International Conference on Applied Energy 2019
Aug 12-15, 2019, Västerås, Sweden
Paper ID: 1088

EXPERIMENTAL INVESTIGATION ON A PULSE-TUBE CRYOCOOLER WITH LINEAR MOTOR PHASE SHIFTER

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ABSTRACT

With the rapid development of high temperature superconducting technologies in the application areas of power transmission, communication and so on, the demand for high reliable and efficient cryocoolers is growing dramatically. Due to the flexibilities of cooling temperature and capacity, the pulse-tube cryocoolers driven by linear compressors are very suitable solutions for these applications. In the pulse-tube cryocoolers, phase shifters are indispensable to construct a suitable acoustic condition for the cryocooler and achieve a high cooling performance. In the traditional pulse-tube cryocoolers, the orifice-reservoir or inertance-reservoir phase shifters are often used, in which the expansion work out of the cryocooler is dissipated into heat. Thus, additional cooling method must be required for the phase shifter especially in a high cooling capacity situation. In this paper, the pulse-tube cryocooler with linear motor phase shifter is proposed. The linear motor can not only provide a suitable acoustic impedance, but also convert the expansion work into electricity, which can possibly reduce the input power of the compressor. In the experiments, a maximum cooling power of 154 W at 80 K and a maximum relative Carnot efficiency of 28.5% were obtained with the charging pressure of 3 MPa, the pressure ratio of 1.2 and the working frequency of 60 Hz, respectively.

Keywords: pulse-tube cryocooler, linear motor, phase shifter

1. INTRODUCTION

Over these years, great advances have been achieved in the high temperature superconducting (HTS) technologies. It is believed that the HTS technologies will be widely used in the near future in the areas of power transmission, communication and so on [1-3]. All HTS devices need cryocoolers to provide low temperature working environment. The cryocooler used for HTS can be divided into recuperative and regenerative types according to the different heat transfer approaches of interior refrigerant. The recuperative type cryocooler mainly adopts the J-T, the inverse Brayton and the Claude cycles. As we known, the throttling process of J-T cycle is irreversible and the efficiency can not be very high. The inverse Brayton and the Claude cycles are more complex and expensive and are suitable for large cooling capacity from several kilowatts to megawatts. The regenerative cryocooler, including the Stirling cryocooler, the G-M cryocooler and the pulse-tube cryocooler (PTC), has the advantage of compactness, simplicity and cost. So, they are often used in the HTS system with cooling capacity from hundred watts to kilowatts. The traditional Stirling cryocooler has a high performance but low reliability because of the sealing problem. The free piston Stirling cryocooler can ensure both efficiency and reliability but has difficulties in design and manufacture. Both the efficiency and reliability of the G-M cryocooler are low.

PTC has advantages of low vibration and high reliability. It can be driven by linear compressors or thermoacoustic heat engines capable of producing cooling power at almost any cooling temperatures [4-6]. In the PTC, phase shifters are used to provide a suitable acoustic field within the regenerator, i.e. the phase relationship between the oscillating velocity and pressure waves, which is crucial to achieve a good cooling performance. The conventional PTCs use orifice-

Selection and peer-review under responsibility of the scientific committee of the 11th Int. Conf. on Applied Energy (ICAE2019).

reservoir or inertance-reservoir phase shifters. The orifice-reservoir phase shifter was first proposed in 1984 and improved in 1986. In order to improve the phase relationship in the regenerator, the inertance-reservoir phase shifter was invented in 1994. Both the orifice-reservoir and the inertance-reservoir phase shifter PTCs have been widely studied around the world and many outstanding achievements have been made [7-10]. However, in these PTCs, the expansion work is completely dissipated into heat in the phase shifters. Thereby, the efficiency of the PTC was low and additional cooling equipment is necessary for the phase shifter, especially when the cooling capacity is large.

In this paper, PTC with linear motor phase adjuster is introduced and investigated. The linear motor can not only provide a suitable phase angle required by a good operation of the PTC, but also recover expansion work of the PTC into electricity. This electrical power can be fed back to the compressor to reduce the input electrical power thereby improve the efficiency. Moreover, the additional cooling for the phase shifter can be avoided and the system control will be much easier. This cryocooler may be suitable for large cooling power applications such as the HTS devices.

2. EXPERIMENTAL SETUP

Fig. 1 shows the schematic and photograph of the experimental apparatus developed in this paper. As demonstrated in Fig. 1(a), the PTC was composed of a main water cooler (MWC), a regenerator (REG), a cold end (CE), a pulse tube (PT) and a linear motor phase shifter. The structure parameters of the PTC are presented in Table I. The homemade linear motor phase shifter has a dual-opposed configuration with two same motors to eliminate vibration. The mechanical and electrical parameters of one motor are listed in Table II. Additionally, the linear motor has a displacement limitation of 8 mm and winding current limitation of 9 A. A load resistance (R) and capacitance (C) are connected in series with the linear motor to serve as the electrical loads to control the acoustic impedance and consume the electric power generated by linear motor. Fig. 1(b) presents the photograph of the experimental setup, the linear compressor is used to provide acoustic work for the PTC. Since the linear compressor is not designed for this PTC, the performance of the linear compressor is not concerned in this paper. In the PTC, the main water cooler is cooled by water at 20℃. A heater wire was mounted on the cold end to measure the cooling capacity. In the experiment, the temperature of the cold end was measured by thermometers. And the pressure waves were monitor by dynamic pressure sensors.

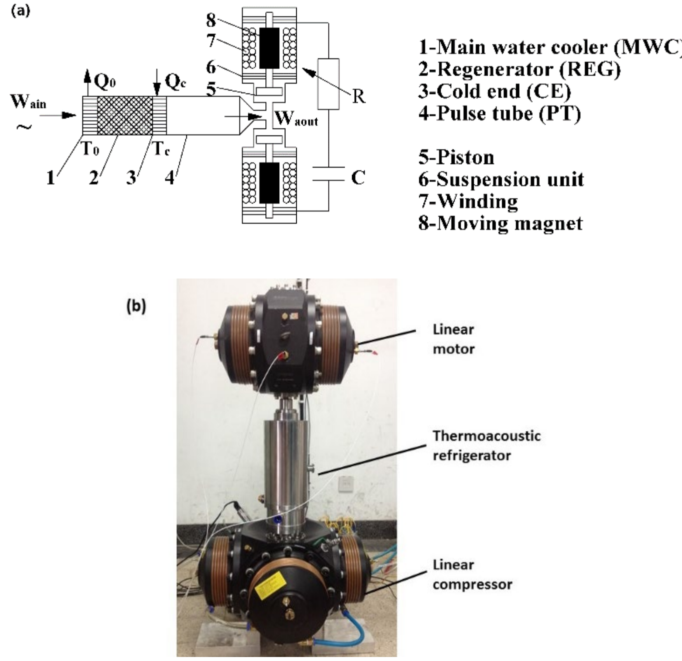

Fig. 1 Experimental apparatus: (a) schematic, (b) photograph

Table I. Structure parameters of the PTC

	D (mm)	L (mm)	Others
Main water cooler	75	64	Shell tube heat exchanger with tube inner diameter of 1.4 mm
Regenerator	75	70	300 mesh stainless steel screen
Cold end	75	30	Finned heat exchanger with fin spacing of 0.25mm
Pulse tube	37	150	/

Table II. Main parameters of one motor

D (mm)	M (kg)	K (kN/m)	R_m (N.s/m)	τ (N/A)	L (H)	r (Ω)
65	1.8	75	25	150	0.155	1.9

3. EXPERIMENTAL RESULTS

During the experiments, when the electricity was input, it the linear compressor converts electrical power into the acoustic work by mean of pressure oscillation. Then acoustic work was consumed to pump heat from low temperature to high temperature within the PTC. Thus, the cooling capacity could be achieved at the cold end. Meanwhile, the expansion work out of the PTC drives the piston and moving magnet of the linear motor to generate electricity in the winding. As we know, the HTS devices generally operate at liquid-nitrogen temperature, so the cooling temperature was fixed at 80K in our experiment.

After the system setup was built, the system performance was tested with 3.0 MPa mean pressure helium, 80 K and 293 K cooling and ambient temperature, 60 Hz working frequency, respectively. Fig. 2 shows the cooling temperature curve of the cold end. The load resistance and equivalent inductance of linear motor were 109 Ω and -0.6 H, respectively. After the compressor was running, the temperature of the cold end began to decline quickly when the input voltage was increased to 171 V responding to a pressure ratio of 1.15. In Fig. 2, we can see the PTC can reach 80 K after about half an hour.

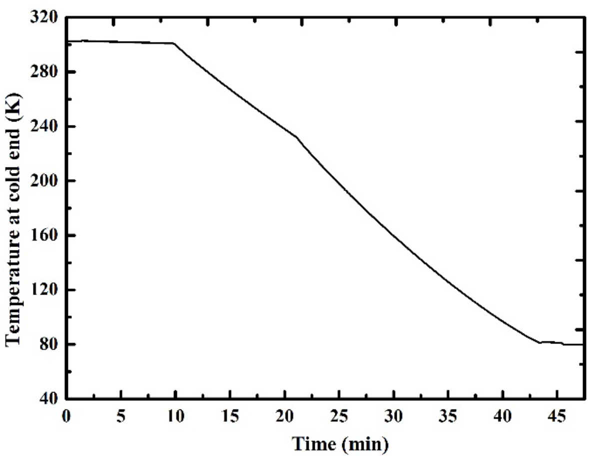

Fig. 2 The cooling curve at the cold end

Next, the input voltage was controlled to fix the pressure ratio as 1.2 and the equivalent inductance was -0.6 H. The impedance coupling relationship between the PTC and the linear motor phase shifter was investigated by adjusting the load resistance. Fig. 3 shows the experimental results of the acoustic impedance of the linear motor as a function of load resistance. In Fig. 3, the increase of load resistance results in the decrease of motor impedance both in magnitude and argument. The motor impedance magnitude goes down from 2.1×10^7 Pa·s/m3 to 1.8×10^7 Pa·s/m3, and the impedance argument decreases from 77.5° to 73°. Fig. 4 presents the cooling power and relative Carnot efficiency of the PTC as functions of load resistance. As shown in Fig. 4, when load resistance increases, the cooling power rises steadily while the relative Carnot efficiency increases quickly to a maximum then drops slightly. In the experiments, a maximum cooling power of 154 w at 80 k and a maximum relative carnot efficiency of 28.5% were obtained. However, maximum cooling power and maximum efficiency were obtained with different load resistances, which means that compromise should be made between the cooling capacity and the cooling efficiency to achieve a acceptable performance.

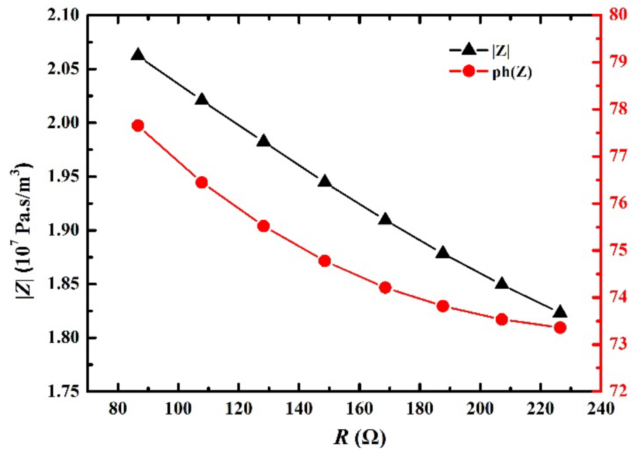

Fig. 3 Acoustic impedance magnitude and argument of linear motor vs. load resistance

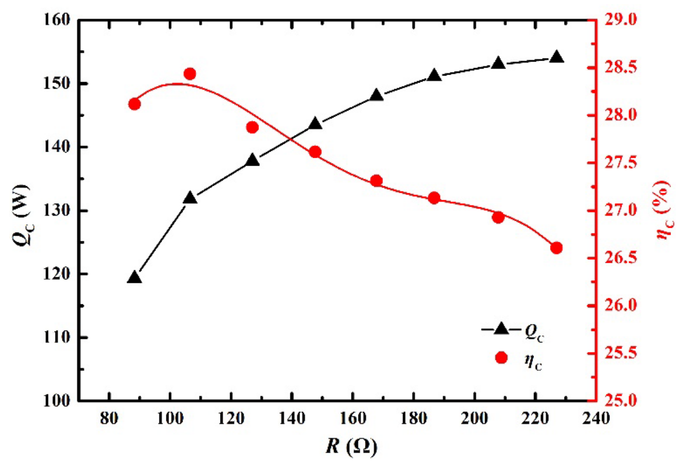

Fig. 4 Cooling power and relative Carnot efficiency vs. load resistance

In order to achieve an optimum performance of the PTC as well as the linear motor, the influence of load resistance on motor performance was also investigated, as shown in Fig. 5 and 6. It can be found in Fig. 5 that higher load resistance brings smaller current, while piston displacement changes slightly with the increase of load resistance. In Fig. 6, the motor prefers a higher load resistance to obtain higher efficiency. The possible reason is as follow. When the current decrease, inherent loss of linear motor such as eddy loss caused by magnetic material may reduce, resulting in advance of motor efficiency. The maximum motor efficiency is about 65%, which is not very high. It is believed that the reason is that the motor deviates from the resonance state of the circuit. So how to improve acoustic-to-electric conversion performance of linear motor needs further study.

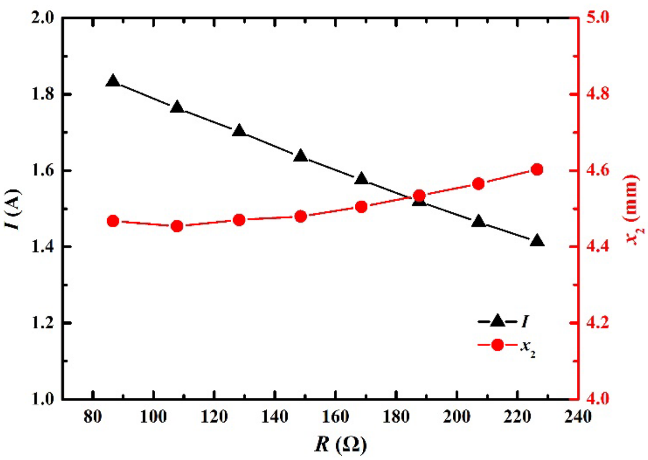

Fig. 5 Current and piston displacement of linear motor vs. load resistance

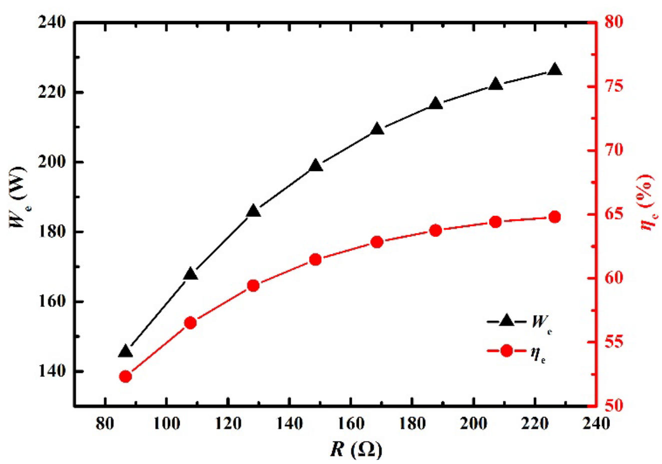

Fig. 6 Electric power and efficiency of linear motor vs. load resistance

4. CONCLUSIONS

In this paper, in order to develop a large capacity cryocooler for HTS application, a PTC with linear motor phase shifter was proposed and experimentally investigated. In comparison to the traditional phase shifter of the PTC, the linear motor can not only provide a suitable phase relationship of the PTC, but can recover the expansion work to electrical power and reduce the input power of the compressor. Moreover, the additional cooling approach of the phase shifter is also avoided. And the control flexibility of the system is greatly improved by adjusting the electrical load of the linear motor other than changing the structure parameters of the phase shifter in traditional PTCs. In the experiments, a maximum cooling power of 154 W at 80 k and a maximum relative Carnot efficiency of 28.5% were obtained. And the electrical power recovered by the motor was always about 10% of the input electrical power of the compressor.

ACKNOWLEDGEMENT

This work is supported the National Key Research and Development Program of China (No. 2016YFB0901403) and Beijing Natural Science Foundation (3181002)

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