Applied Thermal Engineering 51 (2013) 630–634

Contents lists available at SciVerse ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Coupling study of a novel thermocompressor driven pulse tube refrigerator

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HIGHLIGHTS

- ► We present a novel thermocompressor driven pulse tube refrigerator.
- ► We propose the impedance matching method for the coupling work of the refrigerator.
- ► Three different pulse tube refrigerators were tested to verify our method.
- ► We report the lowest no-load temperature of 70.4 K for this type of refrigerator.

ARTICLE INFO

Article history:
Received 13 September 2012
Accepted 23 October 2012
Available online 30 October 2012

keywords:
Thermocompressor
Pulse tube refrigerator
Acoustic power
Impedance matching method

ABSTRACT

The impedance match is important for the efficiency and available acoustic power of thermocompressor (TCP). The filling pressure, hot end temperature, reservoir volume and opening of orifice were changed to test the optimum load impedance for the maximum acoustic power by RC (Resistor and Capacitor) load method. To make use of the acoustic power efficiently, a pulse tube refrigerator (PTR) was designed based on this impedance to match the TCP and relative coupling experiments were conducted for the first time. The refrigerating performance of PTR was observed and the lowest no-load temperature of 70.4 K was obtained at its optimum working frequency 5.6 Hz. Also, the performance characteristics and total impedances of three different PTRs were compared to verify the rationality of the impedance matching method in this paper. The calculation results agree well with the substantial experiments and further optimization methods were also proposed.

1. Introduction

With the energy supply of world is ever growing tense, energy conservation and recycle are increasingly becoming a focus of the research conducted by worldwide scholars [1]. Developing power machinery which can make full use of solar energy, biomass energy and industrial waste heat will greatly improve energy utilization efficiency and reduce electricity consumption [2]. This paper introduces a novel thermocompressor driven pulse tube refrigerator which is based on the principle that gas temperature change will lead to pressure fluctuations and thus the expansion cooling effect will happen in the cold end of PTRs. Compared with traditional refrigerators, it has the advantages of compactness, low vibration and high reliability. The recycle of low-grade heat or waste heat as heat source has a great significance for energy conservation and integrated utilization.

However, most studies on TCPs only concentrated on the working model until now. Few attention were paid to the utilization of their output acoustic power. Peterson [3] studied the engine cycle based on thermocompression, isothermal expansion and isobaric reduction in volume with an external heat source, which led to a high practical efficiency without the increment of dead volume. Kornhauser [4] analyzed the thermal and volumetric efficiency of TCP. It was proved that the thermal efficiency of TCP is higher than that of an ideal Otto engine-driven mechanical compressor. Xue and Wang [5] measured the output pressure ratio of TCPs used as pressure wave generators by comparison of theoretical isothermal model and experimental results. They concluded that large temperature difference can lead to large pressure ratio and the dead volume will deteriorate the performance of TCPs. Wu [6] established the thermodynamic model of TCPs by numerical calculations.

Thus, in order to investigate the utilization of output acoustic power of TCPs, the PTR is chosen as an appropriate load. In recent years, many types of cryocoolers have been developed, including J-T type, Brayton type, Stirling type, G-M type, etc. However, most

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1359-4311/$ – see front matter
http://dx.doi.org/10.1016/j.applthermaleng.2012.10.034

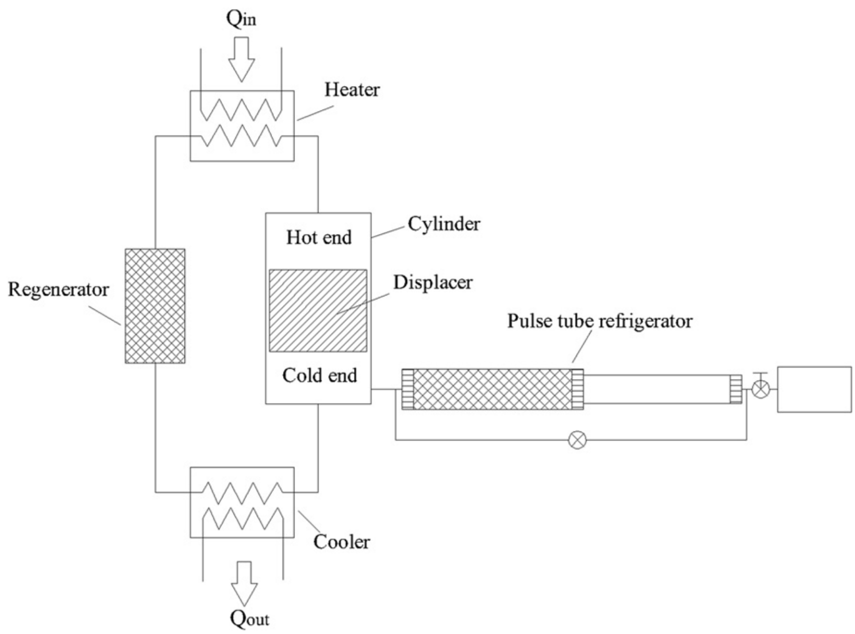

Fig. 1. Schematic of TCP driven PTR.

types are driven by mechanical compressor using electricity while only thermoacoustic engine driven PTR can use waste heat [7,8]. So, this paper has conducted a study on the coupling mechanism of TCP driven PTR by theoretical analysis and experiments.

2. Description of apparatus of TCP driven PTR

2.1. Experimental apparatus

Fig. 1 is the schematic of TCP driven PTR. The displacer is driven by crank link with a frequency of 3–6 Hz. Due to the small pressure difference between the displacer sides, only about 70 W of electrical power is needed to overcome the frictional resistance and flow resistance of the flow passages. The displacer is filled with micro glass balls to reduce the axial heat conduction and weight. Heating rods are used to simulate waste heat to warm up the gas in hot end. In addition, the heater is packed with aluminum silicate as insulation material to reduce heat losses to environment. Gas in the cold end is maintained at room temperature by water chiller. There is a regenerator filled with stainless steel screens between the two ends. It absorbs heat in the hot half cycle and rejects heat in the cold half cycle. Also, thermocouples and pressure transducers are employed in both ends to precisely measure the temperature and pressure. The in-line type PTR designed here is connected to the cold end of TCP with orifice-reservoir and double-inlet as the phase shifter [7]. The phase difference between pressure wave and velocity wave can be adjusted to obtain the optimum performance of refrigerator. All the values of pressure and temperature are collected by computer and analyzed with Labview software.

2.2. Working process

At first, the system is filled with helium gas. When the displacer is in the upper dead point, most of the gas is in the cold end. The gas rejects heat to the water chiller and the system pressure reaches the lowest value as a result of the lowest average system temperature. Then the displacer moves toward to the bottom dead point and the gas is pushed to the hot end through regenerator. The gas absorbs heat from regenerator and hot end heater in this process. Then the system pressure increases as a result of the increment of the average system temperature. When the displacer reaches the bottom dead point, most of the gas is in the hot end and the system pressure reaches the highest value. Thus, the TCP undergoes a cycle in which the system pressure changes from the lowest value to the highest value. Therefore, a periodic sinusoidal pressure wave is generated and exported to the PTR, and then the cooling effect happens at the cold end by adiabatic expansion process.

However, due to the uncertainty of the volume flow rate from cold end to the regenerator and PTR, the process is an unsteady flow of mass variable problem. Compared to traditional compressor, the phase difference between pressure wave and velocity wave is hard to calculate to determine the coupling load. Thereby, the largest output acoustic power is tested firstly and the corresponding load impedance is calculated to design a coupling PTR in this paper.

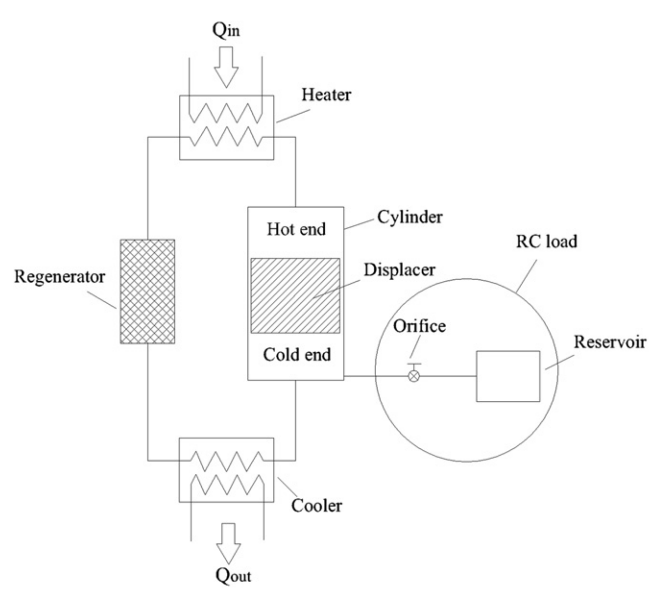

Fig. 2. Schematic of RC load method for acoustic power measurement system.