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Research paper

Theoretical and experimental investigations on the cooling capacity distributions at the stages in the thermally-coupled two-stage Stirling-type pulse tube cryocooler without external precooling

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The two-stage Stirling-type pulse tube cryocooler (SPTC) has advantages in simultaneously providing the cooling powers at two different temperatures, and the capacity in distributing these cooling capacities between the stages is significant to its practical applications. In this paper, a theoretical model of the thermally-coupled two-stage SPTC without external precooling is established based on the electric circuit analogy with considering real gas effects, and the simulations of both the cooling performances and PV power distribution between stages are conducted. The results indicate that the PV power is inversely proportional to the acoustic impedance of each stage, and the cooling capacity distribution is determined by the cold finger cooling efficiency and the PV power into each stage together. The design methods of the cold fingers to achieve both the desired PV power and the cooling capacity distribution between the stages are summarized. The two-stage SPTC is developed and tested based on the above theoretical investigations, and the experimental results show that it can simultaneously achieve 0.69 W at 30 K and 3.1 W at 85 K with an electric input power of 330 W and a reject temperature of 300 K. The consistency between the simulated and the experimental results is observed and the theoretical investigations are experimentally verified.

1. Introduction

The Stirling-type pulse tube cryocooler (SPTC) eliminates any moving component at the cold end and is driven by the linear compressor at the warm end, and thus is endowed with great merits such as low vibrations, high reliability and long life at both ends, which has a strong appeal to a variety of special fields such as in space [1–3]. In practice, there is an increasing interest in providing cooling powers at different temperature levels. For example, for many space-borne cryogenic instruments, some have two detectors with differing operating temperatures, and some need to simultaneously cool both the detector and optics since the cooled optics contributes to minimize background thermal noise and thus can noticeably enhance the detecting sensitivity. Still some need to simultaneously cool the detector and remove the parasitic heat loads originating from the support structures and electrical leads [1,2,4,5]. For most of the above cooling requirements, sometimes the passive radiator might also be possibly used for the higher temperature stage, however, with the rapid progress of the regenerative cooling technology, a much compacter and lighter SPTC is obviously much more attractive. In many cases, the use of two separate single-stage SPTCs for two different temperatures is also often suggested as a viable option in view of the maturity of the single-stage SPTC technology. However, a two-stage SPTC driven by a single compressor will have many definite advantages in terms of weight, compactness and system integration.

The two-stage arrangement of the SPTC was suggested long ago [6]. In recent years, a variety of arrangement types about the two-stage SPTC have been studied [4,5,7–13], including a special variant type in which a split second cold head is added to a single-stage SPTC [14,15]. It should be noted that many of the above two-stage SPTCs mainly aimed to achieve a lower no-load temperature or the cooling capacity at the second stage [9–13], while the first stage was only used as the precooling for the second stage, and in many cases the external precooling were also additionally employed to achieve the goal [10,13]. In practice, the external precooling is often unavailable, especially for some special applications such as in space. And thus in our design, the external precooling is excluded. Moreover, as discussed above, our development of the two-stage SPTC aims to simultaneously achieve the cooling capacities at both stages.

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Nomenclature

A	cross sectional area
b	mechanical damp coefficient
C_p	isobaric specific heat
f	operating frequency
i	current
j	$(-1)^{1/2}$
k_x	axial stiffness of flexure spring
K	coefficient of heat conduct
L	length
m	moving mass
p	dynamic pressure
p_m	mean pressure
Q_{c1}	net cooling power of first stage
$Q_{c1\text{-}tot}$	total cooling power of first stage
Q_{c2}	cooling capacity of second stage
Q_{pre}	precooling power
R_g	gas constant
R_v	resistance
S	perimeter
Δt	time of heat transfer
T_1	cooling temperature of 1st stage
T_2	cooling temperature of 2nd stage
T_H	reject temperature
T_{mid}	middle heat exchanger temperature
$\dot{U}$	volume flow rate
V	volume
x	spatial variable
X	amplitude of piston displacement
$\overline{X}$	average stroke of gas piston
Z	compressibility factor
Z_C	compliance impedance
Z_L	inertance impedance

Subscripts

0	outlet of compressor
1–0	inlet of 1st stage
1–1	inlet of regenerator of 1st stage
1–2	outlet of regenerator of 1st stage
1-*RG*	regenerator of 1st stage
1-*PT*	pulse tube of 1st stage
2–0	inlet of 2nd stage
2–1	inlet of 1st part regenerator of 2nd stage
2–4	inlet of cold heat exchanger of 2nd stage
2-*RG*1	1st part regenerator of 2nd stage
2-*RG*2	2nd part regenerator of 2nd stage
2-*PT*	pulse tube of 2nd stage
cp	compression space
g	working gas
p	piston
str	thermal strap

Greek symbols

ε	regenerator effectiveness coefficient
γ	ratio of specific heat
δ	penetration depth
θ	phase angle ($\dot{U}$ leads p)
μ	dynamic viscous coefficient
ρ	density
φ	porosity
ω	angular frequency
λ	thermal conductivity coefficient
η	coefficient of pulse tube

In practice, there are two widely-used coupling arrangements for the two pulse tube cold fingers (PTCFs) in a two-stage SPTC, namely, thermally-coupled and gas-coupled. In the thermally-coupled arrangement the two PTCFs are connected by the thermal link, while in the gas-coupled arrangement there is no thermal link and the PTCFs are coupled by the internal working gas only. The distribution of the cooling capacities at two stages has an important bearing on the practical applications. The thermally-coupled two-stage SPTC have to take into account both the thermal link and the internal gas, and thus the discussed distribution becomes more complicated, for which little work had been reported. In this paper, the detailed theoretical analyses will be made to reveal the underlying mechanism of the cooling capacity distribution in the system, and then the relevant experimental investigations will be made to verify the theoretical analyses.

2. Analytical model of the thermally-coupled two-stage SPTC without external precooling

Fig. 1 shows a schematic of the thermally-coupled two-stage SPTC without external precooling. The PV power generated in the compressor is divided into two parts with each flowing into the respective stage. The total cooling power of the first stage is further divided into two parts, in which one flows into the mid-part of the second stage as the precooling power while the other remains as the net cooling capacity of the first stage.

Based on the improved electric circuit analogy (ECA) model for the single-stage SPTC developed in the same laboratory [16–18], the SPTC system can be analogized to be an alternating current circuit, and the expressions of each kind of impedance for every control volume can be defined as [16–19]:

$$Z_C = \frac{\gamma p_m}{\omega V} i \tag{1}$$

$$Z_L = -\frac{\omega \rho_m}{A} i \tag{2}$$

$$R_v = \frac{\mu S}{A^2 \delta_v} \tag{3}$$

The regenerator is the superposition of the resistance, inertance, compliance and temperature controlled source of each unit control volume, in which the definition of the resistance can be found in Ref. [18]. The pulse tube and the reservoir are regarded as the compliances paralleled and cascaded into the circuit, respectively. The impedance and the heat transfer of heat exchangers have been described in Ref. [17]. And the impedances of the inertance tubes are the combination of each unit control volume's resistance, inertance and compliance. The specific calculations of each component can be found in Refs. [16–18].

The above analogies can be extended to develop the corresponding model of the thermally-coupled two-stage SPTC, as shown in Fig. 2, in which each stage can be analogized to a current circuit branch. The linear compressor is a current source, the two stages PTCF parallel into the circuit at the outlet of the linear compressor.

For the PTCF part, the current flows into the aftercooler, regenerator, cold heat exchanger, pulse tube, hot heat exchanger, inertance tubes and reservoir of each stage in proper order.