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Free piston expander-linear generator used for organic Rankine cycle waste heat recovery system

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HIGHLIGHTS

- Motion characteristics and power outputs for different cam plates are analyzed.
- Asymmetric motion characteristics are studied.
- Cycle-to-cycle variation characteristics are defined and investigated.

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ABSTRACT

This study presents an experimental investigation of a free piston expander-linear generator (FPE-LG) used for organic Rankine cycle (ORC) waste heat recovery system. A FPE-LG test rig using compressed air as working fluid is established. The motion characteristics, dynamic characteristics and the indicated efficiency of FPE-LG are analyzed. The motion characteristics and power output performance for different valve timings are studied. The degree of symmetry is defined to evaluate the asymmetry motion characteristics of the free piston assembly. The coefficient of cycle-to-cycle variation (COV) is presented to evaluate the cycle-to-cycle variation characteristics of the FPE-LG. Experimental results show that the free piston assembly displacement profile is similar to a sinusoidal wave and the free piston assembly can operate at high and relatively constant speed at the middle portion of the stroke. The maximum power output of 19 W can be achieved when the intake pressure is 2.0 bar and the operation frequency is 2.5 Hz. The valve timing and intake pressure demonstrate a significant influence on the asymmetric motion and the power output performance of the FPE-LG. The indicated efficiency of the FPE (left cylinder) decreases with the increase in the intake pressure. The maximum indicated efficiency reaches 92.8% when the intake pressure is 1.4 bar and the operation frequency is 2.0 Hz. The indicated efficiency firstly increases and then decreases with the increase in the operation frequency. The COV of the FPE-LG decreases with increasing the intake pressure. The motion stability of FPE-LG improves with the increase in the intake pressure. Valve timing and valve train should be optimized in the near future.

1. Introduction

Recently, the increasing electricity demand and cost, in addition to the increasing global energy demands, are the main motivations in seeking for sustainable new technologies in the field of energy conversion and utilization. Various thermodynamic cycles, such as organic Rankine cycle (ORC), supercritical Rankine cycle, Kalina cycle and trilateral flash cycle, have been proposed to convert the low-grade heat sources into electricity [1–5]. ORC has been widely applied in recovering different heat sources, such as industrial waste heat [6,7], solar energy [8,9], geothermal energy [10,11], waste heat from internal combustion engine [12], because of its simple structure, high reliability, easy maintenance, as well as the better potential in converting the low-grade waste heat to high-grade energy than other cycles [5]. As is well known, the useful work produced by fuel combustion in the internal combustion engines (ICEs) accounts for 20–45%. Therefore, improving the total energy conversion efficiency and reducing the fuel consumption by effectively utilizing the exhaust waste heat energy of ICEs are crucial. In previous publications of our research team, the attention is mainly focused on the system performance improvement

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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)
S	the distance from the OTDC or OBDC to RP (m)
COV	coefficient of cycle-to-cycle variation (%)
volt	voltage (V)
SD	sample deviation
X	variable
N	times of the cycles
j	the jth cycle
V	volume of the cylinder (L)
A	area (m^2)

Greek letters

σ	degree of symmetry
η	indicated efficiency

Subscript

1,2	the position of the piston
in	intake
inc	in-cylinder
fri	friction
ac	actual
id	ideal
l	left
r	right

Acronyms

ORC	organic Rankine cycle
ICEs	internal combustion engines
DAS	data acquisition system
AS	actual stroke
VC	vibration center
OTDC	operation top dead center
OBDC	operation bottom dead center
MTDC	mechanical top dead center
MBDC	mechanical bottom dead center
FPE-LG	free piston expander-linear generator
FPE	free piston expander
FPLE	free piston linear expander
FPLA	free-piston linear alternator

[13–15], working fluid selection [16–18], component performance analysis [19–21] and parameter optimization [22–23].

As a key component of ORC system, the selection and design of the expander are of significant influence to the system efficiency of ORC system. Generally, expanders can be categorized into two types: the velocity type and the volume type. The velocity type mainly includes axial turbine expanders, and the volume type mainly consists of screw expanders, scroll expanders and reciprocal piston expanders [4,24]. Turbine expanders are widely used in large scale power systems, whereas the positive displacement expanders are preferred for small scale units [24,25].

Oomori et al. proposed an ORC system which uses scroll expander to improve the fuel economy of a passenger car. The results indicated that energy recovered is almost 3% of engine power output at ambient temperature of 25 °C [26]. The ORC technology, in which a turbine was used as a heat-work conversion unit, was adopted to recover the exhaust waste heat. The results showed that the potential for improving the net fuel consumption of hybrid vehicles is estimated to be as high as 32% [27]. Galindo et al. presented the experimental and thermodynamic analyses of a bottoming ORC of gasoline engine using swashplate expander. Their results indicated that the maximum ideal and real Rankine efficiency values are 19% and 6%, respectively [28]. An optimization analysis of the ORC system has also been conducted [29]. Gnutek et al. presented a preliminary theoretical treatment applicable to micro-ORC systems adopting vane expanders. The analysis indicated that multivane expanders are a cheap and mechanically simple alternative to other expansion devices proposed for small-capacity ORC systems [30]. Wei et al. adopted ORC system using scroll expander to recover the exhaust waste heat of ICE [13]. Shu and Xie conducted research on the ORC system using turbine expander to recover waste heat [31–33]. Gao et al. focused on the performance evaluation and experimental system development of waste heat recovery system utilizing reciprocating piston expander, and their results showed that introducing heat recovery system can increase the engine power output by 12% [34].

The free-piston engine concept was first presented by Pescara [35,36]. Mikalsen et al. discussed the basic features of a piston free-piston engine generator, and investigated the dynamics of the engine and the feasibility of classical control approaches. They also presented a piston motion controller for a free-piston internal combustion engine [37–39]. Zuo et al. analyzed the operation characteristics of a free-piston linear alternator (FPLA) [40–42]. Zhao et al. investigated the piston dynamics, combustion process and hydraulic characteristics of hydraulic free-piston engine [43]. Xiao et al. built up a full simulation model of a free-piston linear engine and investigated the motion characteristics [44].

Heyl and Quack first developed the free piston expander at Technical University of Dresden in the 1990s [45]. Compared with the previously reported expanders, the free piston expander was considered as one of the most suitable expanders for small scale ORC system because of its potential advantages of good sealing, low frictional loss, and simple structure with a promising efficiency of up to 50% [46,47]. The free piston expander has attracted the attention of researchers around the world given its potential advantage. Zhang et al. described the design and experimental validation of a double acting free piston expander used to achieve a full expansion process for the expander, their results indicated that the isentropic efficiency obtained from the *p-V* diagram analysis is 62% [48]. Weiss et al. examined the design and operation of a new, small-scale free piston expander using low temperature waste heat sources to produce useful power output. Their simulation results showed that the *p-V* diagram resembles a constant pressure cycle for certain sets of operating conditions [49]. Weiss et al. also performed initial experimental analysis of a small scale free-piston expander, and examined the operating conditions to improve operational performance of the system. The results indicated that thick lubricants seal well in static configurations, and piston speed is decreased during the testing process [50]. Han et al. proposed an organic Rankine cycle coupling free piston compressor system. The results showed that the system achieved better performances than other thermodynamic states when the heated working fluid is at 11.5 bar and 383 K [51,52]. Li et al. proposed a novel free piston expander-linear generator (FPE-LG) integrated unit to recover waste heat from vehicle engine efficiently and also investigated the dynamic characteristics of an in-cylinder flow field during the gas exchange process. The simulation results indicated efficiency of the FPE can reach up to 66.2% [53]. Wang et al. established a test rig of a dual-piston air-driven free piston linear expander