maximum stroke reaches 30 mm, constrained by the stroke-limiting mechanism, with its primary displacement range between 26 mm and 29 mm.

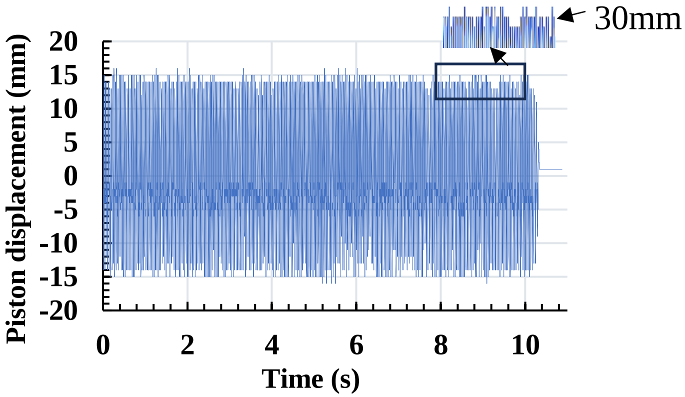


Figure 4.15: Operation Process of the FPE Model in 10 Seconds

4.5. Comparison Between Simulation and Experimental Results

Simulation is considered valid when it ensures accuracy and reliability for the modeled system. Since this is a self-developed engine model, the basis for evaluating the accuracy of the simulation is the experimental results obtained from laboratory tests

Table 4.2: Comparison Between Experimental and Simulation Results

	Experimental Result	**Simulation Result**	**Error Range (%)**
Starting Velocity (m/s)	0.7 - 0.8	0.7	3%
Peak Pressure with 3 mg Fuel Injection (bar)	10	10 – 10.5	0 – 5%
Ignition Timing (ms)	48	50	4%
Piston Reversal Timing (ms)	51	51 – 53	0 – 3%

4.6. Chapter 4 Conclusion

The experimental results have demonstrated the ability to determine the piston motion characteristics in the FPE engine model at different operating speeds. The mechanical starting mechanism operates stably with a starting frequency of 10 Hz (equivalent to a velocity of approximately 0.7 m/s), while the air-fuel ratio (A/F) remains stable at 11.6:1, ensuring proper combustion inside the cylinder. The in-cylinder pressure during the compression phase of the starting process is stable and consistent.

However, when transitioning to the operating mode, the peak in-cylinder pressure becomes unstable and fluctuates continuously with each cycle. This phenomenon is related to the requirement for sufficient gas force to overcome the inertia force of the opposing piston.

CONCLUSION AND DEVELOPMENT ORIENTATION

1. Conclusion

The dissertation introduces a prototype of a dual-cylinder, two-stroke, dual-free-piston engine (FPE) using gasoline and spark ignition. A novel feature of this design is the mechanical resonance-based starting mechanism, replacing the conventional linear electric motor. This mechanism enables faster and more stable startup while reducing dependency on electrical power. To optimize the starting process, a controller guides the piston to move along a fixed 22 mm trajectory. The Culit mechanism utilizes natural oscillations for rapid startup, reducing startup time and increasing reliability, thereby meeting the performance and stability requirements of the FPE. A PIC 18F4550 microcontroller plays a central role in ignition and startup control, ensuring efficient operation. Combined with the NI USB 6212 controller and LabVIEW software, the system precisely controls fuel injection and engine parameters, enhancing overall efficiency.

Simulations using Matlab Simulink indicate that the engine starts at a speed of 0.7 m/s with a compression ratio of 3, reaching a combustion pressure between 8 and 12 bar within 2–5 ms. Experimental results show that applying a pulling force for 1.4 seconds allows the piston to reach a speed of 0.7 m/s, achieving a compression ratio of 3 and a peak pressure of 10 bar, meeting the FPE's performance requirements.

Testing demonstrated that a compression pressure of 4 bar was achieved within 1.4 seconds, sufficient for combustion, proving the feasibility of the mechanical starting mechanism. This system reduces dependence on linear electric motors and opens new research directions for free-piston engines, focusing on performance optimization and cost reduction. Furthermore, once started, the FPE can operate autonomously by utilizing combustion pressure to reverse the piston movement in the opposite cylinder, validating the research hypothesis.

2. Contributions of the Dissertation

The dissertation contributes to synthesizing and analyzing related scientific works, adding theoretical insights into the simulation and modeling of combustion processes in free-piston engines.

It develops and introduces a novel, feasible technical solution for an FPE starting mechanism based on mechanical resonance, specifically designed for a dual-piston, two-stroke, dual-cylinder FPE. The research validates that this FPE design can sustain stable operation without the need for a complex reversal support system.

Additionally, the dissertation proposes a fuel injection and electronic ignition control method for the FPE, based on theoretical combustion principles and experimental validation.

Achieving its primary objective, the dissertation successfully designs and fabricates an efficient FPE model capable of startup and operation (with continuous operation exceeding 10 seconds), serving research on the characteristics of free-piston engines. The methodologies presented in this dissertation can serve as a foundation for the design, modeling, and control of FPEs.

3. Development Orientation

The initial fabrication and successful operation of the two-stroke FPE with a mechanical starting system and self-reversing piston under no-load conditions mark a significant achievement. However, ensuring stable operation under load remains a major challenge.

For practical applications, further research is needed to evaluate theoretical aspects of combustion and heat transfer within the cylinder, lubrication, cooling, and optimization of ignition timing and fuel injection to enhance the engine's thermal efficiency. Additionally, integrating a linear generator into the model is necessary to comprehensively assess the stability and efficiency of the engine's operation.

This contribution was published in the scientific research article:

1. Ho Van Phuc, **Nguyen Huynh Thi**, Huynh Thanh Cong, Nguyen Van Trang, “A Cfd Simulation On Effects Of Methane/Biogas Ratio On 2-Stroke Free-Piston Linear Engine’s Scavenging”,

Journal of Technical Education Science No.59 (08/2020) Ho Chi Minh City University of Technology and Education, pp.130-139, 2020.

2. **Nguyen Huynh Thi**; Nguyen Van Trang; Huynh Thanh Cong; Huynh Van Loc; Dao Huu Huy; Ngo Duc Huy. “A Preliminary Study of a Two Stroke Free-Piston Engine for Electricity Generation”. *5th International Conference on Green Technology and Sustainable Development (GTSD)*,2020. *(IEEE)*

3. **Nguyen Huynh Thi**; Nguyen Van Trang; Huynh Thanh Cong; Huynh Van Loc; Dao Huu Huy; Ngo Duc Huy; Truong Hoa Hiep; Vo Bao Toan. “An

Investigation on Power Generation Characteristics of Linear Generator Driven by a Free-piston Engine”. *2021 International Conference on System Science and Engineering (ICSSE)*, 2021. *(IEEE)*

4. **Nguyen Huynh Thi**; Nguyen Van Trang; Huynh Thanh Cong; Huynh Van Loc; Dao Huu Huy; Ngo Duc Huy; Truong Hoa Hiep; Vo Bao Toan. “A Study of the Scavenging Process in a Two-stroke Free Piston Linear Engine at Low Velocity Using CFD and DPM”. *6th International Conference on Green Technology and Sustainable Development (GTSD)*, 2022. *(IEEE)*

5. Nguyen Van Trang; **Nguyen Huynh Thi**; Huynh Thanh Cong; Dao Huu Huy. “A Preliminary Study of Spark-Ignition System for Free-Piston Linear Engine”. *Journal Of Technical Education Science (JTE)*, 2023.

6. **Nguyen Huynh Thi**; Nguyen Van Trang; Huynh Thanh Cong; Dao Huu Huy. “Preliminary Design of a Single-Phase Linear Generator for Free-Piston Engine Application”. *From Smart City to Smart Factory for Sustainable Future: conceptual framework, scenarios, and multidiscipline perspectives SCFF24*, 2024. (Scopus)