Energy Conversion and Management xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

# Research on the operation characteristics of a free-piston linear generator: Numerical model and experimental results

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ARTICLE INFO

*Article history:*
Received 16 July 2016
Received in revised form 24 October 2016
Accepted 5 November 2016
Available online xxxx

*Keywords:*
Free-piston linear generator
The operation process
Piston dynamics
FPLG performance

ABSTRACT

Free piston linear generator (FPLG) shows unique operation characteristics due to the elimination of crankshaft and connecting rod mechanism. This paper investigates its operation characteristics during each operating process based on the simulation and experiment results. During the starting process, the larger motor force during the starting process, the fewer times of reciprocating pistons which meet the condition of ignition. When the motor force reached 300 N, the prototype could adopt one-stroke starting strategy. During the intermediate process, it was found that the "gradually switching strategy" could help to achieve a smoother operation during the intermediate process. And the values of the operation parameters after the intermediate process were lower than those before the intermediate process. During the generating process, cycle-to-cycle variations were observed for piston TDC and in-cylinder gas pressure from the experimental results. According to the experimental results of the FPLG during the generating process, the calculated engine indicated power is 2.9 kW, and the corresponding indicated thermal efficiency is 37.3%. Additionally, based on the comparison of the FPLG performance, it is found that the parameters of the FPLG during the generating process are smaller than those when it was operated during the second stage of the starting process, while much higher than those during the first stage of the starting process.



## 1. Introduction

The free-piston linear generator (FPLG), as a new energy conversion appliance, is a combination of free-piston engines and a linear electric machine (LEM) [1–5]. The general working principle of the FPLG is that the high-temperature and high-pressure gas are generated during the heat release process in the cylinder, then the gas drives the piston and connecting rod to reciprocate, and the LEM converts parts of the mechanical energy into electricity [6]. Compared with the traditional reciprocating engine (TRE), the FPLG is a kind of crankless engine. As a result it shows various potential advantages, such as variable compression ratios, short energy conversion chains, multi fuel feasibility, and simplified structure since the crankshaft mechanism is eliminated [7–9]. Therefore, the global researchers have strong interest in the FPLG.

The concept of the free-piston engine was first proposed by Pescara as a patent in 1928 [10]. After that, there were a few representative products, such as the free piston compressor and free piston gasifier [11]. However, research on the free-piston engine progressed slowly because of the limited technological conditions at that time [1,4,9]. Nowadays, with the rapid development of technology in recent years, many research institutes have begun to study the free-piston engine again, and the free-piston engine development progressed fast.

The research group from West Virginia University have researched on FPLG since 1995. They conducted numerical simulation for the operation process, and studied the influences of different parameters on the system characteristics [12–17]. And the prototype consisted of two two-stroke free-piston engines. Results indicated that without external load, the operation frequency of the prototype was 1457 rad/min, and the piston motion profile was similar to the sinusoidal state. When the prototype was loaded, its operation frequency was 1361 rad/min, and the maximum output power was 316 W. However, the prototype generation efficiency was low, and the machine could not operate continuously.

The research group from the Sandia National Laboratory (SNL) designed a FPLG prototype from 2000 [18–19]. The prototype showed high efficiency, low emission and was able to operate on a variety of hydrogen-containing fuels. The FPLG employed a homogeneous charge compression ignition (HCCI) mode, and the

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http://dx.doi.org/10.1016/j.enconman.2016.11.010
0196-8904/

Please cite this article in press as: Guo C et al. Research on the operation characteristics of a free-piston linear generator: Numerical model and experimental results. Energy Convers Manage (2016), http://dx.doi.org/10.1016/j.enconman.2016.11.010

**Nomenclature**

| | |
|---|---|
| *FPLG* | free piston linear generator |
| *FPE* | free-piston engine |
| *FPEC* | free-piston energy convertor |
| *FPE* | free-piston engine |
| *TRE* | traditional reciprocating engine |
| *LEM* | linear electric machine |
| *HCCI* | homogeneous charge compression ignition |
| *TDC* | top dead center |
| *ECU* | integrated electronic control unit |
| *PFI* | port fuel injection |
| $F_f$ | friction force (N) |
| $F_m$ | motor force when the LEM runs as a motor (N) |
| $F_g$ | resistance force when the LEM runs as a generator (N) |
| $\varepsilon_1(x)$ | step function |
| $\varepsilon_2(x)$ | step function |
| $m$ | moving mass of the piston and connecting rod (kg) |
| $x$ | piston displacement (mm) |
| $x_1$ | switching position (mm) |
| $x_2$ | switching position (mm) |
| A | top surface area of the piston ($m^2$) |
| $p$ | in-cylinder gas pressure (bar) |
| $p_L$ | pressure in the left cylinder (bar) |
| $p_R$ | pressure in the right cylinder (bar) |
| $\gamma$ | ratio of specific heats (−) |
| $V$ | cylinder volume ($m^3$) |
| $Q_h$ | heat transfer loss (J) |
| $Q_c$ | heat released from the combustion process (J) |
| $a$ | 5 |
| $b$ | 2 |
| $C_d$ | combustion duration (s) |
| $t_s$ | the time at which the combustion process starts (s) |
| $Q_{in}$ | the overall heat input for each cylinder in one running cycle (J) |
| $h$ | the coefficient of heat transfer |
| $A_{cyl}$ | the area of the in-cylinder surface in contact with the gas ($m^2$) |
| $T_w$ | the average surfaces temperature of the cylinder wall (K) |
| $C_f$ | viscosity friction coefficient (−) |
| $k_f$ | thrust coefficient of the motor (N/A) |
| $I$ | current value in the starter coil of the motor (A) |
| $k_\varepsilon$ | coefficient of the counter electromotive force of the generator (V/m/s) |
| $R_S$ | coil resistance (Ω) |
| $R_L$ | external load resistance (Ω) |
| $L$ | inductance of the generator (H) |
| $W$ | indicated work of a cylinder (J) |
| $P_{mean}$ | indicated mean effective pressure of a cylinder |
| $P$ | indicated power of the FPLG |
| $f$ | operation frequency of the FPLG |
| $\eta$ | indicated thermal efficiency of engine |
| $Q_{fuel}$ | input heat from fuel in one cycle |

thermodynamic cycle achieved was close to the Otto cycle. The research group from Czech Technical University developed two FPLG prototypes in 2003 and 2007 respectively [20–23]. Experiment results indicated that the operation frequency of the first prototype was 27 Hz, and the maximum output power was 650 W. However, the systematic generation efficiency was less than 10%.

In 2002, the EU Energy Commission started the Free Piston Energy Converter (FPEC) program [24,25], aiming to apply the HCCI method on the FPEC. They conducted coupling numerical simulation of the operation process of the FPEC [26]. Results suggest that the fuel with low octane number needs high compression ratio, and the high compression ratio will increase the operation frequency, output power and efficiency of the FPEC. And they designed a prototype with an output power of 25 kW, and power intensity larger than 0.6 kW/kg, which was expected to meet the European V discharge standard. However, most of the parameters and engine operation characteristics were simulation results, and very few experiment data were reported.

The research group at Newcastle University began the investigation of the FPLG from 2005 [27–33]. Numerical modelling was conducted to study the characteristics of the internal combustion engine of the FPLG, piston dynamics, and the controlling system. Simulation results suggested that the FPLG operation frequency was 30 Hz, the output power was 44.4 kW, and its efficiency was up to 42%. Compared with the TRE, FPLG showed higher efficiency and lower gas temperature, so as to reduce the NOx emission. Besides that, it was found that the FPLG was very sensitive to load, and the system was easy to reach satisfactory results by using simple controlling strategy. However, most of their work was reported on the numerical simulation analysis.

Researchers from Nanjing University of Science and Technology did research on a single-piston free-piston engine linear generator [34,35]. They designed a prototype and the experiment results indicated that the output power was 2.2 kW and the heat efficiency reached 32%. They designed the controller of stratification of single-piston free-piston linear generator. Its main concept was to modify the piston motion through controlling the electronic magnets so as to ensure that the prototype was able to operate consecutively.

Researchers at the Beijing Institute of Technology have been studying the FPLG since 2006, and several prototypes have been designed [1,6–8,36–41]. They conducted zero-numerical simulation of FPLG and predicted the operation frequency of the FPLG, and the dynamics of the piston. They have analyzed the influence of main parameters of the scavenging system on the scavenging efficiency, and the influence of piston motion on the engine combustion process. Experimental results suggested that the peak in-cylinder gas pressure was above 40 bar for the first prototype, and the operation frequency was 30 Hz. The second prototype of the FPLG could operate stably during the starting process from the papers. Experimental results showed that during the starting process, the peak in-cylinder pressure and compression ratio increased in a non-linear manner and tended to reach a stable state after several operation cycles. After successfully ignition, the peak piston velocity increased significantly to approximately 4.0 m/s.

The FPLG prototype developed by researchers at Toyota Central R&D Labs Inc. consisted of a two-stroke combustion chamber, a linear generator, and a gas spring chamber [42,43]. Experimental results showed that the prototype operated stably for quite a long period of time, despite of the abnormal combustion during the test. And the researchers have analyzed the unique piston motion, which poses its effects on combustion and power generation in the FPLG.

From the discussion above, it is found that researchers from all over the world mainly focused on the simulation of the piston dynamics and the FPLG performances during the generating process, the experimental investigation of the FPLG during the starting