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External load resistance effect on the free piston expander-linear generator for organic Rankine cycle waste heat recovery system

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HIGHLIGHTS

- A test rig of FPE-LG driven by compressed air is established.
- The motion characteristics and output performance of FPE-LG are investigated.
- The external load resistance effect on the performance of FPE-LG is conducted.
- The indicated efficiency and energy conversion efficiency are studied.

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ABSTRACT

For this study, a test rig of free piston expander-linear generator (FPE-LG) for organic Rankine cycle (ORC) waste heat recovery system is built. Based on the free piston expander-linear generator test rig, an experiment of external load resistance effect on the motion characteristics, indicated efficiency, output performance and energy conversion efficiency of the free piston expander-linear generator is conducted. The displacement and velocity of the free piston assembly increase with the external load resistance. The indicated efficiency of the free piston expander (left cylinder) decreases with the external load resistance. As the external load resistance and intake pressure increase, the peak voltage output of the free piston expander-linear generator increases. The maximum peak voltage output is 44.4 V when the intake pressure is 3.0 bar, the operating frequency is 1.5 Hz and the external load resistance is 40 Ω. The peak power output of the free piston expander-linear generator initially shows a non-linear relation increase with external load resistance and tends to stabilize in the end. When the intake pressure is 3.0 bar, the operating frequency is 1.5 Hz and the external load resistance is 30 Ω, the maximum peak power output of 110 W can be achieved. The energy conversion efficiency of the free piston expander-linear generator increases gradually with growing of the intake pressure and external load resistance until the energy conversion efficiency reaches the maximal value, and then the energy conversion efficiency decreases with the intake pressure and external load resistance. The maximum energy conversion efficiency can reach up to 73.33%.

1. Introduction

The growth of global energy consumption has resulted in increasingly depleting non-renewable energy and has resulted in environmental pollution, so green decoration materials, energy recovering and energy saving have been hot research topics [1–3]. Commonly, the useful work from fossil oil in the internal combustion engine (ICE) is only about 20–45%. Therefore, the efficient utilization of the ICE has been attracting increasing interest of researchers around the world. Recovering waste heat from the engines is a promising method to improve the overall energy efficiency [4,5].

Organic Rankine cycle (ORC) has enormous advantages in converting the low-grade waste heat to useful work, and has been widely used in recovering different low-grade waste heat [6–10]. The ORC system efficiency is determined by the expander performance as well as all the other branches of the cycle Thus, the development of the expander is of great significance to ORC waste heat recovery system. Researchers have done much effort on the exploration and development

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Nomenclature

F	force (N)
f	frequency (Hz)
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)
P	power output (W)
U	voltage (V)
E	induced electromotive force (V)
B	magnetic induction (T)
l	the length of wire cutting the magnetic lines (m)
S	stroke (m)
W	work (J)
R,r	resistance (Ω)
v	velocity (m/s)
c	load factor (N·s/m)

Greek letters

η	efficiency

Subscript

in	intake
fri	friction
ac	actual
th	theoretical
l	left
r	right
ind	indicated
con	conversion

Acronyms

ORC	organic Rankine cycle
ICE	internal combustion engine
FPE-LG	free piston expander-linear generator
LG	linear generator
OBDC	operation bottom dead center
OTDC	operation top dead center
FPE	free piston expander
FPC	free piston compressor
FPEG	free-piston engine generator
FPLE	free piston linear expander
FPLA	free-piston linear alternator

of the expander used for ORC waste heat recovery system. Kang presented an ORC using a radial turbine. The results showed that the turbine efficiency is 78.7% [11]. Wu et al. studied the influence of torque of single-screw expander on the performance of ORC [12]. Galindo et al. conducted an experimental testing of a bottoming ORC where a swashplate expander is used. The results indicated that the maximum isentropic of 38.5% is achieved [13]. Gnutek et al. applied vane-expanders to mini-ORC systems. The results showed that: for small-capacity ORC systems, multi-vane expanders are suitable expansion devices [14]. Wei et al. provided an insight into relevant application and studies on the scroll expanders [15]. Gao et al. proposed a Rankine cycle system using a reciprocating piston expander [16].

Since the free piston engine concept is presented by Pescara in the mid-20th century, there have been many different free piston engines studied by research groups all over the world [17]. Johansen et al. provided a detailed investigation on the piston motion control structure [18]. Mikalsen et al. investigated the basic control strategies and the predictive piston motion control strategy. They also investigated the combustion process of a free-piston diesel engine [19–22]. Xu et al. proposed a novel four-stroke free-piston engine equipped with a linear electric generator to achieve efficient energy conversion from fuel to electricity [23]. Li et al. presented a simulation of a two-stroke free-piston engine for electrical power generation [24]. Jia et al. presented the design and simulation of a free-piston engine generator. They also investigated the operating characteristics of a free piston linear alternator (FPLA) and presented a linearization of the dynamic equation for a free-piston engine generator (FPEG) [25–28]. Sun et al. developed full cycle simulation model and the top-level systemic control strategies of the FPEG. The results indicated that the overall system efficiency can reach 36.32% [29].

Since first developed in the 1990s, the free piston expander has received more and more attentions because of its low friction loss, simple structure and good sealing [30–33]. Weiss et al. tested the operation characteristics of a small scale free piston expander (FPE). They also performed initial experiment on the small scale FPE. And the result indicated that higher viscosity lubricants sealed is more effective in static environments than lower viscosity lubricants [34,35]. Zhang et al. proposed a free piston expander to recover work in trans-critical CO_2 cycle [36]. Han et al. firstly proposed the free piston compressor used for organic Rankine cycle system. Their results indicated that low output pressure among specific range benefits the system performance [37,38]. Zhang et al. developed a new free piston expander-linear generator (FPE-LG) applied to ORC waste heat recovery system. They investigated the intake pressure effects on operation characteristics [39,40]. They also investigated the asymmetry motion characteristics and power output performance of the FPE-LG. Their results indicated that demonstrate the performance of the FPE-LG is significantly influenced by the valve timing and intake pressure [1]. Wang et al. tested an air-driven free piston linear expander (FPLE). The results showed that the operation frequency is more sensitive with the driven pressure [41].

In order to promote the application of free piston expander-linear generator (FPE-LG) for engine-ORC waste heat recovery system, more in-depth research need to be done. It is clear that the external load resistance has great significant influence on the motion characteristics of the free piston assembly and has important effect on the output performance of free piston expander-linear generator. However, few research about the external load resistance effect on the free piston expander-linear generator has been investigated in the previous studies and above literature. This paper focuses on a novel free piston expander-linear generator. Detailed analysis of the external load resistance effect on the motion characteristics, indicated efficiency, output performance and the energy conversion efficiency is conducted. This study will provide key guidance for the application of a real ORC system equipped with free piston expander-linear generator that is well suited to engine waste heat recovery.

2. Working principle and experiment configurations

The FPE-LG mainly includes intake-expansion stroke and exhaust stroke. For the left cylinder, when free piston expander-linear generator is in intake-expansion stroke, the working fluid flows into the cylinder and expands. When the free piston expander-linear generator is in exhaust stroke, the free piston moves from OBDC (operation bottom dead center) to OTDC (operation top dead center), and the working fluid flows out of the cylinder. When free piston of left cylinder is in intake-expansion stroke, free piston of right cylinder is in exhaust stroke, and vice versa.

In this study, we define the center of the free piston expander-linear