Numerical study of a cryogen-free Vuilleumier pulse tube cryocooler operating below 10 K

Yanan Wang[1,2], Xiaotao Wang[1,2], Wei Dai[1,2,*], ErcangLuo[1,2]

[1]Key Laboratory of Cryogenics, Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, Beijing 100190, China

[2]University of Chinese Academy of Sciences, Beijing 100049, China

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Technical Institute of Physics and Chemistry
CHINESE ACADEMY OF SCIENCES

1. Introduction

Vuilleumier (VM) type PTC is driven by a thermal compressor and has the potential advantages of compactness, long lifetime and a reasonable efficiency. Our group proposed a VM type PTC in which Stirling type pulse tube cryocoolers are used to provide the required cooling power for the thermal compressor. In this way, a cryogen-free system was built and working temperature difference of the thermal compressor can be easily adjusted. At present, a lowest no-load temperature below 10 K was obtained. Through numeric means, further optimization on the system for liquid helium temperature was carried out. Dependence of system performance on average pressure, frequency, displacer displacement amplitude and thermal compressor pre-cooling temperature were studied. Most importantly, evaluation of the influence of pre-cooling temperature on overall cooling efficiency at 5 K is performed.

2. System configuration

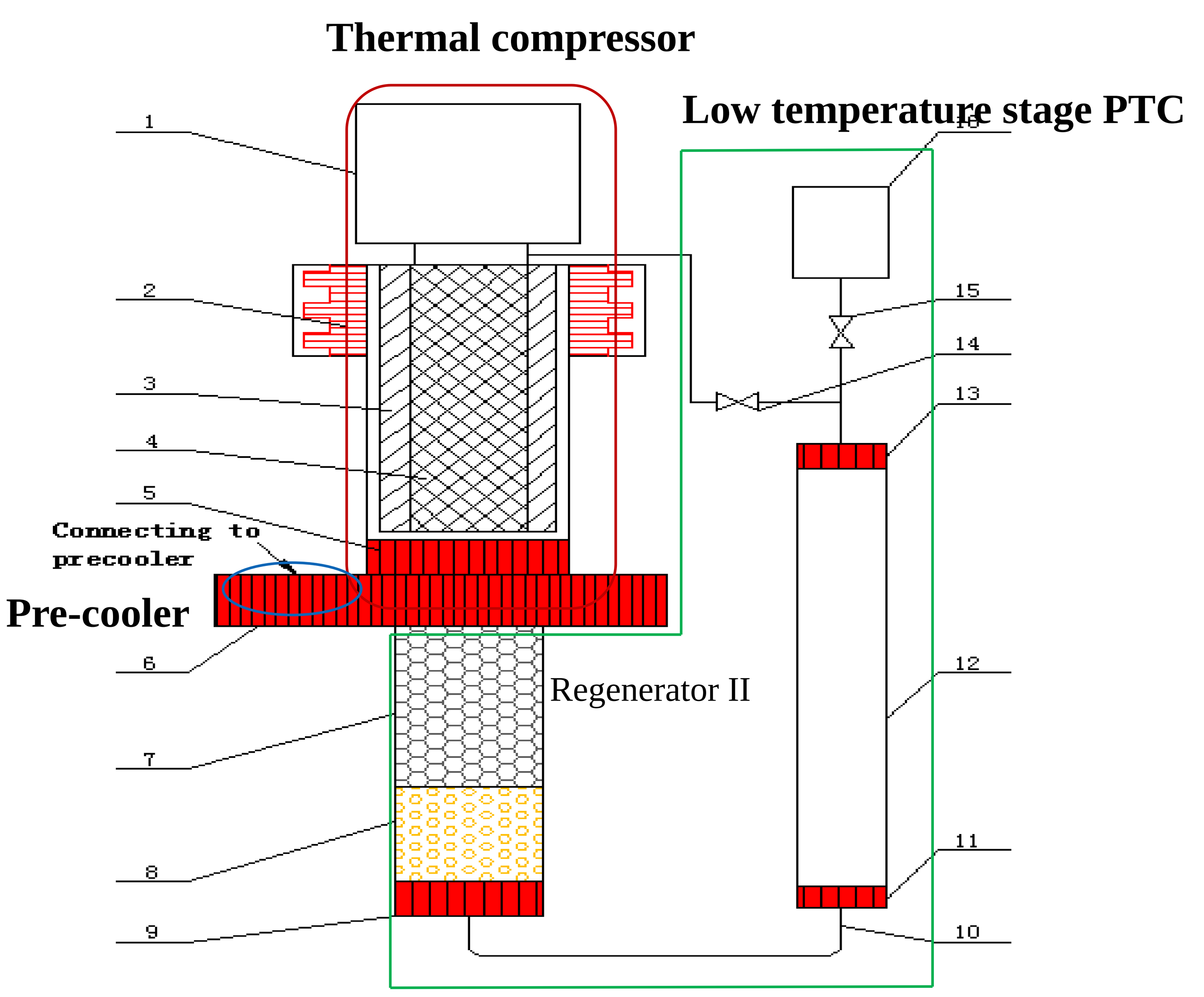


Figure 1. Schematic of the VM type pulse tube cryocooler

Precooler (Stirling Type PTC):

provide the required cooling capacity for the thermal compressor

➢Component parameters

Table 1. Main structure parameters of VM type pulse tube cryocooler

Subsystem	Components	Parameters
Thermal compressor	Ambient HX	Diameter 40 mm, length 52 mm, finned type HX
	Cold heat exchanger	Diameter 18 mm, length 25 mm, finned type HX
	Regenerator I	Diameter 30 mm, length 150 mm,80# stainless steel screens
Low temperature stage PTC	**Regenerator II (ErPr)**	Inner diameter 16.5 mm, length 166 mm, 0.2 mm sphere diameter, with porosity of 0.36.
	Regenerator II ($HoCu_2$)	Inner diameter 16.5 mm, length 80 mm, 0.15 mm sphere diameter, with porosity of 0.4.
	Pulse tube	Inner diameter 12 mm, length 247.5 mm, wall thickness 0.15 mm
	Reservoir	Volume 1 L

Conclusions

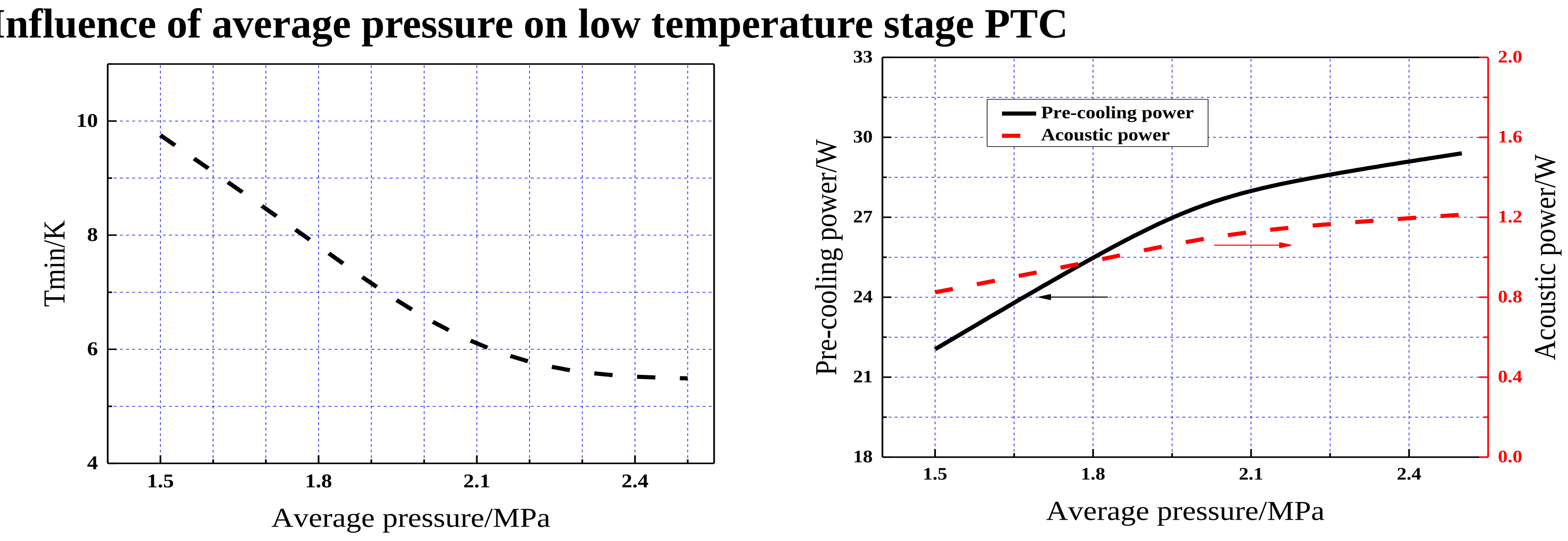
- ➢Frequency and average pressure have significant influences on the lowest no-load temperature.
- ➢There is an optimum pre-cooling temperature to achieve the maximum efficiency.
- ➢At a pre-cooling temperature of 65 K for the thermal compressor, the relative Carnot efficiency reaches to about 0.82%.
- ➢The cryogen-free VM type pulse tube cryocooler has important potential applications.

3. Simulation results and Discussion

3.1 Influence of the operating parameters

The simulation was conducted using the SAGE program. In this section, calculations are carried out to find optimum lowest no-load temperature through investigating the influence of the frequency, average pressure and displacer displacement amplitude for thermal compressor.

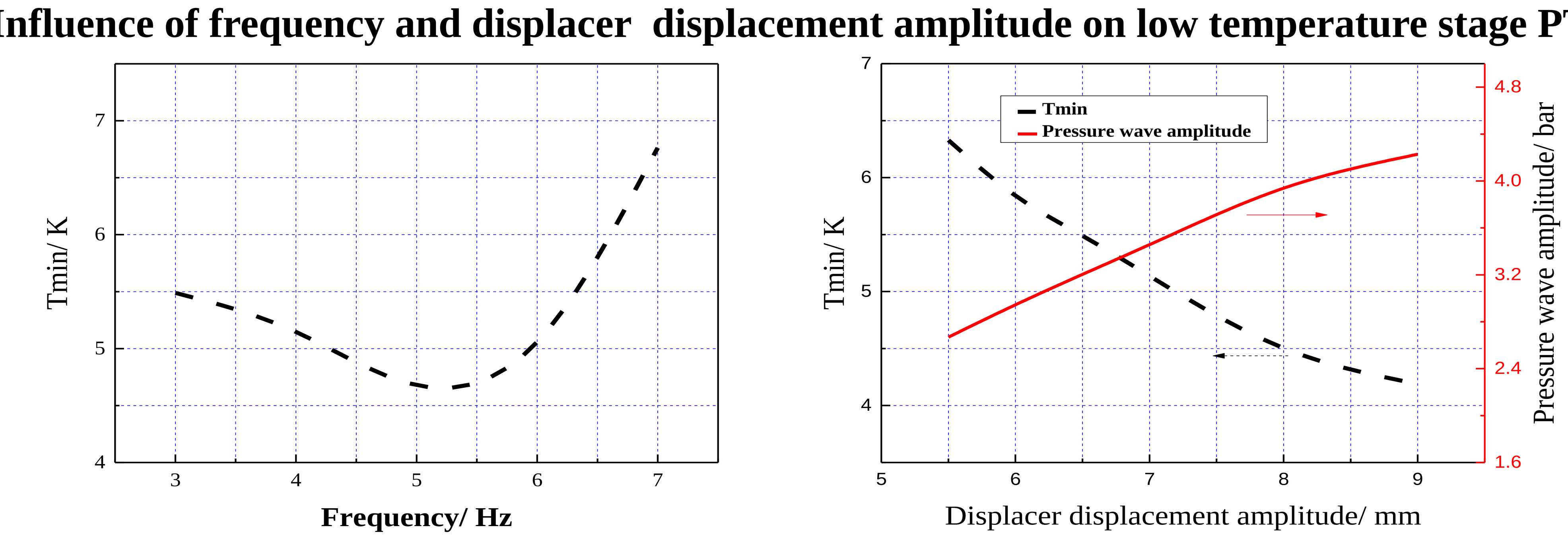
➢ Influence of average pressure on low temperature stage PTC



(3 Hz, 6.5 mm displacement, 90 K pre-cooling temperature)

- ◆The lowest no-load temperature decreases with increase of average pressure.
- ◆The required cooling power for the thermal compressor as well as the acoustic power at the cold end of Regenerator II increase with the average pressure.

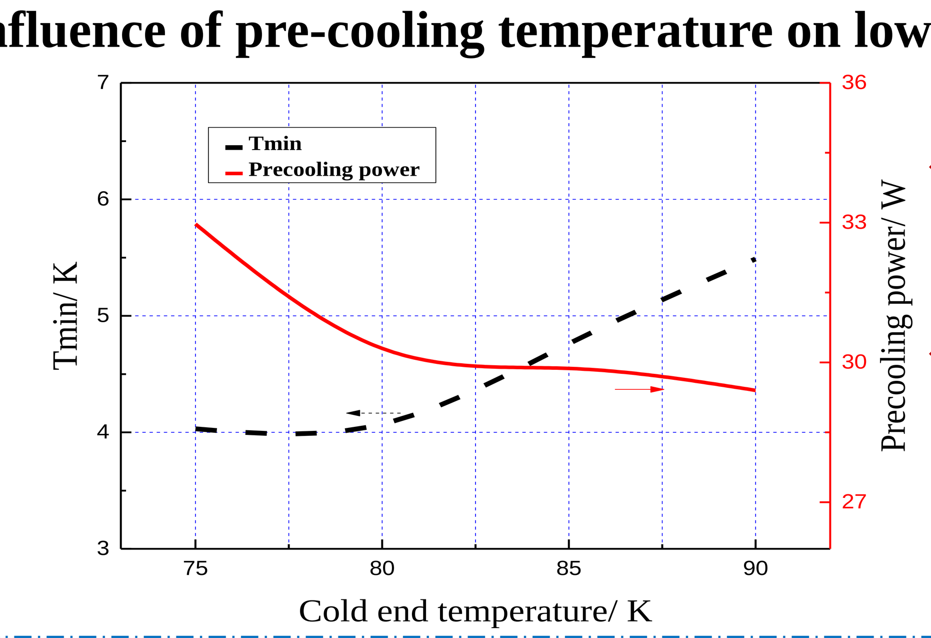
➢Influence of frequency and displacer displacement amplitude on low temperature stage PTC



(2.5MPa, , 90 K pre-cooling temperature)

- ◆The frequency has significant influence on lowest no-load temperature and optimum frequency is around 5 Hz.
- ◆Increasing the displacer displacement amplitude means larger acoustic power provided to low temperature stage PTC.

➢Influence of pre-cooling temperature on low temperature stage PTC



- ◆Lowest no-load temperature decreases with decreasing of the pre-cooling.
- ◆A lowest no-load temperature of **5.0 K** is obtained when pre-cooling temperature for thermal compressor is **87 K**.

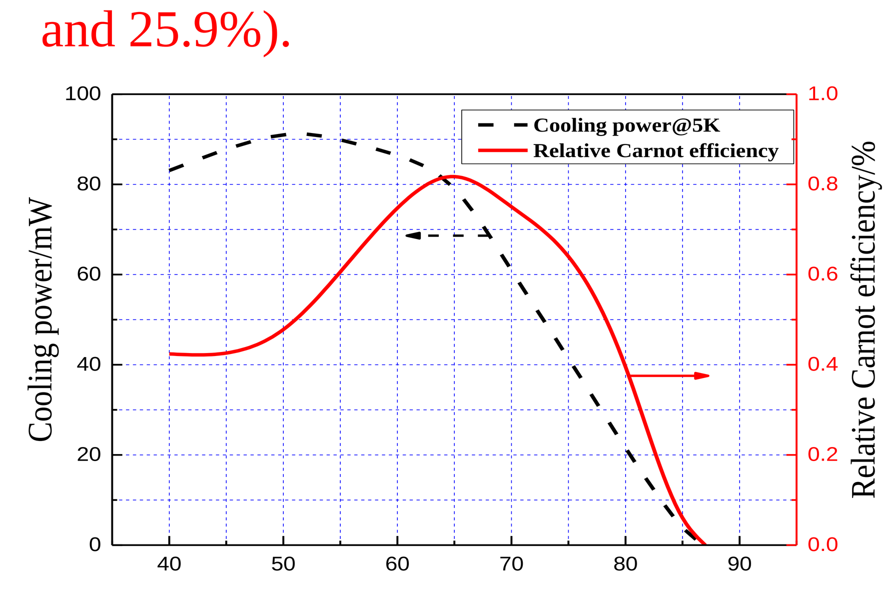
3.2. Overall efficiency evaluation with variable pre-cooling temperature

- ◆a cold end temperature of 5 K is selected
- ➢pre-cooling temperature is modified ,which varies from 40 K to 87 K

Relative Carnot efficiency η is defined as : $\eta = \frac{Q_c}{W_{in}} / \frac{T_c}{T_h - T_c}$

Q_c cooling power of the low temperature stage cold head at 5 K, W_{in} total input power, which is calculated with: $W_{in} = \frac{Q_{pre}}{\eta_{pre}} / \frac{T_{pre}}{T_h - T_{pre}}$

T_{pre} pre-cooling temperature and Q_{pre} required pre-cooling power respectively. η_{pre} estimated based on state of the art of cryocooler technology (relative Carnot efficiency at 40 K and 77 K is 14.8% and 25.9%).



- ◆there is an optimum pre-cooling temperature for the maximum efficiency.
- ◆at a pre-cooling temperature of 65 K for the thermal compressor, the relative Carnot efficiency reaches to about 0.82%.