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STUDY ON A SINGLE-STAGE 120HZ PULSE TUBE CRYOCOOLER

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ABSTRACT

Miniaturization of pulse tube cryocoolers is required for some particular applications where size and mass for devices are limited. In order to pack more cooling power in a small volume, higher operating frequencies are commonly used for Stirling-type pulse tube cryocoolers. To maintain a high efficiency of regenerator with a higher frequency, a higher charging pressure and smaller hydraulic diameters of regenerator material and shorter lengths of regenerator should be applied. A rapid growth of research and development on pulse tube cryocoolers operating at a high frequency over 100Hz in the last 3 years has occurred.

In this study, a single stage pulse tube cryocooler with 120Hz to provide 10W of lift at 80K has been developed by using the numerical model, known as REGEN 3.2. Experiments performed on this cryocooler driven by a CFIC linear compressor shows that a no-load temperature of 49.6K was achieved and the net refrigeration power at 78.5K was 8.0W. Effect of pulse tube orientation was tested, and copper velvet as regenerator matrix was proposed for high frequency operation.

KEYWORDS: high frequency, pulse tube cryocooler, orientation, copper velvet

INTRODUCTION

The past two decades have witnessed a vast development in pulse tube cryocoolers (PTCs) [1], not merely because of its inherent merits, such as simple packaging, high reliability and small vibration, but also by the applications which demand a low temperature environment with is safe, economic, and efficient. In space applications and military applications which naturally need mobility and rapid reaction, it is usually required to miniaturize the cryogenic refrigeration systems.

A high operating frequency is proposed for Stirling-type PTC to greatly miniaturize the linear compressor and cold head, for packing more cooling capacity in a smaller volume with considerable efficiency [2]. Following this idea, a high frequency miniature PTC operating at 120Hz was built in National Institute of Standards and Technology (NIST), which was able to provided 3.35W of cooling power at 80K [3]. Another PTC with a regenerator length of only 27mm, reached 97.5K with 150Hz, and achieved a high speed of cooling down [4]. In Northrop

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Grumman Corporation (NGST), by using high operating frequency of 124Hz, 1.3W of cooling power at 77K was packed in a small volume with a mass below 1kg which can be held in one hand [5]. In the meantime, researchers in Chinese Academy of Science were testing a PTC with a high frequency as high as 300Hz [6-7]. Driven by a thermoacoustic pressure wave generator with a charging pressure of 4.1MPa and a heat power of 1kW, this PTC achieved a no load temperature of 68K and a lift of 1.16W at 80K.

All of those exciting results show the potential of high frequency PTC. However, still a lot of work has to be done to improve the performance, reach lower temperature, produce larger cooling power, or even approach higher frequency to make the system smaller and lighter.

This paper describes a PTC with an operating frequency of 120Hz, designed, fabricated and tested in Zhejiang University. In order to investigate the possibility to apply high frequency to larger capacity PTCs whose payloads include large infrared focal planes, filters or cold optics, a medium cooling capacity of 10W at 80K was chosen as a goal which also was easy for phase shifting by inertance tubes. The pressure driver for this PTC is a CFIC 2S132W linear compressor, whose resonance frequency is 60Hz, half of the operating frequency. That means the compressor has to work at quite low efficiency such as 30%-50% [8].

MODELING AND DESIGN

Matrix material selection

For efficient heat exchange in regenerator, two conditions have to be satisfied [9]:

1. The characteristic dimension of the matrix should be smaller than the thermal penetration of the matrix material, so that the heat capacity of the matrix material is fully used;
2. Hydraulic diameter of the matrix channels should be smaller than the thermal penetration of the working fluid to provide sufficient heat exchange with the fluid.

The thermal penetration depth for oscillating heat transfer is given by

$$\delta_t = \sqrt{\frac{2k}{\omega \rho c_p}} = \sqrt{\frac{k}{\pi f \rho c_p}} \tag{1}$$

Where k is the thermal conductivity, ω is the angular frequency, ρ is the density, c_p is the isobaric heat capacity and f is the frequency.

Stainless steel screens (SSS) is the most widely used matrix in regenerator for liquid nitrogen temperature range. The parameters of 325, 400, 500 and 635 meshes SSS are shown in TABLE 1.

FIGURE 1 shows the temperature and frequency dependence of the thermal penetration in stainless steel as well as the diameters of screen wires. Although the thermal penetration decreases as frequency increases, below 300Hz, the first requirement is still satisfied for common SSS.

TABLE 1. Parameters of commonly used Stainless Steel Screen

Mesh	Wire dia./μm	Hydraulic dia./μm	Porosity
#325	35.6	63.98	0.6422
#400	25.4	55.44	0.6858
#500	25.4	39.28	0.6073
#635	20.3	30.58	0.6014

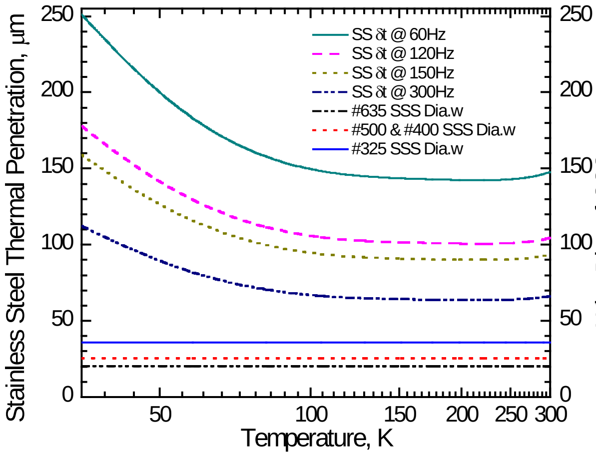

FIGURE 1. Thermal penetration depth of stainless steel at varied frequency in comparison to the wire diameters of typical SSS

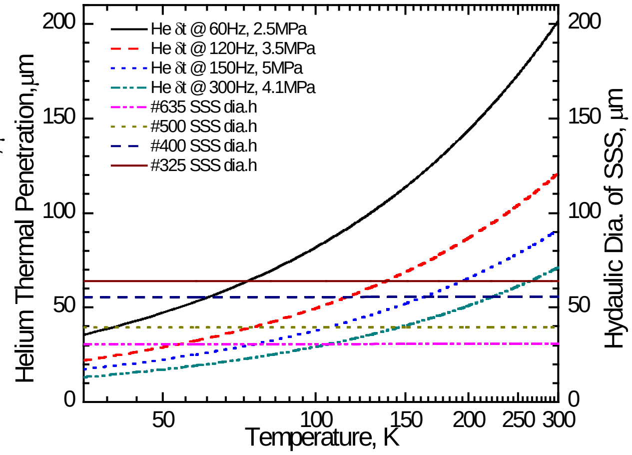

FIGURE 2. Thermal penetration depth of helium at varied frequency in comparison to the hydraulic diameters of SSS

According to FIGURE 2, the thermal penetration of helium gas reduces remarkably as frequency and pressure increase. To meet the second requirement, #635 mesh SSS, the finest commercially available one, whose hydraulic diameter line of 30.58 µm, intersects the curve of helium thermal penetration of 120Hz and 3.5MPa at 53.8K, is the only option for good performance of the regenerator for a frequency of 120Hz as used in this paper.

Regenerator optimization modeling

A well accepted numerical model developed by NIST, known as REGEN 3.2 [10], was used for an iterative optimization to perform a regenerator able to produce 10W at 80K. A charging pressure of 3.5MPa and a pressure ratio of 1.2 at the cold end of regenerator were chosen according to previous experience [3] and compressor restriction.

Initial guesses were made with respect to the regenerator inner diameter of 14.86mm and tube wall thickness of 0.508mm according commercially available cold drawn tube series, as well as a phase shift between mass-flow and pressure at the cold end of the regenerator of -30° which was typically optimal value but would be optimized later.

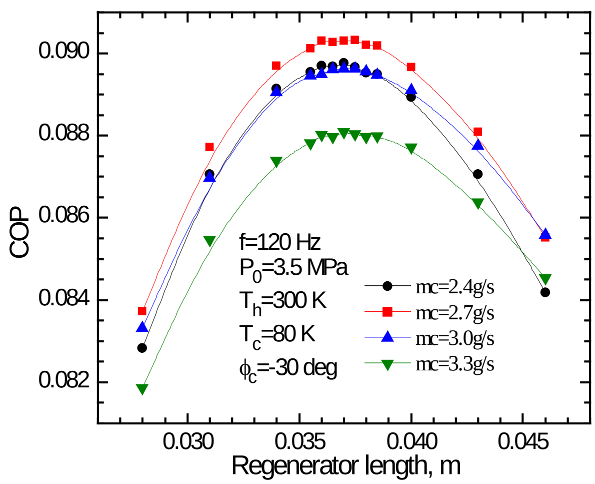

FIGURE 3. COP as a function of regenerator length for different mass-flow at cold end

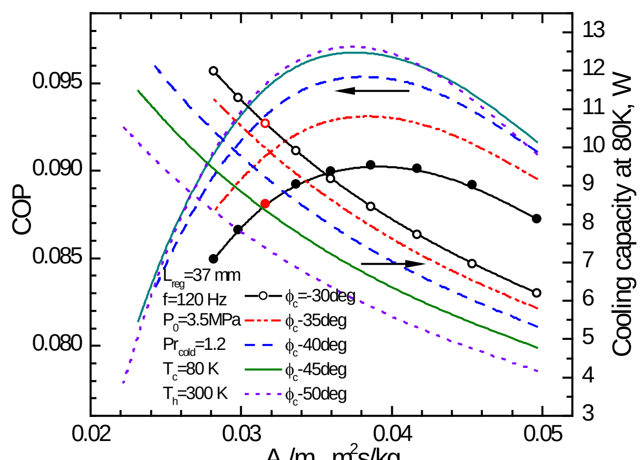

FIGURE 4. COP and cooling capacity as a function of gas area to mass-flow ratio and phase shift at the cold end

Several cases with various regenerator lengths were calculated. FIGURE 3 shows a curve of the COP as a function of different lengths, which indicates that the regenerator length of 37mm should be chosen after taking account of axial heat conduction loss through the tube wall.

With the optimum regenerator length, the mass-flow and the phase shift at cold end were varied respectively to find the higher COP, shown as FIGURE 4. In order to not scaling the regenerator diameter to produce target cooling capacity, a compromise is made to chose the red data point in FIGURE 4 whose cooling power at 80K is 10.6W, though highest COP is gained when the ratio is about 0.53 m^2s/kg. Some other operating points will be tested by using different inertance tubes.

Pulse tube design

The inner diameter of pulse tube should be larger than the thermal penetration of the helium gas to ensure the adiabatic compression and expansion process. And its volume should be at least 3-5 times as the swept volume of the gas at cold end to ensure thermal decoupling between the two ends. According to those rules, a thin-walled, stainless steel tube with an inner diameter of 9.017mm and a length of 32mm, was chosen for pulse tube. With this dimension, the ratio of the pulse tube diameter to the thermal penetration depth of the helium gas is 74.5, and the ratio of the pulse tube volume to the gas swept volume at the cold end, V/V_e, equals 4.4.

Phase diagram and inertance tube design

FIGURE 5 is the phasor diagram of the PTC given the mass-flow amplitude of 3.3g/s and phase shift of -30° at the cold end of the regenerator, which deduces that a corresponding phase shift of -52° must be provided at the interface of the inertance tube for this condition.

FIGURE 6 gives the phase shift as a function of PV work at the interface of the inertance tube with different dimensions of tubes by using a transmission line model [11]. Because the PV work is about 21.6W in this case, a phase shift of -52° can be easily. With a reservoir of 50cc, three inertance tubes for different mass-flow and phase degree at cold end were designed.

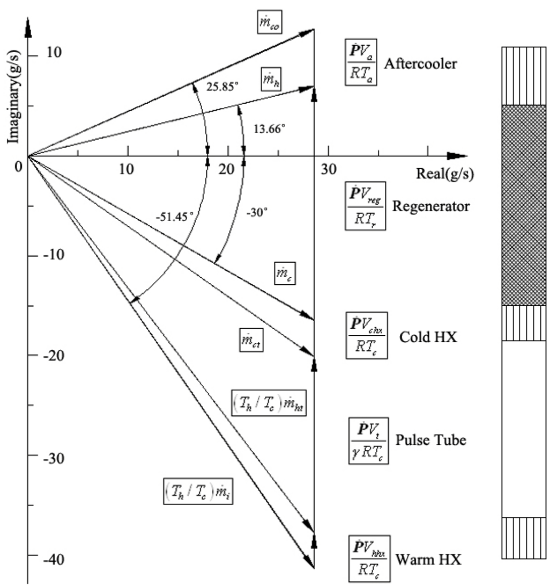

FIGURE 5. Phasor diagram of the PTC for typical working condition

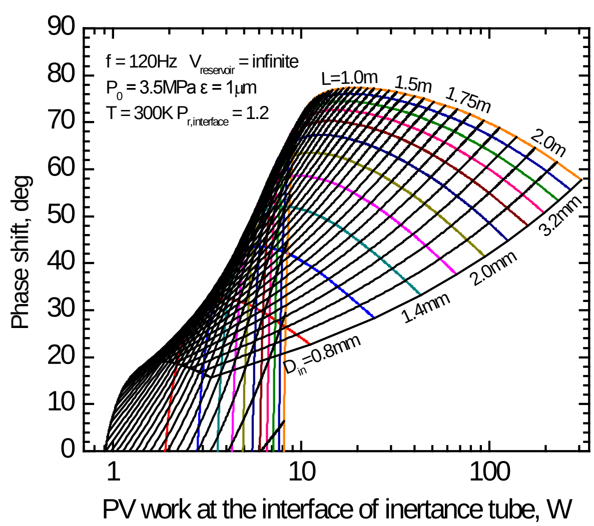

FIGURE 6. Phase shift as a function of PV work with different tube dimensions

Summary for the geometry parameters of PTC

TABLE 2 lists all the geometry parameters of PTC:

TABLE 2. Geometry parameters of PTC

Component	Size(inner dia. ×length)/mm	Matrix
Aftercooler	15.0×10	#80 Copper Screen
Regenerator	14.859×37	#635 SSS
HX@Cold End	9.0×12	#80 Copper Screen
Pulse Tube	9.017×32	-
HX@Hot End	9.0×8	#80 Copper Screen
Inertance Tube 1	1.4×340[phase shift: 37.8º]	-
Inertance Tube 2	1.8×740[phase shift: 53.3º]	-
Inertance Tube 3	2.0×950[phase shift: 59.8º]	-
Reservoir	50cc	

CONSTRUCTION

In this work, an in-line configuration was chosen for better performance of the PTC. The total system is shown in FIGURE 7. All the components were designed to attach to each other by flange connections, so that any component can be exchanged easily.

A rhodium-iron resistance thermometer was installed in the cold end HX, and 5m constantan wire was winded around the outside of the cold end HX for supplying heat load. Two pressure sensors were mounted at the inlet of the aftercooler and the interface of the inertance tube respectively.

EXPERIMENTS

Cooling capacity testing

During the determination of the cooling capacity with different inertance tubes the pressure ratio at the inlet of the aftercooler (Pr1) was fixed via electrical input of the linear compressor. It was not easy to test the pressure ratio at the cold end directly, so the pressure ratio value at the interface of the inertance tube (Pr2) was measured to make an approximation.

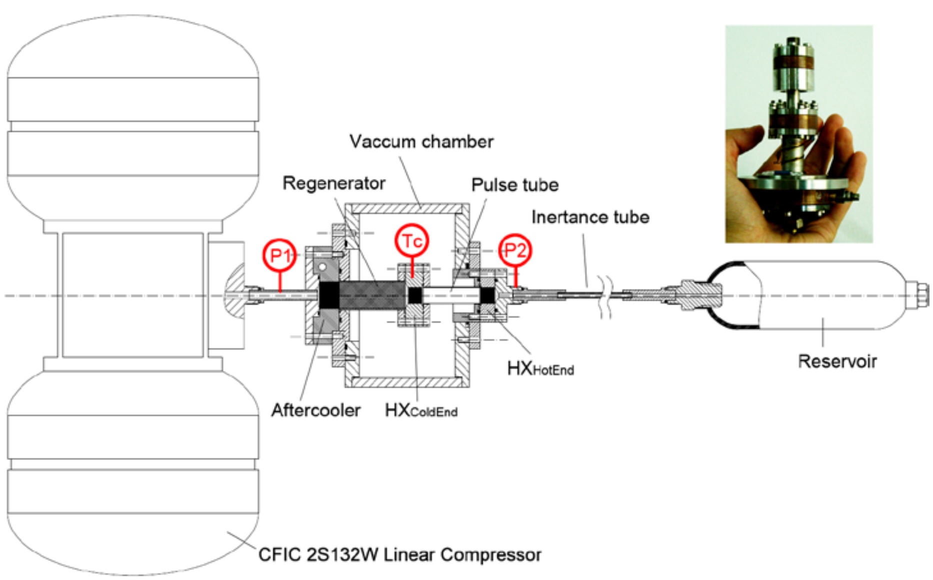

FIGURE 7. 120Hz PTC system sketch

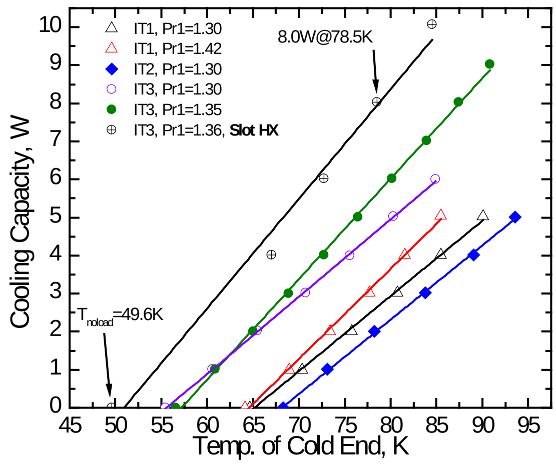

FIGURE 8. Cooling capacity vs. cold temperature

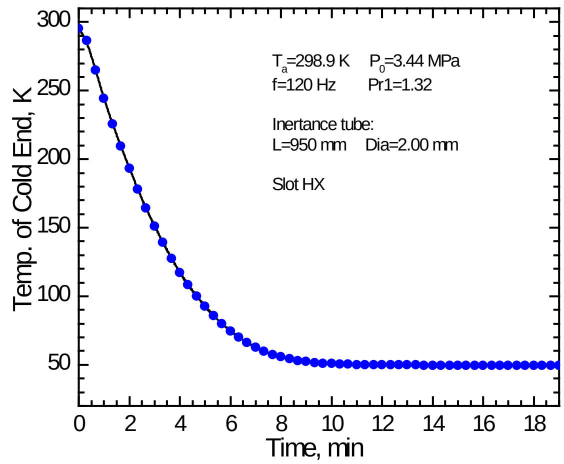

FIGURE 9. Cooling down curve

Shown as FIGURE 8, IT1 and IT2, which provided phases of 0º and -30º at the cold end respectively, result in small cooling capacities. When the inertance tube became bigger and longer, such as IT3 which can offer a phase of about -40º at the cold end of regenerator, the PTC's performance were much better. Large pressure loss were led by copper screens filled HXs at the cold end and the aftercooler with such a high frequency, which results a lower pressure ratio at the cold end than the value predicted in REGEN calculations. In order to decrease the pressure loss and further improve the performance of PTC, slot HXs had been installed instead of copper screen filled aftercooler and HX at the cold end. With the IT3, the performance of the PTC was improved notably. With such modification, a cooling power of 8.0W at 78.5K and a no-load temperature of 49.6K were achieved.

Rapid cooling down

A rapid cooling down capability of the PTC is illustrated in FIGURE 9. It took about 5.7mins to cool down to 79.8K and 15mins to 49.6K.

DISCUSSION

Effect of pulse tube orientation

It is well known that there is an effect of pulse tube orientation with respect to direction of gravity on the performance of PTC [12]. This effect is remarkable in G-M type PTCs whose operating frequencies are generally lower than 10Hz [12-13]. It is also found in Stirling-type PTCs, but less pronounced than that in G-M type PTCs [14-15]. To investigate orientation effect, we also tested the performance of the 120Hz PTC with the cold head in horizontal and cold-end-up orientations. The results are listed in TABLE 3. It is shown that there is almost no effect of pulse tube orientation on the performance of PTC due to the high frequency and small dimension of pulse tube [14]. That indicates that, by using high frequency, PTCs can be more practical for some special situations where the cryocooler systems may be reversed or required to operate in a hypergravity states. More detailed experiments will be carried out very soon.

TABLE 3. Pulse tube orientation testing results

Pulse tube orientation	Cold-end-down	Horizontal	Cold-end-up
Tc with no cooling power, K	49.6	50.7	50.0
Tc with 8.55W, K	79.6	79.0	78.7

Proposal of copper velvet as regenerator matrix for high frequency operation

Copper velvet, a material like cotton wool, composed of random copper wire, was first used as regenerator matrix in Stirling Cryocoolers in 1950s. Thanks to the excellent ductibility, it is easy to make copper into thin wire down to a diameter of 13μm. However, as regenerator material, copper velvet is not widely used in cryocoolers due to its inherent disadvantages, such as high porosity (0.7-0.8) and large axial heat conduction. FIGURE 10 shows electron-microscope images of typical copper velvet and #635 mesh SSS. In high-frequency situations, the pressure loss through matrix will be more dominant because of comparatively large speed and high density of the working gas. Large pressure loss leads low pressure ratio at the cold end of the regenerator, which greatly decreases the cooling capacity of cryocoolers.

Annealed copper velvet, which is very soft, can be filled into regenerator with varied porosity from 0.6-0.8. If keep the hydraulic diameter as same as SSS #635 mesh, the porosity of copper velvet is about 0.67, which is higher than that of SSS #635 mesh. Relatively high porosity will reduce the pressure loss in the regenerator. On the other hand, if keep the porosity as same as SSS #635 mesh, the hydraulic diameter is about 22.6μm, which intersects the curve of helium thermal penetration at 36.1K, lower than that of SSS #635 mesh, in conditions of 120Hz and 3.5MPa. According FIGURE 11 and 12, copper velvet delivers a good heat exchange between matrix and helium below 300Hz. In this paper, the regenerator is designed on the basis of SSS matrix, but later a copper velvet matrix will be tested as well.

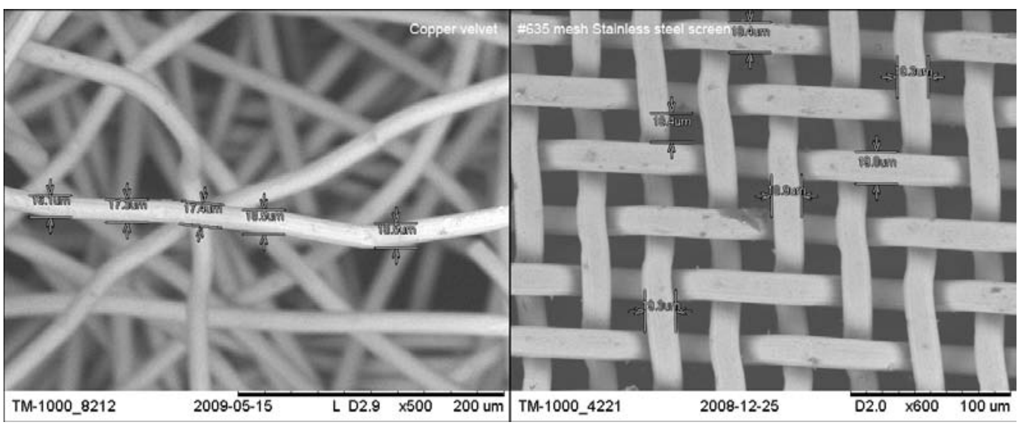

FIGURE 10. Electron-microscope images of typical copper velvet and #635 mesh SSS

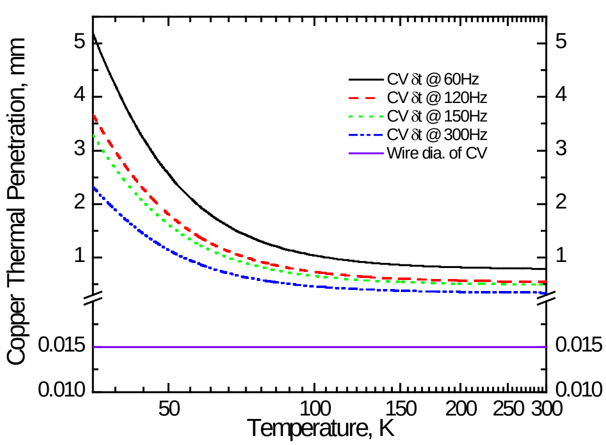

FIGURE 11. Thermal penetration depth of copper at different frequency and wire dia. of typical copper velvet

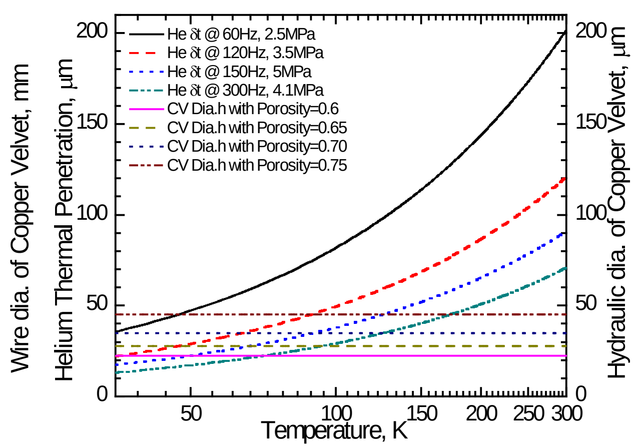

FIGURE 12. Thermal penetration depth of helium at different frequency and hydraulic dia. of typical copper velvet with varied porosity

CONCLUSION

A single stage, Stirling-type pulse tube cryocooler operating at 120Hz with a target cooling capacity of 10W at 80K, was designed, fabricated and tested in Zhejiang University, and a 8.0W of lift at 78.5K as well as a rapid cooling down to 79.8K in 5.7mins was achieved. Experimental results also showed that the performance of the PTC is independent of the pulse tube orientation at high frequency of 120Hz. And copper velvet was proposed as regenerator matrix for high frequency operation.

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