International Conference on Applied Energy 2020
Dec. 1 - Dec. 10, 2020, Bangkok / Virtual
Paper ID: 46

Simulation research of a free piston expander-linear generator under variable operation conditions for small-scale organic Rankine cycle system of vehicle engine

Yonghong Xu[1]*, Fubin Yang[1], Hongguang Zhang[1]

1 MOE Key Laboratory of Enhanced Heat Transfer and Energy Conservation, Beijing Key Laboratory of Heat Transfer and Energy Conversion, Beijing University of Technology, Beijing, 100124, China

ABSTRACT

In order to better match the working conditions of the organic Rankine cycle (ORC) system for vehicle engine waste heat recovery, this paper aims to study the performance of the free piston expander-linear generator (FPE-LG) under variable operation conditions using a simulation model based on Matlab/Simulink software. Firstly, the effect of the mass of the free piston assembly (FPA) and internal resistance of the linear generator (LG) on the electromagnetic force, motion characteristics and output performance are discussed and analyzed. Secondly, the effect of the changing intake pressure and exhaust back pressure on the performance of the FPE-LG are investigated. The velocity reaches the maximum of 3.12 m/s when the intake pressure, operation frequency, external load resistance, mass of the FPA and the internal resistance of LG are 3 bar, 5 Hz, 9 Ω, 0.59 kg and 14.7 Ω, respectively. This study can provide a useful guidance for the application of the FPE-LG in the actual ORC system.

Keywords: Organic Rankine cycle; Free piston expander-linear generator; Motion characteristics; Variable operation conditions; Output performance

NONMENCLATURE

Abbreviations	
ORC	organic Rankine cycle
FPE	free piston expander-linear generator
LG	linear generator
PMLG	permanent magnet linear generator
FPA	free piston assembly
BEF	back electromotive force
Symbols	
p_{in}	intake pressure (bar)
p_{out}	exhaust back pressure (bar)
f	operation frequency (Hz)

1. INTRODUCTION

Due to the lack of energy resources, serious air pollution, and environmental protection needs, new technologies need to be explored to solve the above problems. Organic Rankine cycle (ORC) technology is considered to be one of the most promising technologies in improving the efficiency and reducing emissions of the internal combustion engines (ICEs) [1,2].

However, there is no suitable expander for small-scale ORC system of vehicle engine. The free piston expander (FPE) has the advantages of simple structure, few attachments, high energy conversion efficiency and high-power density, which has attracted the attention of researchers [3]. Jia et al. compared friction between the free piston engine and the conventional engine, the results showed that the total friction loss of the free piston engine is nearly half of the conventional engine [4]. Wang et al. established a test rig of free piston linear expander with air-driver, and the operation characteristics was studied. The results showed that the energy conversion efficiency is 55% when the intake pressure is 3.75 bar [5]. Weiss et al. presented a free piston expander for waste heat energy harvesting, and optimized the piston stroke length and mass, free piston shape and size, intake pressure and lubrication to improve the performance of the free piston expander [6].

Through the above literature review, it is well known that the free piston expander has great potential advantages and a broad application market in the small-scale ORC system. However, few studies have been done on the performance of the free piston expander-linear (FPE-LG) generator under variable working conditions for the small-scale ORC system of vehicle engine. This paper study the performance of the FPE-LG under variable operation conditions using a model based on Simulink / Matlab software. The research contents of this paper are

Selection and peer-review under responsibility of the scientific committee of the 12th Int. Conf. on Applied Energy (ICAE2020).

mainly divided into the following parts: the effects of the FPA mass and internal resistance of the linear generator (LG) on the electromagnetic force, motion characteristics (displacement and velocity) and output performance (current output, voltage output and power output) are discussed and analyzed.

2. Experimental Setup and simulation model

2.1 Experiment setup

Above detailed introduction of the FPE-LG test rig can refer in reference [7], while only a brief overview is given herein. Fig. 1 is the prototype of FPE-LG.

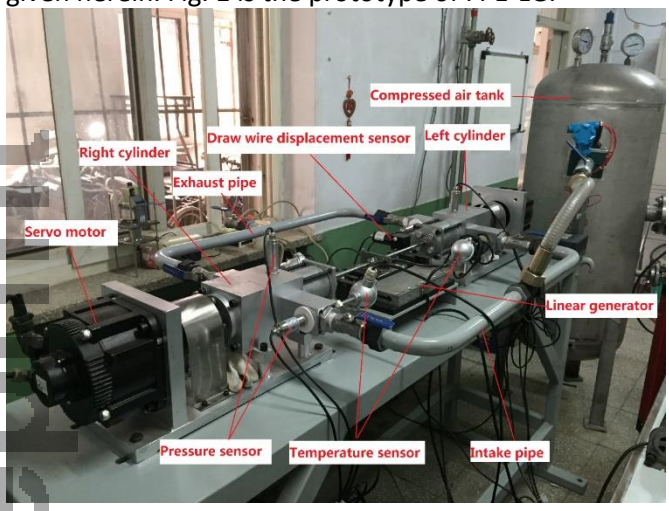

Fig. 1. The prototype of FPE-LG

2.2 Simulation model

A simulation model of the FPE–LG is established with Simulink/Matlab software, based on the first law of thermodynamics. Above the detailed description of the simulation of the FPE–LG can refer in reference [8]. Fig. 2 presents the simulation model of the FPE–LG.

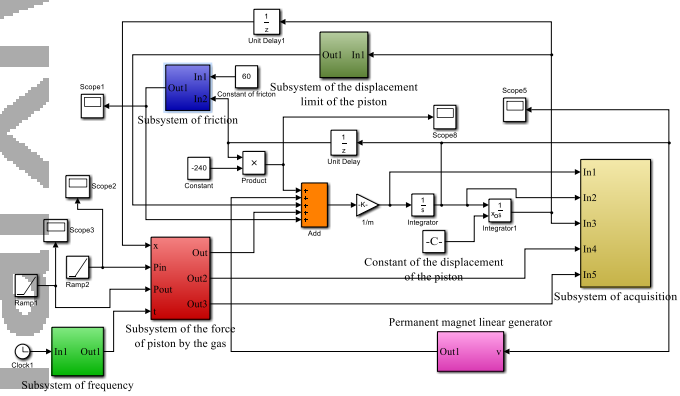

Fig. 2 The simulation model of the FPE–LG

3. Results and discussion

3.1 The effect of FPA mass on the performance of the FPE-LG

Fig. 3 describes the displacement and the corresponding velocity varies with the different mass of FPA. The displacement and the corresponding velocity increase with the mass of FPA decreasing. In order to reduce the mass of moving parts, the FPA is made of high-strength aluminum alloy. The velocity reaches the maximum of 3.12 m/s when the intake pressure, operation frequency, external load resistance, mass of the FPA and the internal resistance of LG are 3 bar, 5 Hz, 9 Ω, 0.59 kg and 14.7 Ω, respectively.

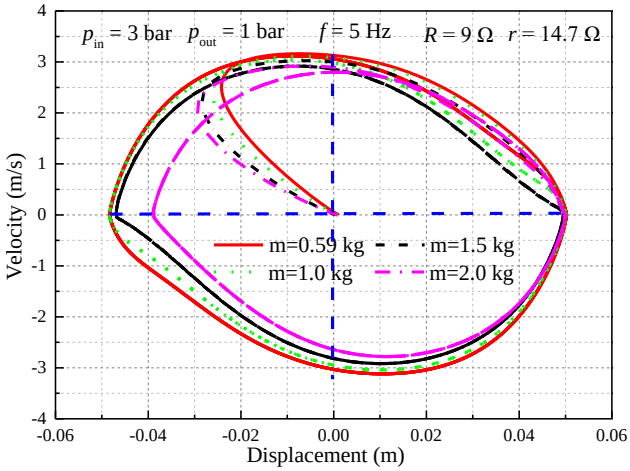

Fig. 3 The displacement and the corresponding velocity varies with the different quality of FPA

The effect of the FPA mass on the voltage output and power output are displayed in the Fig. 4 and Fig. 5. The changing trend of the voltage output is similar with the power output with the different mass of the FPA.

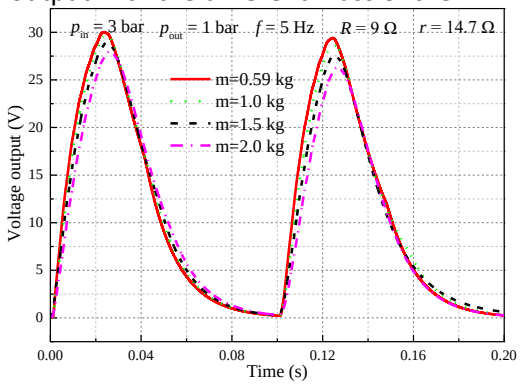

Fig. 4 The voltage output varies with the changing mass of the FPA

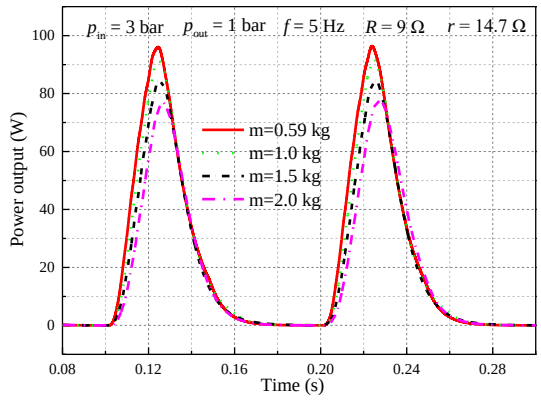

Fig. 5 The power output varies with the changing mass of the FPA

3.2 The effect of the internal resistance of the LG on the performance of the FPE-LG

Linear generator (LG) plays an important role in the performance of free piston expander. The effect of internal resistance on the displacement is depicted in Fig. 6. It is observed that with higher internal resistance of LG, the displacement shows an increasing trend.

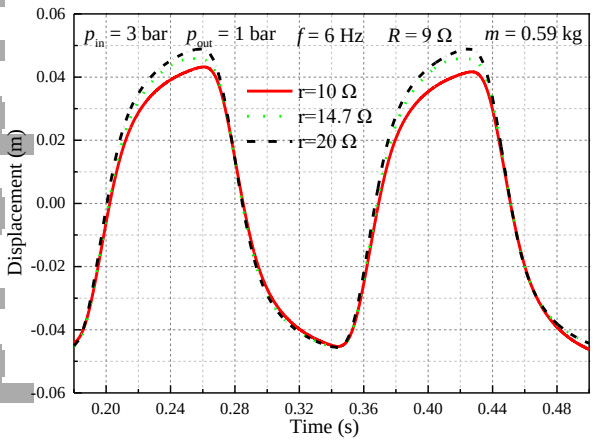

Fig. 6 The effect of the internal resistance on the displacement

The current output with different internal resistance of LG is exhibited in the Fig. 7. The current is rectified by a rectifier. The current reaches the maximum of 4.0 A when the intake pressure, operation frequency, external load resistance, mass of the FPA and the internal resistance of LG are 3 bar, 6 Hz, 9 Ω, 0.59 kg and 10 Ω, respectively.

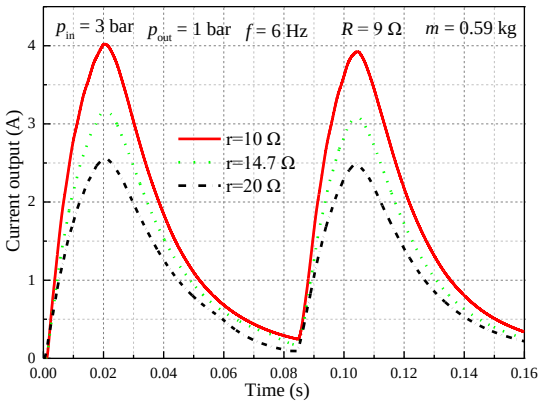

Fig. 7 The effect of the internal resistance on the current output

3.3 The effect of the changing intake pressure on the performance of the FPE-LG

In order to better match the working conditions of the ORC, we study the performance of the FPE-LG under the variable operation conditions. Fig. 8 shows the displacement of the FPA with four variable conditions.

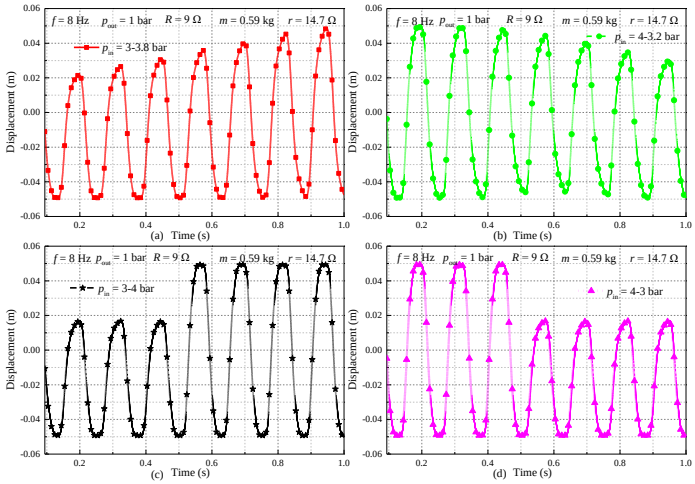

Fig. 8 The displacement varies with the changing of the intake pressure

3.4 The effect of the changing exhaust pressure on the performance of the FPE-LG

The effect of changing exhaust back pressure on the power output is shown in the Fig. 9. The peak power output can reach up to the maximum of 136. W when the exhaust back pressure is 1 bar, while the peak power output can reach up to the maximum of 118.2 W when the exhaust back pressure is 1.2 bar. It is found that the power output and the voltage output show the same trending with the changing exhaust back pressure.

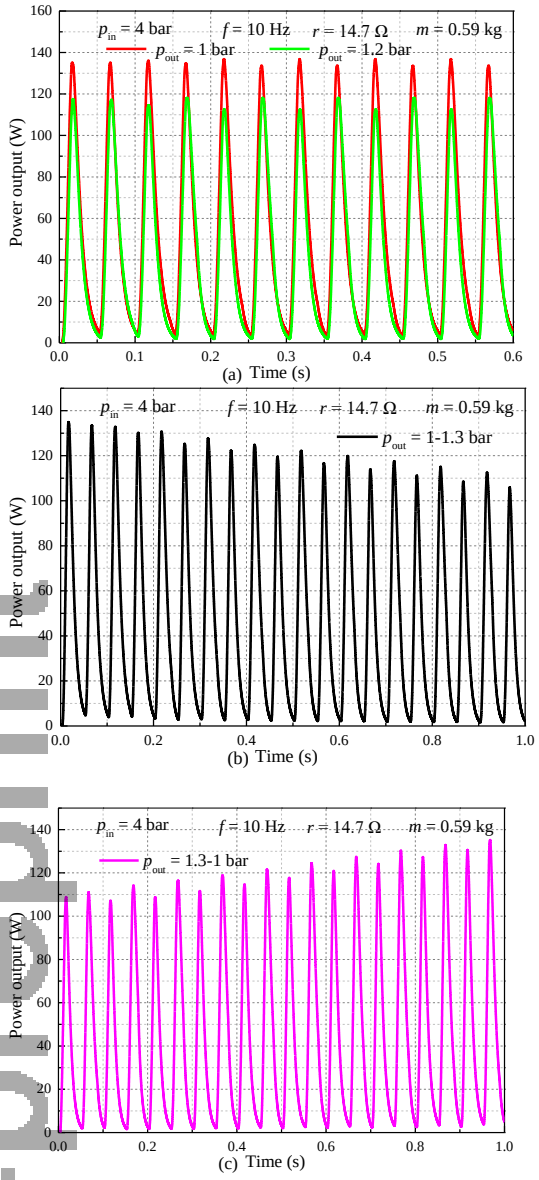

Fig. 9 The effect of the changing exhaust back pressure on the power output

4. CONCLUSIONS

This paper study the performance of the FPE-LG under variable operation conditions using a model based on Simulink / Matlab software. This study can provide a useful guidance for the application of the FPE-LG in the actual ORC system. The main conclusion are as follows:

(1) Reducing the mass of the FPA is benefit to improve the performance of the FPE-LG.

(2) In order to improve the output performance, it is necessary to reduce the internal resistance of the LG.

(3) The intake and exhaust pressure have a greater influence on the motion characteristics and the putput performance of the FPE-LG. The displacement and velocity show upward trending when the intake pressure increasing and the exhaust back pressure decreasing. Increasing the intake pressure and reducing the exhaust back pressure are good ways to improve the performance of the FPE-LG.

ACKNOWLEDGEMENT

This work was sponsored by the Projects of International Cooperation and Exchanges NSFC (Grant No.51911530210), the National Natural Science Foundation of China (Grant No. 51776005), the Beijing Natural Science Foundation (Grant No. 3192014), and the Project funded by China Postdoctoral Science Foundation (Grant No. 2019M650673).

REFERENCE

[1] Cao S, Xu JL, Miao Z, Liu XL, Zhang M, Xie XW, Li Z, Zhao XL, Tang GH. Steady and transient operation of an organic Rankine cycle power system. Renewable Energy 2019; 133: 284-294.

[2] Yang FB, Cho HJ, Zhang HG, Zhang J. Thermoeconomic multi-objective optimization of a dual loop organic Rankine cycle (ORC) for CNG engine waste heat recovery. Applied Energy 2017; 205: 1100-1118.

[3] Mikalsen R, Roskilly A P. A review of free-piston engine history and applications. Applied Thermal Engineering 2007; 27(14-15): 2339-2352.

[4] Jia BR, Mikalsen R, Smallbone A, Roskilly AP. A study and comparison of frictional losses in free-piston engine and crankshaft engines. Applied Thermal Engineering 2018; 140: 217-224.

[5] Wang YD, Chen L, Jia BR, Roskilly AP. Experimental study of the operating characteristics of an air-driven free-piston linear expander. Applied Energy 2017; 195: 93-99.

[6] Champagne C, Weiss L. Performance analysis of a miniature free piston expander for waste heat energy harvesting. Energy conversion and management 2013; 76: 883-892.

[7] Li GS, Zhang HG, Yang FB, Song SS, Chang Y, Yu F, Wang JF, Yao BF. Preliminary development of a free piston expander-linear generator for small-scale organic Rankine cycle (ORC) waste heat recovery system. Energies 2016; 9(4): 300.

[8] Xu YH, Tong L, Zhang HG, Hou XC, Yang FB, Yu F, Yang YX, Liu R, Tian YM, Zhao TL. Experimental and simulation study of a free piston expander–linear generator for small-scale organic Rankine cycle. Energy 2018; 161: 776-791.