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A Whole Process Control Strategy of Free-piston Linear generator

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ABSTRACT

Free-piston linear generator has become one of the new forms of energy conversion devices in the future due to its compact structure, multi-fuel adaptability, and easy modular arrangement. Based on system dynamics, thermodynamics and electromagnetism, this paper proposes the whole working process control structure of the free-piston linear generator, including the top control/monitor layer, the process control strategy layer and bottom actuator control layer, and carried out the control strategy of the system starting process, regulating process and stable generating process. In order to achieve the starting requirements, a muti-objective global optimization strategy based on neural network is established. Aiming at the problem of misfire during stable operation, a fast online identification and treatment based on motion characteristics-cylinder pressure is proposed, and the generator control strategy is changed to enable the system to quickly stabilize. In view of the above strategies, the simulation platform of the system is proposed, to verify the feasibility of each process control strategy of the system.

Keywords: free-piston linear generator, whole working process control structure, starting multi-objective optimization, two-stage rectification strategy, misfire monitoring

NONMENCLATURE

Abbreviations	
FPLG	Free-piston linear generator
ISG	Integrated starter and generator
TDC	Top dead center
Symbols	
m	Moving component mass
x	Piston displacement
F_{Ls}	Left cylinder gas force
F_{Rs}	Right cylinder gas force
F_g	Linear generator thrust
F_f	Frictional force
K_i	Generator thrust constant
A	Piston area
k	Specific heat ratio
m_{in}	Intake gas mass
m_{out}	Output gas mass
m_l	Gas leakage mass
h_{in}	Intake gas enthalpy
h_{out}	Output gas enthalpy
h_l	Gas leakage enthalpy
Q_h	Heat transfer loss
Q_{com}	Combustion heat release
V	Working volume
f	Friction coefficient of piston
C_k	Friction coefficient of generator

1. INTRODUCTION

Free piston linear generator (FPLG) is a promising power generation system due to its compact structure, multi-fuel combustion mode possibility and less friction loss [1-3]. It is mainly composed of a linear combustion engine and a linear electrical motor. Saiful A. Zulkifli et al. proposed a cold start method, which used the air-spring quality of the cylinders to help the motor drive the piston [4]. A rectangular current is injected to the motor to expect a constant force to be output. However, the simulation and experimental results showed that the linear motor under an open loop strategy did not produce an increasing amplitude but steady-state operation after the first cycle. B. Jia et al. proposed a mechanical resonance start-up method with a closed loop control [5]. The results showed that the piston amplitude grew with a constant force in the direction of the piston velocity. Then they investigated the piston displacement with different motor forces during the engine cold start process. From the simulation results, if a shorter engine cold start-up process was desired, then

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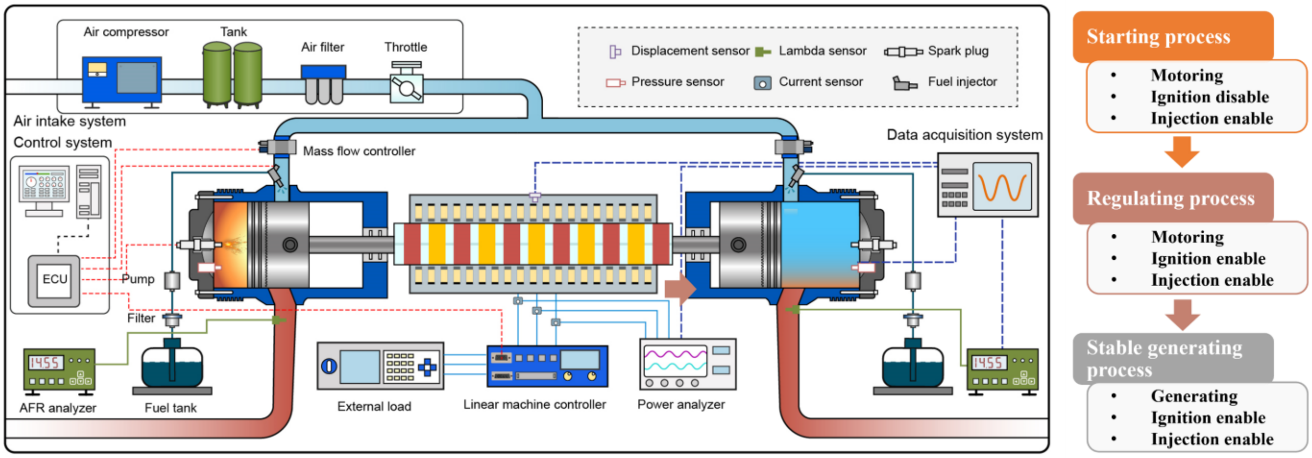

Fig. 1. *Structure of FPLG*

a higher motor force should be selected. H. Feng et al. investigated the optimal compression ratio of FPEG during cold start process to explore the range of working conditions of FPEG during cold start process [6].

The results showed that the target compression ratio was the most important parameter to finish successful ignition, the frequency had least influence on the engine performance. A full-cycle simulation model for single-piston free-piston engine was established to predict the TDC through the piston velocity in the compression process [7]. Based on the full-cycle simulation model, a control strategy of the TDC piston control using the pseudo-derivative feedback with disturbance feedforward controller (PDF+FF), which provided optimum responsiveness on the step change in the load, was proposed [8,9]. A pure resistive load was considered in the dynamic-multidimensional model [10,11], and the electric load of the generator was proportional to the velocity of the piston.

At present, the simulation and control of the whole working process of the FPLG is less, and more for a specific working process, such as starting process, combustion power generation process, etc. This study establishes the simulation whole working process of FPLG, including starting process, regulating process, stable power generation process, proposes the whole control structure and each process control strategy. and the feasibility of the strategy is verified by the simulation platform, aiming at improving the operating stability of the system and promoting the practical application of FPLG.

2. FUNDAMENTAL ANALYSIS ON WHOLE PROCESS OPERATION OF FPLG

2.1 FPLG configuration

The free-piston linear generator structure diagram is shown in Fig. 1. The system is mainly composed of combustion cylinders on both sides and tubular linear generator in the middle. The pistons and connecting rods on both sides together with the mover of the linear generator constitute the main moving part of the FPLG. The tubular linear generator works in two modes in the FPLG, including driving mode and generating mode, which makes the FPLG can be used as an Integrated Starter and Generator (ISG). The whole working process of FPLG can be divided into three processes, starting process, regular and stable generating process. During the starting process, the linear generator works in driving mode, pushing the pistons assembly in reciprocating motion to compress the gas in the cylinder until the gas state reaches the ignition condition, end the starting process. Then the spark plugs are enabled to try ignition, while the linear generator still working in the driving mode. When the combustion in the both sides cylinders is continuous and system operation is stable, the FPLG completes the second stage and enters the stable generating process. In this process, the linear generator works in the generating mode, and the in-cylinder pressure generated by the alternating ignition drives the mover to reciprocate to achieve the electrical energy output.

2.2 Operation analysisection

In the starting process of the FPLG, the thermodynamic state of the cylinder, including in-cylinder pressure and gas temperature, is the key factor for the subsequent successful ignition. At the same time, the operating frequency and stroke of the starting process directly affect the stability. Therefore, accurate control of the thermodynamic and dynamic performance of FPLG becomes the key in the starting process. The

FPLG needs to meet the conditions, such as intake gas mass, compression ratio, in-cylinder pressure, frequency, stroke, etc. in the starting process. The FPLG is a complex nonlinear system with multi-field coupling, and the system characteristics are interrelated and influence each other, which brings difficulties to the control decision.

When the FPLG enters the regulating process, with the success of the ignition, the frequency and stroke will be further changed. In order to prevent the FPLG from discontinuous ignition or abnormal cycle, the linear generator is still in the driving mode. The driving force control should be aimed at avoiding damaging abnormal phenomena such as hitting cylinder and stall during operation.

In the stable generating process, in order to use or store electric energy, the rectifier bridge, load or energy storge components are connected to the electrical circuit, and the rectifier bridge takes the DC voltage and current as the control target. There may be abnormal cycles such as ignition failure and abnormal combustion, which may cause the operating frequency to decrease, stroke to decrease and even system instability to stop. Monitoring and intervention of abnormal cycle is particularly important, timely detection of system anomalies, early intervention, so that the system quickly returns to stability.

Through the above operation analysis, the main control objects, control objectives and process switching judgment basis of the FPLG are clarified, which lays a foundation for the judgment of the system operation process and the formulation of each process control strategy.

2.3 FPLG numerical model

For the FPLG, the piston operating state is mainly determined by the resultant force due to the absence of mechanical structure restrictions, the dynamic equation can be described as follows:

$$\sum F = m\ddot{x} = F_g + F_{Ls} - F_f - F_{Rs} \tag{1}$$

where, m is the mass of the piston moving component, x is the displacement of the piston, F_{Ls} and F_{Rs} are gas force in the left cylinder and right cylinder, F_g is the linear generator thrust, F_f is the combined force of the piston friction and generator friction.

The following assumptions are made when describing the thermodynamic state in the cylinder: The working medium in the cylinder is ideal gas and in uniform state; The change of kinetic energy caused by intake and exhaust during air exchange is ignored. The tubular linear generator is modeled in the natural coordinate system based on the following assumptions: ignoring eddy current and hysteresis losses in the generator; and ignoring the harmonics of the magneto-dynamic potential in the air gap. Table 1 summarizes the expressions of the force in Eq. (1), where K_i is the thrust constant of the linear generator; I_q is the q-axis current of the linear generator; A is the piston area; k is the specific heat ratio; m_{in} is the intake gas mass; m_{out} is the output gas mass; h_{in} is the intake gas enthalpy; h_{out} is the output gas enthalpy; m_l is the mass of gas leakage; h_l is the enthalpy of gas leakage; Q_h is the heat transferred through the cylinder wall; and V is the working volume; Q_{com} is the combustion heat release (the value is zero in starting process); f is the Friction coefficient of piston, C_k is the friction coefficient of linear generator. The main parameters of the FPLG are shown in Table 2.

Table 1 The forces expression in the FPLG

Force type	Expression
F_g	$K_i I_q$
F_{Ls} or F_{Rs}	$A\int \dot{p}\,dt = A\int \frac{k-1}{V}(\dot{Q}_{com}-\dot{Q}_h)-\frac{pk}{V}\dot{V}+\frac{k-1}{V}\dot{m}_{in}h_{in}\frac{k-1}{V}\dot{m}_{out}h_{out}-\frac{k-1}{V}\dot{m}_l h_l$
F_f	$(f+C_k)\dot{x}$

Table 2 The forces expression in the FPLG

Parameters	Value
Mass of the moving part (kg)	5.0
Cylinder diameter (m)	0.0525
Design stroke (m)	0.058
Intake pressure (MPa)	0.11
Peak current (A)	20

3. WHOLE PROCESS CONTROL STRATEGY

3.1 Control structure

The proposed control structure for the FPLF is shown in Fig. 2, which is a multi-layer control structure, mainly including the top control/monitor layer, the process control layer, and the bottom actuator control layer. The functions and principles of each control layer are discussed below, and control strategies are further explained in the following section.

1) The top control/monitor layer, which mainly completes the operation monitor, process judgement/process control instruction, system instability monitoring and intervention instruction. The system's dynamics and thermodynamics is monitored, and the monitoring results are sent to the process judgment/process control level in real time, which mainly completes the system's working process judgment and sends process switching instructions. The

instability monitoring and intervention level mainly monitors the status in the cycle in real time and makes timely intervention during the stable operation.

2) The process control strategy layer mainly includes starting process strategy, regulating process strategy and stable generating process strategy. The intra-layer strategy is not carried out in parallel, and is carried out one by one according to the change of working process and upper-level instructions.

3) The bottom actuator control layer is mainly the control of the main executive components of the system, including tubular linear generators, injectors, spark plugs, auxiliary systems, etc. The decisions and instructions of the upper layer, such as the motor current, DC terminal voltage injection position, ignition position, etc., are carried out in this layer.

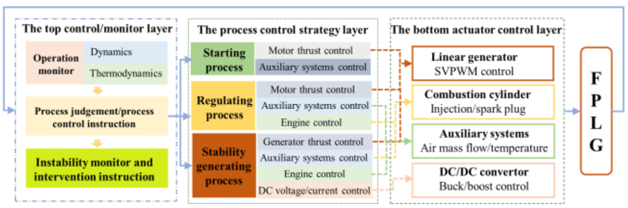

Fig. 2 Proposed FPLG control structure

3.2 Starting process control

The starting process requires that the control system can quickly do the control decision for a given starting demand, the specific control decision process includes:

Firstly, the starting experiments of FPLG is parameterized by using the prototype of continuous operation. The thermodynamic and dynamic characteristics including frequency, stroke, and peak in-cylinder pressure, etc. are obtained through data processing, and the databased of multi-conditions is established. Then, RBF neural network is used to establish the prediction model between the control variables, including intake air flow, intake air temperature, motor thrust, etc. and thermodynamic and dynamic characteristics, and the coefficient of determination is used to complete the training and verification of the model. Furthermore, the multi-objective optimization model of the starting process is established according to the requirement such as compression ratio and economic. Based on NSGA-II algorithm, global optimization is developed to obtain the optimal motor control and auxiliary system control variables values. After the online decision is completed, the control variables are directly written into the process control strategy layer, waiting to be executed, as shown in Fig. 3.

3.3 Regulating process control

This process follows the gradual motor/generator switching strategy proposed by our research group [13].

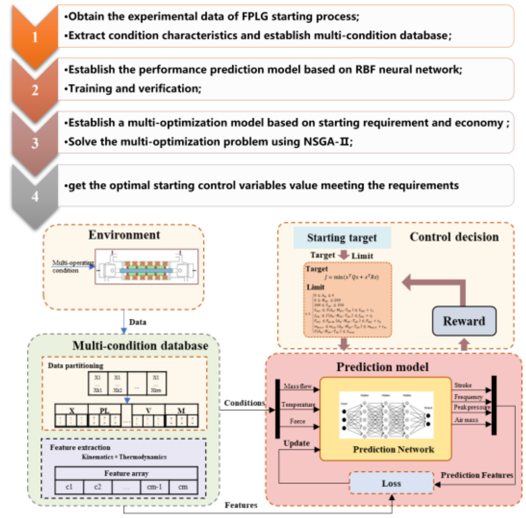

Fig. 3 Starting process control strategy

3.4 Stability process control

3.4.1 Electric power transformation

In order to ensure the stability of the FPLG output voltage, a two-stage rectifier circuit topology is adopted, with a controlled rectifier bridge and a DC/DC converter in the generator output circuit, as shown in Fig. 4. The voltage/current double closed-loop control strategy is adopted respectively. The DC terminal voltage depends on the maximum AC side line voltage. The DC/DC convertor in form d) used a bidirectional buck/boost circuit. As in Fig. 4, the circuit can only be in mode during a switching cycle (i.e., buck mode or boost mode), where the dive signal of one switching tube is active while the drive signal of the other switching tube is blocked. In buck mode, the switching tube S1 drive signal is active, and energy flows from the high-voltage terminal to the low-voltage terminal. In boost mode, the switching tube S2 is active, and the energy flows from the low-voltage terminal to the high-voltage terminal.

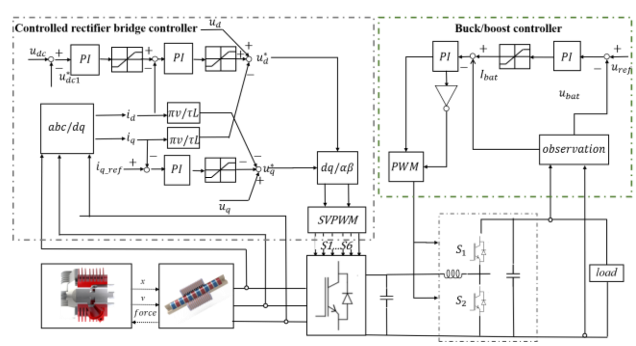

Fig. 4 Two-stage rectifier circuit topology

3.4.2 Misfire treatment

The premise of misfire control is to be able to accurately and quickly identify the occurrence of misfire in the cylinder. Through a large number of experimental studies, it is found that the piston kinematics characteristics will change significantly in most cases of misfire, such as the decrease of the peak velocity and reduction of the stroke, etc. However, due to the cyclic fluctuation of the FPLG, when only kinematic characteristics are used as the judgement condition, the selection of the threshold of the judgement condition completely depends on experience, which may misjudge or miss the misfire cycle, resulting in system shutdown. This study proposes a fast online recognition method based on kinematic characteristic and in-cylinder pressure. By comparing the P-V diagram of misfire cycle and fire cycle, the fire state of the current cycle can be quickly identified by the position of the expansion line, as shown in Eq. 2.

$$mis=\begin{cases}1, & p_{x_{exp,}\,{}^{x_{max}-x_{ig}}/_{2}}-p_{x_{comp,}\,{}^{x_{max}-x_{ig}}/_{2}}<0\\ 0, & p_{x_{exp,}\,{}^{x_{max}-x_{ig}}/_{2}}-p_{x_{comp,}\,{}^{x_{max}-x_{ig}}/_{2}}\geq 0\end{cases} \qquad (2)$$

Detect the in-cylinder pressure difference between the expansion process and the compression process at a certain position. When the pressure difference is less than 0, it indicates that the cylinder is misfiring in the current cycle, and vice versa. In order to ensure that the piston of the misfiring cycle can reach the ignition position again, the generator takes the optimal motor thrust during the starting process as the control target, drives the piston to the ignition position, tries to ignite, and then the motor thrust is withdrawn.

4. WHOLE PROCESS CONTROL STRATEGY

4.1 Simulation platform

Based on the above working principle, working process and process control strategies of the FPLG, a simulation platform for the whole working process is established, which mainly completes the operating process performance simulation from starting process to regulating process to the stable generating process and control strategy of FPLG. Fig. 5 shows the visualization window of the simulation platform, which is mainly divided into control panel, process monitoring, performance calculation and GUI.

4.2 Simulation results

Fig. 6 shows the simulation results of the whole working process of the FPLG under a given target working condition. In the starting process, the generator drives the piston assembly to reciprocating with a constant current of 1.28 A. After 2 cycles, the compression ratio reaches 7 in the right cylinder, and the piston reached the preset ignition position of 0.018m. Then the system enters to the regulating process, and the peak in-cylinder pressure rises to 3 MPa. At this time, in order to prevent the moving components from stalling or hitting the cylinder, the target generator current is set at 0.9 A, and the operating frequency is 28 Hz. Then the system enters to the stable generating process, the linear generator is converted into the generating mode, and the left and right cylinders are ignited successively. With the periodic operation of the FPLG, the dynamic and thermodynamic characteristics are gradually stabilized, the frequency is stabilized at 30Hz, the peak pressure is gradually stabilized to 2.63 MPa, and the total stroke of is 0.043 m.

Fig. 5 Simulation platform of FPLG

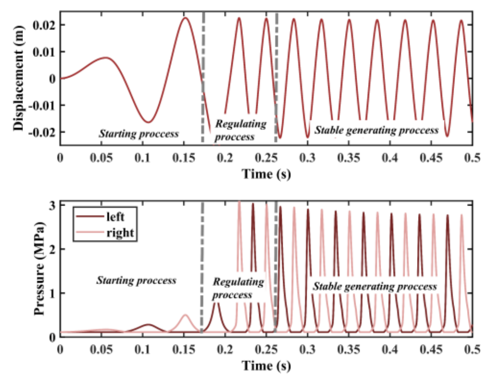

Fig. 6 FPLG Whole working process performance

For the tubular linear generator with reciprocating operation, the no-load characteristics are shown in Fig. 7. With the reciprocating operation of the mover, the voltage also presents a periodic change, and the overall shape is spindle, the peak voltage is contained by the speed. The peak value of voltage in the middle part of the piston stroke has little fluctuation, and the velocity near the dead center is lower than the velocity leaving the dead center in the early expansion process, and the corresponding peak voltage is lower than the peak value in the expansion process.

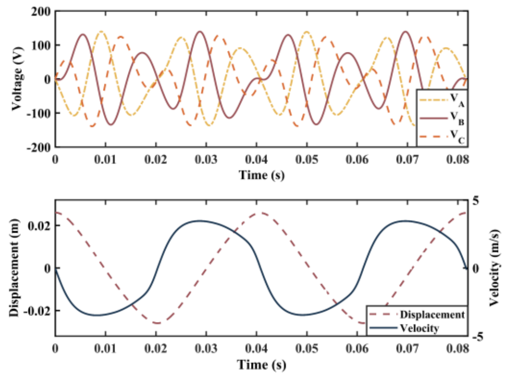

Fig. 7 No-load characteristics of linear generator

Fig. 8 simulates the monitoring and treatment of misfire when it occurs during stable generating process. When the ignition failure of the left cylinder was artificially injected at 0.32 s, the system quickly detected the misfire in the left cylinder after the BDC, and the generator current control iq = 1.28 intervened to push the piston to the opposite ignition position of the right cylinder, when the piston reaches the ignition position, the generator current control changed to iq = 0, and the right cylinder was successfully ignited. After two misfire treatments, the system returned to stability, and the operating frequency returned to 29.5 Hz.

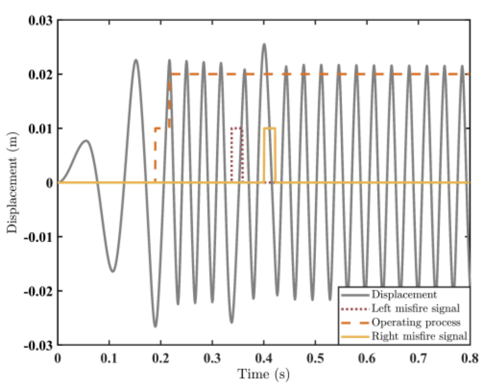

Fig. 8 Misfire identification and treatment

5. CONCUSION

Based on the analysis of the requirements and operation characteristics of the FPLG in the starting, regulating and stable generating process, a multi-layer whole working process control structure including the top control/monitor layer, the process control strategy layer and bottom actuator control layer is proposed in this study. The multi-objective optimization starting strategy, two-stage rectification strategy and misfire treatment strategy are formulated respectively. Finally, the system simulation platform is established to complete the control structure and strategy verification. Our future work will be focused on the verification of the control strategies through experimental tests, and also on the optimization of the performance.

DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

REFERENCE

[1] Jiming Lin, Zhaoping Xu. Finite-time thermodynamic modeling and analysis of an irreversible Miller cycle working on a four-stroke engine[J]. International Commu-nications in Heat and Mass Transfer, 2014, 54(5): 54-59.

[2] R. Mikalsen, A.P. Roskilly, A review of free-piston engine history and applications,Applied Thermal Engineering. 27 (2007) 2339–2352.

[3] N.B. Hung, O. Lim, A review of free-piston linear engines, Applied Energy. 178 (2016) 78–97.

[4] Saiful A. Zulkifli et.al. Starting of a Free-Piston Linear Engine-Generator by Mechanical resonance and Rectangular Current Commutation. IEEE Vehicle Power and Propulsion Conference (VPPC), Harbin, China, September 3-5, 2008.

[5] B. Jia, Z. Zuo, H. Feng, G. Tian, A. Smallbone, Effect of closed-loop controlled resonance based mechanism to start free piston engine generator: Simulation and test results, Appliey Energy 164 (2016) 532–539.

[6] H.Feng, Z.Zhang, B. Jia, A. Smallbone, A. Roskilly. Investigation of the optimum operating condition of a dual piston type free piston engine generator during engine cold start-up process. Applied Thermal Engineering, 2020, 182.

[7] R. Mikalsen, E. Jones, A. Roskilly. Predictive piston motion control in a free-piston internal combustion engine. Applied Energy. 87 (2010) 1722-8.

[8] R. Mikalsen, A. Roskilly. The control of a free-piston engine generator. Part 1: Fundamental analyses. Applied Energy. 87 (2010) 1273-80.

[9] R. Mikalsen, A. Roskilly. The control of a free-piston engine generator. Part 2: Engine dynamics and piston motion control. Applied Energy. 87 (2010) 1281-7.

[10] B. Jia, R. Mikalsen, A. Smallbone, Z. Zuo, H. Feng, A.P. Roskilly. Piston motion control of a free-piston engine generator: A new approach using cascade control. Applied energy. 179 (2016) 1166-75.

[11] B. Jia, A. Smallbone, H. Feng, G. Tian, Z. Zuo, A. Roskilly. A fast response free-piston engine generator numerical model for control applications. Applied energy. 162 (2016) 321-9.
[12] B. Jia, R. Mikalsen, A. Smallbone, A.P. Roskilly, A study and comparison of frictional losses in free-piston engine and crankshaft engines, Applied Thermal Engineering. 140 (2018) 217–224.
[13] Feng H, Guo C, Jia B, Zuo Z, Guo Y, Roskilly T. Research on the intermediate process of a free-piston linear genera-tor from cold start-up to stable operation: Numerical model and experimental results. Energy Conversion and Management, 2016,153-64.