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Investigation on a three-cold-finger pulse tube cryocooler

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ABSTRACT

This paper introduces a new type of pulse tube cryocooler, three-cold-finger pulse tube cryocooler (TCFPTC), which consists of one linear compressor and three cold fingers, i.e., CFA, CFB and CFC. Those three cold fingers are driven by the linear compressor simultaneously. This paper investigates two aspects. First, it studies the mass flow distribution among the three cold fingers by varying the input electrical power. The cooling powers of the three cold fingers at constant cooling temperatures and the cooling temperatures of the three cold fingers at constant cooling powers with various input electrical powers are investigated. Secondly, the interaction among the three cold fingers is investigated by varying the heating power of any one cold finger. Generally, if the heating power applied on one cold finger increases, with its cold head temperature rising up, the cold head temperatures of the others will decrease. But, when the cooling power of CFC has been 4 W, the cold head temperature of whichever cold finger increases, the cold head temperature of CFA or CFB will seldom change if its heating power keeps constant.

1. Introduction

Pulse tube cryocoolers are widely used for its long life, high reliability, and low vibration. In practical application, such as weather satellites [1], cooling systems usually need several cold sources. Multi-cold-finger pulse tube cryocoolers suit the situation well because they not only have the advantages of pulse tube cryocoolers, but also occupy less space and weight. NGST reported a two-cold-finger pulse tube cryocooler which includes a linear pulse tube cold finger and a coaxial pulse tube cold finger in 2009. The cryocooler is applied to US weather satellites and can simultaneously achieve 1.9–2.3 W at 53 K and 5.1–8.0 W at 183 K cooling capacity [1]. In 2011, Technical Institute of Physics and Chemistry, CAS demonstrated a cryocooler of two coaxial pulse tube cold fingers driven by a compressor, which could simultaneously provide the cooling capacity of 0.5 W at 60 K and 0.5 W at 80 K [2].

Investigation on a three-cold-finger pulse tube cryocooler is carried out in this paper. The challenges of multi-cold-finger pulse tube cryocooler are from two aspects. Firstly, as a result of sharing one compressor, the mass flow distribution at the cross that connects the three cold fingers and the compressor, as shown in Fig. 1, depends on the impedances of the compressor and the three cold fingers. Secondly, the interaction among the three cold fingers is also a challenging problem.

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2. Experimental apparatus

The structure of the three-cold-finger cryocooler, shown in Fig. 1, consists of one compressor and three cold fingers, CFA, CFB, and CFC. The geometrical parameters of the three cold fingers are listed in Table 1. A moving-coil linear compressor with two pistons of 25 mm diameter and 5 mm piston stroke is adopted in this investigation. The compressor weighs about 40 Kg. The compressor is a cylinder with a diameter of 30 cm and a length of 40 cm. The compressor, the cold fingers and the following investigative contents are selected according to the actual requirements. Three heating plates and PT100 resistances are fixed on the cold head heat exchangers of the three cold fingers respectively. The PT100 resistances are used to measure the cold head temperatures of the three cold fingers and the heating plates are used to apply thermal load to the cold heads of the three cold fingers.

3. Experiments and discussion

3.1. Mass flow distribution among the three cold fingers

The mass flow distribution process is that the gas displacement of the compressor is distributed to the three cold fingers depending on their impedances. The variation of the input electrical power results in the change of gas displacement of the compressor. So, the mass flow in each of the cold fingers changes. The enthalpy flow of the cold head of each of the three cold fingers, one of the

Nomenclature

A	flow area
C	compliance
l	length
j	imaginary number
L	inductance coefficient of inertance tube
$\dot{m}$	mass flow
m	mass
$\dot{M}$	amplitude of mass flow
$\dot{M}'$	amplitude of mass flow for unit regenerator flow area
p	pressure
P	amplitude of dynamic pressure
Q_n	net cooling power
r	radius
R	flow resistance
R_g	gas constant
t	time
T	temperature
τ	period
V	volume
w	angular frequency
x	position
Z	impedance
Δ	difference

Subscripts

C	cold end
CFA	cold finger A
CFB	cold finger B
CFC	cold finger C
H	hot end
iner	inertance tube
pt	pulse tube
reg	rengerator

most crucial parameters to cooling power, which is closely related to mass flow also changes. Hence, the mass flow distribution can be reflected in the cooling performances (cooling powers and cooling temperatures) of the three cold fingers.

Fig. 2 shows the experimental results achieved under the condition that the input electrical power varies from 170 W to 250 W. It shows that under the condition that the heating powers loaded on the cold heads of the three cold fingers keep constant, the cold head temperature of CFC decreases about 20 K, while the cold head temperatures of CFA and CFB decrease less than 5 K. In the case that the cold head temperatures of the three cold fingers keep constant, the cooling power of CFC increases more than 1.5 W, whereas the cooling power of CFA or CFB increases about 0.5 W.

Fig. 3 illustrates the experimental results which are presented in Fig. 2 in another way, Qn vs. electrical power at constant T_C (60, 80 and 120 K for CFA, CFB and CFC) and T_C vs. electrical power at constant Qn (0.2, 0.5 and 4 W for CFA, CFB and CFC). When the input electrical power increases, the compressor will support more gas displacement. The additional gas displacement will incrementally increase the mass flow amplitudes in the regenerators of the three cold fingers. So, the cooling powers of the three cold fingers at constant T_C will increase and the cold head temperatures of the three cold fingers at constant cooling powers will decrease. The curves in Fig. 3(b) are linear but with a slight roll-off. The roll-off can be caused by any number of non-linear effects, such as reduced compressor efficiency at higher input power caused by higher electrical coil temperature, reduced regenerator efficiency due to higher mass flow, etc.

How does the incremental mass flow influence the cooling performance of the three cold fingers is an interesting problem. Because the working temperatures and dimensions of the three

Table 1
Key dimensions of the three cold fingers.

	Regenerator				Pulse tube	
	Length (mm)	Inner diameter (mm)	Outer diameter (mm)	Porosity	Length (mm)	Diameter (mm)
CFA	66.0	7.0	14.0	0.589	66.0	6.7
CFB	66.0	7.0	14.0	0.589	66.0	6.7
CFC	75.0	9.3	20.0	0.589	75.0	9.0

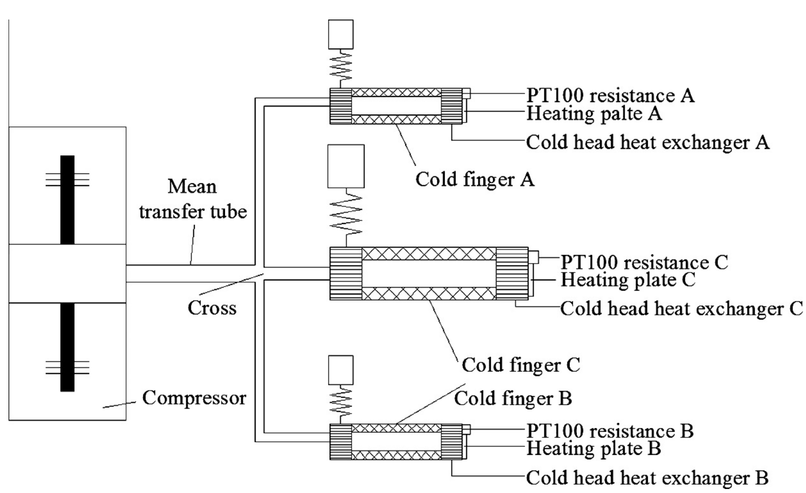

Fig. 1. Schematic of three-cold-finger pulse tube cryocooler.