Gravity Effect in High Frequency Coaxial Pulse Tube Cryocoolers

X.F. Hou[1,2], L.W. Yang[1], J.H.Cai[1], and J.T. Liang[1]

[1]Technical Institute of Physics and Chemistry, CAS
Beijing 100080 China

[2]Graduate University of Chinese Academy of Sciences,
Beijing 100039 China

ABSTRACT

In this paper, the gravity effect at various inclination angles in high-frequency pulse tube cryocoolers is investigated. The cooler can reach a no-load temperature of 42 K and has a cooling capacity of 6 W at 80 K with 150 W of input power. The corresponding coefficient of performance (COP) is about 4% at 80 K. Tests show that increasing input power and increasing the length-to-diameter ratio of pulse tube can reduce the gravity effect. Frequency and charge pressure can also have an impact on the gravity effect and it is different when the inclination angle is greater than 90^{0}, or less than 90^{0}. The influence of heat load at the cold end of the PTC is also discussed in the paper.

INTRODUCTION

Pulse tube cryocoolers (PTC) has no cold moving part, and have many advantages, such as structural simplicity, high reliability, and low cost. Because there is a large end-to-end temperature gradient inside the empty pulse tube, there exists the convective heat loss due to the gravity field. The cooling performance of a PTC may change drastically when the angle between pulse tube axis and gravity vector is inclined from 0° to 180°, where angle 0° is defined as cold end downward.

The gravity effect at various inclination angles in Gifford-McMahon (G-M) type PTC has been systematically studied. [1,2] Some approaches for reducing the effect involve introducing an internal structure in the pulse tube [3], modifying the pulse tube shape [4] or introducing an additional DC flow by a second orifice valve [6], but these approaches seriously degrade the cooling performance.

Smoke-wire flow visualization techniques and computational fluid dynamic (CFD) simulations have been carried out to investigate the mechanism of the gravity effect inside G-M type pulse tube cryocoolers.[5, 6, 13, 15] No theory is available to explain the gravity effect mechanism in PTCs, in detail.

The classic Oxford-type linear compressor driven high-frequency PTC is thought to be free of any strong gravity effect with inclination angle. However, many experiments [7~14] show that there is a considerable gravity effect on the inclination angle in high-frequency PTC. The frequency and input power are in the range of 40~57 Hz and 2.0~3.5 kW, respectively.

In this paper, detailed tests have been carried out to study the gravity effect on the high-frequency PTC. These high-frequency coaxial PTC are designed and manufactured by Technical Institute of Physics and Chemistry/Chinese Academy of Sciences (TIPC/CAS). Experiments show that the changes in the

Cryocoolers 14, edited by S.D. Miller and R.G. Ross, Jr.

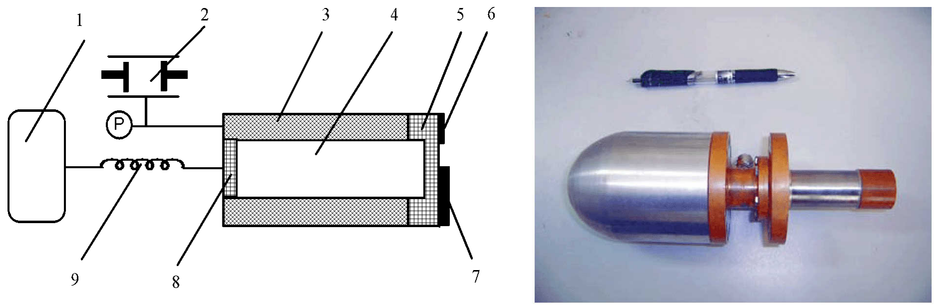

Figure 1. Schematic diagram of the PTC and prototype of the cooler. 1 - reservoir, 2 - compressor, 3 - regenerator, 4 - pulse tube, 5 - cold heat exchanger, 6 - thermometer, 7 - heat resistance, 8 - hot heat exchanger, 9 - inertance tube.

frequency, the charge pressure, the input power, and the length-to-diameter ratio of pulse tube can influence the gravity effect. Detailed results are presented in this paper.

DESCRIPTION OF EXPERIMENTAL SYSTEM

A schematic diagram of the cooler with a pressure wave generator is shown in Fig. 1. The cooler utilizes a coaxial configuration with an inertance tube to provide a phase shift at the warm end of pulse tube. The pressure wave generator is a dual-piston linear compressor which is developed by TIPC/CAS. The regenerator matrix consists of 400# stainless steel wire mesh. The heat exchangers, connected to the hot and cold ends of regenerator, consist of cooper cylinders with thin axial channels which provide for heat exchange and flow straightening. The inertance tube is wrapped inside the reservoir and the reservoir is fixed to the hot end flange. A prototype of the PTC is shown in Fig. 1. Figure 2 shows the test facilities which provide operating at various inclination angles. The cold finger is contained inside a vacuum chamber.

In order to facilitate the measurements of the cooler performance at various inclination angles, the cooler is connected to the compressor by an active nut. The compressor is fixed and the cooler is rotated with the active nut, and the performance of PTC at various inclination angles is measured. The angle made by the gravity vector and cold finger axis is measured with a protractor.

EXPERIMENTAL RESULTS AND DISCUSSION

The best performance of the PTC is achieved in the vertical position with the cold end downward ($\theta = 0^0$), in theory, gravity has no negative effect on the performance at this position. The effects of the input

Figure 2. PTC test facility, it allows the operation of various inclination angles.

Table 1. Prototype of cryocooler

Disposal	Coaxial
Compressor	Dual-piston, moving coil
Shape	Split-typed
Frequency	45Hz
Charge pressure	3.1MPa Helium
Cooling	Wind cooling

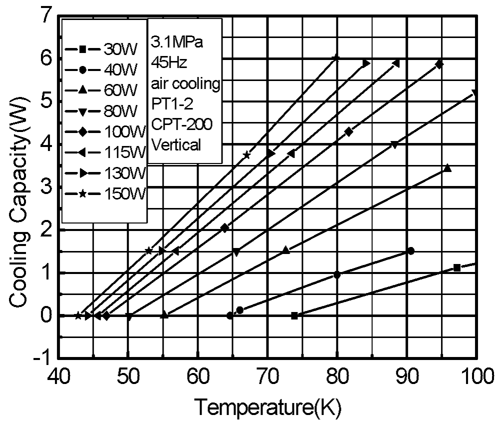

Figure 3. Cooling performance of a PTC at vertical mode

power (50~150 W), the frequency (30~50 Hz), and the charge pressure (1.8~3.5 MPa) at different inclination angles are investigated.

Cooler Performance

Figure 3 shows the change of refrigeration temperature vs. cooling capacity for input powers of 30 W to 150 W using a CPT200 linear compressor. The data is obtained when the cold finger is in a vertical position. Table 1 shows the characteristics of the cryocooler used in these experiments. At this time, the cooler can reach a minimum no-load temperature and obtain the highest cooling capacity. With 150 W of input power, the cooler can reach a no-load temperature of 42 K and a cooling capacity of 6 W at 80 K. The corresponding coefficient of performance (COP) is 4% at 80 K.

Characteristics of PTC with Inclination Angle

Figure 4 shows the dependence of the no-load temperature on inclination angle. The input power is set at three power level: 50 W, 100 W and 150 W with the compressor frequency of 44 Hz. With 150 W

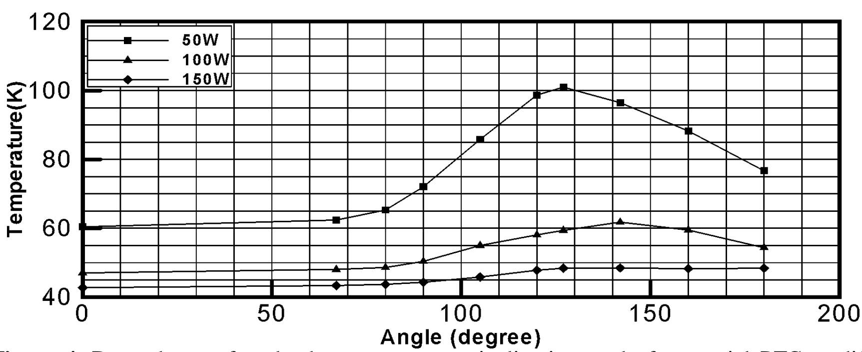

Figure 4. Dependence of no-load temperature on inclination angle for coaxial PTC at different compressor input power.

power input, the compressor's maximum stroke is almost reached. The result indicates that there is a significant increase in temperature when the inclination angle is greater than 90°. The cold end temperature changes less significantly with increased input power.

As we know, there are two types of convective movement in a PTC, one is natural convection, and the other is forced convection. The natural convection is determined by a buoyancy force caused by a temperature difference between the hot and the cold end. The forced convection is determined by the pressure wave amplitude. With small input power, the ratio of natural convection to force convection is larger, and the influence of natural convection is more evident. With high input power, the influence of natural convection is weakened.

Influence of Frequency and Charge Pressure

Kasthurirengan[2] studied the gravity effect influenced by frequency and charge pressure in a Gifford-McMahon (G-M) type PTC. Here, the gravity effect of frequency and charge pressure are carried out in the high-frequency PTC.

Figure 5 shows the cold end temperature change as a function of frequency at various inclination angles. When the inclination angle is less than 90^0, the cold end temperature reaches a minimum at a specific frequency and the gravity effect is very small. When the inclination angle is greater than 90^0, the cold end temperature increases dramatically with frequency.

Figure 6 shows the lowest cold end temperature at various inclination angles as a function of charge pressure. In the experiments, the inclination angles include 45^0, 70^0, 110^0, 120^0, and 135^0. Similar to frequency, the lowest cold end temperature reaches a minimum at a specific charge pressure and the gravity effect is very small when the inclination angle is less than 90^0. The cold end temperature changes dramatically and increases with charge pressure when the inclination angle is greater than 90^0. At the same time, the gravity effect increases with charge pressure.

Influence of Length-to-Diameter Ratio and Heat Load

Until now, there has been no effective method to reduce the gravity effect in PTC, although the gravity effect decreases with increasing input power. In general, using a small diameter pulse tube can reduce the convective heat loss and reduce the gravity effect. The temperature difference between 0^0 and 90^0 for three different length-to-diameter ratios of the pulse tube is compared in Fig. 7. Tests show that either increasing the length-to-diameter ratio of the pulse tube, or increasing the input power can reduce the gravity effect in the pulse tube.

In the test the length-to-diameter ratio of model 1 is the largest value, model 2 is the modest value, and model 3 is the smallest value. With the same input power, decreasing the diameter of the pulse tube can decrease the temperature difference and the gravity effect is weakened. The input power also influences the temperature difference greatly. The temperature difference is very large with a small input power. When

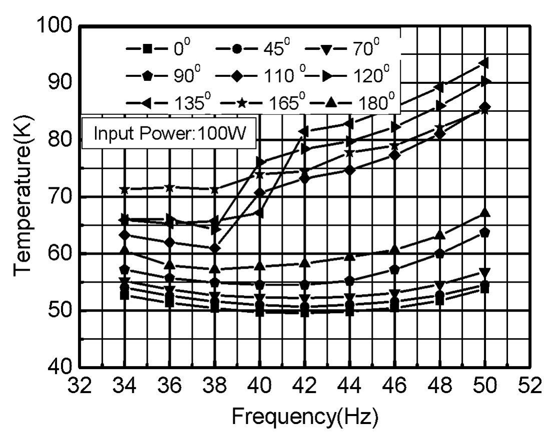

Figure 5. Effect of frequency on the no load temperature at various inclination angles.

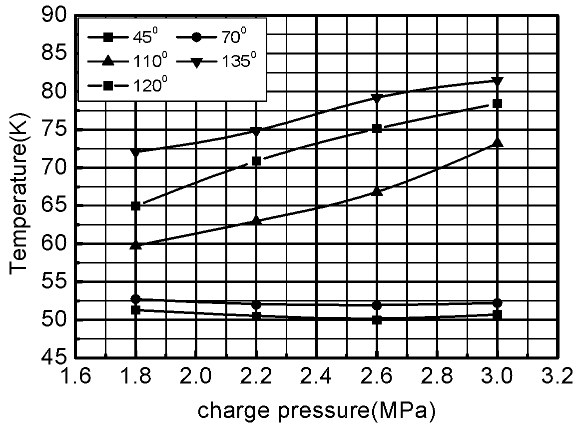

Figure 6. Effect of charge pressure on the no load temperature at various inclination angles

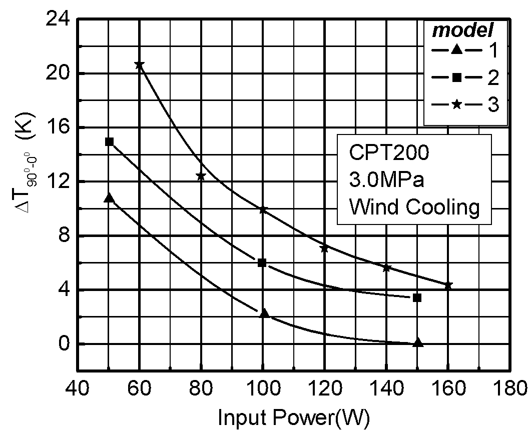

Figure 7. Temperature difference between 0^0 and 90^0 as a function of input power with different length-to-diameter ratio of pulse tube in PTC. (L/D (1) > L/D (2) > L/D (3))

the input power increases, the temperature difference is reduced. In the model 1, the temperature difference is almost absent when the input power is 150 W. In the other PTC, the temperature difference also exists with an input power of 160 W.

When we change the heat load at the cold end of the PTC, the gravity effect in the pulse tube will also change. In the test, the Leybold Polar SC7 linear compressor is used.

Figure 8 shows the temperature difference between 0^0 and 90^0 as a function of input power at different heat loads. The temperature difference decreases with the input power at the same heat load. Comparing the curves showing the temperature difference as a function of the input power, we find that the temperature difference decreases with increasing heat load when the input power is larger than 100 W. Otherwise, the temperature difference can't be changed by heat load. Changing the heat load of the pulse tube changes the temperature difference between the cold and hot end of pulse tube. In natural heat loss, reducing the temperature difference will decrease the natural convective heat loss.

CONCLUSIONS

The gravity effect at various inclination angles of high-frequency PTC is investigated. The highest efficiency PTC is obtained when the gravity effect is almost absent. With 150 W of input power, the cooler can reach a no-load temperature of 42 K and a cooling capacity of 6 W at 80 K. The gravity effect is systematically studied by changing the inclination angle and other factors in the PTC.

The gravity effect is different when the inclination angle is greater than 90^0 or less than 90^0. When the inclination angle is less than 90^0, the gravity effect is small. When the inclination angle is greater than 90^0, the

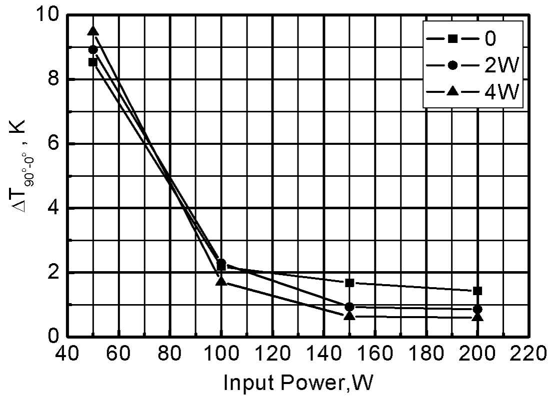

Figure 8. Temperature difference between 0° and 90° as a function of input power at different heat load.

gravity effect is very strong, and maximum gravity effect is obtained when the inclination angle is about 135°. Increasing the input power can reduce this effect, but the cooler's performance is strongly degraded. Increasing the length-to-diameter ratio of the pulse tube can also reduce this effect. Increasing frequency and charge pressure could increase the effect oppositely.

ACKNOWLEDGMENT

The work is supported by the Natural Science Foundation of China with project number: 50206025.

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