Fundamental investigation of a superconducting level sensor for liquid hydrogen with MgB\textsubscript{2} wire

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Abstract. The feasibility study of a superconducting level sensor for liquid hydrogen with a magnesium-diboride (MgB\textsubscript{2}) wire is carried out from an experimental point of view. The sample wire consists of a mono-cored MgB\textsubscript{2} superconductor and a cupronickel sheath, and several potential taps are attached to it at even intervals in order to understand the position of a threshold between the superconducting and resistive states roughly. The fabricated sensor is vertically located in a glass dewar vessel with an infill of liquid hydrogen, and the position of a preselected potential tap is adjusted by eye and hand to liquid level before starting a new measurement. Simulated operations with constant currents finally yield the future possibilities as the level sensor for liquid hydrogen with MgB\textsubscript{2} wire although the fabricated sensor has a few problems at present. In order to improve the performance of the sensor, the specifications required for MgB\textsubscript{2} wires will be reported elsewhere by applying the stability theory in superconductor composites and by simulating the operation with a numerical code.

1. Introduction
Possibilities of the future society with hydrogen utilization have been investigated as one of the advanced technologies for improvement of energy and environmental problems in recent decades. In order to obtain effective energies by oxidizing the hydrogen with a fuel cell etc., it is necessary to produce, transport, store and transfer the hydrogen safely and stably. In such situations, it can also be essential to use the hydrogen as a liquefied gas as well as a compressed gas. Although the remaining amount of liquid hydrogen in a container has to be known exactly, in the former case, the observation technology with reliable accuracy has not been established yet because the
mass density of hydrogen is very low and also the difference in dielectric constants between the liquid and vapor phases is small.

In this study, the feasibility of a level sensor for liquid hydrogen with an MgB$_2$ superconducting wire is investigated from only an experimental point of view although the similar discussion for MgB$_2$ wires with different sheath material has already been carried out [1,2]. The test results for the fabricated sensor with liquid hydrogen are reported as well as those with liquid helium, and positive experimental results toward its realization are shown finally.

2. Sample preparation
The sample wire for level sensor has the cross-sectional structure of an MgB$_2$ monofilamentary superconductor surrounded by a CuNi sheath. The diameter and length of the MgB$_2$ wire are 0.3 mm and 200 mm, respectively. This wire is located straight on a flat face of long Bakelite rod, and both its ends are soldered to copper terminals for current transport. Figure 1 shows the schematic diagram of the level sensor for cryogenic liquid used in this study. In order to observe a normal zone propagation phenomenon mainly, eight potential taps, which consist of a very thin constantan wire with low thermal conductivity, are soldered to the MgB$_2$ wire at even intervals of 20 mm, and they are numbered from #1 on the top to #8 on the bottom. Moreover, the voltages between two adjacent taps are signified by $V_1$ to $V_7$, respectively, as shown in figure 1. Another additional potential tap is also prepared on the upper terminal, and the effective length for the voltage $V_0$ between uppermost two taps is 10.6 mm. Although a resistive heater, which is not depicted in figure 1, is mounted in advance near the upper terminal to generate a small normal zone in the sample wire, it is never needed in a series of experiments as mentioned in the following sections. The fabricated level sensor is placed vertically in a glass dewar vessel with an infill of cryogenic liquid, and the position of a preselected potential tap is adjusted by eye and hand to liquid level before starting a new measurement.

3. Preliminary tests with liquid helium
3.1. Thermal stability for helium
In order to check the reliability of the fabricated level sensor first, its whole body was immersed in liquid helium. When a transport current gradually increased, a small normal zone arose near the upper terminal at about 2.7 A without input energy of the heater, but did not propagate up to 3.0 A, where the current rise was interrupted to avoid a burnout of the sample.

Next, the upper end of level sensor was pulled out of liquid helium, and the position of tap #4 was almost fixed at the liquid level. The gradual rise of the transport current from zero triggered again the automatic development of normal zone beside the upper terminal around

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**Figure 1.** Schematic diagram of fabricated level sensor with several potential taps.
1.7 A without the heater input. For further increase in the current over 1.9 A, the normal zone expanded downward and the traveling of its front, the boundary between the superconducting and normal states, became stagnant near the liquid level, as shown in figure 2. Table 1 shows the experimental results of normal zone propagation velocity in gaseous helium estimated from figure 2. The velocity in each section was defined by a time interval between 10% and 90% of a saturated voltage just after passing of the normal front. It can be found that the velocity becomes slow when the normal front approaches the liquid level. Moreover, the order of millimeter per second in the normal zone propagation velocity for the present MgB$_2$ wire cooled by gaseous helium seems to be much slower than several tens meters per second for a NbTi multifilamentary wire in liquid helium [3].

### Table 1. Normal zone propagation velocity of sample wire in gaseous helium.

| Observed section         | Propagation velocity (mm/s) |
|--------------------------|-----------------------------|
| Tap #1 to #2             | 5.9                         |
| Tap #2 to #3             | 3.6                         |
| Tap #3 to #4             | 2.7                         |

3.2. Tests of simulated sensor operation with liquid helium

Experimental results of simulated operation for the fabricated level sensor with liquid helium are given in figure 3, where the total voltage of sensor for a constant current of 2 A is observed. Each number alongside the stepwise voltage profile in figure 3 indicates the position of potential tap, around which the liquid level exists for a period of time after the manual adjustment. It can be seen that the response of the sensor is very fast for the relative displacement between the sensor and the liquid level, and that the output voltage in the sensor for the fixed position is almost constant and stable.

The relationship between the total voltage of sensor and the liquid level of helium is plotted in figure 4, where an approximated line is obtained by means of the least squares method. It can be seen that the repeatability during pushing and pulling the sensor is quite good. Furthermore, the observed voltage is almost proportional to the wire length just outside the liquid helium, and the liquid level can be detected to an accuracy of about 1 mm.
4. Main tests with liquid hydrogen

4.1. Normal zone propagation in gaseous hydrogen

In order to find out an optimum current for sensor operation, the thermal stability of the fabricated level sensor was measured in a glass dewar vessel with liquid hydrogen. Figure 5(a) shows a typical example of the normal zone propagation of the sensor whose position of tap #7 is fixed at the liquid level. It is found that the voltages $V_0$ to $V_3$ increase along with the transport current. In order to understand details of the observed results, the vertical axis in figure 5(a) is converted into a resistance, as shown in figure 5(b), by dividing each voltage between the taps by the current. Here, the resistance $R_0$, for example, corresponds to the voltage $V_0$ and the others are similar. It can be seen that $R_0$ to $R_2$ already have an almost invariant resistance just after the beginning of current transport. On the other hand, the resistance $R_3$ approximately has a half of saturation value at the beginning and then increases with time. After that, the resistance $R_3$ becomes almost constant, and $R_4$ to $R_6$ increase in sequence up to their own saturation. Although the resistance $R_7$ does not vary at all, the normal front finally stays around the position of tap #7. Since the part of sensor over the middle of section #3 to #4 has a finite resistivity without applying current, it seems that an initial temperature at the position of about 70 mm above the liquid level is equal to the critical temperature $T_c$ of the sample wire. Furthermore, there may be a type of defect near the position of tap #6 because rising of the resistance $R_6$ is not smooth.

4.2. Tests of simulated sensor operation with liquid hydrogen

The simulation of level sensor operation with liquid hydrogen was carried out just like for liquid helium as mentioned in the previous section. Figure 6(a) shows the experimental results of simulated operation for the fabricated level sensor with a constant current of 2 A. It can be seen that the observed total voltage has a fluctuation with time when the liquid level is in the vicinity of the position of tap #5. Moreover, the total voltages at tap #7 in the cases where the liquid level relatively goes up and down differ from each other obviously. In order to improve these responses of the level sensor, the constant transport current is increased up to 4 A as shown in figure 6(b). Although both problems of the stability at tap #5 and the repeatability at tap #7 become clear, as can be seen, the observed total voltages at tap #6 are always small as compared with the others. This may be caused by an enhancement of cooling characteristics.
Figure 5. Typical example of normal zone propagation of sample wire in gaseous hydrogen. (a) represents observed voltages between potential taps, and they are converted into resistances in (b).

Figure 6. Experimental results of simulated sensor operation with liquid hydrogen for constant current of (a) 2 A and (b) 4 A. Each number in this figure represents a liquid level to which the position of potential tap is adjusted by eye and hand.

around the position of tap #6 during the sample preparation process.

Figure 7 represents the relationship between the total voltage of sensor and the liquid level of hydrogen. The least squares method gives approximated lines in figure 7 for the experimental data except unsuitable results mentioned above. It can be seen that the observed total voltage of the sensor with the current of 4 A has a fine repeatability and is proportional to the wire length above liquid level of hydrogen within the error of 1% except for the position of tap #6. This means that the liquid level can be detected to an accuracy of below 1 mm with the fabricated sensor. However, an input power more than 10 W at maximum is so large that its reduction is very important for practical application in the near future.
5. Conclusions
The measurements of normal zone propagation and the tests of simulated sensor operation for the MgB$_2$ monofilamentary wire developed at present were carried out with both liquid helium and hydrogen as coolants. It has been found that the superconducting wire composed of MgB$_2$ and CuNi may have a way applicable to the level sensor for liquid hydrogen although the fabricated sensor has an unidentified problem around the potential tap #6. Since the huge input power over ten watts is needed for normal operation of the sensor, however, its reduction has to be accomplished for realization and practical use. A possible plan for the reduction of input power would be to downsize the wire diameter and suppress its operation current, as already predicted by the stability theory for superconductor composites [4]. Such a discussion toward an optimal design of the level sensor will be made with a numerical analysis in the near future.

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Figure 7. Relationship between terminal voltage of sensor and liquid level of hydrogen.