# Stabilized Pulse Tube Cryocooler system with infrared lamp heater for SQUID magnetic sensor

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## Abstract

A pulse tube cryocooler SQUID cooling system, which temperature was controlled by an infrared source was proposed. A high-Tc SQUID magnetometer was mounted and cooled by a coaxial pulse tube cryocooler. A light from a halogen lamp was guided by a quartz flexible bundle fiber and was introduced to the cold head. The output power of the lamp was controlled by a temperature controller in accordance with the cold stage temperature. As a result, the flux noise of the SQUID output was not changed in the range of 1Hz to 1000Hz regardless of the lamp power. The temperature could be controlled at 77K with accuracy of ± 0.03K for long time duration more than 2 hours. This demonstrated that the system can be applied to any applications such as NDE systems.

*Keywords: Cryocooler, SQUID, Halogen lamp, low Noise*

## 1 INTRODUCTION

High Tc SQUID based NDE system is considered to be marketed [1, 2]. For the operation of such a system in a factory, liquid nitrogen-free-cryocooler is required because of the less daily maintenance. Recently, low noise pulse tube cryocooler (PTC) has come on to the market [3]. However, in the most of the system a resistive heater is employed for the temperature control. Since the current associated with the resistive heater causes magnetic noise, an alternative noise less method is desired. Although controlling the flow of the cooling medium of the refrigerator by adjusting a valve is one alternative method to control the temperature, it is hard to control precisely in a matter of minutes. It has also a problem in a stability of the temperature. We propose use of an infrared heat source for the temperature control system. In this paper we will describe the design of the pulse tube cryocooler SQUID cooling system, which temperature is controlled by an infrared source. The temperature stability and the noise performances of the SQUID magnetometer mounted on the cryocooler will be discussed.

## 2 SYSTEM DESIGN

The whole system diagram is shown in Fig. 1. It consists of three major components: a cryocooler, SQUID driving electronics and a temperature controller. We designed the system based on a co-axial pulse tube cryocooler (PR111 Aisin), which refrigerating capacity is 6 W below 90 K. This coaxial type PCT gives smaller mechanical vibration than two- axial one. This cryocooler consists of a cold head, a rotary valve motor and a GM compressor. The cold head and the valve motor are connected each

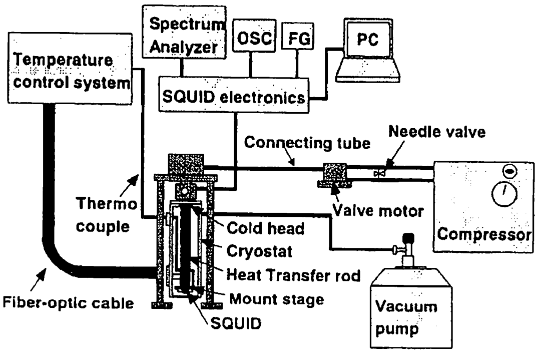


Fig.1 System diagram of pulse tube cryocooler with infrared temperature controller.

other by a 3 m long copper connecting tube. The cylindrical cryostat (ϕ90 mm x L230 mm), which keeps high vacuum condition around the cold head, was made of aluminum alloy. Since the compressor and the rotary valve generate magnetic noises, they are separated from the cryostat and installed out of a magnetically shielded room. The pressure oscillation frequency of the cryocooler generated by the motor-driven rotary valve is 4.5 Hz. The temperature of the cold head can be primarily controlled by the amount of helium gas flow. The cold head was extended by connecting a copper heat transfer rod of ϕ20 x 208 mm to prevent magnetic noise generated by parts in the base of the cold head. The detail of the temperature control system is shown in Fig. 2. A halogen lamp with a total reflection parabolic mirror was used as an infrared source. The light was guided by a multi component bundle optical fiber (3 m) with core diameter of 10mm and was introduced to the cold head. We measured the transfer efficiency of the fiber by power meter (TPM-300CE with PS-330, gentec). As a result, it was about 20 % at the infrared wavelength. The output power of the lamp was controlled by a LakeShore 331 temperature controller in accordance with the stage temperature measured by a gold - normal silver thermocouple. Close up view of the cryostat is shown in Fig.3. A short quartz rod with diameter of ϕ10 mm was connected to the heat transfer rod with silver paste. This rod was set near the view port with spacing of 20 mm for thermal insulation. The optic fiber outlet was set outside of the view port so that the axis of the fiber core mate with that of the quartz rod inside the cryostat. A SQUID magnetometer was mounted on the copper stage via a sapphire disc with dimension of (ϕ25 mm x 5 mm). The sapphire disc reduces the Johnson noise generated from the metallic copper stage. The SQUID is made of $Y_1Ba_2Cu_3O_{7-y}$ thin film [4]. The junctions utilized in the SQUID are of the bi-crystal type. The washer size of the SQUID is about 5 x 4.5 $mm^2$ and the effective area is 0.05 $mm^2$. The SQUID was operated in a flux-locked loop with a flux modulation frequency of 256 kHz. The flux noise spectra of the SQUID was measured by a dynamic signal analyzer (36570A, Agilent Technologies).

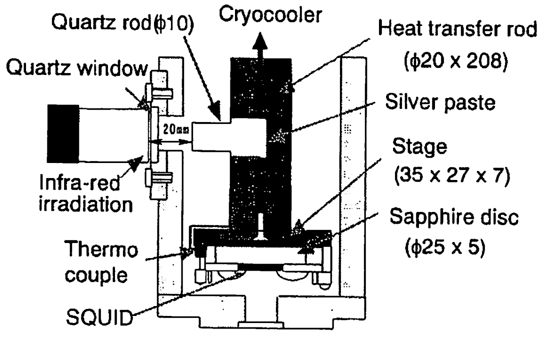


Fig. 2 Detail of the temperature control system. The light was guided by a multi component bundle optical fiber (3 m) and was introduced to the cold head.

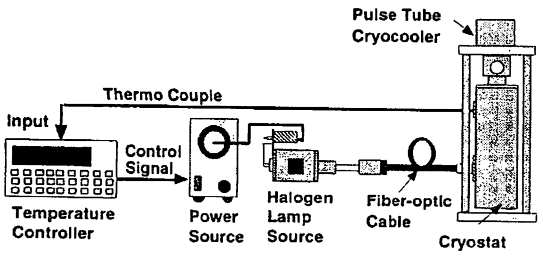


Fig. 3 Close up view of cold stage and infrared irradiation port.

We estimated the required energy to control the stage temperature of the cryocooler. The energy $Q$ is calculated by the following equations (1),

$$Q = \rho V \Delta T C p \qquad (1)$$

where $\rho$, $V$, $\Delta T$ and $Cp$ are density of Cu, the volume of transfer rod, temperature difference and specific heat at constant volume, respectively. The weight of the rod $\rho V$ is 560 g; $\Delta T$ is supposed 5 K and $Cp$ at 70 K is 0.2 J/(gK) [5]. From that calculation, we could find that the calorie of 560 J is required to increase the temperature of the transfer rod from 70 K to 75 K. If the increasing time of 10 minutes is assumed, heat flow of 0.9 W is at least required. This value can be afforded by our halogen source heating system.

## 3 MEASUREMENT

### 3.1 Temperature Stability

First, temperature stability of the cold stage without feedback control was investigated. Figure 4 shows the results for the duration of 1.5 hrs. The flow control valve of the coolant gas was manually controlled so that the stage temperature was maintained at 77 K. However the temperature could not be stabilized and moved up and down with the deviation of 0.5 K. Even if the temperature successfully achieved at the target temperature, it easily drifted. This means that it is hard to control the temperature by controlling the follow of the coolant for long time.

Second, we utilized feedback system using a halogen lamp irradiation. The coolant valve was adjusted so that the temperature of the cold stage becomes almost 1 K below the 77 K and then the feedback system was turned on. The time trace of the stage temperature is shown in Fig. 5(a). The temperature increased at the target temperature 77 K in about 20 minutes and was maintained for more than 2 hrs. The magnified scale is shown in Fig 5(b). It shows that the temperature is maintained at 77.00 K with deviation of ± 0.03 K. This stability is high enough for high-Tc SQUID operation in most of the applications.

### 3.2 System Noise

Flux noise spectra of the SQUID magnetometer mounted on the cold stage at various temperatures were measured. The temperature was controlled by adjusting the coolant gas flow; the temperature controller was not used here. The results are shown in Fig. 6. The flux noise of the SQUID measured in liquid nitrogen is also indicated for the comparison. The temperature shown in the figure is the stage

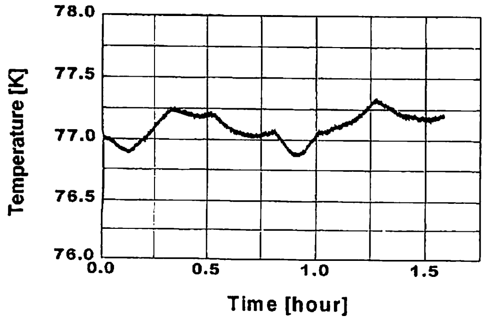
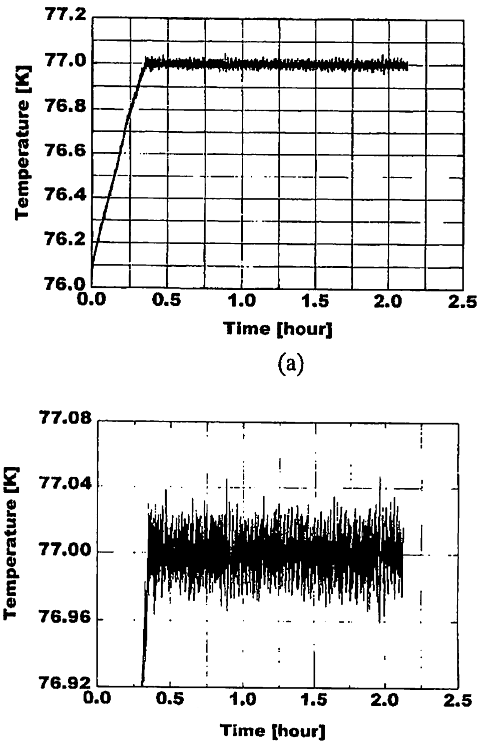


Fig. 4 Time trace of temperature at cold stage.



(a)

(b)

Fig. 5 The time trace of the stage temperature for two hours when the infrared temperature controller was turned on. (a): time trace for 2hrs and (b): magnified scale view for the same time duration.

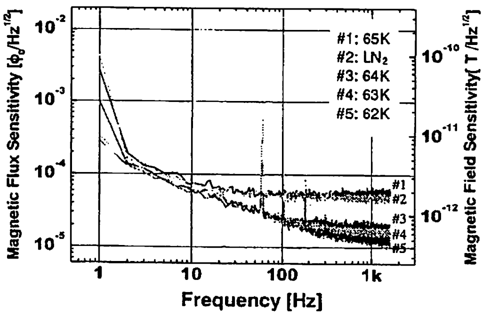


Fig. 6 Flux noise spectra of the SQUID magnetometer mounted on the cold stage at various temperatures.

temperature. As indicated in the figure, the noise spectrum taken at 65 K is almost the same as that measured in liquid nitrogen, which boiling temperature is 77 K. This means that the temperature of the SQUID mounted on the stage via a sapphire disc is 12 K higher than that of the cold stage. This difference comes form poor thermal conduction between the sapphire disc and the copper stage.

Then the flux noise spectra of the SQUID on the cold stage were measured with the feedback system using the infrared irradiation. Before turning on the feedback, the temperature of the cold stage was set at about 1 K below the target temperature of 63 K by adjusting the coolant flow. This stage temperature of 63 K corresponds to the SQUID temperature of 75 K. The flux noise spectra taken at SQUID temperature of 75 K are shown in Fig. 7. One is spectrum with the feedback and the other is that without the feedback. There is almost no difference between them. This means that the operation of the infrared heating feedback system does not make additional flux noise.

## 4 SUMMARY

We have proposed a pulse tube cryocooler SQUID cooling system, which temperature was controlled by an infrared irradiation. The temperature could be controlled at 77K with accuracy of ± 0.03 K for long time duration more than 2 hours in this scheme. The operation of the infrared heating feedback system does not make additional flux noise.

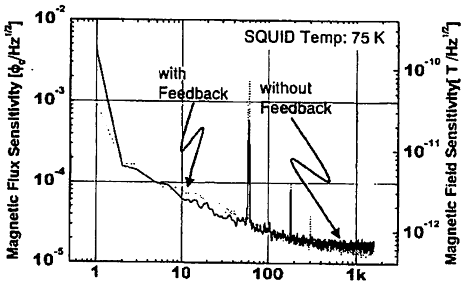


Fig. 7 The flux noise spectra taken at SQUID temperature of 75 K.

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## Biographies

Saburo Tanaka received his B.E. and M.E. from Toyohashi University of Technology in 1981, and 1983, respectively. He received his Doctoral Degree in engineering from Osaka University in 1991. Since 1987 he has been involved in the research of high-temperature superconductors at Sumitomo Electric Itami Research Lab. He was engaged in the development of multichannel high-Tc SQUID systems at the Superconducting Sensor Laboratory from 1991 to 1995. He was a visiting research associate at the Department of Physics, University of California at Berkeley from 1996 to 1997. Currently, he is a professor and a director of the Research Center for Future Technology at Toyohashi University of Technology. He is a member of the Japan Society of Applied Physics, the Institute of Electronics, Information and Communication Engineers, the Institute of Electrical Engineers of Japan, and the Institute of Electrostatics Japan.

Soichiro Iwao was born in Oita Japan in 1982. He received his B.E. from Toyohashi University of Technology in 2004. At present, he is studying toward M.E. degree at the graduate school. His research interest is cooling system for High Tc-SQUID magnetometer and its applications. He is a member of the Japan Society of Applied Physics.

Yoshimi Hatsukade received his B.E. and M.E. from Waseda University in 1998 and 2000, respectively. He received his Doctoral Degree in engineering from Waseda University in 2003. Since 1998 he has been engaged in the research of nondestructive evaluation technique using SQUIDs for conductive materials. Currently he is a research associate at Toyohashi University of Technology. He is a member of the Japan Society of Applied Physics, and the Cryogenic Association of Japan.