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Research paper

Theoretical and experimental investigations on the three-stage Stirling-type pulse tube cryocooler using cryogenic phase-shifting approach and mixed regenerator matrices

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ABSTRACT

Theoretical analyses and experimental verification for a three-stage Stirling-type pulse tube cryocooler (SPTC) expected to operate at 5–12 K are conducted. Cryogenic phase-shifting and mixed regenerator matrices are employed to improve the performance at the third stage. Simulations of the phase relationship, dynamic pressure and mass flow rate are presented with third-stage phase-shifters at 40 K, 50 K and 293 K, respectively. Mixed regenerator matrices of conventional stainless steel meshes and rare-earth materials such as Er_3Ni, $HoCu_2$ and $Er_{0.6}Pr_{0.4}$ are optimized theoretically. Different ratios and combinations are analyzed and compared, and the quantitative analyses by the entropy analysis are made. A three-stage SPTC without external precooling is developed based on the theoretical analyses, and experiments were conducted. The results show a good agreement between simulations and experiments. With an overall input electric power of 370 W, the three-stage SPTC has experimentally reached a no-load temperature of 6.82 K and achieved a cooling capacity of 112 mW at 10 K.

1. Introduction

The pulse tube cryocooler (PTC) is acknowledged as a significant technological innovation in regenerative cooling technology since it eliminates the moving component at the cold end. The Stirling-type PTC (SPTC) driven by a linear compressor with clearance seal and flexure springs further realizes the long life of the driver at the warm end, and thus, has appeal to a variety of applications such as in space [1–4]. Cooling at 10 K and below has played a key role in the fields of security defense, deep space exploration, and low-Tc superconducting. In practice, for a SPTC, three stages are usually needed to meet the cooling requirements [5–13].

Normally, the third stage of a three-stage SPTC is the focus because it achieves the target temperature. To pursue lower no-load temperature, some researchers employ external precooling approaches for the former stages, such as additional cryocoolers or cryogens. However, for most practical applications, the external precooling is not feasible because it makes the system much more complicated, and furthermore, external precooling is not always available. Therefore, our design excludes any external precooling approaches and only depends on the three-stage SPTC itself.

The cryogenic phase-shifting approach refers to the third-stage inertance tube and reservoir placed at cryogenic temperatures rather than in the ambient environment. This approach can significantly reduce the heat load at the warm end of pulse tube and decrease the temperature gradient in pulse tube to improve the third-stage performance. The impedance amplitude of the inertance tubes with different temperatures and lengths is analyzed, and the phase relationship, the dynamic pressure and the mass flow rate of the third stage with the optimal inertance tubes is proposed when the phase-shifters are at 40 K, 50 K and 293 K, respectively.

Regenerator irreversible losses usually account for most of the system losses. Mixed regenerator matrices were proposed and used to develop single-stage and two-stage SPTCs with minimized the regenerator losses [14–17]. The principle was to minimize the flow resistances while keeping the necessary thermal penetration depths of the regenerator matrix along the whole regenerator. Third-stage regenerators have a larger temperature gradient making the successful implementation of rare-earth mixed matrices with the high heat specific capacity at 10 K and below including $Er_{0.6}Pr_{0.4}$, Er_3Ni and $HoCu_2$ more

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Nomenclature

A	cross-section area, m^2
c_p	specific heat capacity of the gas
c_s	specific heat capacity of the matrix
d_h	hydraulic diameter, m
E	time-averaged energy flux, W
f	frequency, Hz
H	time-averaged enthalpy
h	convective heat transfer coefficient
i	imaginary unit
K	complex propagation function
k	thermal conductivity
p_1	dynamic pressure, Pa
p_0	charge pressure, Pa
R	tube radius, m
R_g	gas constant
S_c	heat conduction entropy generation
S_p	pressure drop entropy generation
S_h	heat transfer entropy generation
T	temperature, K
U	volume velocity, m^3/s
u	velocity, m/s
x	spatial variable
Z	impedance amplitude

Greeks

α	specific surface area
β	coefficient of expansion
μ	viscosity
ρ	density
σ	heat capacity ratio
φ	porosity
ω	angular velocity
γ	ratio of specific heat
λ	thermal conductivity
θ	phase angle

Subscripts

1	first-order
c	cold end
g	gas
h	warm end
k	thermal
m	mean value
x	calculation position
s	solid
v	viscous
IT	inertance tube

challenging. Regenerator performance with these rare-earth matrices is analyzed quantitatively using the entropy analysis method [11]. The different ratios and combinations of the mixed matrices are analyzed, compared and summarized.

The improved electrical circuit analogy (ECA) model developed for single- and two-stage SPTCs [4,18,17] is employed to build the third-stage model. The fourth-order Runge-Kutta method, which has been used successfully in the analysis of the single-stage SPTCs [16], is used to solve the equations.

2. Theoretical model and analyses

The three-stage SPTC schematic in Fig. 1 shows the first two stages driven by one linear compressor while the third stage by another. The third stage is precooled by the first two stages via Thermal link I and Thermal link II.

The first two stages adopt the coaxial arrangement, and their inertance tubes and reservoirs are at ambient temperature. The third stage adopts the linear arrangement, and its inertance tubes and reservoir are in the Dewar and work at the cryogenic temperature. The main geometrical parameters of the three-stage SPTC are shown in Table 1.

2.1. Physical model of the third stage

Fig. 2 shows the analogy electric circuit [4,18,17] for the third stage. The dynamic pressure and the volume flow rate of the regenerator and the heat exchanger are expressed as follows [18]:

$$\boldsymbol{p}_{1x} = \boldsymbol{p}_{1h} - \int_h^x \left(\frac{i\omega\rho}{\varphi A} + r_g\right)\dot{\boldsymbol{U}}_x \cdot dx \tag{1}$$

$$\dot{\boldsymbol{U}}_x = \dot{\boldsymbol{U}}_h - \int_h^x \left(\frac{i\omega\varphi A}{\gamma p_0}\boldsymbol{p}_{1x} + \dot{\boldsymbol{U}}_x \cdot \frac{1}{T_m}\frac{\partial T_m}{\partial x}\right) \cdot dx \tag{2}$$

The temperature profile based on the energy conservation equation is [11]:

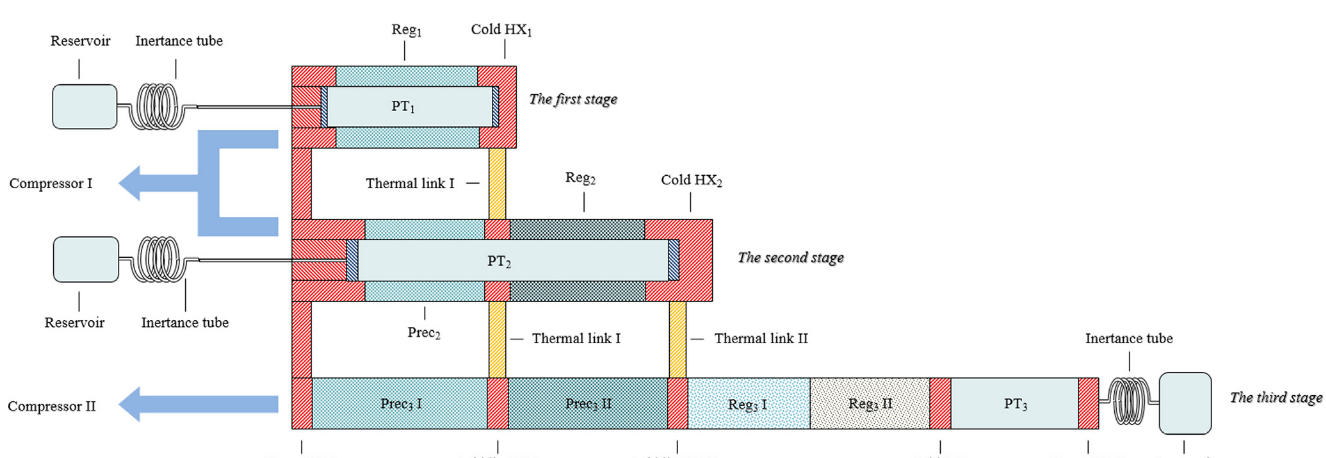

Fig. 1. Schematic of the developed three-stage SPTC.