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Theoretical and experimental investigations on the optimal match between compressor and cold finger of the Stirling-type pulse tube cryocooler

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ABSTRACT

The match between the pulse tube cold finger (PTCF) and the linear compressor of the Stirling-type pulse tube cryocooler plays a vital role in optimizing the compressor efficiency and in improving the PTCF cooling performance as well. In this paper, the interaction of them has been analyzed in a detailed way to reveal the match mechanism, and systematic investigations on the two-way matching have been conducted. The design method of the PTCF to achieve the optimal matching for the given compressor and the counterpart design method of the compressor to achieve the optimal matching for the given PTCF are put forward. Specific experiments are then carried out to verify the conducted theoretical analyses and modeling. For a given linear compressor, a new in-line PTCF which seeks to achieve the optimal match is simulated, designed and tested. And for a given coaxial PTCF, a new dual-opposed moving-coil linear compressor is also developed to match with it. The simulated and experimental results are compared, and fairly good agreements are found between them in both cases. The matched in-line cooler with the newly-designed PTCF has capacities of 4–11.84 W at 80 K with higher than 17% of Carnot efficiency and the mean motor efficiency of 81.5%, and the matched coaxial cooler with the new-designed compressor can provide 2–5.5 W at 60 K with higher than 9.6% of Carnot efficiency and the mean motor efficiency of 83%, which verify the validity of the theoretical investigations on the optimal match and the proposed design methods.

1. Introduction

The Stirling-type pulse tube cryocooler (SPTC) has found a wide variety of important applications in civilian, aerospace and military defense fields [1,2]. Generally, a SPTC can be divided into two parts: one is the linear compressor and the other including all of the remaining components named here as the pulse tube cold finger (PTCF). The optimal match between the PTCF and the linear compressor of the SPTC plays a vital role in optimizing the compressor efficiency and in improving the PTCF cooling performance. Several researchers had made some relevant studies on the match. For instance, Heun et al. [3] carried out the experimental investigation of gas effects on cryocooler resonance characteristics, but detailed theoretical analyses explaining the experimental results were not carried out. Wakeland [4] studied some issues involved in matching electrodynamics drivers to thermoacoustic cryocoolers, and the result indicated that matching the acoustic load to the optimum mechanical load for the particular driver could be used to maximize the electroacoustic efficiency or the input power. Based on the study of Wakeland, Swift [5] investigated the parameters which would affect the compressor efficiency and acquired the relation between the cooler acoustic impedance and efficiency. Both studies made by Wakeland [4] and Swift [5] treated the whole cold finger as the entire acoustic impedance, but not the individual ones. Ko and Jeong [6] and Ko et al. [7] studied the dynamic behavior of the linear compressor in a SPTC and proposed a new design approach considering the dynamics of the linear compressor and the thermo-hydraulics of the SPTC, but further studies on the method have not been reported.

In this paper, results of a theoretical investigation are given on the two-way matching in a detailed way, namely, how to match the PTCF to a given linear compressor and how to match the linear compressor to a given PTCF. A design method of the PTCF to achieve the optimal matching for the existing linear compressor will be proposed, which is based on an electrical circuit analogy

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Nomenclature

A	cross area
A_p	piston surface area
b	mechanical damp coefficient
B	magnetic field intensity
c	constant
D_{cg}	diameter of the clearance gap
i	motor current
I_{RMS}	effective current
k_x	axial stiffness of flexure springs
L	coil length
L_{cg}	length of the clearance gap
L_e	coil inductance
m	mass of moving part
p	dynamic pressure
P_m	mean pressure
r	flow resistance
R_e	coil resistance
S	perimeter
t	time
t_g	thickness of clearance gap
$\dot{U}$	volume flow rate
V	voltage
V_{cp}	volume of compression space
V_e	coil volume
$\dot{W}_{cf}$	PV power in cold finger
$\dot{W}_{cg}$	PV power in clearance gap
$\dot{W}_e$	motor electric power
$\dot{W}_{PV}$	PV power at the piston surface
x	piston displacement
X	amplitude of piston displacement
Z_0	impedance of compression space
Z_a	Impedance at the piston surface
Z_f	impedance of clearance gap
Z_{ptc}	impedance of PTCF
ρ_e	resistivity of motor coil
η_{PV}	PV power efficiency
η_{motor}	motor efficiency

Subscripts

v	viscous
out	out let of the component

Greeks

γ	ratio of specific heat
δ	penetration depth
θ_a	phase angle of piston impedance
θ_{ptc}	phase angle of PTCF impedance
μ	dynamic viscosity
ρ	density
φ	porosity
ω	angular frequency

(ECA) model considering the influence of each component of the PTCF, and a counterpart design method of the linear compressor to achieve the optimal matching for the existing PTCF will be put forward as well. Specific simulations and experiments will be carried out subsequently to verify the validity of the theoretical analyses. First, for a given dual-opposed linear compressor, a new in-line PTCF which provides the impedance to achieve the optimal match for the compressor will be simulated, designed and tested. Simulations and experimental performance of both compressor and PTCF will be described. Second, for a given PTCF, a new linear compressor will be simulated, designed and tested, and the corresponding simulations and experimental results will be discussed as well.

2. Interactions between the PTCF and the linear compressor

Fig. 1 shows a schematic of a typical moving-coil linear compressor with dual-opposed configuration developed in the authors' laboratory. Each half comprises a cylinder, a piston with a shaft, two sets of flexure springs, a pressure vessel, and a linear motor composed of a permanent magnet, a moving coil and two return irons, in which the piston, the coil and the flexure springs will oscillate during operation, and the clearance seal acts as the dynamic seal between the piston and the cylinder, thereby eliminating the source of rubbing wear and the necessity of oil lubrication. Fig. 2 shows the schematic of a typical SPTC with inertance tube acting as the phase shifter. The PTCF consists of a connecting tube, an aftercooler, a regenerator, a cold heat exchanger, a pulse tube, a hot heat exchanger, the inertance tube and a reservoir. Through the connecting tube, the PTCF is connected to the linear compressor.

To simplify the analysis, oscillations in the linear compressor and the PTCF are all assumed to be sinusoidal, and the displacement of the piston is written as Eq. (1) as a reference point.

$$x(t) = X\sin(\omega t) \tag{1}$$

For each linear motor of the compressor, neglecting the influence of the back pressure, the force balance of each motor of the dual-opposed piston linear compressor can be written as Eq. (2) [8].

$$LBi(t) = m\frac{d^2x(t)}{dt} + b\frac{dx(t)}{dt} + k_x x(t) + p(t)A_p \tag{2}$$

Meanwhile, the volume flow rate at each piston surface can be calculated by the following Eq. (3) [9]:

$$\dot{U}(t) = A_p\dot{x}(t) = A_p\omega X\cos(\omega t) \tag{3}$$

The volume flow rate is proportional to the surface area of the piston, the working frequency and the piston amplitude. Through Eqs. (2) and (3), the relation between the PTCF and linear compressor has been established.

In addition, according to the previous work based on the ECA model [10], the ratio of the dynamic pressure to the volume flow rate has a strong effect on the cooling performance of the SPTC. Here, an impedance $|Z_a|$ and a phase angle θ_a are introduced to describe this ratio at the piston surface. It can not only present the relation between the dynamic pressure and volume flow rate, but it also can simplify the analysis processes, through replacing two complex variables into one. The specific relation is shown in Eq. (4):

$$p(t) = \dot{U}(t)|Z_a|\cos(\omega t + \theta_a) = A_p\omega X|Z_a|\cos(\omega t + \theta_a) \tag{4}$$

Based on the similar approaches suggested by Wakeland [2] and the above relevant discussions, the relations between the parameters of the linear compressor and those of the PTCF will be re-deduced in the following sections. Specific simulations and experiments will be carried out together with the theoretical investigations to show it in a detailed way.