Development of monitor system for parallel-type superconducting level sensor for liquid hydrogen

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Abstract. We develop a monitor system to control a parallel-type superconducting (SC) level sensor and to indicate the level of liquid hydrogen in a container. The parallel-type level sensor is composed of an MgB₂ wire and non-SC wire, which are vertically located in parallel and electrically connected in series. We assemble the monitor unit using a power supply, central processing unit (CPU), analog-to-digital (AD)/digital-to-analog (DA) converter, touch panel, voltage dividers and isolators. The terminal voltages of the MgB₂ wire and non-SC wire with a constant current produced by the power supply are stored in the memory of CPU through the isolators, voltage dividers and AD converter. The liquid level is calculated in the CPU according to a pre-written program code. The obtained result is displayed on the touch panel and also output externally via the DA converter and isolator. Furthermore, the normal operation of the developed monitor system is validated using dummy voltages from an oscillator.

1. Introduction

Hydrogen that produces only water after its combustion is expected as a clean energy, and the liquefied hydrogen might be used for mass storage and transport in near future. At that time, it is necessary to understand the accurate amount of liquid hydrogen in the container. Superconducting (SC) level sensors for liquid hydrogen using MgB₂ wires, which have a critical temperature of about 39 K [1] and which becomes SC state in the liquid hydrogen with the boiling temperature of about 20 K at atmospheric pressure, have been studied [2–4]. Haberstroh et al. have investigated an SC level sensor for liquid hydrogen using the MgB₂ wire reinforced by stainless-steel (SS) sheath [2]. Takeda et al. have studied an external-heating-type level sensor in which a heater wire is wholly wound on the MgB₂ wire to improve the sensitivity [3]. Our group has proposed a parallel-type SC level sensor composed of MgB₂ wire A and non-SC wire B [4]. This sensor has an advantage that it is hardly affected by various conditions of gas such as temperature, pressure and object, and therefore it is expected that the reproducibility of sensor output is very good. Our group has also developed a monitor system to control the parallel-type SC level sensor and to indicate liquid level in the container. This monitor unit was composed of a power supply, central processing unit (CPU), touch panel and so on. Although the installed monitor system has been working properly for more than six years [5], it was expensive because a commercial programmable logic controller (PLC) was used there.

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In this study, another type of monitor system for the parallel-type SC level sensor is developed to reduce the costs of components. Moreover, it is confirmed using dummy voltages from an oscillator whether the fabricated monitor system works properly or not.

2. Principle of parallel-type SC level sensor

Figure 1 shows the principle diagram of the parallel-type SC level sensor [4]. The level sensor is composed of two thin wires, SC wire A and non-SC wire B, and they are vertically located in parallel and electrically connected in series in the container. When an optimal current \( I \) is applied to these wires, the upper part of the SC wire A in gas generates a voltage drop \( V_G \), whereas its lower part in liquid has no voltage drop due to the SC state. Thus, the terminal voltage of the SC wire A, \( V_A \), is equal to \( V_G \). In the case of the non-SC wire B, the upper part in gas also generates a voltage drop \( V_G \) if the temperature dependence of resistivity is identical to that for the SC wire A. On the other hand, the lower part of the non-SC wire B generates a voltage drop \( V_L \) depending on liquid temperature \( T_b \). So the terminal voltage of the non-SC wire B, \( V_B \), is given by \( V_B = V_G + V_L \). When the difference voltage, \( V_P = V_B - V_A \), is observed, at that time, the voltage drop of the non-SC wire B in liquid, \( V_L \), is finally obtained. Therefore, this sensor has an advantage that it is hardly affected by the conditions of gas, so that the reproducibility of sensor output is expected to be very good.

The MgB\(_2\) wire fabricated by the powder-in-tube (PIT) method [6] has been used as the SC wire A up to now. On the other hand, the non-SC wire B might be prepared from some candidates such as a wire just after drawing process for the SC wire A (as-drawn wire), a wire made of only sheath material (solid wire) and so on. Figure 2 shows the temperature dependence of electrical resistivity for the SC wire A with SS sheath and its as-drawn wire for numerical simulation [7]. The diameters and lengths of these wires are assumed to be 0.1 mm and 1 m, respectively. The temperature profiles in these wires are numerically calculated by using a one-dimensional heat balance equation. It has been well known that these temperature profiles are determined by only the balance between local heating and cooling, and not affected by the thermal conduction of the wires [8]. Figure 3 shows the numerical results of output voltages for the SC wire A and as-drawn wire B, \( V_A \) and \( V_B \), during slowly filling or spontaneously evaporating the liquid hydrogen [7]. It is found that the output voltage \( V_A \) increases with rising up or falling down of the liquid level, whereas the output voltage \( V_B \) doesn’t vary so much. Contrary to the ideal principle explained in the antecedent paragraph, the voltage drops \( V_G \) for the SC wire A and non-SC wire B in gas are different from each other due to the discrepancy between their dependence of
resistivity on temperature as shown in figure 2. In order to realize the difference voltage $V_P$ equal to zero when the liquid level is at the bottom, therefore, $V_P$ plotted by a dotted line in figure 3 is estimated as

$$V_P(y) = V_B(y) - \alpha V_A(y),$$

where $y$ is the vertical position of liquid level, and the adjustment parameter $\alpha$ is given by

$$\alpha = \frac{V_{B1}}{V_{A1}},$$

with $V_{A1} = V_A(0)$ and $V_{B1} = V_B(0)$ when the origin of the liquid level $y$ is set at the bottom of the sensing wire. It can be seen that the difference voltage $V_P$ has an almost linear relationship with the liquid level $y$, and thus the calibration method of linear approximation using only five parameters, $V_{A1}$, $V_{B1}$, $V_{A2}$, $V_{B2}$ and $L$, is carried out in this study, where $V_{A2} = V_A(L/2)$ and $V_{B2} = V_B(L/2)$ with the effective length $L$ of sensing wire. By using the temporary parameter $c$ expressed by

$$c = \frac{L/2}{V_{B2} - \alpha V_{A2}},$$

the liquid level $y$ can be finally estimated as

$$y = c(V_B - \alpha V_A).$$

3. Development of monitor system

A monitor system adaptable to the parallel-type SC level sensor is constructed. Figure 4 shows the circuit diagram of the monitor system. The monitor system is composed of a power adapter, CPU, analog-to-digital (AD)/digital-to-analog (DA) converter, touch panel, power supply for level sensor, voltage dividers and isolators. Figure 5 shows the flowchart of monitor system operation. The output voltages, $V_A$ and $V_B$, are stored in the memory of CPU through the isolators, voltage dividers and AD converter. After that, the liquid level is calculated in the CPU by following a pre-installed program code. The calculation result is displayed on the touch panel and also output externally via the DA converter and isolator. Moreover, the touch panel can display not only the liquid level in the units of both millimeters
and percent, but also output voltages, $V_A$ and $V_B$, individually. Furthermore, the start or stop operation of level sensor can be controlled on the touch panel.

The Raspberry Pi 3 Model B is used as the CPU [9]. The Raspberry Pi is a series of small single-board computers developed in United Kingdom to promote teaching of basic computer science in

![Circuit Diagram](image)

**Figure 4.** Circuit diagram of monitor system.

![Flowchart](image)

**Figure 5.** Flowchart of monitor system operation.

![Display Screen](image)

**Figure 6.** Example of display screen.
schools, and popular among users such as robotics. The monitor system using the Raspberry Pi is much cheaper than that developed previously using the commercial PLC [5]. However, there is no AD/DA function in the Raspberry Pi itself, and thus the High-Precision AD/DA Board for the Raspberry Pi is used [10]. This AD/DA board is composed of the AD converter with 8 channels and 24-bit resolution, and the DA converter with 2 channels and 16-bit resolution, which have enough performance for the monitor in this study. Figure 6 shows one of display screens for the developed monitor system. An application code adaptable to touch panel operation is developed by using the Kivy that is one of open source libraries of the Python [11]. The 7-inch touch screen monitor for the Raspberry Pi is used for display, and the level sensor can be controlled on this touch screen.

4. Preliminary confirmation test of monitor operation

In order to confirm whether the developed monitor system works properly or not, the preliminary test is carried out. The setting parameters for the test are listed in Table 1. The time-varying voltages are input to the monitor so as to simulate rising up and falling down of the liquid level. The program code, in which the liquid level of 0-100% corresponds proportionally to the output voltage of 0-10 V, is prepared in advance. Figure 7 shows the result of preliminary confirmation test, in which $V_A$ is changed from 0 V to 4 V.

| Symbols | Values |
|---------|--------|
| $V_{A1}$ | 4 V    |
| $V_{A2}$ | 2 V    |
| $V_{B1}$ | 3 V    |
| $V_{B2}$ | 3 V    |
| $L$      | 180 mm |

Table 1. Setting parameters for preliminary confirmation test of monitor system operation.

![Figure 7. Result of preliminary confirmation test of monitor system operation.](image.png)
to 4 V and $V_B$ is kept constant at 3 V. The reproducibility is good for both rising up and falling down of the liquid level, and the output voltage is displayed on screen correctly.

5. Conclusions
The monitor system for the parallel-type SC level sensor for liquid hydrogen was developed. The monitor unit was composed of the power adapter, CPU, AD/DA converter, touch panel, power supply for the level sensor, voltage dividers and isolators. The liquid level was calculated in the CPU by storing the output voltages from the level sensor in its memory, and then the calculation result was displayed on the touch panel screen and also output as the analog voltage. The cost of the monitor unit was reduced very much by using the Raspberry Pi, which is the small single-board computer, as the CPU. Furthermore, the application code to control the level sensor via the touch panel was developed by using the Kivy. Finally, the preliminary confirmation test of monitor system operation was carried out, and then the good reproducibility was obtained.

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