September 13-15, 2017, Karlsruhe, Germany

Karlsruhe Institute of Technology

European Cryogenics Days 2017 and

2nd International Workshop on Cooling Systems for HTS Applications

Numerical and Experimental Studies of Two-stage Pulse Tube Cryocoolers Working Around 20K

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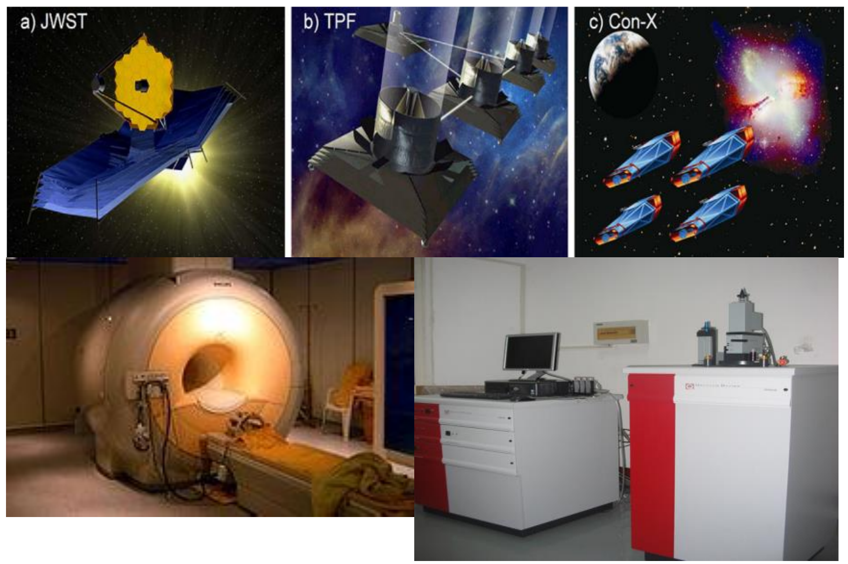
Introduction

◆ **Small scale cryocoolers** working at liquid hydrogen temperature has many important applications

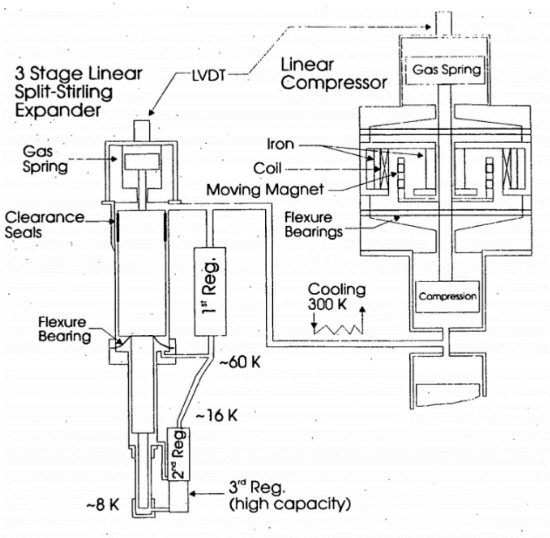


- ✓ **Space exploration**
- ✓ **Mid-infrared sensors**
- ✓ Cooling superconductors
- ✓ Low temperature physics

Introduction

- G-M or G-M type pulse tube cryocooler
- Multi-stages Stirling cryocooler

G-M cryocooler



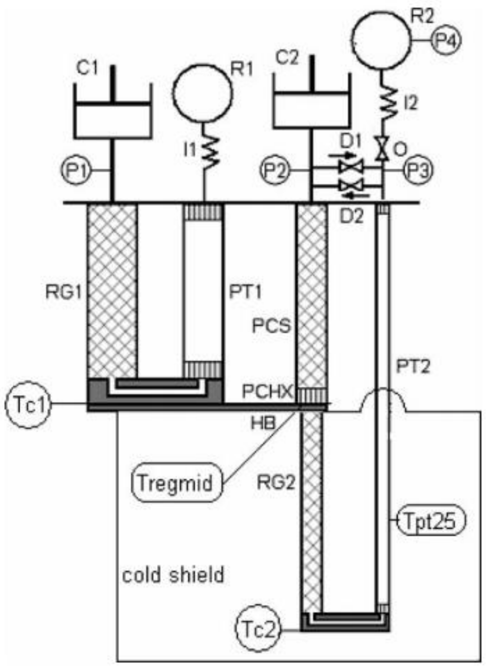
Multi-stages Stirling cryocooler

✓ **Regular Maintenance**
✓ **Oil Lubricated Compressor**

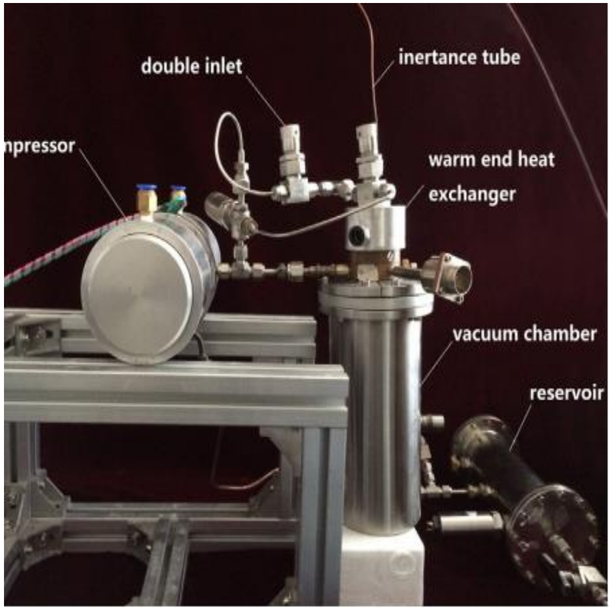
✓ **Linear compressor**
✓ **Low temperature displacer**

Introduction

- Stirling type two stage pulse tube cooler working at 20 K



L. Yang et. al,
thermally-coupled, 12.8 K

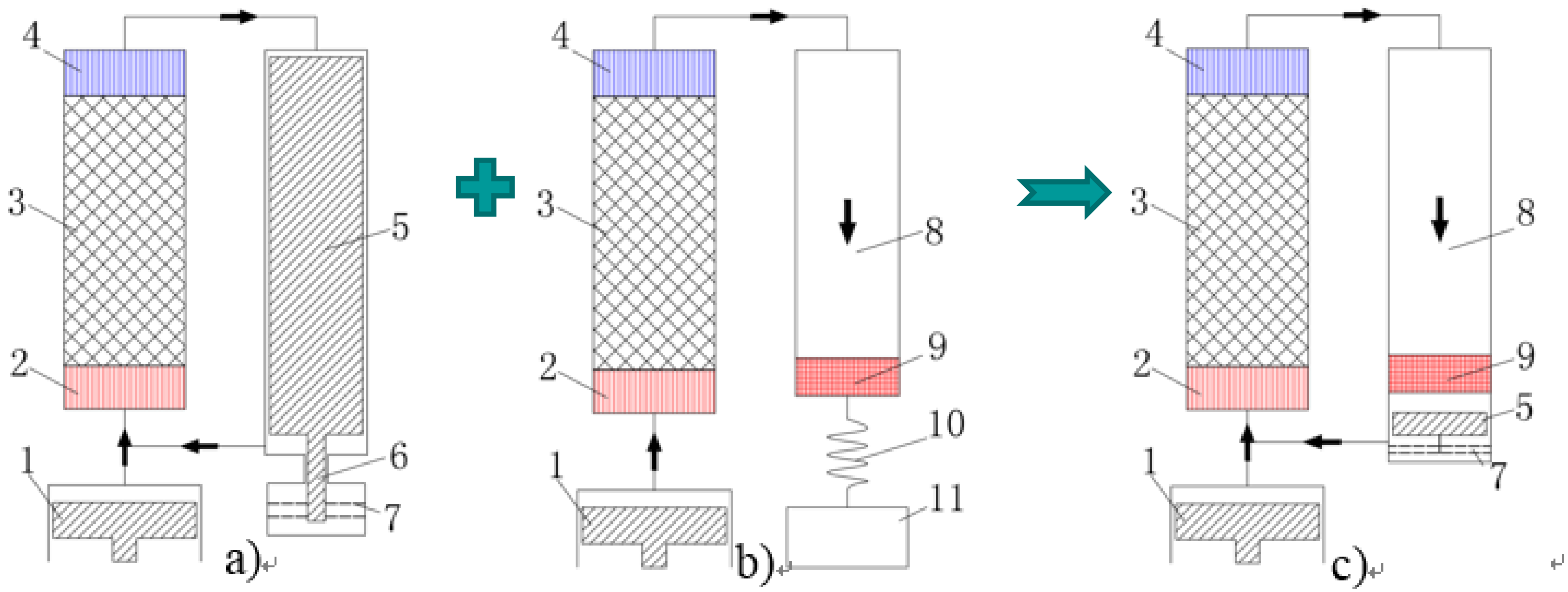


Q. Zhou et. al
13.9 K, 0.3 W @20K

✓ **Low thermal efficiency**

Introduction

- How to obtain a high efficiency and compact pulse tube cooler system?
- Warm displacers can be used in the two-stage pulse tube cryocooler



✓ **High Efficiency** ✓ **No moving parts at cold area**

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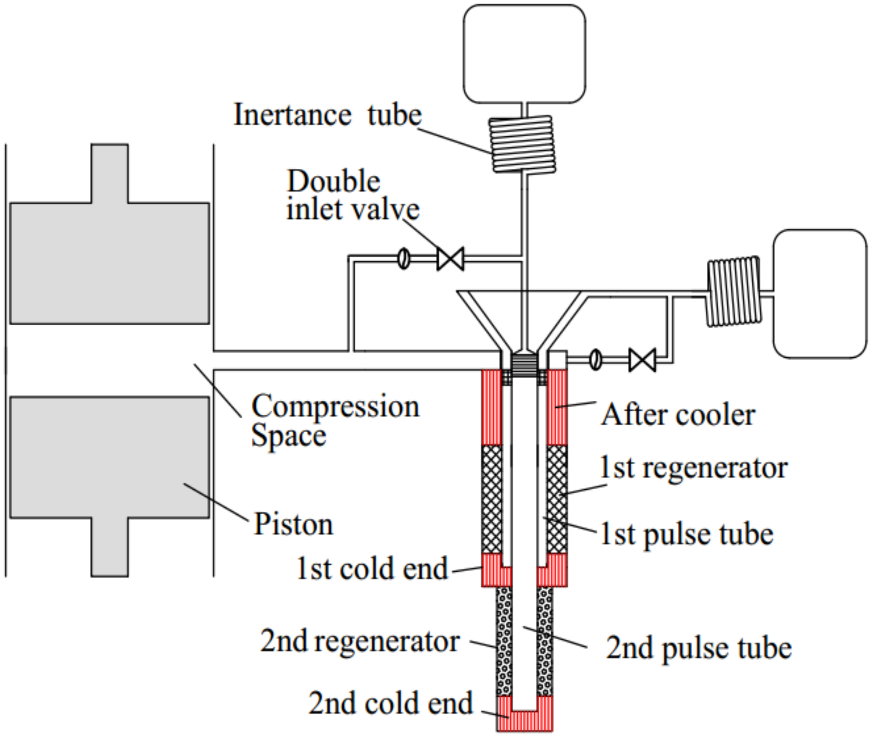
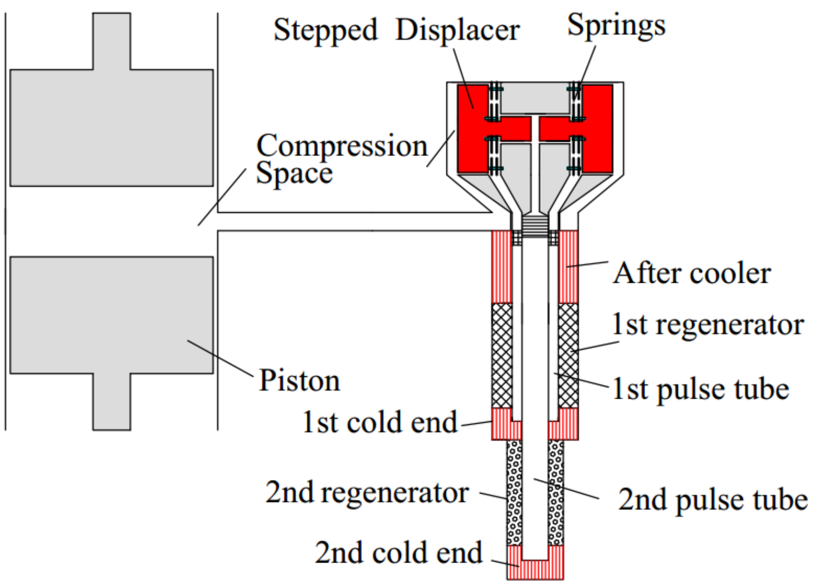
System configurations

- Two stage gas-coupled pulse tube cryocooler
- Dual-opposed stepped warm displacer configuration is adopted



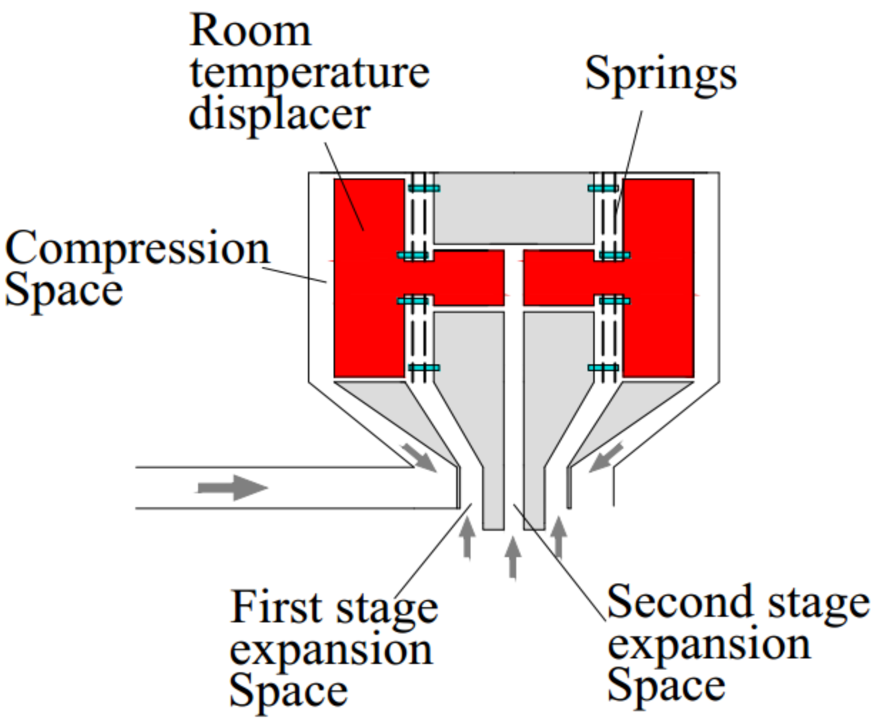
a. Double inlet type



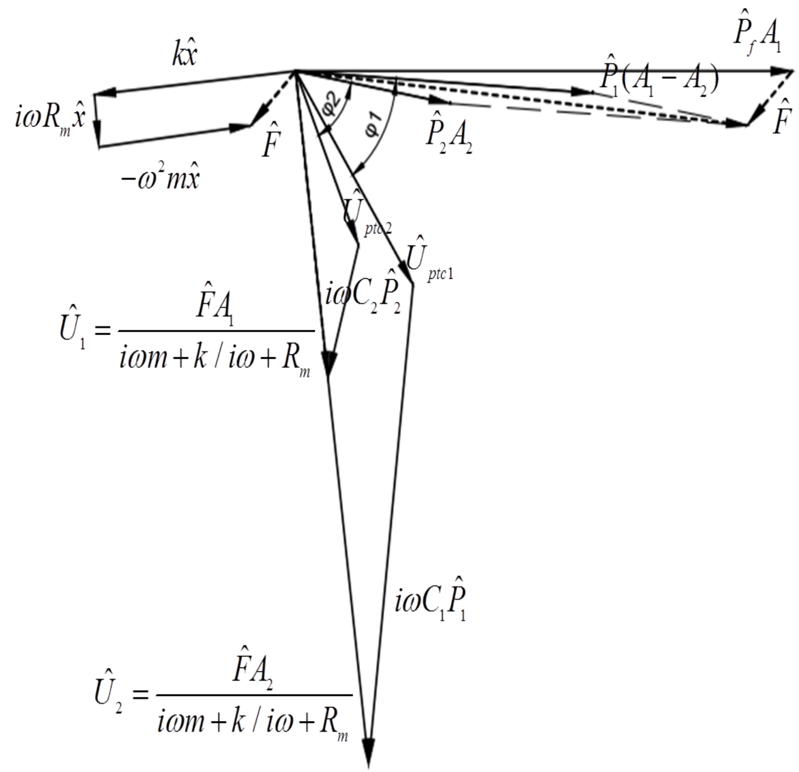
b. Stepped warm displacer type

Theoretical analyses

- Expansion acoustic power can be recovered
- An appropriate phase relationship between the pressure wave and volume flow rate can be realized



Acoustic power flow



Phasors diagram for the stepped warm displacer

Numeric Model And Simulation

- Our simulation is based on a quasi-one-dimensional numeric model using the thermoacoustic theory and Sage 10 software
- Geometric and operating parameters are selected according to the numerical calculation results

Components	Details
First stage regenerator	i.d. 20.17 mm, length 60 mm, filled with 300# stainless steel mesh
First stage pulse tube	Annular, Outer diameter 16.4 mm, inner diameter 7.3 mm, length 70 mm
Second stage regenerator	i.d. 12.64 mm, length 50 mm, filled with $HoCu_2$
Second stage pulse tube	i.d. 7.3 mm, length 148 mm,

✓ **Frequency: 30 Hz**

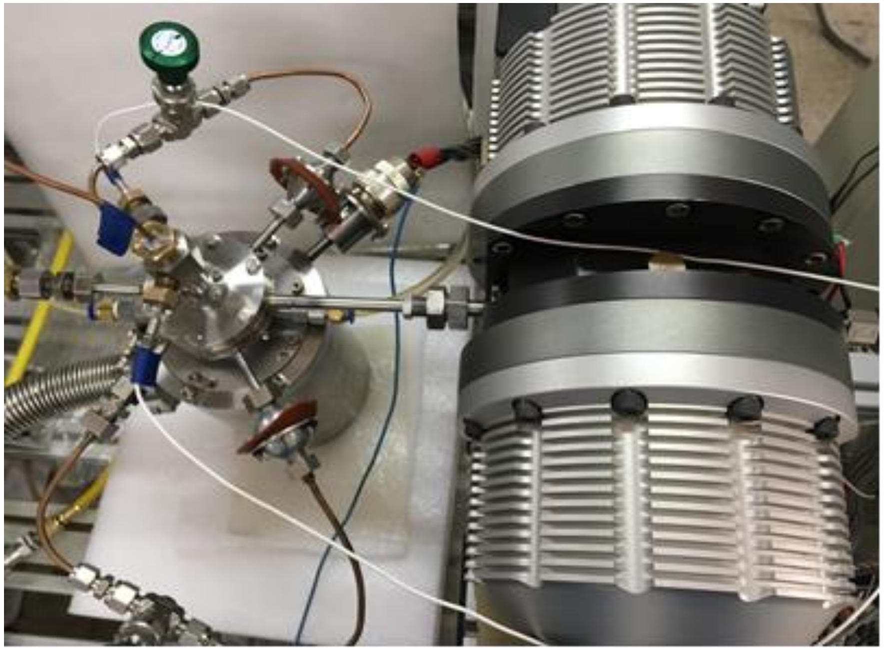
Numerical simulation results

- Expansion acoustic power can be recovered
- The dimensions of the phase shifter are optimized to obtain the highest efficiency and the results are shown in table
- An appropriate phase relationship between the pressure wave and volume flow rate can be realized

Parameters	Double inlet	Stepped warm displacer
Acoustic power input (W)	421	211
Pressure ratio	1.37	1.37
First stage cold end temperature (K)	45.9	45.3
No-load temperature (K)	12.0	12.0
Recover acoustic power (W)	0	15
Cooling power at 20 K(W)	1.45	1.47
Relative Carnot efficiency (based on the acoustic power input)	**4.8%**	**9.7%**

Experimental setup

- The system includes a moving-magnet linear compressor and a completely co-axial gas-coupled two stage pulse tube cooler
- The compressor uses dual-piston configuration to cancel vibration
- Two elastic membranes are used to eliminate the DC flow



Experimental systems using double inlet valve and inertance tube

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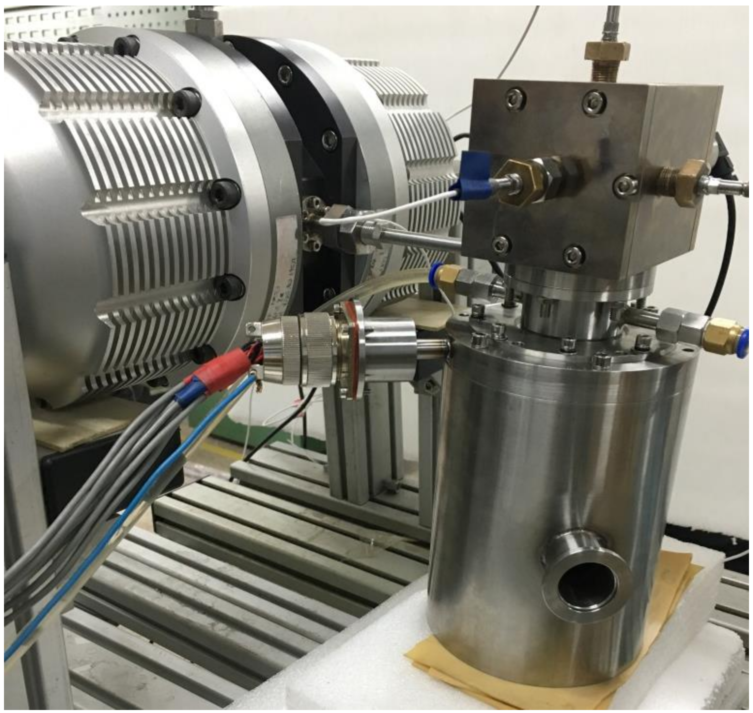
Room temperature displacers

- The parameters are kept the same with the double inlet type
- Each ambient displacer is supported by four flexure springs with a total stiffness of 19 kN/m. The natural resonance frequency is 73.6 Hz

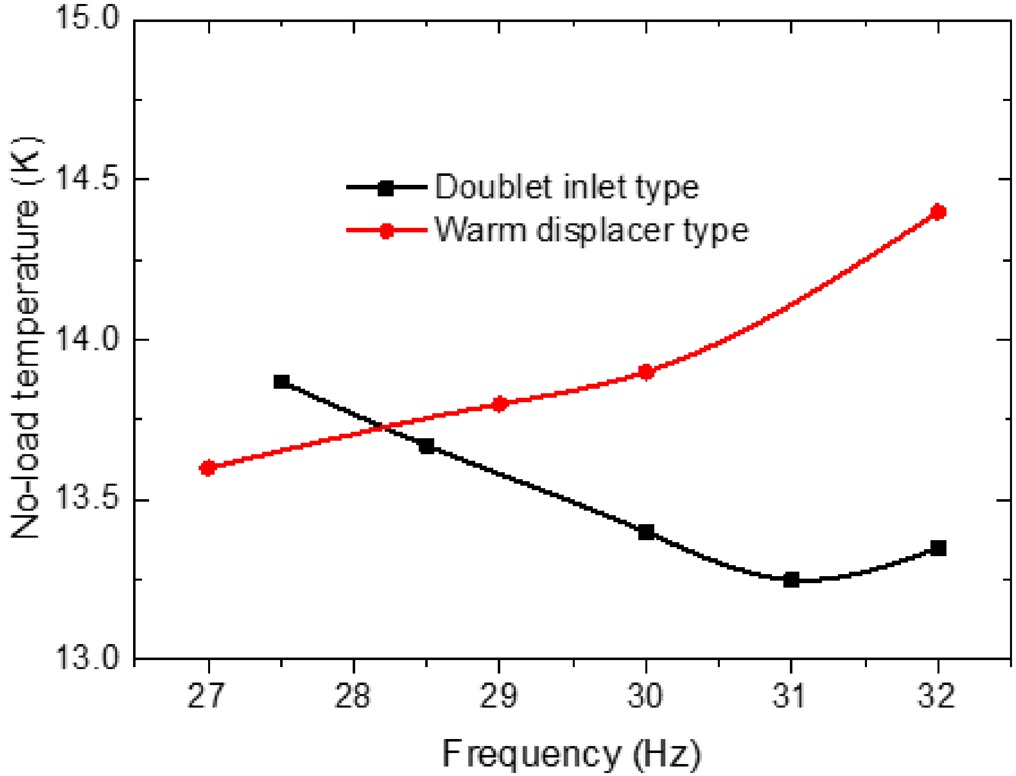


Experimental systems using stepped displacers

Photo of stepped displacer

Experimental results and discussions

- A no-load temperature of **13.9 K**

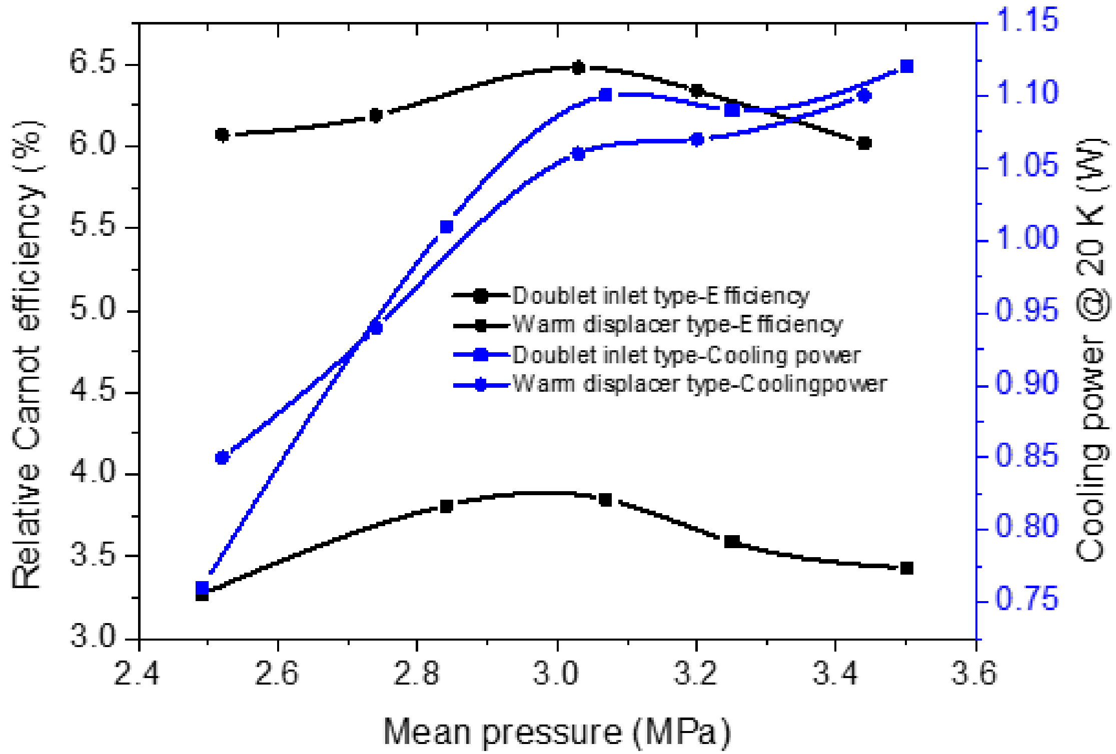


Pressure ratio: 1.37
Mean pressure:3.0 MPa

Temperature of the first stage and second stage cold end vs. frequency

Experimental results and discussions

- With double inlet phase shifter, 1.1 W cooling power at 20 K can be obtained and the relative Carnot efficiency is only **3.85%**
- while with stepped warm displacer phase shifter, it results in 1.06 W cooling power at 20 K and the relative Carnot efficiency reaches **6.5%. The optimum efficiency is far higher than the value of double inlet type**



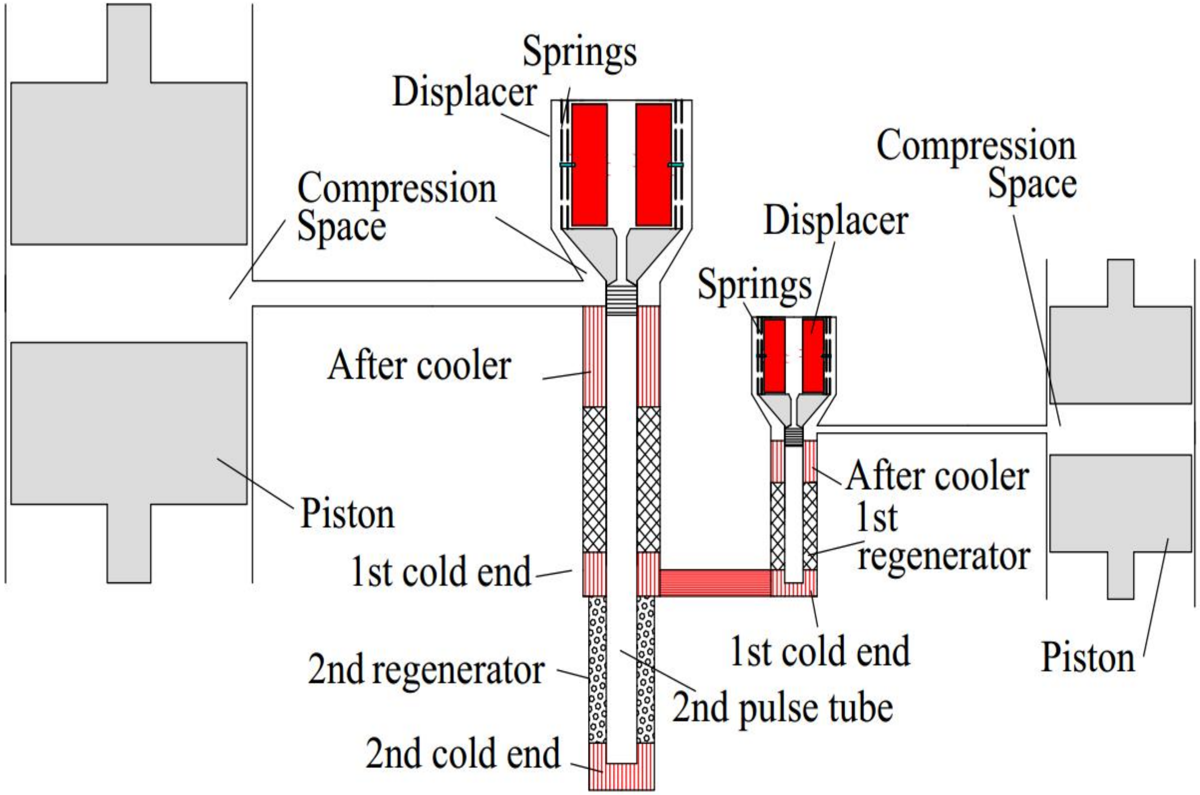
Pressure ratio: 1.37
Frequency: 30 Hz

Cooling capacity with warm displacer as phase shifter

Contents

Thermal-coupled two-stage cryocooler

- At the first stage, an ultrahigh frequency operation of 100 Hz is utilized to precool the second stage for seeking a higher power density
- At the second stage, a relative lower frequency of around 30Hz is used for improving system efficiency



Numeric Model And Simulation

- Our simulation is based on a quasi-one-dimensional numeric model using the thermoacoustic theory and Sage 10 software
- Geometric and operating parameters are selected according to the numerical calculation results

Components	Details
First stage regenerator	i.d. 20.0 mm, length 35 mm, filled with 600# stainless steel mesh
First stage pulse tube	Diameter 10.0mm, length 52 mm
Second stage regenerator	i.d. 20 mm, length 60 mm, filled with $HoCu_2$
Second stage pulse tube	i.d. 10.0 mm, length 122 mm,

Numerical simulation results

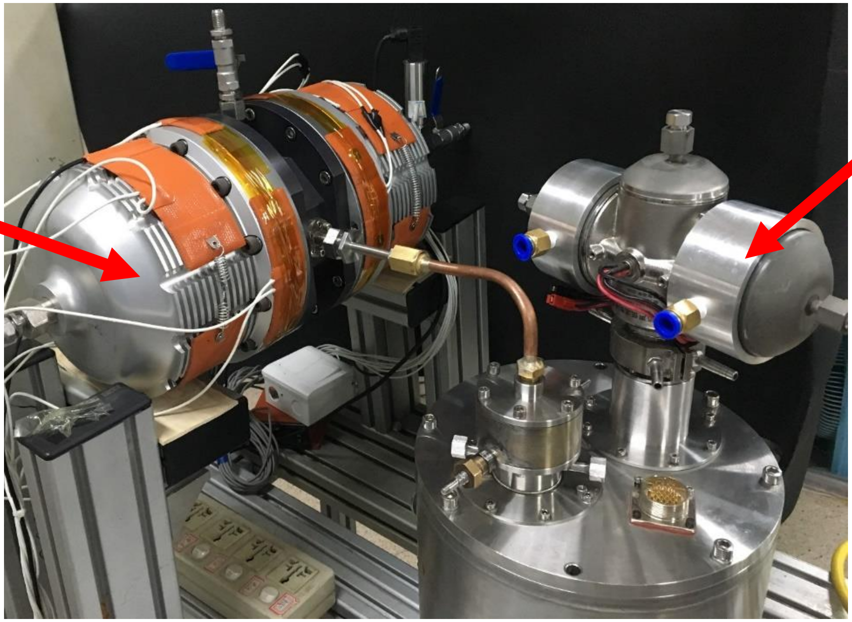
- The first stage provides 17-18 W cooling power at 77K to precool the second stage
- The efficiency of the system can be improved by 90% when using displacer as the phase shifter

Parameters	Double inlet	Stepped warm displacer
Acoustic power input at 1st stage (W)	154	167
Acoustic power input at 2nd stage (W)	150	150
Pressure ratio of second stage	1.26	1.32
First stage cold end temperature (K)	77	77
Precooling power(W)	17.1	18.7
Cooling power at 20 K(W)	1.2	2.3
Relative Carnot efficiency (based on the acoustic power input)	**5.5%**	**10.2%**

Experimental setup

- Co-axial configuration for each stage
- The thermal bridge is composed of 0.1 mm copper plates
- Test and more optimization are on the way

Linear compressor for the second stage



Linear compressor for the first stage

Experimental systems using stepped displacers

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Conclusions

- A two-stage gas-coupled pulse tube cooler system with a completely co-axial configuration is presented.
- A stepped warm displacer, working as the phase shifter for both stages, has been studied theoretically and experimentally.
- The experiments show that compared with double inlet type, the efficiency of the system improves by 70% with stepped warm displacer as the phase shifter
- A thermal-coupled two stage pulse tube cooer has been developed.

THANKS

This work is financially supported by the National Natural Science Foundation of China under contract number of [51376187] and [51576205], Youth Innovation Promotion Association CAS (No.2017040)