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Research Paper

Experimental investigation of a free piston expander-linear generator with different valve timings

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HIGHLIGHTS

- Effect of three kinds of cam plates on the performance of FPE-LG is analyzed.
- Effect of intake and exhaust duration on the performance of FPE-LG is studied.
- The external load resistance effects on the performance of FPE-LG is investigated.
- The indicated efficiency for FPE-LG is conducted.

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ABSTRACT

In this paper, a new free piston expander-linear generator (FPE-LG) prototype for small-scale organic Rankine cycle (ORC) waste heat recovery system has been developed. Firstly, the in-cylinder pressure, motion characteristics and output performance of the FPE-LG with different valve timings are investigated. Then, the effect of external load resistance on motion characteristics and output performance with cam plate A is analyzed. Finally, the effect of external load resistance on the indicated efficiency with cam plate A is studied. The results show that the intake duration and exhaust duration have significant influence on the motion characteristics and output performance of FPE-LG. Compared with other cam plates, cam plate A (the intake exhaust duration is 60°, and the exhaust duration is 180°) can be considered as the best choice for FPE-LG. The external load resistance not only influences the motion characteristics but also effects the output performance. The displacement and velocity increase with increasing the external load resistance. The peak power output with cam plate A is up to 18.6 W. The indicated efficiency shows a downward tendency when the external load resistance increases, and the maximum indicated efficiency of 66.2% is achieved.

1. Introduction

In recent years, there has been a significant increase in the awareness of environmental effects resulting from the use of fossil fuels. Both academia and industry are paying more and more attention to developing more efficient and environmentally friendly energy chains. However, it is well-known that the room left for the improvement of the internal combustion engines (ICEs) is limited. Thus, there is a growing interest in alternative power generation systems and unconventional engine technology, which could open up new research opportunities for engine efficiency.

1.1. Free piston engine

The free piston engine, an alternative to the conventional ICEs, has significant potential for improvement in efficiency and emission reduction. The free piston engine removes the crankshaft that constrains the movement of the piston and has both a reduced friction loss and a simpler design over traditional ICEs. Furthermore, the removal of the crankshaft means that the compression ratio in the free piston engines becomes variable. This may allow the possibility of using alternative fuels and reducing emissions.

Free piston engines were first proposed around 1920, and a number of different configurations have been put forward as air compressors

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Nomenclature

F	force (N)
f	frequency (Hz)
ε	the back electromotive force (V)
m	mass of the free piston assembly (kg)
a	the free piston assembly acceleration (m/s^2)
p	pressure (bar)
V	volume of the cylinder (L)
A	area (m^2)
L	the inductance (H)
R	the external load resistance (Ω)
r	the internal resistance of linear generator (Ω)

Greek letters

η	indicated efficiency

Subscript

fri	friction
ac	actual
id	ideal
l	left
r	right
in	intake
ep	expansion
f	frequency
mag	magnetic

Acronyms

FPE	free piston expander
LG	linear generator
FPE-LG	free piston expander-linear generator
ORC	organic Rankine cycle
ICEs	internal combustion engines
PMLG	permanent magnet linear generator
FPA	free piston assembly
ORC-FPC	organic Rankine cycle-free piston compressor
EMF	electromotive force

and gas generators [1]. At present, free piston engines are equipped with a linear generator (LG) used to generate electricity. In general, free piston engines can be divided into three different architectures: single piston, dual piston and opposed piston [2].

The single piston architecture holds its main strength in the simplicity of its design compared to the other architectures. Researchers of the German Aerospace Center developed a prototype with the frequency of 50 Hz and the power output of 25 kW for a single piston system [3,4]. While, Toyota Technology Center developed a 10 kW grade free piston linear generator prototype and established a one-dimensional simulation model [5-7]. Lastly, Xu et al. proposed a four-stroke single free piston engine with an integrated liner generator power system, and 2.2 kW power output could be obtained [8].

The dual piston configuration has garnered widespread attention due to the absence of rebound device with higher power to weight ratio. Xiao et al. established a mathematic model to explain the motion characteristics and investigated the performance of free piston engine for electrical power generation [9,10]. Jia et al. presented a numerical model free piston engine generator and validated with the experimental results [11,12]. Feng et al. investigated the intermediate process from cold start-up to stable operation of a free piston linear generator [13]. Yuan et al. researched the heat release characteristics, performance and combustion characteristics of a free piston engine generator [14–16].

Lastly, the opposed piston configuration essentially consists of two single pistons and a common combustion chamber. Each piston needs to connect a rebound device, and an electric generator is coupled to one or both of the pistons. Li et al. presented an effective solution for the challenge of piston motion control for the free piston engine [17,18]. Hibi developed a hydraulic free piston engine and measured the hydraulic thermal efficiency [19].

Out of the three previously described architectures, the single and opposed piston configuration need rebound device, for example, a gas-filled bounce chamber. The rebound chamber force is dependent on the gas pressure of bounce chamber. However, the gas-filled bounce chamber has two major challenges of heat loss and gas leakage. Due to the simple and more compact architecture, the dual piston configuration allows a higher power to weight ration. The free piston expander-linear generator (FPE-LG) adopted in this study is dual pistons and cylinders.

1.2. Free piston expander

Organic Rankine cycle (ORC) system has been regarded as the most promising method to improve the efficiency of the ICEs [20–23]. However, there is no ideal expansion machine for small-scale ORC system [24]. Researchers of Technical University Dresden firstly presented the Free-piston expander in the 1990s [25]. The free piston expander, which has the advantages of low frictional loss, high thermal efficiency, and simple structure, was considered as one of the most suitable expanders for the ORC waste heat recovery system for a vehicle [26,27]. Cha et al. proposed an idea of reducing complexity of the free-piston expander, studied the effect of parameters such as the reservoir volume and the pressure ratio on the performance of the expander [28]. Bouvier et al. presented an experimental study conducted on an oil-free steam piston expander, and an empirical model was developed in order to conduct a sensitivity analysis of the system by varying working variables such as supply and exhaust pressures, rotational speed and supply temperature. Their results showed that overall isentropic efficiency (including electrical generator efficiency) was between 19% and 40% [29]. Kornhauser presented a free-piston expander-compressor, the results showed that the expander and compressor have different relationships between force and position; the balance between the expanding fluid, the moving mass, and the compressed fluid can be described either dynamically (force and momentum) or thermodynamically (work and energy) [30]. Peng et al. developed a free piston expander with a slider was designed to control the expander inlet/outlet, and an adjustable clearance volume of the auxiliary compressor was applied for adjustment of the operating conditions for the expander-compressor unit [31]. Zhang et al. presented a prototype expander, and it was manufactured and validated experimentally based on the air test system. The experimental results showed that the expander could operate stably with different pressures. The optimal operating frequency was from 10 Hz to 17 Hz and the isentropic efficiency could reach 62% [32]. Weiss et al. presented a small-scale free piston expander to produce power output from low-temperature waste heat. The effect of inlet pressure, piston mass, viscous loss, operating frequency and membrane displacement was studied [33]. In order to obtain the optimal performance of the free piston expander, they optimized the operation conditions such as input pressure, lubrication, piston mass and length, and free piston expander shape and size [34]. The results showed that the total power increases and the operation frequency reduced when the heat input increased [35]. Han et al.