A Hybrid Cooling System for HTS Devices

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ABSTRACT

A hybrid cooling system for high temperature superconductor (HTS) devices is a zero-boil-off (ZBO) liquid-nitrogen dewar system. It mainly consists of a pulse tube cryocooler (PTC), a thermosiphon, and a liquid nitrogen dewar. As a hybrid cooling source for HTS devices, it has the advantages of a stable temperature, good system reliability, ease of moving, no required supplemental liquid nitrogen, and freedom of vibration and electromagnetic interference. In this paper, the structural form of a ZBO system was designed with special insulation technology to reduce the dewar heat leak and also to reduce the demand of cryocooler cooling power. Considering the heat leakage and the heat load of HTS devices, a matched PTC was selected. It's a 5W at 80 K PTC developed by the Technical Institute of Physics and Chemistry. A matched cryogenic thermosiphon was also developed; its heat transfer performance was tested earlier. The whole cooling system was tested recently, and the results show that it has achieved the design goals with zero boil-off, and it can provide excellent cooling for small HTS devices.

INTRODUCTION

Without cryogenic cooling technology development, superconducting technology can't come to fruition. Nowadays there are two different cooling solutions for high temperature superconductor (HTS) devices: one is the use of cryogenic liquids, the other is conductive cooling to a mechanical cryocooler. The former has advantages of stable and uniform temperature, but it requires frequent supplying of the cryogen. The later is easy to control and move, but has the disadvantages of vibration and electromagnetic interference. So a hybrid cooling system is considered that mainly consists of a pulse tube cryocooler (PTC), a cryogenic thermosiphon, and a liquid nitrogen dewar.

This hybrid cooling system actually is a liquid-nitrogen zero-boil-off (ZBO) system. The HTS devices are soaked in liquid nitrogen for cooling, and the cryocooler remotely cools the nitrogen by the thermosiphon of 1.2 m length. So there are no evaporative emissions or loss of liquid nitrogen, and the cooling temperature can be maintained for a long time. It is really an appropriate cooling source for special HTS devices.

This paper describes the design, fabrication, and step-by-step testing of this hybrid cooling system, from the cryogenic thermosiphon, to the liquid nitrogen dewar, and, finally, the complete integrated system.

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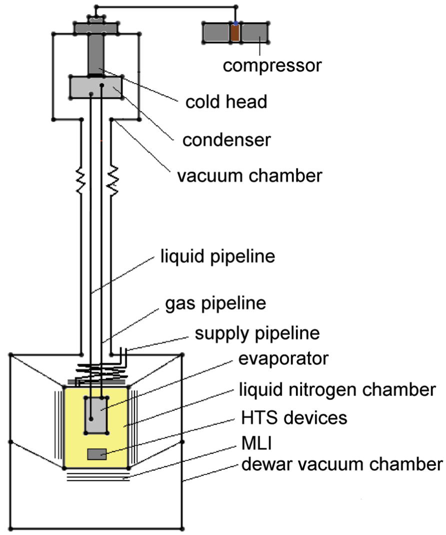

Figure 1. Schematic Diagram of the System

SYSTEM ARCHITECTURE

A schematic diagram of the cooling system is shown in Figure 1. At the top is the PTC composed of a compressor and a pulse tube coldhead. The coldhead of the pulse tube cools the copper condenser of the thermosiphon by conduction. The copper evaporator of the thermosiphon is inserted into the liquid nitrogen chamber to cool or condensate nitrogen with some fins. The evaporator and the condenser are connected by stainless steel liquid pipeline and gas pipeline with an outer diameter of 6 mm, and the working fluid is also nitrogen, which is enclosed and cycles inside. All of these items are sealed in the vacuum chamber. The liquid nitrogen chamber is suspended in a dewar vacuum chamber by Kevlar fiber ropes, and there are two spiral stainless steel pipes across the vacuum chamber to supply liquid nitrogen and discharge the nitrogen vapor.

THERMAL DESIGN

The thermal design is primarily focused on calculating the heat leakage of the cryogenic liquid nitrogen chamber from the room temperature dewar vacuum chamber, designing and developing a matched cryogenic thermosiphon with a suitable heat transfer performance, and choosing a matched PTC with a suitable cooling capacity as the cold source.

There are only three heat leak paths in the dewar: radiation heat transfer between the inner and outer chamber surfaces, and heat conduction through the rope support structure and the two spiral pipes. The heat leakage of the cryogenic chamber is reduced by some new and special designs. The radiation is reduced by covering the walls with multilayer insulation (MLI). The Kevlar ropes have a very small thermal conductivity but a great tensile strength, so they are suitable for cryogenic supports, and their heat conduction is quite low in comparison to other ropes or solid supports. The stainless steel pipes are spiraled to increase the length to reduce heat conduction too.

It would be very complicated to calculate the radiation heat transfer directly with many layers of MLI, so the process was simplified as two coupled series of heat transfer computations: 1) the equivalent heat conduction of the MLI, and 2) the heat radiation between the inner surface of the dewar vacuum chamber and outer surface of the MLI. They were calculated as follows:

$$Q_1 = \lambda A_m (T_m - T_i) / \delta \tag{1}$$

$$Q_2 = \sigma \varepsilon_m A_m (T_o^4 - T_m^4) \tag{2}$$

where, λ is the equivalent thermal conductivity of the MLI, and ε_m is the equivalent emissivity of

Table 1. Heat Transfer Performance of Thermosiphon

Heat Transfer Capacity /W	0.5	1	1.5	2	3	5
Temperature Difference /K	1.75	2.0	2.2	2.4	2.6	2.8
Thermal Resistance K/W	3.5	2.0	1.47	1.2	0.87	0.56

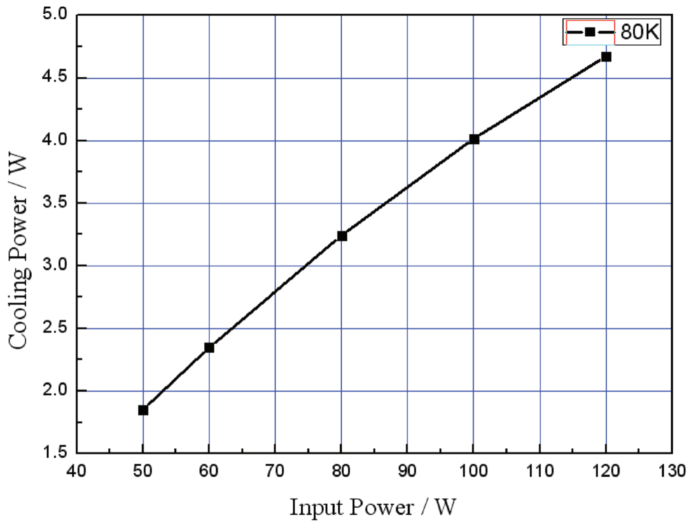

Figure 2. PTC Cooling Performance

the radiation system. T_i, T_m and T_0 are the temperature of liquid nitrogen (77 K), MLI outer surface (unknown), and room temperature (about 295 K), respectively. When the heat transfer reaches a steady state, the radiation heat leakage meets the equation $Q_r = Q_1 = Q_2$. So it can be calculated. The result is that $Q_r = 1.03$ watts (W) and $T_m = 282$ K.

There are twelve Kevlar ropes whose diameter is about 0.3 mm and length 0.1 m each. The temperatures of each end are about 77 K and 295 K, respectively. Their heat conduction can be calculated as follows:

$$Q_k = n\bar{\lambda}A(T_o - T_i)/L \quad (3)$$

The value here is less than 0.005 W, so it is extremely low and can probably be ignored compared with the radiation heat load.

The heat conduction calculation for the pipes is similar to that for the ropes. They are about 1 m long with a 6 mm outer diameter and 1 mm wall thickness. The calculated value is about 0.096 W.

So, the total heat leakage of the cryogenic chamber is about 1.13 W. The heat load of the HTS devices is about 3 W or less. To transfer these heat loads, the heat transfer capacity of the thermosiphon is required to be no lower than 4.13 W. We chose to design it with a nominal 5W heat transfer capacity and a maximum temperature difference about 3 K. Before the ZBO system tests, the thermosiphon was produced and tested earlier. The tested performance is shown in Table 1. It can fully meet the requirements of the cooling system with some margin.

The cold source was determined next; it is a "5W at 80K" Stirling-type pulse tube cryocooler (PTC) with a small linear compressor that was developed by the Technical Institute of Physics and Chemistry. Its stand-alone cooling performance is shown in Figure 2. The cooling power increases with the increase of electrical input power. When the temperature of the coldhead is 80 K, it can provide 4.7 W cooling power with 120 W input power. This capacity should meet the requirements of the hybrid cooling system, and it can be adjusted by changing its input power during tests.

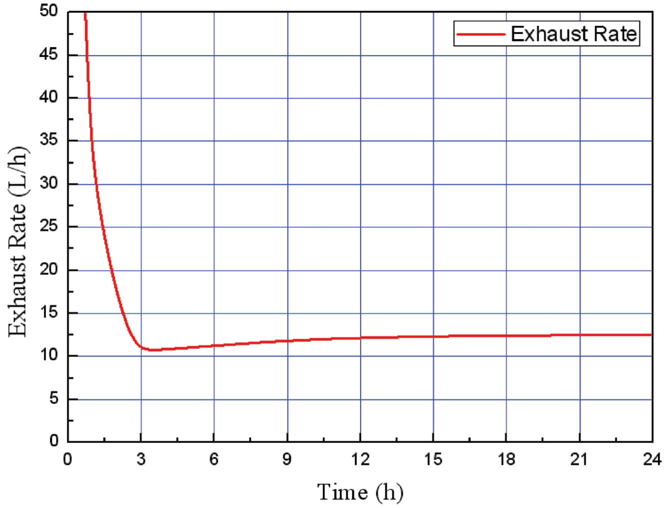

Figure 3. Dewar Evaporating Test

TEST RESULTS

The PTC, the thermosiphon, and the dewar were assembled into the hybrid cooling system for experimental evaluation. Firstly, the dewar cryogenic chamber heat leakage was measured without the PTC and the thermosiphon.

The dewar vacuum chamber was pumped to 0.001 Pa by a vacuum pump unit. Then, the liquid nitrogen was filled into the inner chamber through supply pipes. After ten minutes it was stopped and the charging pipe was closed; it was almost filled to 2/3 of chamber volume. A flow meter was installed in the discharge pipe to measure the nitrogen evaporation rate. The measured gas exhaust rate is shown in Figure 3. After about 3 hours, the dewar reached thermal equilibrium and its exhaust rate is about 12 L/h. So its heat leakage can be calculated considering the sensible heat partially and the latent heat fully of nitrogen. The value is about 1.5 W. This is a little more than the previously calculated value, perhaps because of some other unconsidered factors such as heat conduction of residual gas in the vacuum chamber, conduction of sensor leads, and radiation to the pipes.

The whole cooling system was tested several times. To monitor the system working state, several Platinum resistance temperature sensors (PT100) were installed in the cryogenic chamber (at the bottom, in the middle and on the top of the chamber) and on the evaporator and condenser of the thermosiphon. As before, the cryogenic chamber was also filled with liquid nitrogen, and then the two pipes for charge and discharge were both closed while a pressure sensor was installed in the discharge pipe. At the same time the PTC was powered on to cool the system. The monitored temperature values of each point during one experiment are shown in Figure 4, while Figure 5 shows the temperature curves between 75 K and 110K together with the pressure inside the cryogenic chamber.

The system status can be deduced from the measured temperature curves. Firstly, the temperatures of the dewar and evaporator drop down to nearly 77 K as the liquid nitrogen is filled. Then, at 60 minutes, the temperature of the condenser begins to drop as the PTC is powered on with an input power of 100 W. At the same time, the pressure inside the liquid nitrogen chamber begins to rise as the pipes are closed while the heat leakage continues unchanged. As the condenser and the working fluid of the thermosiphon are cooled by the PTC coldhead, their temperatures are gradually lowered. At 170 minutes, the temperature of the condenser outlet suddenly drops while the temperature of the inlet rises; this is because the condensate appears in the condenser when the condenser is cooled down to nearly 85 K, and the liquid flows through the liquid pipe to the evaporator. Then it evaporates to gas in the evaporator and flows back to the condenser through the gas pipe with a

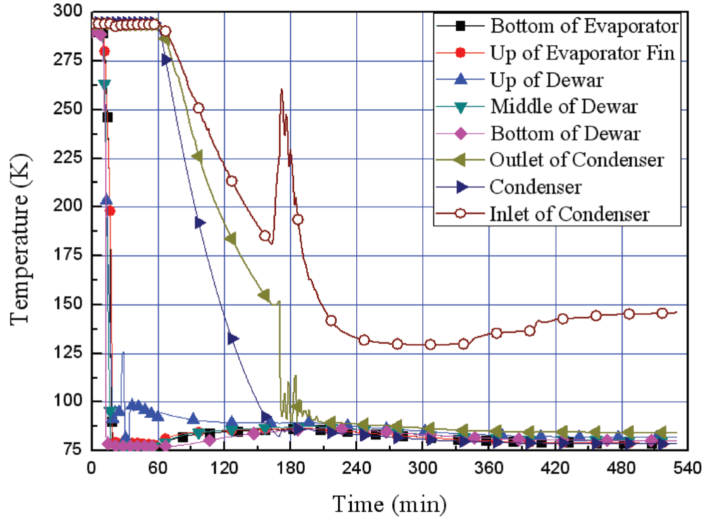

Figure 4. Temperature Curves During ZBO Test

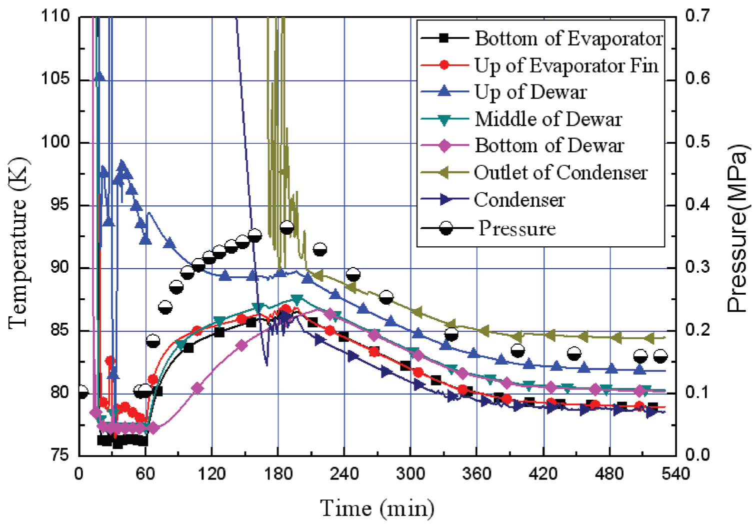

Figure 5. Temperatures and Pressure Curves During ZBO Test

temperature rise as it absorbs the specific heat of the gas pipe and the heat leakage along the way. This phenomenon means that the thermosiphon starts to work. Before this time, the three temperatures of the liquid nitrogen chamber and the temperatures of evaporator and fins rise gradually, but the rate of rise decreases; the pressure has the same variation. After 180 minutes, all these temperatures (except that of the condenser inlet) decrease gradually with the PTC and the thermosiphon continues working. After 400 minutes, the system reaches a thermal equilibrium state with 65 W input power to the PTC. The temperature and pressure of liquid nitrogen remain almost unchanged (about 80 K and 0.17 MPa), and it can be maintained for a much longer time. This is the ZBO status and this cooling system is actually a ZBO system.

The maximum temperature difference between the PTC and the liquid nitrogen is only 1.8 K, referring to the temperature of the condenser and the bottom of the dewar. It indicates that the thermosiphon works very well to transfer the cooling power, and the heat exchangers, such as the condenser and evaporator, are also efficient. The PTC's actual cooling power (2.5 W with 65 W input power from Figure 2) is larger than the actual heat leakage of the dewar (1.5 W). Therefore the heat leakage of the thermosiphon pipes and the condenser is about 1.0 W when they are working at cryogenic temperature.

Some other tests were done similarly with other different conditions. For example, filling the liquid nitrogen to a lower or higher percentage of the chamber volume (one-third, half or two-thirds), or changing the input power of the PTC during testing (with a large power at first and decrease after thermosiphon working). The processes are almost the same, and the phenomenon and governing physics are also similar. In the end, the systems all reached a thermal equilibrium state. The only difference was that the last stable temperature and pressure values were different.

CONCLUSION

In this paper, a hybrid cooling system for HTS devices has been introduced. It is actually a zero-boil-off liquid nitrogen dewar system. The nitrogen is remotely cooled by a pulse tube cryocooler with a thermosiphon. Firstly, the thermal design calculations for the system were carried out, and a matched thermosiphon was produced. Then the heat leakage of the liquid nitrogen chamber was measured, and the value was about 1.5 W. Lastly, the whole cooling system was tested several times. The cooling power of the PTC is larger than the heat leakage of the cryogenic chamber. It can provide more cooling power to cool the HTS devices. The temperature and pressure of the liquid nitrogen could be maintained stable over the long-term in the tests. The maximum temperature difference between the PTC and the liquid nitrogen was only 1.8 K. Thus, the tests proved that a ZBO status for liquid nitrogen was achieved with high efficiency. And, the system could also provide a stable cooling environment for small HTS devices.

In the future, it is expected that this hybrid cooling system will be very useful for some special cooling requirements. It has the advantages of cooling temperature uniformity and stability, isolation of vibration and electromagnetic interference, and long lifetime cooling without any working fluid supply.

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