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A cascade pulse tube cooler capable of energy recovery

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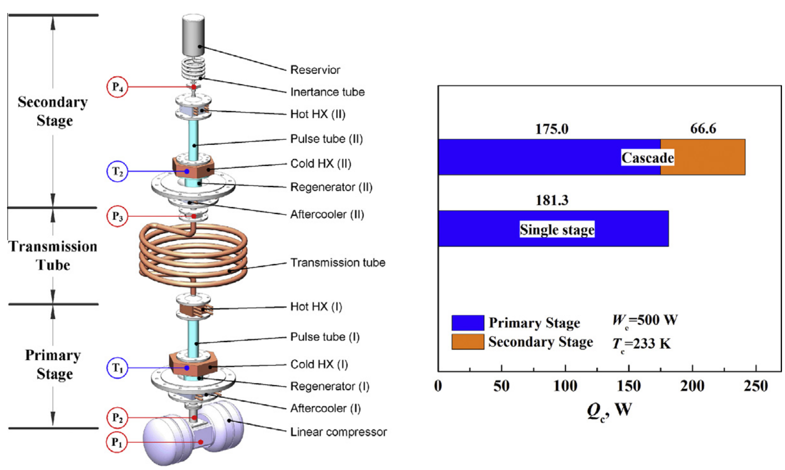
HIGHLIGHTS

- A cascade pulse tube cooler configuration is proposed capable of energy recovery.
- The cooling efficiency approaches Carnot efficiency as the number of stages increases.
- A two-stage cascade pulse tube cooler is designed, fabricated and tested.
- Experimental results show an improvement of 33% at 233 K.

GRAPHICAL ABSTRACT



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ABSTRACT

A pulse tube cryocooler (PTC) cannot work with Carnot efficiency due basically to the expansion work that has to be dissipated thermally at the warm end of the pulse tube, this dissipation is especially phenomenal with high cooling capacity or at high temperatures which reduces the COP and limits the application of PTC above 120 K. Therefore, how to recover this amount of dissipated work becomes a critical issue in a high efficient PTC. Here, we proposed a cascade PTC with a built-in transmission tube between stages for energy recovery. The key point of this new configuration is that the acoustic power at the outlet of the primary stage can be recovered through the transmission tube which provides proper phase angle to drive the secondary stage. This idea is verified both theoretically and experimentally. The cooling efficiency can be improved by 33% when the machine works at 233 K.

1. Introduction

Cryocoolers with large cooling capability are highly sought-after components of high temperature superconductor (HTS) and liquefied natural gas (LNG) facilities [1–3]. Pulse tube coolers (PTC), which have no moving parts at the cold end, hold great potential in such applications due to its high reliability and long maintenance intervals [4,5]. There are several types of pulse tube coolers: the basic type [6], the orifice type [7], the double inlet type [8] and the inertance tube type [9]. Among them, the basic type has the lowest efficiency; while for the others, additional phase shifting devices were introduced so as to obtain a better phase relation between the pressure wave and mass flow in the regenerator.

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Nomenclature

c	acoustic compliance per unit length (m^2/Pa)
D	diameter (m)
E	acoustic power (W)
f	frequency (Hz)
i	$\sqrt{-1}$
L	length (m)
l	acoustic inertance per unit length (kg/m^5)
m	mass flow rate (kg/s)
m_v, m_l, m_c, m_k	correction factors for turbulent flow
p	pressure (Pa)
Q	cooling power (W)
r_k	thermal-relaxation resistance per unit length (Pa s/m^4)
r_v	acoustic resistance per unit length (Pa s/m^4)
T	temperature (K)
U	volume flow rate (m^3/s)
ω	angular frequency (Hz)
θ	phase angle (deg)
$\|\|$	magnitude of complex number

Subscripts

0	mean value
1	first order, primary stage
2	secondary stage
h	hot end
c	cold end
hpt	hot end of pulse tube
res	reservoir
in	inlet
out	outlet

However, the expansion work at the warm end of the pulse tube is always dissipated as heat. This intrinsic limitation limits its capability of reaching Carnot efficiency even in ideal case. That is, the ideal efficiency of the PTC is only T_c/T_h, which is lower than the Carnot efficiency $T_c/(T_h - T_c)$ [10].

In order to improve the efficiency, various kinds of pulse tube coolers with work recovery have been suggested. In 1988, Matsubara and Miyake proposed a pulse tube cooler with a warm expander, which could recover the expansion work to drive the compressor [11]; subsequent researches have shown its feasibility [12,13]. In 1999, Swift et al. used thermoacoustic theory to theoretically analyze the feasibility of recovering acoustic power, and two possible configurations were suggested [14]. One was a pulse tube cryocooler with transmission-line feedback, with the acoustic power delivered to the back space of the linear compressor through the transmission-line. Another was a pulse tube cryocooler with lumped boost configuration. However, both of the configurations are looped, introducing a time-averaged mass flow called 'Gedeon streaming' which deteriorates their performance [15]. In 2007, Zhu et al. proposed a step piston type pulse tube cooler which also recovers acoustic power to drive the compressor. Their theoretical calculations showed that a higher efficiency could be obtained [16,17], yet no experimental results have been published so far. In 2012, Ki and Jeong proposed a work recovery phase shifter composed of a mass-spring-damper and a linear generator system [18]. In 2013, Hu et al. proposed a double-acting pulse tube cooler, which was also capable of acoustic power recovery [19]. Although the above researches provide some possible methods to recover the acoustic power from the cold end, these configurations either introduce moving parts which weakens the high reliability of the PTC, or caused streaming through the looped configuration which reduces the cooling performance. In 2011, Swift proposed a quarter-wavelength pulse tube cooler, in which a second pulse tube cooler was added after the quarter-wavelength pulse tube to use the expansion work [20,21]. In this configuration, there are neither moving parts nor streaming brought in, so it is a good choice for applications calling for higher cooling power. Here the traditional pulse tube is replaced by a quarter wavelength pulse tube, this quarter wavelength pulse tube has two roles: One is to work as a pulse tube, which thermally isolates the cold end and the ambient end; the other role is to recover acoustic power from the cold end of the regenerator by turning the phase relation between pressure wave and velocity to a reverse situation. But in this configuration, the long pulse tube should be placed at cryogenic temperature, which makes it difficult to construct; also, the phase angles between pressure wave and mass flow at two ends of this tube are fixed to be opposite number due to the fixed length of the tube, which makes the design inflexible.

In this work, we propose a cascade pulse tube cooler which is capable of work recovery. The cascade PTC consists of sub-PTCs which are connected by transmission tubes in between. The dissipated work is recovered by the long transmission tube and thus can be used to drive the subsequent stages. Compared with the Swift's structure, the traditional pulse tube is kept in each stage. We realize the recovery of acoustic power and the reverse of phase relation by using a well-designed transmission tube. This enables us to easily connect separate sub-PTCs without the need to change their current configurations, with the long transmission tubes, which can be placed at room temperature but not inside the vacuum chamber. The length of the transmission tube can be determined from the phase relation. Theoretical analysis shows that the more stages it has, the closer the efficiency will approach to Carnot efficiency. For proof of concept, a two-stage cascade pulse tube cooler working at 233 K is designed, and experimental results show that the cooling efficiency can be improved by 33%.

2. Theoretical analysis

2.1. Cascade pulse tube cooler concept

Fig. 1(a) shows a schematic diagram of a multi-stage cascade PTC. It consists of *n*-stages of sub-PTCs with transmission tubes in between (here *n* is a positive integer number not less than 2). Each sub-PTC works at same hot end and cold end temperatures T_h and T_c respectively. The linear compressor provides the original driving power, the acoustic power at the outlet of the former stage is transferred to the latter one by the transmission tube. Fig. 1(b) shows the configuration of the two stage cascade PTC which consists of two sub-PTCs (primary and secondary stage) and a transmission tube in between.

Assuming that the original acoustic power provided by the linear compressor is E_1, and there is no loss in each stage of sub-PTC, then the cooling efficiency of each stage is T_c/T_h. We can obtain the cooling power of the first stage:

$$Q_{c1} = E_1 \frac{T_c}{T_h} \tag{1}$$

For the second stage, the acoustic power inlet should be the same as the cooling power of the first stage, that is:

$$E_2 = Q_{c1} = E_1 \frac{T_c}{T_h} \tag{2}$$