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Research Paper

Performance investigation of a free piston expander-linear generator for small scale organic Rankine cycle

Xiaochen Hou[a,b], Hongguang Zhang[a,b,*], Yonghong Xu[c], Yaming Tian[a,b], Tenglong Zhao[a,b], Jian Li[a,b], Fei Yu[a,b]

[a] MOE (Ministry of Education) Key Laboratory of Enhanced Heat Transfer and Energy Conservation, College of Enviromental and Energy Engineering, Beijing University of Technology, Pingleyuan No.100, Beijing 100124, China
[b] Beijing Key Laboratory of Heat Transfer and Energy Conversion, College of Enviromental and Energy Engineering, Beijing University of Technology, Pingleyuan No.100, Beijing 100124, China
[c] School of Electrical and Mechanical Engineering, Beijing Information Science and Technology University, Beijing 100192, China

HIGHLIGHTS

- FPE-LG test rig driven by compressed air is developed.
- Different efficiencies of FPE-LG are investigated.
- The entropy generation of FPE-LG under various conditions is studied.
- The output performance of FPE-LG are identified.

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ABSTRACT

This paper presents a free piston expander-linear generator (FPE-LG) for small scale organic Rankine cycle (ORC). Based on FPE-LG experiment configuration, performance investigation and efficiency analysis on FPE-LG are conducted. Experiment results show that intake pressure and external load resistance have great influence on actual stroke, velocity and exhaust temperature. The exhaust pressure is hardly relevant to intake pressure and operation frequency. When FPE-LG operates with low operation frequency, the entropy generation decreases with intake pressure, whereas it increases with intake pressure when the operation frequency is high. The indicated work increases when increasing the intake pressure and external load resistance, whereas it decreases when increasing operation frequency. The indicated efficiency decreases with the intake pressure and external load resistance, and the maximum indicated efficiency can reach up to 81%. The voltage and power output increase when the intake pressure and external load resistance increase, and the maximum voltage and power output can reach 44.4 V and 111.6 W, respectively. High energy conversion efficiency can be achieved in the area of high external load resistance and intake pressure. Generally, the higher power output is, the higher energy conversion efficiency is. The maximum energy conversion efficiency of 73.4% is achieved.

1. Introduction

The rapid development in global economic has resulted in the great increase of the energy consumptions. As an important part of the republic economic, the automotive industry has made great contribute to the fuel consumptions and hazardous emissions. As we all known, the effective thermal efficiency of the internal combustion engine (ICE) is less than 45% [1,2]. Thus, how to improve the efficiency of the engine and reduce the emissions has been hot topics all over the world.

Organic Rankine cycle (ORC) has been a promising method to improve the efficiency of the ICE. As one of the most important components in ORC system, the expander has significant influence on the ORC system performance [3–7]. The global researchers have explored different types of expanders to achieve as high power output as possible in power cycle system [8–12]. Zheng et al. applied a kilowatt-sized rolling-piston expander to ORC system to generate power. The results

* Corresponding author at: MOE (Ministry of Education) Key Laboratory of Enhanced Heat Transfer and Energy Conservation, Beijing Key Laboratory of Heat Transfer and Energy Conversion, College of Enviromental and Energy Engineering, Beijing University of Technology, Pingleyuan No.100, Beijing 100124, China.
E-mail address: zhanghongguang@bjut.edu.cn (H. Zhang).

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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)
h	enthalpy (kJ/kg)

Greek letters

η	efficiency

Subscript

in	intake
fri	friction
ac	actual
th	theoretical
l	left
R	right
m	magnetic
ind	indicated
con	conversion

Acronyms

ORC	organic Rankine cycle
ICE	internal combustion engine
FPE-LG	free piston expander-linear generator
LG	linear generator
FPE	free piston expander
FPC	free piston compressor
FPLE	free piston linear expander

showed that the maximum isentropic efficiency can reach up to 43.3% [13]. Zhang et al. conducted the experimental study on an ORC system for diesel engine waste heat recovery using a single screw expander. Their results indicated that the highest shaft efficiency was around 57.88% [14]. Kang proposed an ORC with a radial turbine. The results showed that the turbine efficiency of 78.7% can be achieved [15]. Galindo et al. performed an experimental testing of a bottoming ORC where a swashplate expander is used. The results showed that the maximum isentropic efficiency can reach 58.81% [16,17].

Due to the advantages of low friction loss, simple structure and good sealing, the free piston expander has received more and more attentions once developed by 1990s [18–21]. Zhang et al. presented a double acting free-piston expander to replace the throttling valve in transcritical CO_2 cycle. Their research results showed that the maximum isentropic efficiency of 62% can be obtained [22]. Weiss et al. performed initial experiment on a small scale free piston expander (FPE). The result indicated that higher viscosity lubricants sealed is more effective in static environments than lower viscosity lubricants [23,24]. Han et al. proposed a free piston compressor (FPC) to recover the exhaust waste heat from the internal combustion compressor and compress natural gas to a designed pressure. The simulation model of combined ORC and FPC system was established in GT-suite software to evaluate the effects of thermodynamic state of working fluid and input power on its operation performance under various working conditions. The maximum working efficiency of the power cylinder of 44.3% could be achieved [25,26]. Kodakoglu et al. presented a free-piston linear expander (FPLE) and compared the FPLE with the currently existing expander types. Their results indicated that the FPLE achieved the maximum isentropic efficiency of 21.5%, and produced maximum actual expander work of 75.13 W, respectively [27]. Wang et al. investigated the piston dynamic performances of a compressed air driven free-piston linear expander. The results showed that the maximum energy conversion efficiency of 55% is obtained [28]. Zhang et al. conducted experimental investigation on a new free piston expander-linear generator. They discussed the effects of intake pressure, operation frequency and external load resistance on its output performance indicators, mainly including power output, conversion efficiency and coefficient of cycle-to-cycle variation [7,29–32].

As can be seen from above literature review, the performance of free piston expander-linear generator is effected by different factors, and different factors are mutual coupled with each other. This study focuses on a developed free piston expander-linear generator (FPE-LG), details

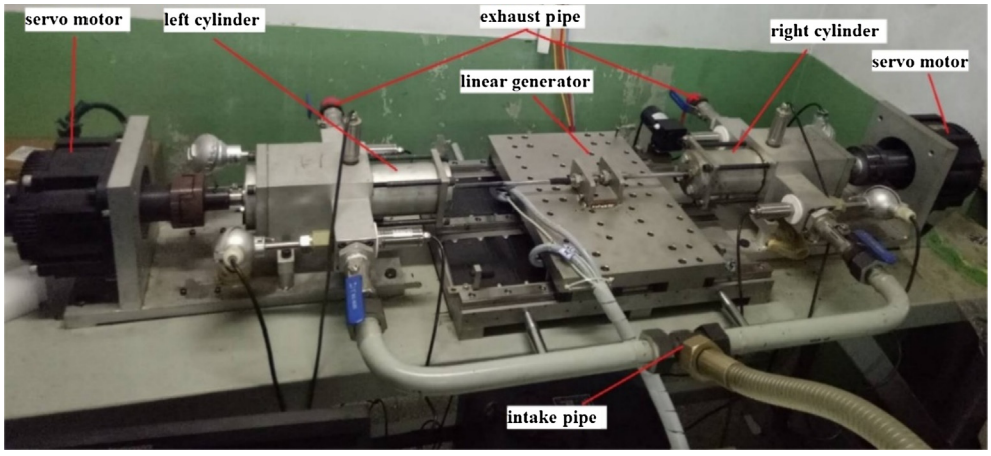

Fig. 1. Appearance of free piston expander-linear generator.