Theoretical and experimental investigations on the dynamic and thermodynamic characteristics of the linear compressor for the pulse tube cryocooler

Lei Zhang[1,2], Haizheng Dang[1], Jun Tan[1,2], Dingli Bao[1,2]

1. National Laboratory for Infrared Physics, Shanghai Institute of Technical Physics, Chinese Academy of Sciences, No. 500 Yutian Road, Shanghai 200083, China
2. University of Chinese Academy of Sciences, No.19A Yuquan Road, Beijing 100049, China

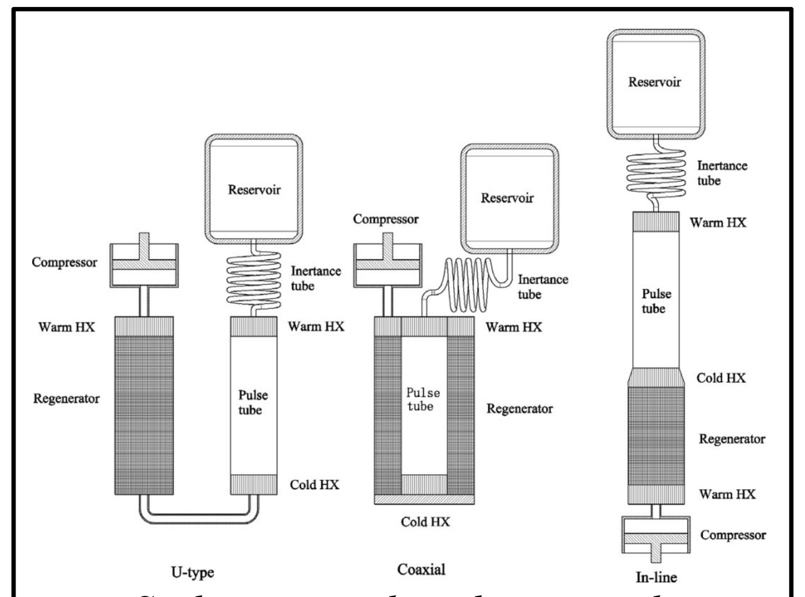
ID: C2PoB-08

NATIONAL LABORATORY FOR INFRARED PHYSICS
SHANGHAI INSTITUTE OF TECHNICAL PHYSICS
CHINESE ACADEMY OF SCIENCES

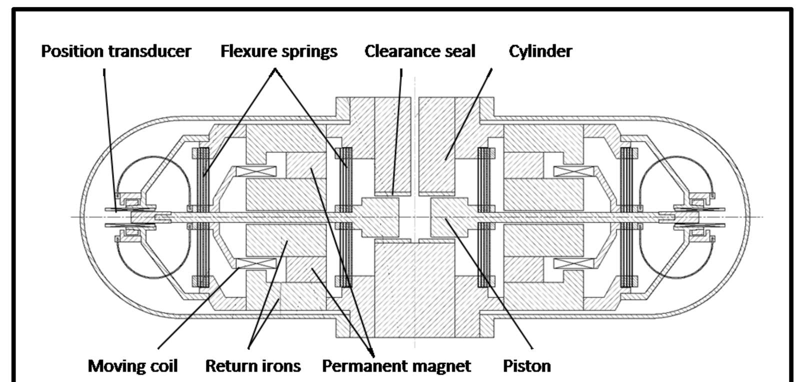
Introduction

The Stirling-type pulse tube cryocooler (SPTC) driven by the Oxford-type moving-coil linear compressor has become the new generation enabling space regenerative cryocooler. The efficiency and capacity of the compressor is determined by its dynamic and thermodynamic characteristics, which mainly include:

- input current
- Stroke
- volume flow rate
- phase angle between dynamic pressure and displacement
- forces on the piston
- dynamic pressure
- operating frequency



Stirling-type pulse tube cryocooler



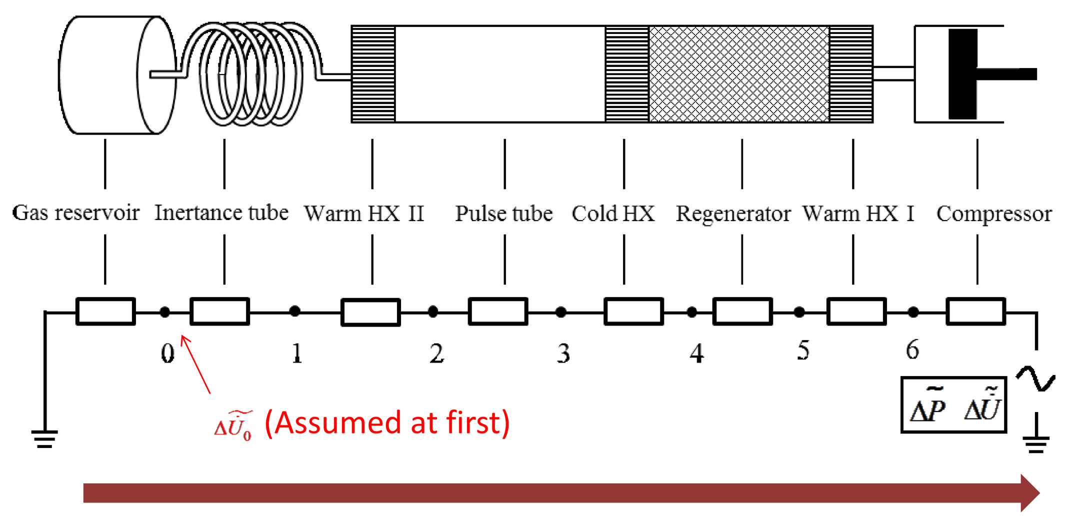
Oxford-type Moving-coil linear compressor

For a typical SPTC, the linear compressor and the pulse tube cold finger are coupled together, and they act on each other.

Objective

Investigate the dynamic and thermodynamic characteristics of the linear compressor in consideration of the characteristics of the cold finger, in which the latter mainly includes the cooling temperature, the cooling capacity and the frequency of the working gas, etc.

Analytical model of SPTC



Calculations of the characteristics of the working gas should start from the reservoir.

Governing equations of the cold finger

Gas reservoir

$\Delta\tilde{U}_0$ (Assumed at first)

$$\Delta\tilde{P}_0 = \frac{\gamma P_m}{i\omega V_r}\Delta\tilde{U}_0$$

Inertance tube

$$\Delta\tilde{P}_1 - \Delta\tilde{P}_0 = \int_0^{l_{IT}} \left(\frac{4i\omega}{\pi D_{IT}^2} + \frac{64 f_r \left|\Delta\tilde{U}_x\right|}{\pi^3 D_{IT}^5}\right)\rho\Delta\tilde{U}_x \mathrm{d}x$$

$$\Delta\tilde{U}_1 - \Delta\tilde{U}_0 = \int_0^{l_{IT}} i\omega\frac{\pi D_{IT}^2}{4\gamma P_m}\Delta\tilde{P}_x \mathrm{d}x$$

Pulse tube

$$\Delta\tilde{P}_3 = \Delta\tilde{P}_2$$

$$\Delta\tilde{U}_3 - \Delta\tilde{U}_2 = \frac{i\omega V_{PT}}{\gamma P_m}\Delta\tilde{P}_2$$

Regenerator

$$\Delta\tilde{P}_5 - \Delta\tilde{P}_4 = \int_0^{l_{reg}} \frac{\mu}{2\varepsilon d_h^2 A_{reg}}(a + b\,\mathrm{Re})\Delta\tilde{U}_x \mathrm{d}x$$

$$\Delta\tilde{U}_5 - \Delta\tilde{U}_4 = \int_0^{l_{reg}} \left(i\omega\frac{\varepsilon\pi D^2}{4\gamma P_m}\Delta\tilde{P}_x + g\Delta\tilde{U}_x\right)\mathrm{d}x$$

Heat exchangers

$$\Delta\tilde{P}_{in} - \Delta\tilde{P}_{out} = \int_0^{l_{HX}} r_{HX}\Delta\tilde{U}_x \mathrm{d}x$$

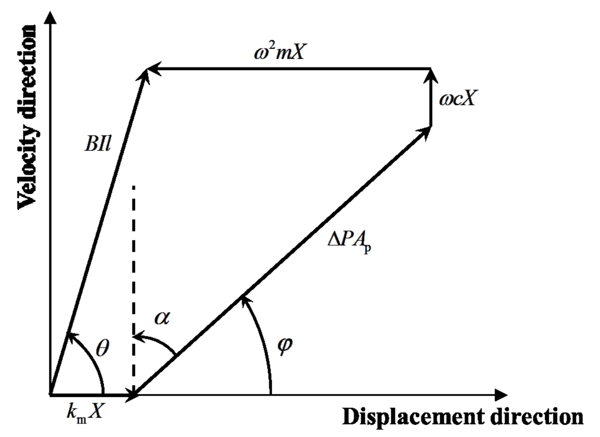
$$\Delta\tilde{U}_{in} - \Delta\tilde{U}_{out} = \int_0^{l_{HX}} i\omega\frac{A_{HX}}{\gamma P_m}\Delta\tilde{P}_x \mathrm{d}x$$

Compression space

$$\Delta\tilde{P} = \Delta\tilde{P}_6 \qquad \Delta\tilde{U} = \Delta\tilde{U}_6 + i\omega\frac{V_{com}}{\gamma P_m}\Delta\tilde{P}_6$$

$$\alpha = \arctan\left(\left|\mathrm{Im}[\Delta\tilde{P}/\Delta\tilde{U}]\right| / \left|\mathrm{Re}[\Delta\tilde{P}/\Delta\tilde{U}]\right|\right)$$

Governing equations of the linear compressor



Forces on the piston

Forces balance

$$BIl\cos\theta + \omega^2 mX = k_m X + \Delta PA_p\cos\varphi$$

$$BIl\sin\theta = \omega cX + \Delta PA_p\sin\varphi$$

Electric power

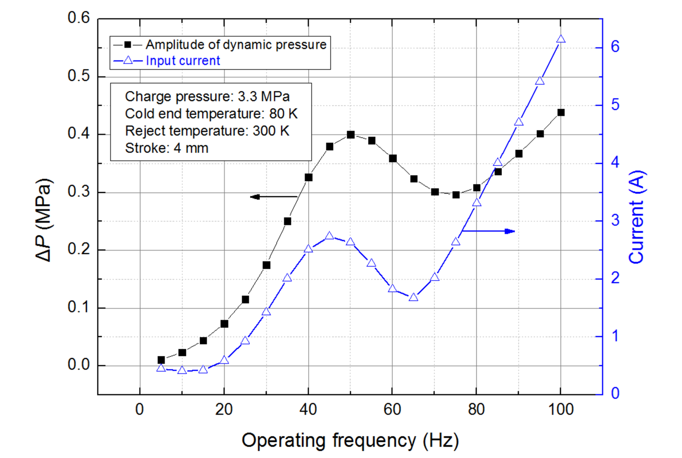
$$u = Ri + L_e\frac{\mathrm{d}i}{\mathrm{d}t} + BL\frac{\mathrm{d}x}{\mathrm{d}t}$$

$$W_e = \frac{1}{\tau}\int_0^{\tau} ui\,\mathrm{d}t = \frac{1}{2}I^2R + \frac{1}{2}\omega X(\omega cX + \Delta PA_p\sin\varphi)$$

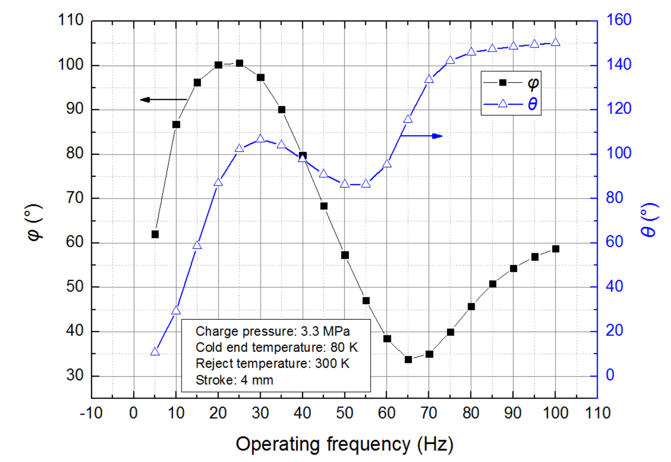
Systematical Simulations of SPTC

TABLE. The geometrical parameters of the SPTC

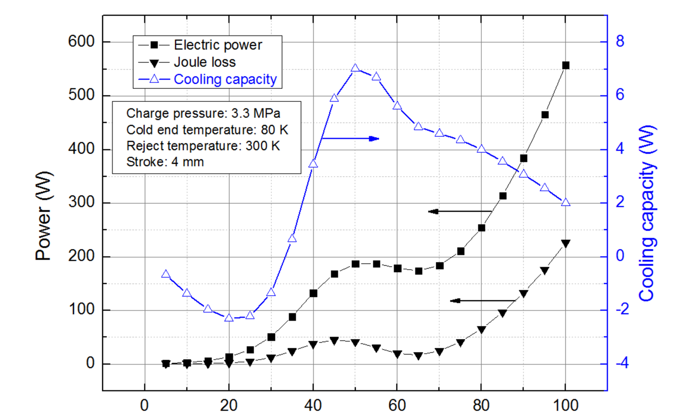
Linear compressor		Cold finger	
Piston diameter	20 mm	Regenerator	Φ16 × 67 mm
Moving mass	200 g	Pulse tube	Φ10.5 × 92 mm
BL	15 N/A	Inertance tube I	Φ2.7 × 2100 mm
Wire resistance	3 Ω	Inertance tube II	Φ3.3 × 1600 mm
Damping coefficient	4.5 N·s/m	Reservoir volume	400 cm3
Stiffness of flexure springs	4500 N/m		



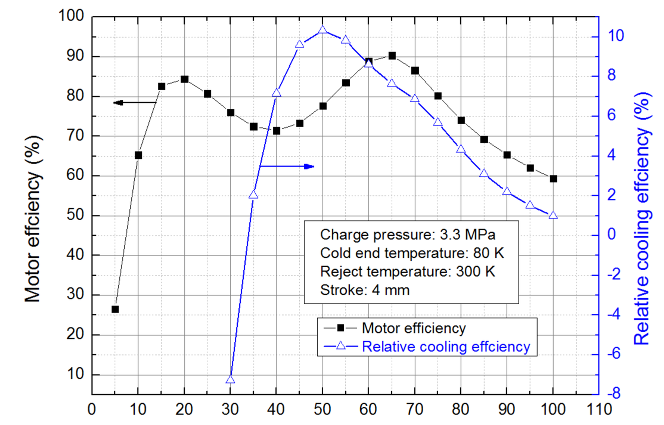
Simulated I and ΔP varying with f



Simulated θ and φ varying with the f



Simulated input electric power, Joule loss, and cooling capacity varying with f



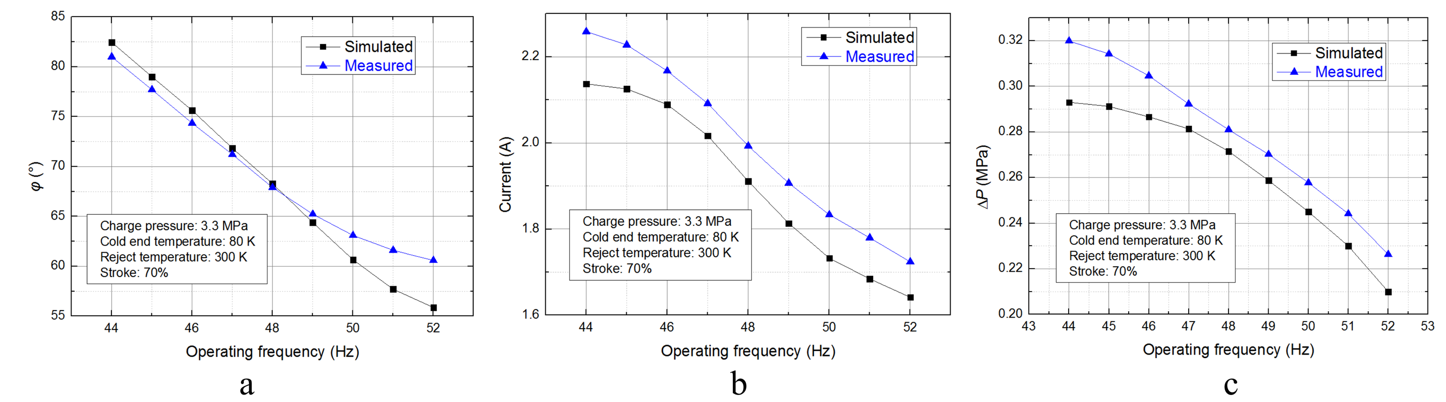
Simulated motor efficiency and relative Carnot efficiency versus f

- The operating frequency exerts important and complicated effects on the dynamic and thermodynamic characteristics of the linear compressor.
- The changing tendencies of the cooling capacity are distinctly different from those of the powers, which is mainly determined by the cold finger.
- The cold finger often exerts a greater influence on the optimal frequency of the SPTC than the compressor.

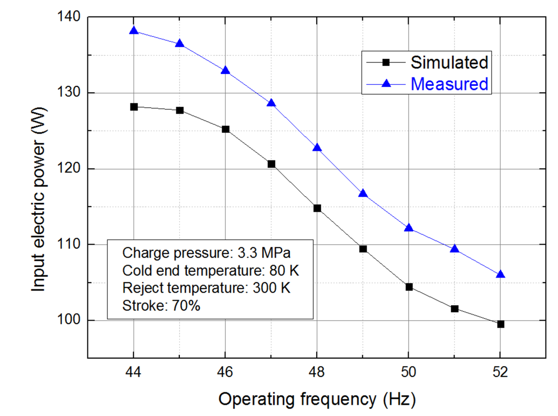
Experimental investigations

Experimental investigations：

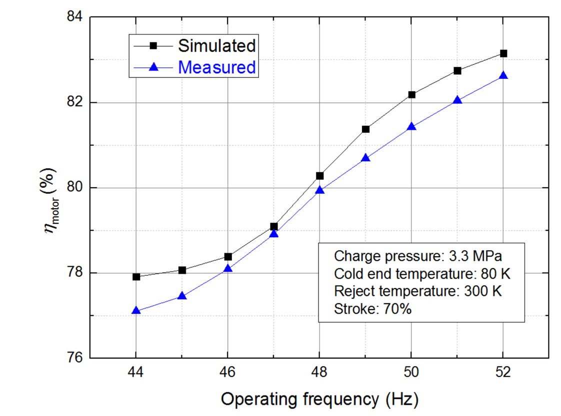
- A linear compressor coupled with a coaxial pulse tube cold finger developed in authors' laboratory is chosen.
- The SPTC is tested at 80 K with 70% of the stroke, and the frequency changes from 44 Hz to 52 Hz.



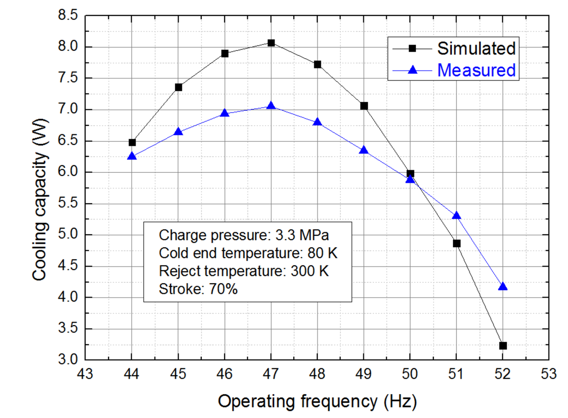
Simulated and measured values versus the operating frequency: (a) φ; (b) I; (c) ΔP



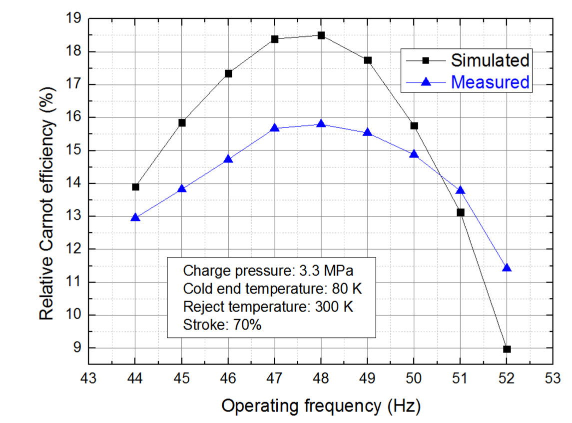
The electric power versus the frequency



The motor efficiency versus the frequency



The cooling capacity versus the operating frequency



The relative Carnot efficiency versus the operating frequency

Conclusions

- An analytical model of the SPTC is established to calculate the dynamic and thermodynamic characteristics of the working gas at any position of the SPTC, including the linear compressor and pulse tube cold finger.
- The characteristics of the linear compressor are investigated and simulated with a specific case, which indicates that The frequency exerts great and complex influence on I, θ, ΔP and φ, and the optimal frequency of the SPTC is mainly determined by the cold finger, but not by the compressor.
- The experimental investigations are conducted on a linear compressor coupled with a coaxial pulse tube cold finger developed in the authors' laboratory. The simulated results of the dynamic and thermodynamic characteristics indicate the fairly good agreement with the corresponding experimental results, which verify the validity of the theoretical analyses.