The effect of supercritical helium natural convection on the temperature stability in a cryogenic system

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Abstract: With high specific heat and density, supercritical helium can be used to reduce the temperature oscillation and improve temperature stability in the low temperature conditions. However, the natural convection of the supercritical helium has a complex influence on the suppression of the temperature oscillation. In this paper, a transient three-dimensional numerical simulation is carried out for the natural convection in the cylinder to analyze the effect of natural convection on transferring of temperature oscillation. According to the results of numerical calculation, a cryogenic system cooled by GM cryocooler is designed to study the influence of natural convection of supercritical helium on temperature oscillation suppression.

1. Introduction

In recent years, with the rapid development of small-scale cryocooler technology, especially GM cryocooler and pulse cryocooler, the cooling capacity and performance of which have been made great progress, and the cryostat using small-scale cryocooler also has been widely used in the measurement of thermo-physical properties and mechanical properties at low temperatures, cooling of small superconducting magnets, infrared remote sensing and superconducting electronics etc. [1]. Compared with the cryostat using cryogen, cryostat with GM cryocooler is simpler and easier to operate, and there is no additional cost of the cryogen [2], which is also dangerous. However, a GM cryocooler will cause greater mechanical vibration and temperature oscillation due to the thermal cycle in the cryocooler. It is unacceptable for precise experimental studies such as the measurement of the Sabbeck and Nernst coefficients at low temperatures.

Temperature oscillation of a GM cryocooler is cyclical, and the range is about 0.1K which to a certain extent limits the application. Only if the oscillation is reduced can it be used in high-tech areas. In the 4-20K temperature range, supercritical helium is preferred to reduce temperature oscillation for two reasons [3]: (1) the specific heat capacity of supercritical helium at low temperature is very large, even larger than most of the metals; (2) compared with metals, density of supercritical helium is smaller, it can effectively reduce weight of the cold head on the cryocooler, thereby reducing deformation.

In this paper, the effect of natural convection in different helium cylinders is studied. Temperature difference of the cylinder forced the helium to form a natural convection in the cylinder. Since the viscosity coefficient and the thermal diffusivity of the supercritical helium at low temperatures are very small, the Ra number can be large to 1010 even if when the temperature difference of the helium cylinder is 0.1 K, resulting in a very strong turbulent natural convection. When using a GM cryocooler, the temperature oscillation and the natural convection of turbulence are both a periodic dynamic process. It is important to study the natural convection, which can reveal how it helps to suppress the temperature oscillation, so as to design a helium vessel structure to improve temperature stability in the low temperature conditions.

2. Simulation of the Effect of Natural Convection on Temperature Oscillation

Figure 1 is an empty helium cylinder, and figure 2 is a helium cylinder with copper rods inside, which helps strengthen the heat transfer. According to the working conditions of GM cryocooler, it is assumed that the temperature of the upper wall of the helium cylinder changes as sine wave, and the lower wall is heated by a constant heating power to form a temperature different between the upper and lower wall of the cylinder.

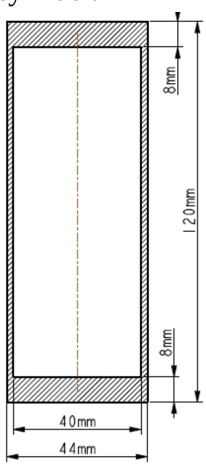


Figure 1. Empty helium cylinder

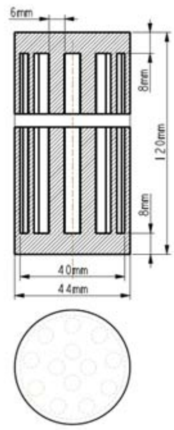


Figure 2. Cylinder with copper rods

2.1. Modeling

The numerical calculation is carried out by Fluent software. The finite volume method is used for the control equations discretization. The SIMPLEC algorithm is used to solve the problem of velocity-pressure coupling. Convective term is discrete by high precision QUICK scheme. The diffusion term uses a central difference with second order accuracy. The algebraic equations obtained after discrete are solved by iterative method. Non-uniform mesh is adopted, and the meshes are intensified at the boundaries due to larger temperature and velocity gradients near the wall.

2.2 . Calculating

*2.2.1. Empty cylinder.*The upper wall temperature is assumed as $T_c = 5.6 + 0.2sin(2\pi t)$, and a constant heating power of 0.8W is given on the lower wall. Cylinder material is stainless steel. The calculated result (peak-peak value) is shown in the figure 3. It can be seen that the temperature oscillation reaches 464.64mK on the lower wall with no sinusoidal, which is even beyond the temperature oscillation of the upper wall. In order to analyze the effect of supercritical helium natural convection on the temperature oscillation, the result of FFT transformation is shown in the figure 4. It is shown that the temperature oscillation of the lower wall does not conform to the sinusoidal distribution, which maybe mainly determined by the low frequency oscillation due to the natural convection of the supercritical helium.

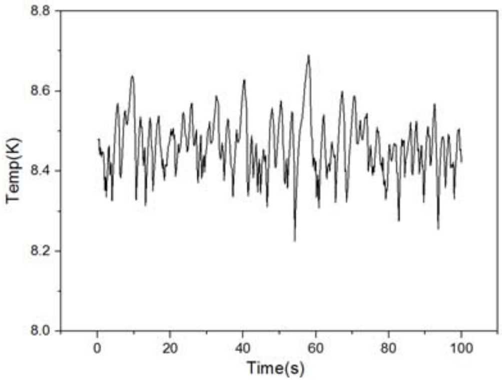


Figure 3. Temperature of the lower wall

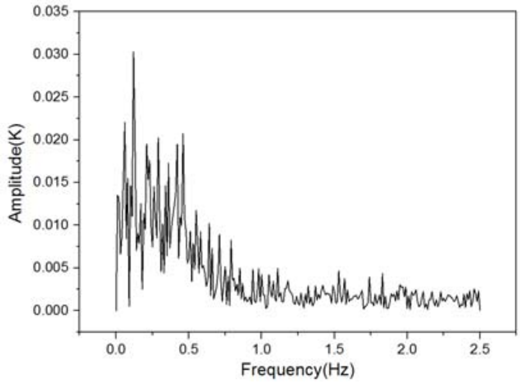


Figure 4. Temperature FFT transform result

The Ra number of natural convection is about 1.4x10^{12} when the helium pressure is 0.25MPa and the lower wall temperature is 8.5 K. Figure 5 shows the flow field distribution on the central cross section of the helium cylinder at different times. It can be seen that the flow field distribution of natural convection is very complicated and the complex vortex is formed at the center and the wall of the cylinder. There is no obvious periodicity within 1s. The natural convection of helium is in a turbulent state and shows no obvious two-dimensional properties.

(a) 50s (b) 50.5s (c) 51s

Figure 5. Flow field distribution at different times

If cylinder material is replaced by copper, the peak-peak value of the temperature oscillation of the lower wall is reduced to 158.23mK, which is smaller than the upper wall. The calculated result (peak-peak value) is shown in the figure 6. Result of FFT transformation is shown in the figure 7. The temperature oscillation at 1 Hz is transferred to the lower wall, with only slight oscillation at lower frequency. The temperature oscillation of the lower wall is mainly determined by the sine wave at the upper wall. This is because the thermal conductivity of stainless steel is low, heat is mainly transferred by the natural convection of helium. While the thermal conductivity of copper is larger, the heat transfer in the copper cylinder mainly depends on the heat conduction of the wall. However, natural convection of supercritical helium plays an important role in suppressing the temperature oscillation.

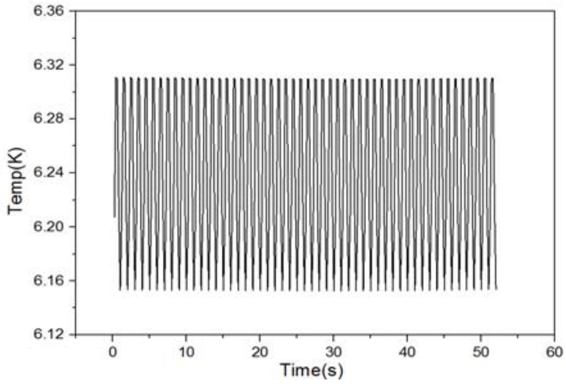


Figure 6. Temperature of the lower wall

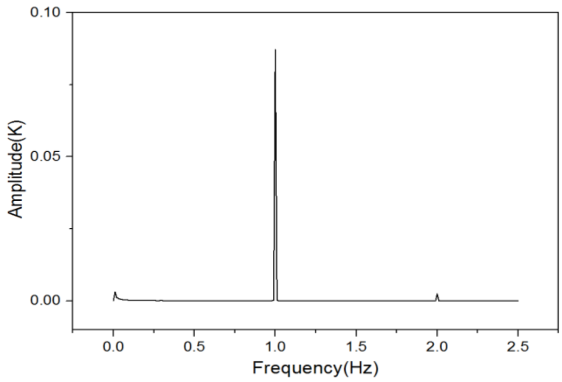


Figure 7. Temperature FFT transform result

2.2.2 Cylinder with copper rod. If the cylinder is filled with copper rods inside, boundary conditions are exactly the same with the empty cylinder. Temperature of the lower wall changes with time as shown in figure 8. The peak-peak value of the temperature oscillation on the lower wall is reduced to 149.27mK. The results of the FFT transformation temperature are shown in figure 9. The temperature oscillation of the lower wall contains both low frequency and 1 Hz oscillation. Temperature oscillation of the lower wall is determined both by the temperature oscillation of the upper wall and the low frequency oscillation caused by supercritical helium natural convection.

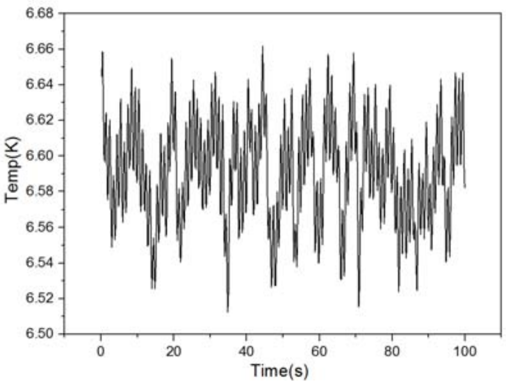


Figure 8. Temperature of the lower wall

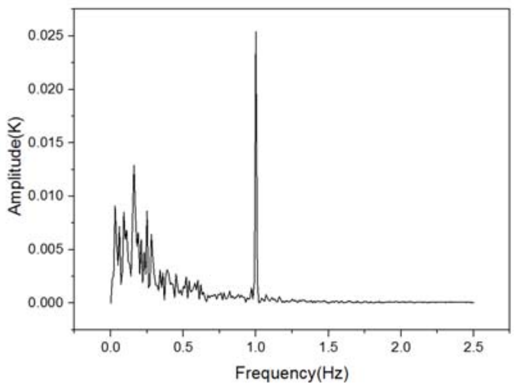
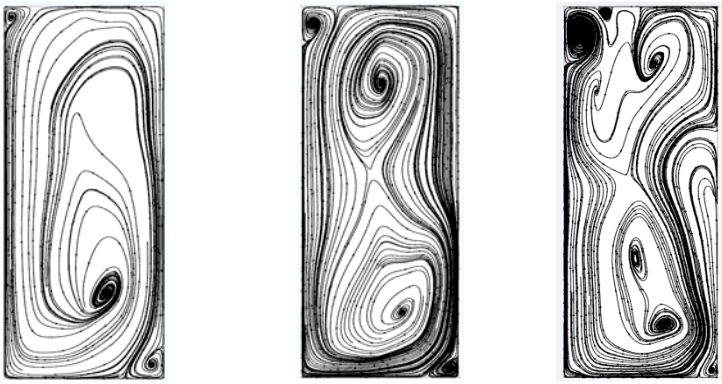


Figure 9. Temperature FFT transform result

Figure 10 shows the flow field distribution of the helium cylinder at a central point at different times. When the pressure is 0.25MPa and the lower wall temperature is 6.59K, the Ra number of natural convection is about 2.2×10^{12}. It can be seen that the flow field distribution is also complicated, but more regular. This is significantly different from the flow field in figure 5. It can be concluded that the internal insertion of copper rods helps to form a more stable flow field. Steady flow field is more conducive to the formation of an opposite trend with the low frequency oscillation, thereby improving the temperature stability of the lower wall.



(a) 50s (b) 50.5s (c) 51s

Figure 10. Flow field distribution at different times

2.3 Conclusion of the simulation

In the numerical simulation of cylinders with different material and structures, it can be concluded that the temperature oscillation at the bottom of the stainless steel cylinder is mainly determined by the low frequency oscillation caused by natural convection. The temperature oscillation at the bottom of the copper cylinder is mainly determined by the upper wall temperature. The temperature oscillation with copper rod inside is determined both by the low frequency oscillation and the upper wall temperature. With the same temperature oscillation of the upper wall, and the same heating power on the lower wall, cylinder with copper rods inside is the most effective to improve the temperature stability of the lower wall. Therefore, the cylinder with high thermal conductivity filled with helium can effectively suppress temperature oscillation, improving the temperature stability of a cryogenic system.

3. Experiment and results

Because of the error in numerical calculation, especially the turbulence natural convection with large Ra number, the upper wall temperature is also not strictly follow the sine wave, it is difficult to predict the convection accurately and necessary to build an experimental system.

3.1. Experimental system

A cryogenic system with GM cryocooler was established. The experimental system is mainly composed of cryostat system, temperature measurement and control system, helium cylinder pressure measurement and control system and data acquisition system.

3.1.1. Cryostat. The cryostat composed of a G-M cryocooler, a cryostat cylinder, heat exchanger, radiation protection screens, helium cylinder and testing sample. A two-stage G-M cryocooler (model NO. RDK-415D) manufactured by Sumitomo Company is applied as the cold resource. Cooling capacity of the G-M cryocooler is 35W@50 K on the first stage and 1.5W@4.2 K on the second stage. Heaters are used on the second stage of the GM cryocooler and the testing sample to control the temperature precisely.

3.1.2. Temperature measurement and control system. CERNOX thermometer manufactured by Lakeshore Co., Ltd., which has a thermal response time of 4.2ms at 4.2K [4], meets the requirements for temperature stabilities measurement on cold heads and samples. Lakeshore's germanium resistance thermometer is applied for accurate temperature measurement on the sample. Both of the thermometers are calibrated by Lakeshore. Since The CERNOX thermometer and the Ge resistance thermometer are not calibrated for the entire temperature zone, rhodium iron thermometer produced by TIPC, CAS is used as an entire temperature zone thermometer, and by their given calibration data. All thermometers were measured by four-wire system. Lakeshore's 340 temperature controller is adopted for data acquisition with a frequency of 5 Hz. Nickel-chromium alloy wire is used as the heating resistor. Temperature control is achieved by Lakeshore 340 which can both manage manual and PID control function.

3.1.3. Pressure measurement and control system. Inflator system of the helium cylinder is composed of a 40 L high purity helium cylinder, Fluke 7250i pressure controller connecting helium cylinders and helium cylinders, buffer tanks, pressure transmitter, vacuum pump and helium cylinder in the cryostat.

*3.1.4. Data acquisition system.*NI PXI-1042 system is used for data acquisition. 340 temperature controller, Fluke 1594A thermometer and the computer are connected by GPIB interface bus, the communication is 8-bit parallel digital interface, and transfer rate can be up to 8 MB /s. The pressure transmitter is connected to the computer using an RS232 serial cable, which is suitable for data transmission in the range of 0-20000 b/s. Acquisition program is programmed by LABView, the data acquisition program can simultaneously capture and record two channels of four thermometer data, and control the 340 temperature controller remotely. Figure 11 shows the schematic diagram of the cryogenic system. Figure 12 shows the picture of cryostat with a GM cryocooler.

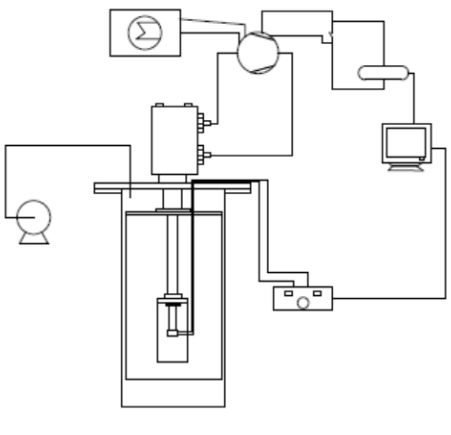


Figure 11. Schematic diagram of cryogenic system

Figure 12. Cryostat with a GM cryocooler

3.2. Analysis of experimental process and results

Seven thermometers are applied in the cryogenic system for accurate temperature measurement. Two (one rhodium iron thermometer and CERNOX thermometer)are arranged on the second stage of the cryocooler, with calibration range of 1.4-300K. Two (one rhodium iron thermometer and CERNOX thermometer) are arranged on the bottom of the helium cylinder. Two CERNOX thermometers are arranged on the upper wall of the sample and the Ge resistance thermometer is arranged in the hole of the lower wall of the sample. Cryostat assembly is shown as figure 10. Leak detection is performed before the experiment. Once the leakage rate is less than $1x10^{-9}Pa.m^3/s$, it indicates that the system leakage rate is in line with the requirement.

Experimental steps are as follows:

(1) Vacuum system starts until the pressure is below $1x10^{-5}Pa$.

(2) Fill helium into the helium cylinder until the pressure reaches 0.25MPa.

(3) Cryocooler starts until temperature of the second stage reaches 5.6 K. At the same time, keep the helium pressure stabilized at 0.25MPa.

(4) Record temperature of each thermometer.

In the previous chapter, the effect of supercritical helium natural convection on the temperature stability is analyzed by numerical simulation. In the calculation, it is assumed that the temperature on the cold head changes at sine wave. However, in the actual experimental process, the cold head of the temperature oscillation is more complex than the sinusoidal oscillation. Therefore, standard deviation is used to describe the temperature oscillation of the experimental results.

As shown in the figure13 and 14 are the experimental results of the lower wall temperature. Comparing the results with numerical simulation, it can be concluded that the numerical simulation predicts the effect of natural convection on the temperature oscillation transfer, and shows the low frequency motion of the bottom of the helium cylinder, which is mainly determined by the natural convection. The results of the cylinder with copper rods are roughly the same which is in agreement with the experimental results. It can be concluded that the simulation helps to improve the design of the helium cylinder therefore to achieve better temperature stability.

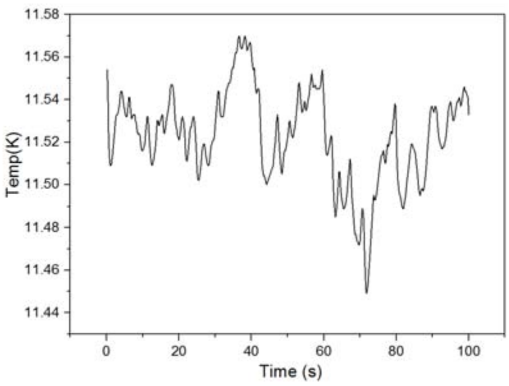


Figure 13. Temperature of the lower wall

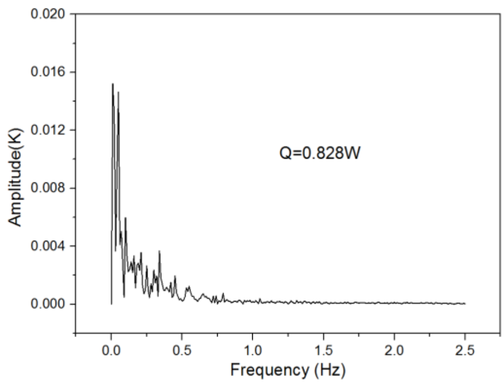


Figure 14. Temperature FFT transform result

3.3 Experimental study on different pressure and heating power

Natural convection effect is generally sensitive to the pressure and heating power on the lower wall. Therefore, working conditions under different helium pressure and heating power are performed on the stainless steel cylinder with copper rods inside to find the rule of oscillation suppression of the supercritical helium. Results are shown in figure 15 and figure 16.

It can be seen that temperature oscillation is irrelevant with heating power under lower heating power. But it goes higher when the heating power increases and reaches a critical point (for example

0.4W@0.5MPa). The helium pressure has an effect on the critical point of the heating power but shows irrelevant on the value of temperature oscillation on the lower wall. That is because when the heating power is lower, temperature oscillation on the upper wall is higher which mainly determines the temperature oscillation on the lower wall. When the heating power rises, heat transfer through the helium cylinder is stronger, which leads to a higher temperature oscillation. Helium pressure is not a significantly factor because the Ra number is not quite relevant with the helium pressure.

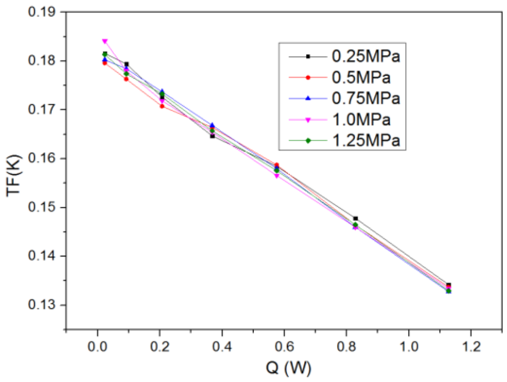


Figure 15. Temperature oscillation on the upper wall

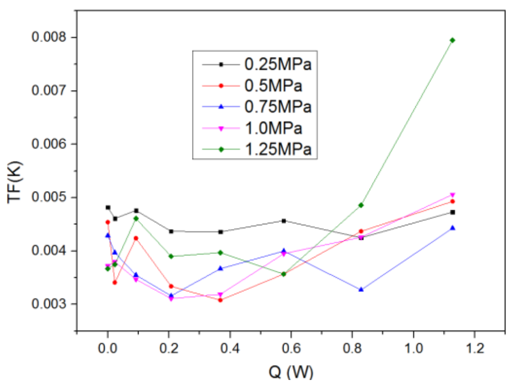


Figure 16. Temperature oscillation on the lower wall

4. Conclusion

Transient three-dimensional numerical simulation is carried out for the natural convection in different structures of cylinder to analyze the effect of natural convection on transferring of temperature. It can be seen from the results that the cylinder with high thermal conductivity filled with helium can effectively suppress the temperature oscillation of the cryocooler. A cryogenic system with GM cryocooler is designed and built. Natural convection effect of helium is researched on the system. According to the experimental results, it can be concluded that temperature oscillation could be suppressed by natural convection of supercritical helium so that cryogenic systems cooled by GM cryocooler can be applied to high precision low temperature measurement.

References

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[4]*Cernox is the trademark of Lake Shore Cryogenics* (Westerville, OH)