Applied Energy 160 (2015) 746–760

Contents lists available at ScienceDirect

Applied Energy

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

A study of operating parameters on the linear spark ignition engine ☆

Ocktaeck Lim [a,*], Nguyen Ba Hung [a], Seokyoung Oh [a], Gangchul Kim [b], Hanho Song [c], Norimasa Iida [d]

[a] *School of Mechanical and Automotive Engineering, University of Ulsan, San 29, Mugeo2-dong, Nam-gu, Ulsan 680-749, South Korea*
[b] *Korea Institute of Energy Research, 102 Gajeong-ro, Yuseong-gu, Daejeon 305-343, South Korea*
[c] *Department of Mechanical and Aerospace Engineering, Seoul National University, South Korea*
[d] *Department of System Design Engineering, Keio University, Yokohama, Japan*

HIGHLIGHTS

- An experimental and simulation study of a linear engine is conducted.
- The effects of operating parameters on the generating power are investigated.
- The air gap length has a significant influence on the generating power.
- The generating power of the linear engine is optimized with the value of 111.3 W.
- There are no problems for the linear engine after 100 h of durable test.

ARTICLE INFO

Article history:
Received 6 November 2014
Received in revised form 2 June 2015
Accepted 16 August 2015
Available online 12 September 2015

Keywords:
Linear engine
Free piston engine
Linear alternator
Spark timing
Equivalence ratio
Air gap

ABSTRACT

In this paper, we present our experiment and simulation study of a free piston linear engine based on operating conditions and structure of the linear engine for generating electric power. The free piston linear engine includes a two-stroke free piston engine, linear generators, and compressors. In the experimental study, the effects of key parameters such as input caloric value, equivalence ratio, spark timing delay, electrical resistance, and air gap length on the piston dynamics and electric power output are investigated. Propane is used as a fuel in the free piston linear engine, and it is premixed with the air to make a homogeneous charge before go into the cylinder. The air and fuel mass flow rate are varied by a mass flow controller. The experimental results show that the maximum generating power is found with the value of 111 W at the input caloric value of 5.88 kJ/s, spark timing delay of 1.5 ms, equivalence ratio of 1.0, electric resistance of 30 Ω, and air gap length of 1.0 mm. In order to check the durability of the linear engine, a durable test is conducted during 100 h. The experimental results show that there are no problems for the linear engine after about one hundred hours of the durable test. Beside experimental study, a simulation study is conducted to predict operating behavior of the linear engine. In the simulation study, the two-stroke free piston linear engine is modeled and simulated through a combination of three mathematical models including a dynamic model, a linear alternator model and a thermodynamic model. These mathematical models are combined and solved by a program written in Fortran. Besides, the effects of key parameters such as reciprocating mass, spark timing and spring stiffness on the piston dynamics and electric power output of the linear engine are also investigated. The simulation results show that the simulation and experimental data are nearly similar at the same initial conditions. In addition, a highest generating power of the linear engine can be easily found by optimizing the key parameters.

1. Introduction

The crisis of global warming and shortage of fossil fuels are being a motivation for the scientists as well as the institutes to develop new energy conversion devices and environmentally friendly fuels. One of the methods to solve the crises is using a free-piston linear engine (FPLE). A free-piston linear engine is considered to be a crankless internal combustion engine with free motion of piston in cylinder. In terms of structure, the engine

Abbreviations: FPLE, free piston linear engine; HCCI, homogeneous charge compression ignition; ECU, electronic control unit; DSP, digital signal processing; DAQ, data acquisition.

☆ This article is based on a short proceedings paper in Energy Procedia Volume 161 (2014). It has been substantially modified and extended, and has been subject to the normal peer review and revision process of the journal. This paper is included in the Special Issue of ICAE2014 edited by Prof. J Yan, Prof. DJ Lee, Prof. SK Chou, and Prof. U Desideri.

* Corresponding author.
E-mail address: otlim@ulsan.ac.kr (O. Lim).

http://dx.doi.org/10.1016/j.apenergy.2015.08.035
0306-2619/

Nomenclature

A	area on the top of piston, m^2	x_m	the maximum stroke of piston, m
P_l	pressure in the left cylinder, Pa	γ	specific heat ratio
P_r	pressure in the right cylinder, Pa	V	instantaneous volume in the cylinder, m^3
F_f	friction force, N	Q_c	heat released in combustion, J
F_e	electromagnetic force, N	Q_{in}	heat input, J
F_{sl}	spring force in the left, N	Q_{ht}	heat transfer, J
F_{sr}	spring force in the right, N	χ	mass fraction burned
k	spring stiffness, N/m	t_0	start of combustion, s
Δx_l	deformation of the left spring, m	Δt	duration combustion, s
Δx_r	deformation of the right spring, m	MMF	mean magneto motive force, A
m	reciprocating mass, kg	H_c	magnetic field strength, A/m
x	displacement of the piston, m	h_m	thickness of permanent magnet, m
x_0	initial position of the piston, m	τ	pole pitch, m
t	time, s	τ_p	width of permanent magnet, m
p	instantaneous pressure in the cylinder, Pa	τ_1	distance between coils, m

consists of two main components: the free-piston engine, and a linear alternator. Unlike conventional engines with a crankshaft mechanism, the combustion process of the FPLE can be optimized through the variable compression ratios [1–14]. Besides, the variation of compression ratios in FPLE also allows the engine to operate with various kinds of fuels as well as HCCI combustion [15–26]. In general, the FPLE can be classified into three types including single piston, dual piston and opposed piston [1]. Of there, the dual piston engine has a higher power/weight ratio than others [26]. However, the operation of the dual piston engine is mainly controlled by an electronic system, and the piston crown may hit the cylinder head if the piston is not controlled correctly [27–31]. Therefore, a damping device (e.g. metal spring) is needed to install in the engine for avoiding the collision between the piston crown and cylinder head. In a FPLE, one of the most important components is the linear alternator or linear generator, which is used to start up the engine in the beginning mode or motoring mode. Two kinds of linear alternators used in the FPLE are tubular-type and flat-type linear alternators. Therein, the flat-type linear alternator is rarely used in FPLE, although it has higher efficiency, output voltage, and current [32]. There were many previous studies for the dual piston engine using tubular-type linear alternator. Atkinson et al. [33] presented a parametric study of a spark ignition dual piston engine using the combination of two numerical models such as dynamic model and thermodynamic model. Shoukry et al. [34] established a series of dynamic and thermodynamic numerical equations to predict the behavior of a direct injection dual piston engine over a wide operating range. In addition, there were many other simulation studies for the dual piston engine, which could be found in [35–43]. As can be seen above, most of the previous studies for the dual piston engine focused only on simulation as well as numerical analysis of this engine. Therefore, an experimental research is needed to conduct on a dual free-piston engine to find out how is the operation of the engine changed under real operating conditions.

This paper presents experiment and simulation study for a power pack using the dual piston free-piston engine combined with the flat-type linear generators. Therein, an experimental study is presented as a main part of this paper. In the experimental study, the effects of the main parameters such as input caloric value, spark timing delay, equivalence ratio and air gap length on the piston dynamics, electric power output and in-cylinder pressure of the linear engine are investigated. To check the durability of the linear engine, a durable test is carried out to examine the behavior of the linear engine after 100 h of the durable test. Beside experimental study, a simulation study is conducted to predict the piston dynamics and electric power output of the linear engine under the effects of key parameters such as reciprocating mass, spark timing and spring stiffness. The operation of the linear engine is modeled and simulated based on a combination of three mathematical models including a dynamic model, a linear alternator model and a thermodynamic model. The dynamic model includes an analysis of the piston motion, based on Newton's second law. The linear alternator model includes an analysis of electromagnetic force, which is considered to be a resistance force for the piston motion. The thermodynamic model is used to analysis thermodynamic processes in the engine cycle including compression, combustion, expansion and scavenging processes. Therein the scavenging process is assumed to be a perfect process. The linear engine uses propane as a fuel, because propane has a high octane number and can be easily mixed with air to make a homogeneous charge.

2. Experimental study

2.1. Experimental apparatus

The experimental apparatus consists of the free-piston engine with kind of dual piston, flat-type linear generators, ignition device, sensor parts, engine control parts and data acquisition parts. Figs. 1 and 2 show the photography and schematic diagram of experimental system, respectively. The optical displacement sensor (Kais Co.; KL3A-N1) is used to measure the position of translator in real time. Besides, the position of translator is detected by two photo sensors (Sharp GP1S092HCPIF), and then a digital signal generated from the photo sensor is delivered to ECU. After the

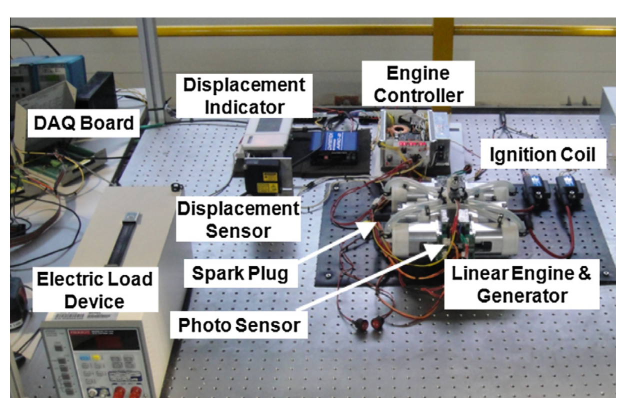

Fig. 1. A photograph of experimental system.