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Regenerator performance improvement of a single-stage pulse tube cooler reached 11.1 K

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Abstract

In order to improve the cooling performance of pulse tube cooler (PTC) at 20–40 K, hybrid regenerators are often employed. In this paper a three-layer regenerator, which consists of woven wire screen, lead sphere and Er_3Ni is optimized to enhance the cooling performance and explore the lowest attainable refrigeration temperature for a single-stage PTC. The efforts focus on the temperature range of 80–300 K, where woven wire screens are used. Theoretical and experimental studies are carried out to study the metal material and the mesh size effect of woven wire screens on the performance of the single-stage G-M type PTC. A lowest no-load refrigeration temperature of 11.1 K was obtained with an input power of 6 kW. The PTC can supply 17.8 W at 20 K and 39.4 W at 30 K, respectively.

Keywords: Pulse tube cooler (E); Regenerator (E); Heat transfer (C); Pressure drop

1. Introduction

In comparison with the traditional regenerative cryocoolers such as G-M and Stirling coolers, the pulse tube cooler (PTC) with no moving parts in low temperature range has the advantages of simple structure, low cost, high reliability, low mechanical vibration and low electromagnetic noise [1]. With the development of phase shift method, flexure bearing compressor and magnetic regenerator material, the efficiency of PTCs working at 77 K and 4.2 K was significantly enhanced [2–4], which can be comparable with that of G-M and Stirling coolers.

The development of single-stage G-M type PTC at 20–40 K is also promising for the applications of superconductor cooling, cryopump and so on. A refrigeration temperature of 13 K was obtained by a single-stage PTC with an input power of 13 kW at University of Giessen in 2003 [5]. However, the cooling performance of single-stage PTC at 20–40 K is still lower than that of G-M coolers [6]. The regenerator losses become especially large at low temperature range, at which the matrix heat capacities of known regenerator materials becomes less than that of helium gas and leads to increased losses. Besides, the PTC needs relatively bigger mass flow rate compared to the G-M cooler, which further decreases the efficiency of regenerator. Obviously, a small reduction in these losses can lead to a significant increase in the net refrigeration power for the same power input [7].

An efficient regenerator must have a large thermal inertia per unit volume to support high volumetric heat transfer with the working fluid, and at the same time with small pressure drops. Meeting all these goals is evidently not feasible in practice, and optimization and compromise are often needed. In order to improve the performance of the PTC working at 20–40 K, we performed the study of regenerator optimization. In 2004 a G-M type single-stage PTC was designed and manufactured at Zhejiang University. A lowest no-load refrigeration temperature of 13.8 K and cooling capacity of 55.9 W at 40 K were obtained when the regenerator was packed with phosphor–bronze screens in the warm part and lead spheres in the cold part with an input power of 6 kW [4]. In order to further improve the

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efficiency of regenerator below 20 K, the regenerator was modified to a three-layer structure with Er_3Ni located in the coldest part in 2005. A lowest no-load refrigeration temperature of 12.6 K and cooling capacity of 59.0 W at 40 K were obtained with an input power of 6 kW [8].

In this paper we focus on regenerator improvement at temperature range of 80–300 K. Woven wire screens have the advantages of low pressure drop, low axial conduction, high heat transfer area and high heat capacity at 80–300 K. Woven wire screens made of phosphor–bronze and stainless-steel are commonly used. Theoretical calculation and experimental study were carried out about the metal material and mesh size effect of woven wire screens on the performance of single-stage G-M type PTC. Experimental results show that the cooling performance with stainless-steel woven wire screens are better than that with phosphor–bronze screens. Then heat transfer capacity and pressure drop of stainless-steel screens of different mesh sizes were calculated to find the optimum mesh size number for the PTC. At last the results of calculations and experiments are compared and analyzed.

2. Performance comparison of PTC with the regenerator packed with stainless-steel and phosphor–bronze woven wire screens

The detailed experimental setup of the single-stage double-inlet PTC can be found in Refs. [4,8]. A three-layer matrix, consisting of woven wire screens, lead spheres and Er_3Ni from warm to cold end of regenerator was used. The volume ratios of the three types of regenerator materials are fixed as 77.0%, 18.4% and 4.6%, respectively. Experiments were first carried out to compare the performance of the regenerator packed with screens between stainless-steel and phosphor–bronze. With 250# stainless-steel screens packed at the warm part, we define this set of experiments as CASE-SS; for 250# phosphor–bronze screens we call it CASE-PH. In these two cases lead spheres and Er_3Ni packed at the cold part remains unchanged. If not otherwise stated, the operating frequency of the PTC is 1.4 Hz, the rotary valve timing (defined as time ratio of exhaust process to intake process of rotary valve) is 1.22 and the rated input power of the compressor (Leybold CP6000) is 6 kW.

Fig. 1 shows the performance comparison of the PTC between stainless-steel and phosphor–bronze screens with filling pressure of 1.7 MPa. Lower refrigeration temperature and higher cooling capacity have been obtained for CASE-SS. With the filling pressure of 1.4 MPa, a no-load refrigeration temperature as low as 12.2 K was obtained, which is 0.4 K lower than that in CASE-PH. When the filling pressure is 1.7 MPa, a cooling capacity of 37.5 W at 30 K has been obtained, which is 0.5 W larger than that of CASE-PH; the maximum coefficient of performance (COP, i.e. cooling capacity over the actual input power to the compressor) of the PTC was 2.5×10^{-3} at 20 K and 5.7×10^{-3} at 30 K, respectively.

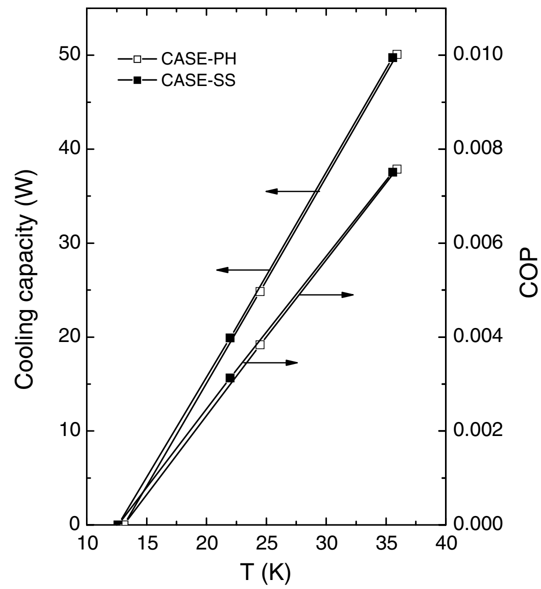

Fig. 1. Performance comparison of PTC between stainless-steel and phosphor–bronze screens with filling pressure of 1.7 MPa.

The experimental results are reasonable if we compare the thermodynamic properties of stainless-steel and phosphor–bronze. Fig. 2 shows the volumetric specific heat capacity and heat conductivity of phosphor–bronze and stainless-steel from 30 to 300 K. We can find that the volumetric specific heat capacity and bulk heat conductivity of phosphor–bronze and stainless-steel both increase with the increase of temperature. Though the heat capacity difference between phosphor–bronze and stainless-steel is not so big, the heat conductivity of phosphor–bronze is almost 4 times bigger than that of stainless-steel, which will introduce larger axial conduction loss in the regenerator.

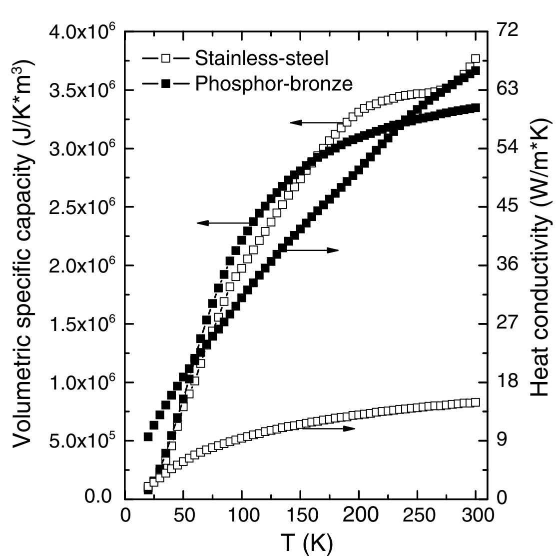

Fig. 2. Comparison of volumetric specific heat capacity and heat conductivity between stainless-steel and phosphor–bronze from 30 to 300 K.