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Research Paper

Entropy analyses of the three-stage thermally-coupled Stirling-type pulse tube cryocooler

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HIGHLIGHTS

- A model of three-stage thermally-coupled SPTC is set up by entropy analyses.
- Three irreversible losses are considered to evaluate the performance at each stage.
- Proportions of different losses vary considerably in different stages.
- Optimal operating parameters can be obtained by the deduced expressions.
- An example for 10 K is given to quantitatively analyze effects of parameters.

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ABSTRACT

This paper establishes a theoretical model of the three-stage thermally-coupled Stirling-type pulse tube cryocooler based on entropy analyses, in which irreversible losses in regenerators and heat exchangers including the axial conduction, pressure drop and ineffective heat convection are considered, and then the cooling performance of each stage is analyzed according to the second law of thermodynamics, respectively. The results indicate that the pressure drop is the primary loss for all stages, whereas in the third stage, the ineffective heat convection increases sharply and accounts for a much larger proportion. Losses in heat exchangers are much smaller compared with those in regenerators and can thus be ignored in many cases. Furthermore, the optimal values of several selected important operating parameters, including coupling positions, cooling temperatures, charging pressures, pressure ratios, operating frequencies and input acoustic powers for the three stages, can be obtained according to the deduced expressions. A specific example aiming at 10 K is given to provide elaborate explanations and quantitative analyses about the effects of these parameters on the cooler performance.

1. Introduction

The temperature range of 10 K and below has played an important role in the fields of low temperature physics, low-T_c superconducting applications, advanced medical industry, security defense and deep space exploration, etc. Generally, two main approaches are employed to achieve the temperature range, namely, liquid helium cryostats and cryocoolers. The liquid helium cryostat often has a large volume and high mass that lead to a clumsy system, and furthermore, it normally has a short operating lifetime and requires a complicated thermal insulation system as well. The cryocooler can realize a cryogen-free system that features the continuous operation and a longer lifetime. Both the GM cryocooler and the GM-type pulse tube cryocooler (PTC) with the multi-stage arrangements, using the oil-lubricated compressor and employing a rare-earth regenerator matrix in the colder stages, are the two widely-used approaches to achieving liquid helium temperatures. In recent years, the multi-stage Stirling-type PTC (SPTC) driven by an oil-free linear compressor has made important progress, which has several remarkable merits such as low noise, high reliability and long operation lifetime, and thus has a strong appeal to some special fields, especially in space.

Important progress has been made in the practical development of multi-stage SPTCs. Olson et al. [1] first reported a three-stage SPTC operating at 10 K, and another four-stage SPTC that could simultaneously provide cooling at 6 K and 18 K was subsequently developed [2]. Raab et al. [3] built a three-stage SPTC to precool a J-T cryocooler to 6 K, and Jaco et al. [4] summarized the performance data of the 10 K Engineering Model (EM) three-stage SPTC. Wilson and Gedeon [5] developed a three-stage gas-coupled SPTC with a predicted no-load temperature of 5.5 K. Bradley et al. [6] designed a hybrid three-stage SPTC employing He-4 at both the first and the second stages to precool a He-3 third stage to 4 K. Duval

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et al. [7] developed a three-stage SPTC as the precooler for a J-T cryocooler at 15 K.

In general, there are two types of coupling approaches for the multi-stage arrangement of the SPTC cold fingers, namely, the thermally-coupled and the gas-coupled. The former is simple in design and easy to control the internal flow, while the latter avoids the thermal link and may achieve higher efficiency. For both types, most previous studies focused on the structural design, practical manufacture, and performance optimization, whereas the detailed theoretical analyses of the inner process and working mechanism were seldom conducted. Kirkconnell and Curran [8] discussed the thermodynamic optimization of the multi-stage SPTC with a sketchy analysis of the irreversible losses. Radebaugh et al. [9] qualitatively analyzed the regenerator performances at 4 K with He-3 and He-4 serving as the working fluid, respectively. de Waele et al. [10] investigated the optimal position at which the first stage connecting to the second one, in which the axial heat conduction was assumed to be the only irreversible loss. Razani et al. [11] compared the differences between thermally-coupled and gas-coupled multi-stage arrangements based on the exergy flow analyses under a simplified regenerator model, in which a given flow conductance was applied.

Based on the above survey, the in-depth analysis of the inner process of the three-stage SPTC is rare. Actually, some analyzing approaches about the single-stage or other types of PTCs can be used for the reference for the establishment and analysis of the theoretical model of the multi-stage SPTCs, for example, Ju [12] made the thermodynamic analyses of the GM-type PTC by using the first and second laws of the thermodynamics, Kittel [13] made systematic analyses of enthalpy, entropy and exergy flows in single-stage SPTCs, and He et al. [14] made first and second law analyses of the orifice-type and double-inlet type single-stage PTCs, etc.

This paper will set up a theoretical model of the three-stage thermally-coupled SPTC based on the entropy analyses. The important irreversible losses in the regenerators and heat exchangers including the axial conduction, pressure drop and ineffective heat convection will be taken into account. A specific example aiming at 10 K based on the model will be given to discuss in detail the effects of some important operating parameters, such as coupling position, cooling temperature, charging pressure, pressure ratio, operating frequency and input acoustic power, on the system efficiency.

2. Model of the three-stage thermally-coupled SPTC

A schematic of the three-stage thermally-coupled SPTC is shown in Fig. 1. The system is driven by linear compressors, and the acoustic power of each stage is W_1, W_2 and W_3, respectively. The gross input acoustic power is defined as W:

$$W = W_1 + W_2 + W_3 \tag{1}$$

For the first stage, at the cooling temperature of T_{c1}, the gross cooling capacity Q_{g1} is divided into two parts, namely, the cooling capacity Q_{c1}, which can be extracted directly, and the precooling capacity Q_{p1}, which is transferred to the next two stages by Thermal link 1:

$$Q_{g1} = Q_{c1} + Q_{p1} \tag{2}$$

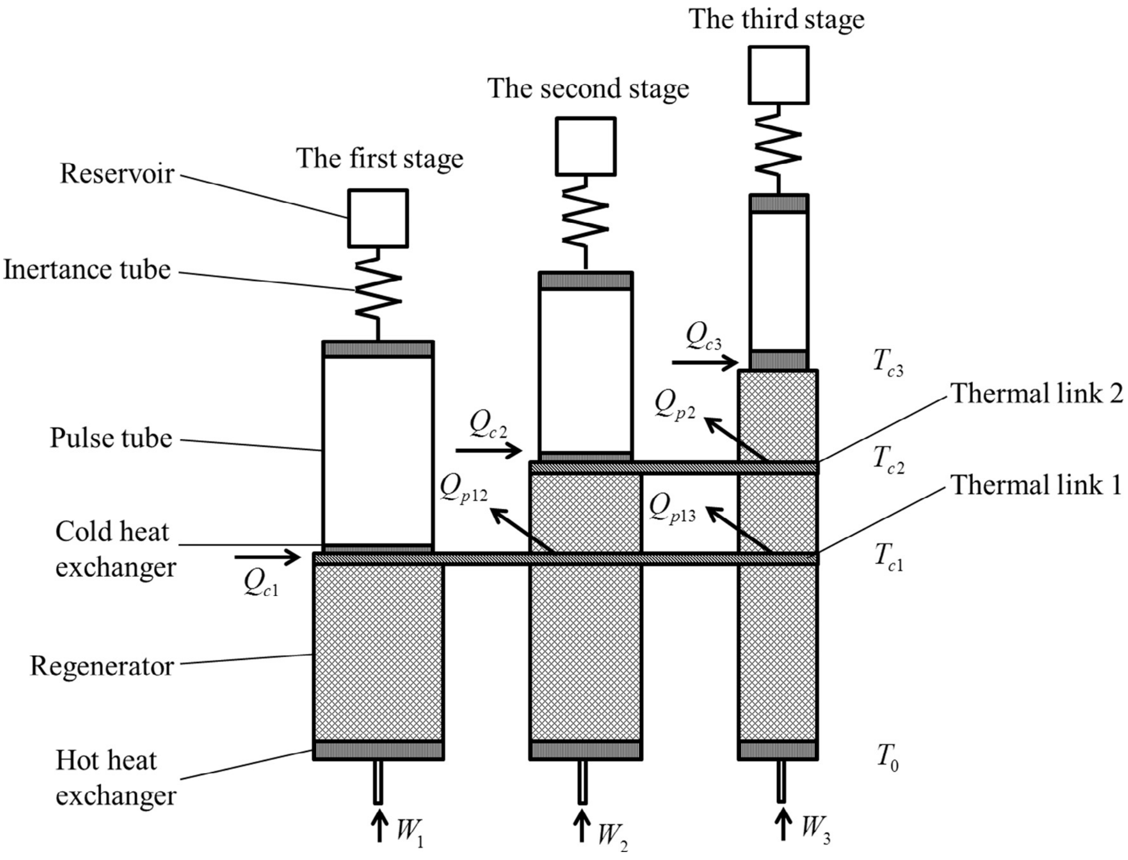

Fig. 1. Schematic of the three-stage thermally-coupled SPTC.