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

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Background

With the rapid development of small-scale cryocooler technology, cryogenic system using small-scale cryocooler has been widely used. However, a GM cryocooler will cause mechanical vibration and temperature oscillations. In the 4-20K temperature range, supercritical helium is preferred to reduce temperature oscillation. Since the viscosity coefficient and the thermal diffusivity of helium at low temperatures are very small, the Ra number is very large resulting in a strong turbulent natural convection. It is important to study the natural convection, which can reveal how it helps to suppress the temperature oscillation, so as to design a structure to improve temperature stability.

Objectives

- Study turbulent natural convection of supercritical helium at low temperature.
- Find the oscillation transfer rule through supercritical helium and metal vessels.
- Design a vessel structure of supercritical helium to suppress temperature oscillation and to improve temperature stability at low temperature.

Conclusion

- 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.
- Cylinder with high thermal conductivity filled with helium, can effectively suppress the temperature oscillation of the cryocooler and improve the temperature stability.
- A cryogenic system with GM cryocooler is designed and built. Natural convection effect of helium is researched on the system.
- Experimental results are in agreement with the simulation. It helps to improve the design of the helium cylinder in order to achieve better temperature stability.
- Temperature oscillations 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.

Numerical Simulation

Modeling

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.

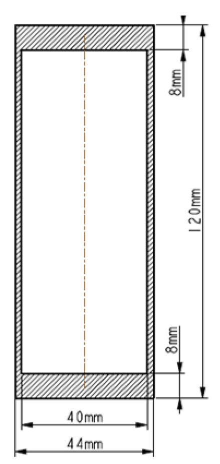

Figure 1.

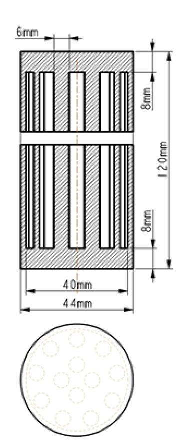

Figure 2.

Empty helium cylinder

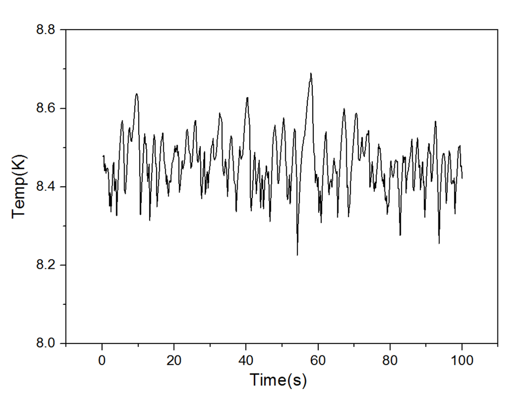

Figure 3. Temperature of the lower wall

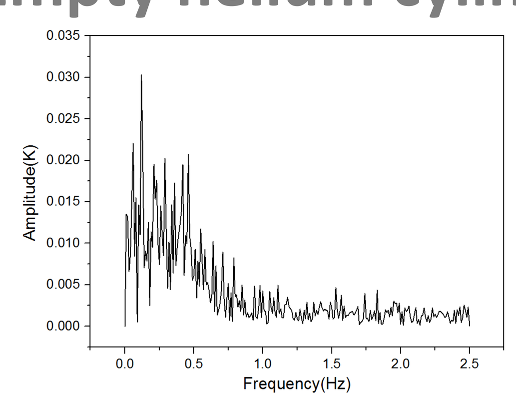

Figure 4. Temperature FFT transform result

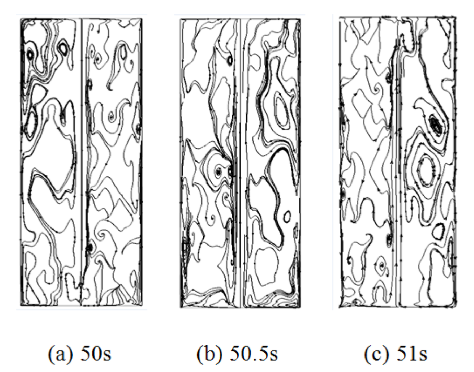

Figure 5. Flow field

The temperature of the lower wall is shown in figure 3, temperature oscillation reaches 464.64mK with no sinusoidal. The result of FFT transformation is shown in figure 4. The temperature shows no periodicity, the oscillation amplitude fluctuates at low frequency, and there is no obvious oscillation at 1 Hz.

Figure 5 shows the flow field distribution on the central cross section of the helium cylinder at different times.

Cylinder with copper rods inside

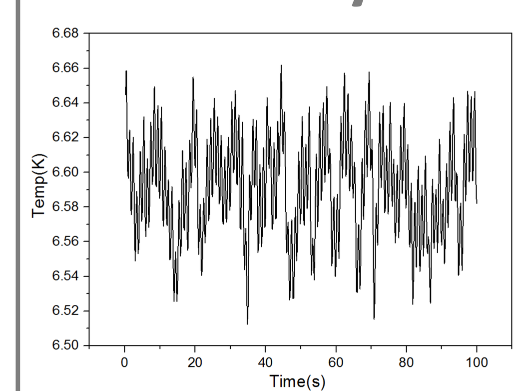

Figure 6. Temperature of the lower wall

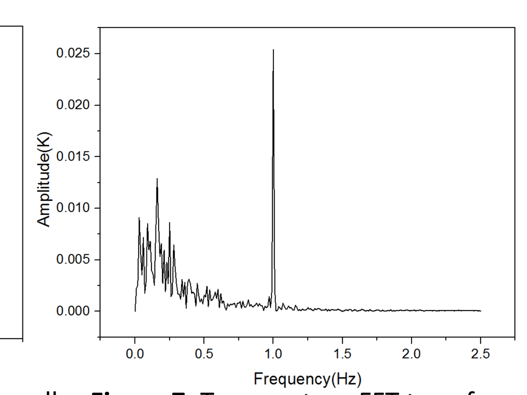

Figure 7. Temperature FFT transform result

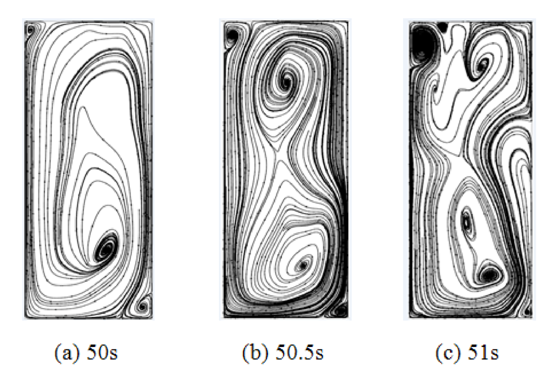

Figure 8. Flow field

Temperature of the lower wall is shown in figure 6 showing the temperature oscillation reduced to 149.27mK. The results of the FFT transformation temperature are shown in figure 7. The temperature oscillation of the lower wall contains both low frequency and 1 Hz oscillation.

The flow field distribution is also complicated, but more regular. The internal insertion of copper rod helps to form a more stable flow field.

Simulation Conclusion

The temperature oscillation at the bottom of the stainless steel cylinder is mainly determined by the low frequency oscillation caused by natural convection. For the copper cylinder, it is mainly determined by the upper wall temperature. For cylinder with copper rod inside, it 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.

Experiment System

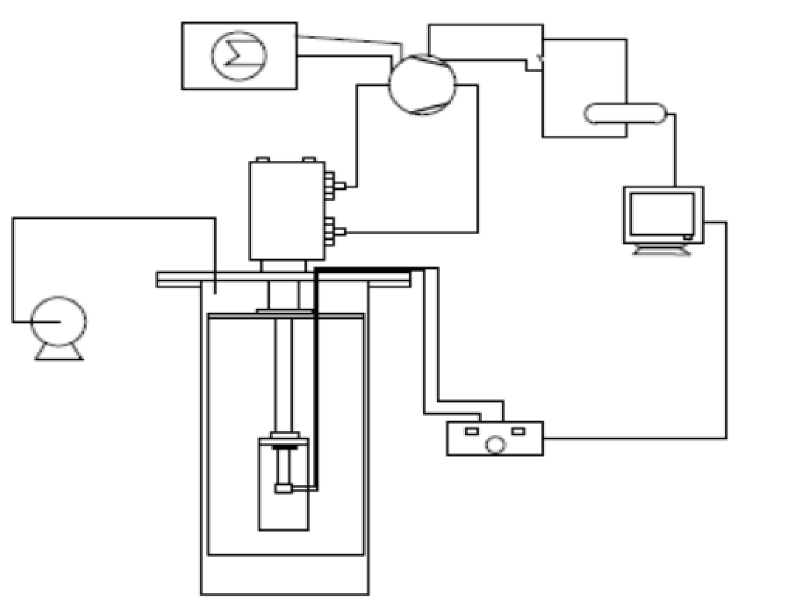

Figure 9. Cryogenic System

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.

Figure 10. 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 manufactured by Sumitomo Company is applied as the cold resource.

- Temperature measurement and control system. CERNOX thermometer, Lakeshore's germanium resistance thermometer, rhodium iron thermometer produced by TIPC, CAS are used in the system. Lakeshore's 340 temperature controller is adopted for data acquisition with a frequency of 5 Hz.
- 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.
- NI PXI-1042 system is used for data acquisition. 340 temperature controller, Fluke 1594A thermometer and the computer are connected by GPIB interface bus. Acquisition program is programmed by LABView.

Experimental process and results

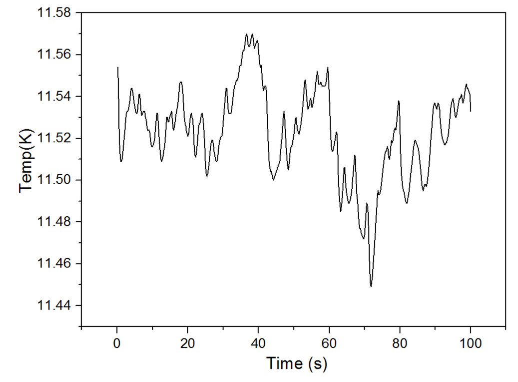

Figure 11. Temperature of the lower wall

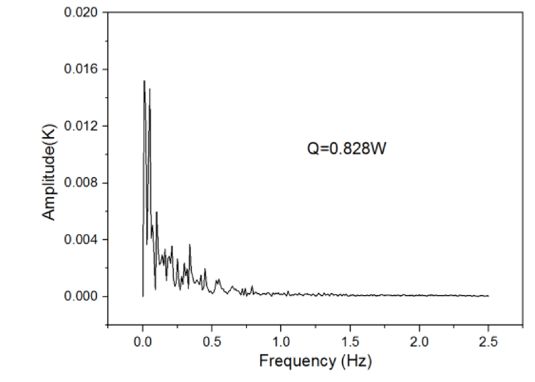

Figure 12. Temperature FFT transform result

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.

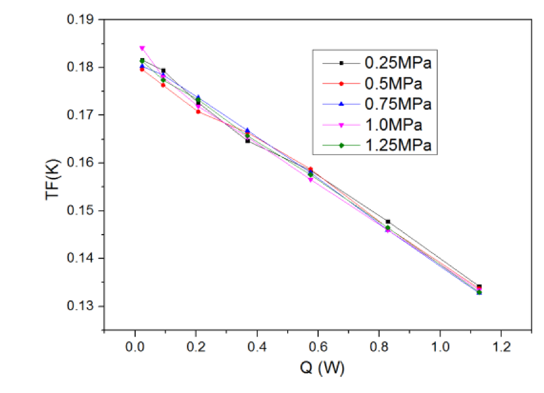

Figure 13. Temperature oscillation on the upper wall

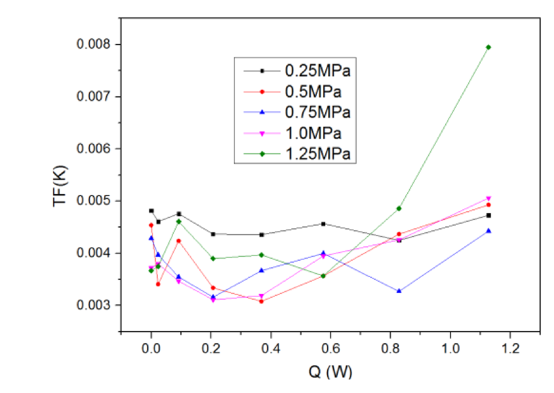

Figure 14. Temperature oscillation on the lower wall

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.

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