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Experimental investigation on sub-miliKelvin temperature control at liquid hydrogen temperatures

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ABSTRACT

Temperature control around 20 K with a tolerance of better than 1 mili-Kelvin is challenging but essential for applications like cooling deuterium/tritium target in fusion ignition experiments. To explore the practicability of cryogenic temperature control on this level with a cryocooler as the cold source instead of a cryogen bath, experimental investigations were conducted to approach the best performance by optimizing configurations of effective measures. A special heat sink was fabricated and attached to the second-stage cold head of a G-M cryocooler which could reach temperatures down to 2.5 K and provide 13 W cooling power at 18 K. A thermal reservoir and/or temperature transmission damping were incorporated, as well as a manganin resistance wire electrical heater attached to the heat sink. Experimental results show that an optimal stability of the temperature of the shielded heat sink within ±0.4 mK at 20 K was achieved by choosing proper excitation for the sensors, control mode for the heater and capacity for the thermal reservoir.

1. Introduction

Cryogenic system is necessary for the advanced step of controlled fusion ignition experiments to maintain the deuterium/tritium fuel ice layer in the target capsule [1]. The capsule is positioned at the center of a hohlraum hold by a silicon arm which transfers the cooling power from a cryocooler. To meet the temperature and uniformity requirements of the target, the assembly should be maintain precisely to a tolerance of better than 1 mili-Kelvin [2]. We intended to study the practicability and critical factors of cryogenic temperature control on this level. And it is believed that the significance of that is far beyond the specific application to fusion experiments, for instance, enabling higher accuracy measurement of thermophysical properties of fluids in the vicinity of their critical points.

Instead of cryogenic fluid bath, cryocoolers are competitive cold sources for compact cooling applications, especially convenient for temperature control at any specified point in its valid range. However, temperature oscillation caused by the periodic expansion of the working fluid (usually helium) is an intrinsic characteristic of common regenerative cryocoolers. At the cold fingers of the 4 K stage of a G-M cryocooler and a pulse tube cooler, the peak to peak temperature oscillation is typically on the order of several hundred mili-Kelvin [3], which can be rather disturbing in some temperature sensitive systems. Attaching an additional mass with high heat capacity to the cold head of a G-M cryocooler [3–7] as well as pulse tube cryocooler [8,9] can effectively improve the temperature stability. Li et al. [3] mounted a helium pot onto the 4 K stage of a G-M cryocooler and reduced the temperature oscillation down to about 50 mK. Okidono et al. [4] and Shen et al. [5] utilized the same method for G-M coolers and successfully suppressed the temperature oscillation to 10 mK below 4.5 K. Nakamura et al. [6,7] installed two fiber-reinforced-plastic (FRP) dampers on the cold head of a G-M cryocooler and on the sample stage and successfully suppressed the temperature fluctuations within 0.7 mK at 4.2 K. Allweins et al. [9] used ErNi, a kind of magnetic rare-earth compound with high volumetric specific heat at liquid helium temperatures, to dampen out the intrinsic temperature oscillations of a 4 K pulse tube cooler to 14.5 mK.

In this paper, to meet the requirement of an oscillation less than 1 mK at around 20 K, a temperature measurement and control system in that range was designed and fabricated. Experiments were conducted to show that the stability of temperature is related to the excitation mode of the sensor, the control methods, the heat capacity and the cold shield. A result of stability within ±0.4 mK was achieved by using an optimized configuration.

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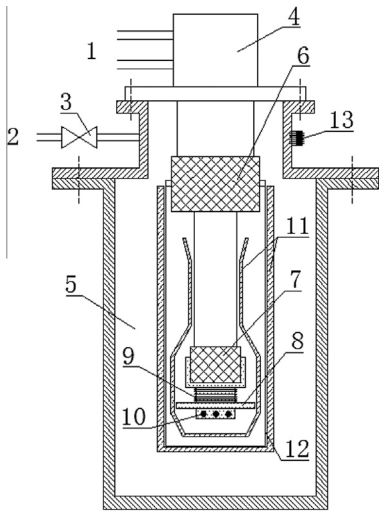

Fig. 1. Schematic of the cryogenic temperature-control experimental system. 1: to compressor; 2: to high vacuum pump; 3: vacuum shut-off valve; 4: G-M cryocooler; 5: vacuum chamber; 6: first stage cold head; 7: second stage cold head; 8: heat sink; 9: manganin resistance wire; 10: temperature sensors; 11: multilayer insulation materials; 12: radiation shield; 13: multi-pins feed-through.

2. Experimental setup of the system

The experimental setup for evaluating the stability and accuracy of the temperature control system is shown schematically in Fig. 1. A SHI® 408D G-M cryocooler is used as the cold source, whose second stage cold head can provide 1 W and 13 W cooling power at 4.2 K and 18 K, respectively. The heat sink is specially designed to attach firmly to the second stage cold head. Manganin wire powered by a high precision DC power supply is uniformly twined around the cylindrical surface of the heat sink as a heater. Different temperatures can be approached by adjusting the power loaded on the heater. Cernox negative temperature coefficient (NTC) sensors were firmly mounted to the surface of the heat sink. A radiation shield is connected to the first-stage cold head for thermal protection of the second stage. Multi-layer insulation is placed inside and outside the radiation shield. All the above components are placed in a vacuum chamber. Data were collected automatically by a LabVIEW®-based data acquisition system, which consists of a computer, a Cryocon® 24C temperature controller and an Agilent® 34970A unit with module 34901A (6 ½ digits).

The performance of the temperature sensors themselves can greatly influence the accuracy of the temperature control activity. Lakeshore® Cernox resistance cryogenic temperature sensors were utilized in our temperature measurement, whose advantages have been well accepted in world-wide cryogenic systems. The calibrated Cernox 1050 sensors (1 CU package and 3 bare-chip) are tightly mounted to the heat sink. The CU packaged one was set to monitor the temperature of the thermal shield and the bare-chip sensors are for the heat sink. According to the datasheet of the Lakeshore CX-1050 product, the sensitivity dR/dT of the sensor at 20 K is $-480.08\ \Omega/K$. The response time for the bare-chip is 1.5 ms at 4.2 K, 50 ms at 77 K. By interpolating the data linearly, the response time for bare-chip at 20 K is estimated to be around 12 ms. The inherent frequency of the cooler cycle is about 1 Hz which means the period 1 s is much larger than the sensor's response time. So, the sensors are thought to be good for the measurement. A thin layer of Apiezon® N Grease is pasted between the sensors and the mounting surface to enhance thermal contact. The accuracy (not stability) of the sensors at different temperatures is shown in Table 1. The sensors are wired to the Cryocon® 24C temperature controller for both temperature measurement and control. The resolution of the data acquisition system is 0.1 mK. Three different constant voltage excitations (1 mV, 10 mV and 100 mV) are offered for the sensors. Higher accuracy can be assured when using larger excitation at relatively higher temperatures. However, at extremely low temperatures, smaller excitation should be used to suppress self-heating effect, which is usually negligible above 3 K. The 100 mV excitation mode is preferred since the experiments are conducted around 20 K.

Two control methods were compared in the experiments. One was to load constant power on the heater with a programmable DC power supply, model IT6123 from Itech®. Its resolutions for voltage and current are 0.5 mV and 0.01 mA, respectively. That is, the power resolution is 0.005 mW. When the heat transfer reaches an equilibrium state, stable temperature can be recorded. The other method was to directly control the temperature through PID (proportion, integral and derivative) mode of the temperature controller.

To investigate how the performance of temperature control can be affected by heat capacity of the materials, we make the heat capacity changeable by inserting or removing lead blocks between the second-stage cold head and the heat sink. The heat sink was made of copper. Though the volumetric heat capacity of copper is quite large at room temperature, it decreases quickly when the temperature decreases and reaches 0.07 J/(cm^3 K) at 20 K as shown in Fig. 2 [11]. However, the heat capacity of lead, also shown in Fig. 2, is 0.6 J/(cm^3 K) at 20 K, which is larger than that of copper by an order of magnitude. In other words, the volume of lead is much smaller than that of copper for the same total heat capacity at 20 K. Therefore, lead blocks were prepared to augment the heat capacity of the heat sink.

A small cold shield made of copper is designed to further diminish the radiation heat transfer besides the multi-layer insulation. The cold shield matches the size of the heat sink and can be connected to the heat sink through bolt fastening. Installation of the lead block and the cold shield is demonstrated in Fig. 3.

3. Results and analysis

To investigate how the performance of temperature control is affected by the excitation of the sensor, control methods, heat capacity size and the cold shield, groups of contrasting experiments were carried out. Factors that were not investigated, such as the resistance of the heater, the wrapping of the multilayer heat insulation materials and vacuum degree, are all maintained the same condition for all experiments. To avoid redundancy, results of only one of the sensors will be discussed in detail as follows.

In order to set up a reference for the comparison between applying different measures, we measured the temperature directly on the cold head of the 2nd stage of the cryocooler first of all. The excitation for the sensor was chosen as 1 mV. Fig. 4 shows that the amplitudes of the temperature fluctuation in 20 s at ~4.2 K and ~20 K are ±140 mK and ±55 mK, respectively. That is

Table 1
Accuracy of the Cernox 1050 series sensors [10].

Temperature	1.4 K	4.2 K	10 K	20 K	30 K	50 K	100 K	300 K
Accuracy	±4 mK	±4 mK	±4 mK	±8 mK	±9 mK	±12 mK	±16 mK	±40 mK