Performance Analysis of Free Piston Expander-Linear Generator for Organic Rankine Cycle Waste Heat Recovery System

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***Abstract*—This study presents a test rig of Free Piston Expander-Linear Generator (FPE-LG) for Organic Rankine Cycle (ORC) waste heat recovery system. Based on the FPE-LG test rig, an experiment investigation on the motion characteristics, indicated efficiency, output performance and energy conversion efficiency of the FPE-LG is conducted. The displacement and velocity of the free piston assembly increase with the external load resistance. The indicated efficiency of the FPE (left cylinder) decreases with the external load resistance. As the external load resistance and intake pressure increase, the peak voltage output of the FPE-LG increases. The maximum peak voltage output is 44.4 V. The peak power output of the FPE-LG initially shows a non-linear relation increase with external load resistance and tends to stabilize in the end. The maximum peak power output of 110 W can be achieved. The energy conversion efficiency of the FPE-LG 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%.**

***Index Terms*—organic Rankine cycle, free piston expander-linear generator, experiment investigation, motion characteristics, energy conversion efficiency**

I. Introduction

Due to the ever-growing global energy crisis and demands, energy recovering and energy saving have been hot research topics [1]. Commonly, the useful work from fossil oil in the Internal Combustion Engine (ICE) is about 20–45%, while the remaining energy is wasted. Recovering waste heat from the engines is a promising method to improve the overall energy efficiency.

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. The ORC system efficiency is determined by the expander performance to some extent. Thus, the development of the expander is of great significance to ORC waste heat recovery system.

Since first developed in the 1990s, the free piston expander has received more and more concerns because of its low friction loss, simple structure and good sealing [2]-[5]. 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 effectively in static environments than lower viscosity lubricants [6], [7]. 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 [8], [9]. Zhang *et al.* developed a new free piston expander-linear generator (FPE-LG) applied to ORC waste heat recovery system [10], [11]. 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 [12].

This paper focuses on a novel FPE-LG. 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 FPE-LG that is well suited to engine waste heat recovery.

II. Working Principle and Experiment Configurations

The FPE-LG prototype and the schematic diagram of FPE-LG experiment configurations are shown in Fig. 1. The FPE-LG experiment configurations mainly includes a compressed air tank, load circuit, FPE and all kinds of sensors. In this paper, the external load resistance variation is adjusted by the resistance box. The adjustment of the intake and exhaust valve is determined by the servo motor, which can realize the control of the operating frequency of the FPE-LG. As the driven power, the compressed air is stored in an air tank. The data from

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the sensors, such as displacement, temperature, pressure and voltage output *et al.*, is acquired by data acquisition system.

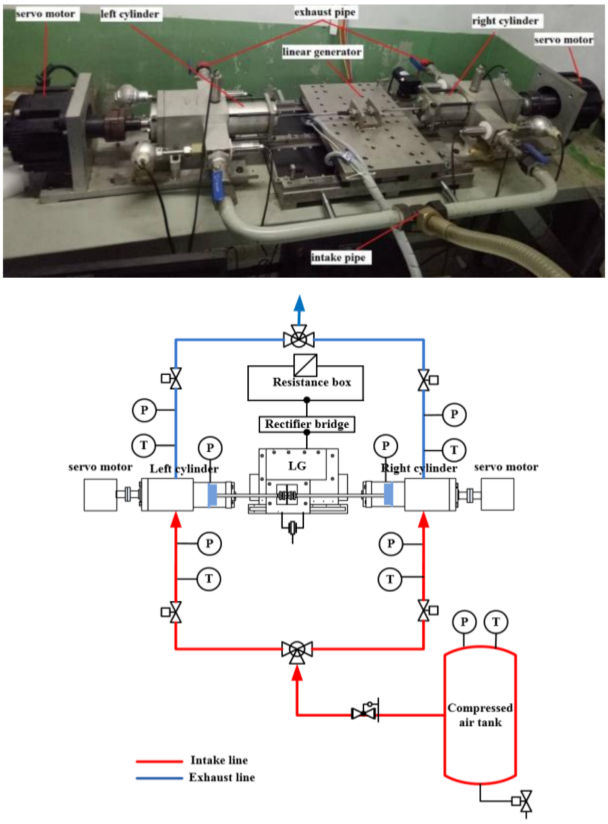
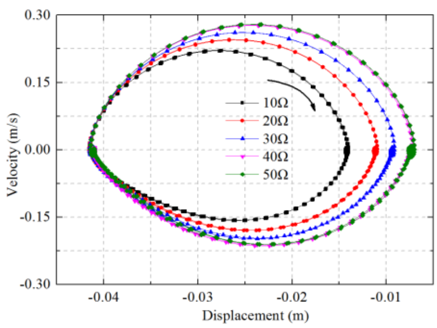


Figure 1. The prototype and schematic diagram of the FPE-LG experiment configurations

III. Experiment Results and Discussion

A. Motion Characteristics

Fig. 2 displays the varying trend of free piston assembly velocity vs free piston assembly displacement (f= 1.0 Hz). The actual stroke and velocity of the free piston assembly shows an increasing trend with increasing the intake pressure and external load resistance. Higher intake pressure leads to greater force which acts on the free piston assembly. This then results in the increase of the free piston assembly velocity. Furthermore, higher intake pressure benefits the symmetric motion of the free piston assembly. Thus, higher intake pressure and external load resistance are helpful to achieve stable operation of the FPE-LG in terms of the practical power output.



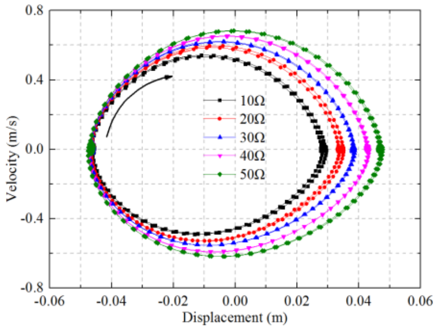


Figure 2. Varying trend of free piston assembly velocity vs free piston assembly displacement

B. Indicated Efficiency

The indicated efficiency is defined to evaluate the efficiency of the thermal energy converting into mechanical energy, and the energy loss during every process. It can be calculated as the ratio of the actual area *p-V* diagram (A_{ac}) to the theoretical area *p-V* diagram (A_{th}).

$$\eta_{ind} = \frac{A_{ac}}{A_{th}} \times 100\% \tag{1}$$

Fig. 3 demonstrates the indicated efficiency of FPE (left cylinder) vs the external load resistance for different intake pressures and operating frequencies. As the figure shows, the indicated efficiency decreases with increasing the external load resistance.

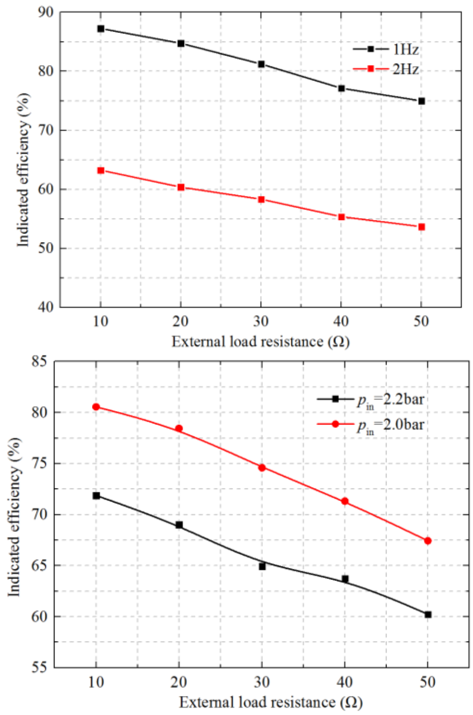


Figure 3. Varying trend of indicated efficiency of left cylinder

C. Output Performance

Fig. 4 shows the varying trend of peak voltage output of the FPE-LG vs the external load resistance for different intake pressures (*f*= 1.5 Hz). As the figure shows, in general, the peak voltage output increases with external load resistance. It also can be seen that the peak voltage output of the FPE-LG reaches up to 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. In addition, the variation amplitude of the peak voltage output for different intake pressure is different. The higher the intake pressure is, the higher the peak voltage output of the FPE-LG is. When the external load resistance varies in the range of 5-50 Ω, the peak voltage output can increase from 13.4 V to 44.4 V.

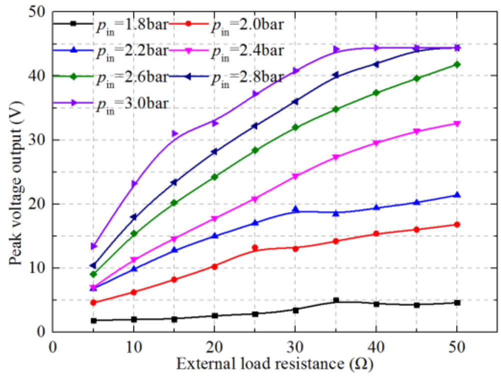


Figure 4. Varying trend of the peak voltage output of the FPE-LG vs external load resistance

Fig. 5 shows the varying trend of peak voltage output of the FPE-LG vs operating frequency for different intake pressures (R= 20 Ω). In general, as the operating frequency increases, the peak voltage output decreases. When the intake pressure is low, the variation trend is slightly different from that of the operating conditions with operating frequency. When the intake pressure is 1.8 bar and 2.0 bar, the peak voltage output of the FPE-LG initially decreases and then increases with operating frequency. This may result from the unstable motion of the free piston assembly with low intake pressure.

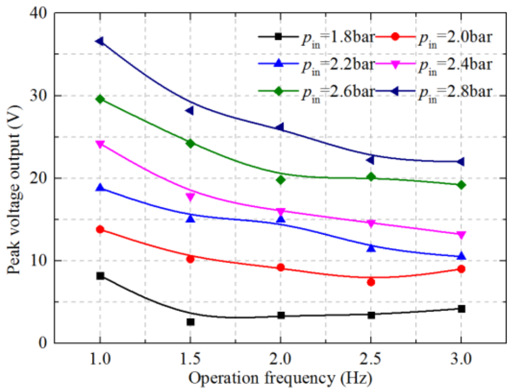


Figure 5. Varying trend of the peak voltage output of the FPE-LG vs operating frequency

The varying trend of peak power output of the FPE-LG vs intake pressure is presented in Fig. 6 (f=1.5 Hz). The peak power output increases with the intake pressure. When the intake pressure varies from 1.8 bar to 3.0 bar, the peak power output increases from 0.8 W to 110 W (the external load resistance is 30 Ω). The higher the intake pressure, the more thermal energy flows into the cylinder, which leads to the higher free piston assembly velocity. When the free piston assembly velocity increases, the induced electromotive force (E) increases which results in the increase of the peak power output.

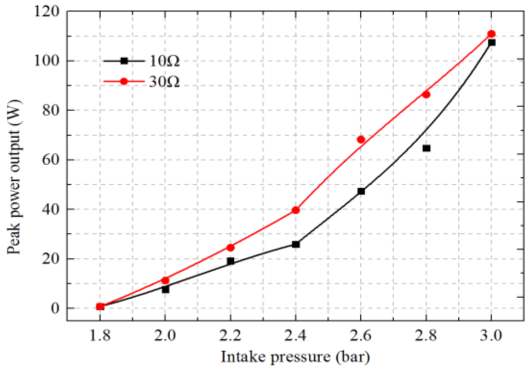
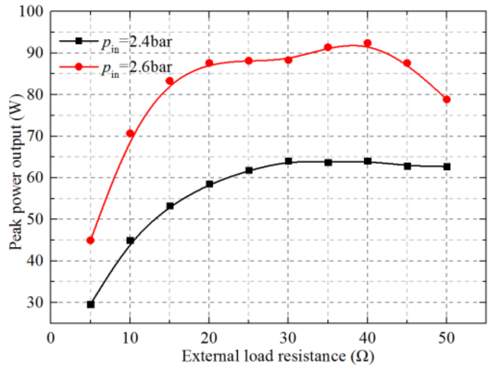
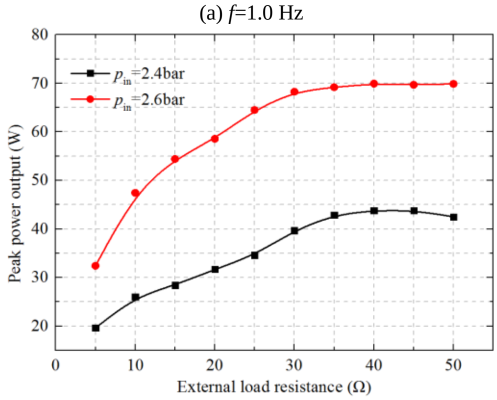


Figure 6. Peak power output of the FPE-LG vs intake pressure

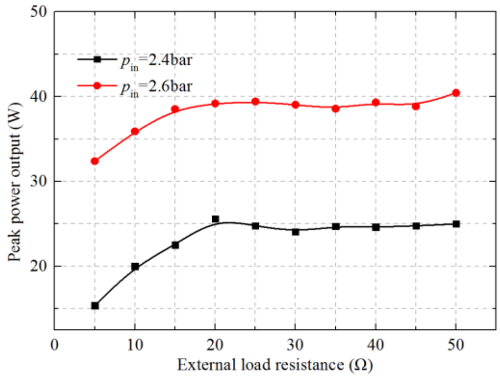
The peak power output of the FPE-LG for different operating frequencies is presented in Fig. 7. Generally, the peak power output of the FPE-LG initially shows a non-linear increase and then tends to stabilize with increasing the external load resistance. When the FPE-LG operates at 1.0 Hz and 1.5 Hz, the maximum peak power output is achieved with the external load resistance of 40 Ω. However, when the FPE-LG operates at 2.0 Hz and 2.5 Hz, the maximum peak power output is achieved with an external load resistance of 30 Ω. Thus, the optimal external load resistance decreases with increasing the operating frequency. The main reason is that: for one thing, the peak voltage output of the FPE-LG increases rapidly initially, and then the increasing amplitude tends to slow until it remains stable. In addition, the external load resistance increases steadily. Therefore, the peak power output of the FPE-LG stabilizes in the end with the external load resistance in a certain range.



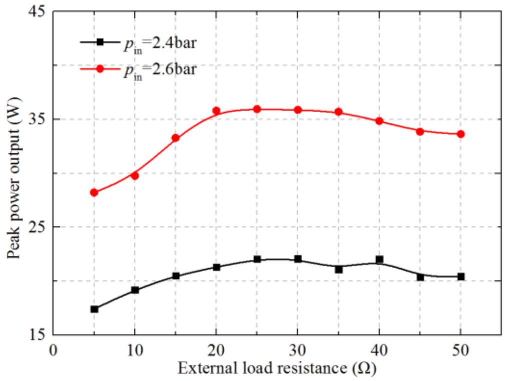
(a) *f*=1.0 Hz



(b) *f*=1.5 Hz



(c) f=2.0 Hz



(d) f=2.5 Hz

Figure 7. Peak power output of the FPE-LG vs external load resistances

D. *Energy Conversion Efficiency*

The energy input of FPE-LG is determined by the intake pressure p_{in}, the piston area A and the free piston assembly stroke (S).

$$W_{in} = p_{in} \times A \times S \tag{2}$$

The work output of the FPE-LG in one working cycle can be calculated as:

$$W_{out} = \frac{P_{out}}{f} \tag{3}$$

According to the calculation of energy conversion efficiency, it can be presented by:

$$\eta_{con} = \frac{W_{out}}{W_{in}} \times 100\% \tag{4}$$

Fig. 8 shows the varying trend of energy conversion variation efficiency of the FPE-LG vs intake pressure for different external load resistances (f= 1.5 Hz). The energy conversion efficiency of the FPE-LG increases gradually with growing of the intake pressure until the energy conversion efficiency reaches the maximal value, and then the energy conversion efficiency decreases with intake pressure. It also can be seen from the figure that the optimal intake pressures which achieves the maximum energy conversion efficiency for different external load resistances are different. When the FPE-LG operates with the external load resistance of 40 Ω, 30 Ω and 20 Ω, the maximum energy conversion efficiency is 72%, 71% and 73.33%, and corresponding optimal intake pressure is 2.6 bar, 2.7 bar and 2.8 bar, respectively. Moreover, when the intake pressure is less than 2.6 bar, the order of energy conversion efficiency for different external load resistances decreasing in sequence is: 40 Ω, 30 Ω, 20 Ω; when the intake pressure is higher than 2.7 bar, the order of energy conversion efficiency for different external load resistances decreasing in sequence is: 20 Ω, 30 Ω, 40 Ω.

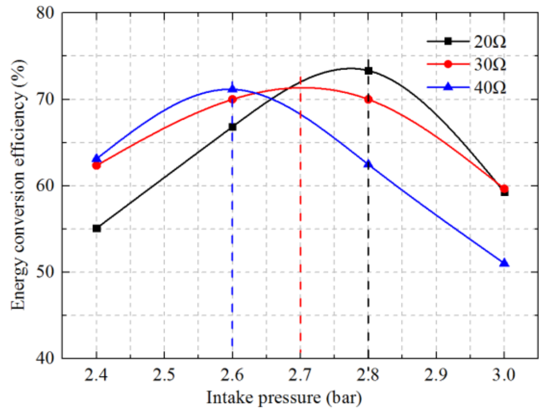


Figure 8. Varying trend of conversion efficiency vs intake pressure

Fig. 9 shows the varying trend of energy conversion efficiency of the FPE-LG for different intake pressures (f= 1.5 Hz). The energy conversion efficiency increases gradually with growing of the external load resistance until the energy conversion efficiency reaches the maximal value, and then the energy conversion efficiency decreases when external load resistance is still growing. The optimal external load resistances which achieves the maximum energy conversion efficiency for different pressures are different. The optimal external load resistance decreases with growing intake pressure. When the intake pressure is 2.6 bar, 2.8 bar and 3.0 bar, the maximum conversion efficiency is 73.33%, 71% and 72%, and corresponding optimal external load resistance is 40 Ω, 20 Ω and 10 Ω, respectively.

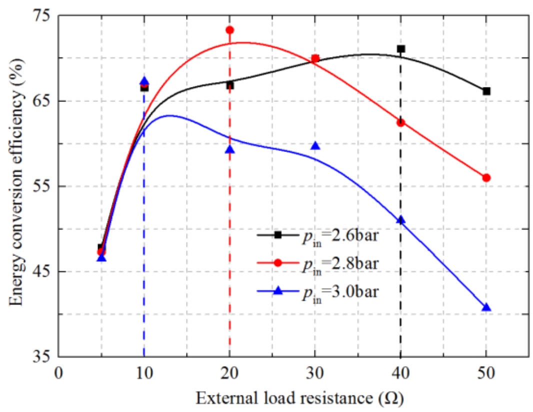


Figure 9. Varying trend of conversion efficiency vs external load resistance

IV. Conclusion

This research presents a new FPE-LG with compressed air as working fluid and performs an experimental study to explore the effect of external load resistance on the FPE-LG performance. The findings indicate that:

- The displacement, velocity and actual stroke of free piston assembly increase with the external load resistance and intake pressure. The external load resistance and intake pressure have significant influences on the motion characteristics of the free piston assembly.
- The indicated efficiency decreases when the operating frequency increases. The peak voltage output of the FPE-LG grows with the external load resistance and it will stabilize in the end. The peak voltage output presents an increasing trend with growing the intake pressure, whereas it decreases with operating frequency. When the intake pressure is 3.0 bar and the operating frequency is 1.5 Hz, the maximum peak voltage output can reach up to 44.4 V with an external load resistance of 40 Ω.
- The peak power output initially shows a non-linear increasing trend when growing the external load resistance and stabilizes in the end. The optimal external load resistance which achieves maximum peak power output shows a decreasing trend with increasing the operating frequency. When the intake pressure is 3.0 bar and the operating frequency is 1.5 Hz, the maximum peak power output is about 110 W with an external load resistance of 30 Ω.
- The energy conversion efficiency of the FPE-LG increases gradually with growing of the intake pressure until the energy conversion efficiency reaches the maximal value, and then the energy conversion efficiency decreases when intake pressure is still growing. The optimal intake pressure which achieves the maximum energy conversion efficiency decreases with growing of the external load resistance. Similarly, when the external load resistance increases, the energy conversion efficiency of the FPE-LG first increases and then decreases after reaching its maximum. And the optimal external load resistance which achieves the maximum energy conversion efficiency shows a decreasing trend with the growing of the intake pressure. When operating frequency is 1.5 Hz and external load resistance is 30 Ω, the maximum energy conversion efficiency can reach up to 73.33% with an intake pressure of 2.8 bar.

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References

[1] X. C. Hou, *et al*., "Free piston expander-linear generator used for organic Rankine cycle waste heat recovery system," *Applied Energy*, vol. 208, pp. 1297-1307, 2017.

[2] J. Nickl, G. Will, W. E. Kraus, and H. Quack, "Design considerations for a second generation CO2-expander," in *Proc. Fifth IIR-Gustav Lorentzen Conference on Natural Working Fluids*, 2002, pp. 189–196.

[3] J. Nickl, G. Will, W. E. Kraus, and H. Quack, "Third generation CO2 expander," in *Proc. 21th International Congress of Refrigeration*, Washington, 2003.

[4] L. Weiss, "Study of a mems-based free piston expander for energy sustainability," *Journal of Mechanical Design*, vol. 132, no. 9, p. 091002, 2010.

[5] B. S. Preetham and L. Weiss, "Investigations of a new free piston expander engine cycle," *Energy*, vol. 106, pp. 535–545, 2016.

[6] C. Champagne and L. Weiss, "Performance analysis of a miniature free piston expander for waste heat energy harvesting," *Energy Conversion and Management*, vol. 76, pp. 883–892, 2013.

[7] B. Zhang, X. Y. Peng, Z. L. He, Z. Xing, and P. Shu, "Development of a doubleacting free piston expander for power recovery in transcritical CO2 cycle," *Applied Thermal Engineering*, vol. 27, pp. 1629–1636, 2007.

[8] Y. Q. Han, J. J. Kang, X. F. Wang, Z. C. Liu, J. Tian, and Y. Q. Wang, "Modelling and simulation analysis of an ORC-FPC waste heat recovery system for the stationary CNG-fuelled compressor, *Applied Thermal Engineering*, vol. 87, pp. 481–490, 2015.

[9] Y. Q. Han, J. J. Kang, G. P. Zhang, Z. C. Liu, and J. Tian, "Performance evaluation of free piston compressor coupling organic Rankine cycle under different operation conditions," *Energy Conversion and Management*, vol. 86, pp. 340–348, 2014.

[10] G. S. Li, *et al.*, "Preliminary development of a free piston expander-linear generator for small-scale Organic Rankine Cycle (ORC) waste heat recovery system," *Energies*, vol. 9, p. 300, 2016.

[11] Y. M. Tian, *et al.*, "Experimental study on Free Piston Linear Generator (FPLG) used for waste heat recovery of vehicle engine," *Applied Thermal Engineering*, vol. 127, pp. 184–193, 2017.

[12] Y. D. Wang, L. Chen, B. R. Jia, and A. P. Roskilly, "Experimental study of the operation characteristics of an air-driven free-piston linear expander," *Applied Energy*, vol. 195, pp. 93–99, 2017.

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Xiaochen Hou, Hongguang Zhang, *et al.*, "External load resistance effect on the free piston expander-linear generator for organic Rankine cycle waste heat recovery system," *Applied Energy*, vol. 212, pp. 1252-1261, 2018.

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Fubin Yang, Heejin Cho, Hongguang Zhang, Jian Zhang, and Yuting Wu, “Artificial Neural Network (ANN) based prediction and optimization of an Organic Rankine Cycle (ORC) for diesel engine waste heat recovery,” *Energy Conversion and Management*, vol. 164, pp. 15-26, 2018.