Proposal of a new type of superconducting level sensor for liquid hydrogen with MgB$_2$ wires

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Abstract
A new configuration of superconducting level sensor for liquid hydrogen is proposed. The proposed sensor has an advantage that it is difficult to be affected by various conditions of gas such as temperature, pressure and object, so that it is expected that the reproducibility of sensor output becomes very good. The operation of the proposed sensor is numerically simulated with a one-dimensional heat balance equation to evaluate the time evolution of temperature distribution for an ideal MgB$_2$ wire. The proposed configuration of sensor with an MgB$_2$ wire with stainless-steel sheath is also fabricated, and its operation is experimentally evaluated with the liquid hydrogen.

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Keywords: Heat balance equation; Liquid hydrogen; Magnesium diboride; Numerical simulation; Superconducting level sensor

1. Introduction
Level sensors for liquid hydrogen using MgB$_2$ wires are one of the promising applications of superconductivity [1, 2, 3, 4, 5, 6]. This is because the MgB$_2$ material with a critical temperature of about 39 K becomes a superconducting state in the liquid hydrogen with a boiling temperature of about 20 K at atmospheric pressure [7]. In the previous work, a level sensor fabricated with a monofilamentary MgB$_2$ wire with double-layer sheath of iron and stainless steel has been tested in a cryogenic Dewar vessel with an infill of the liquid hydrogen [8]. Although the experimental results have successfully shown the one-to-one relationship between the liquid level and the output voltage of sensor, the reproducibility for the output voltage has been somewhat poor due to the status of gas such as its temperature, pressure and object. Thus, the development of level sensors for liquid hydrogen unaffected by the gas status would be required for their realization.

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In this study, a new type of superconducting sensor is proposed to detect the liquid level of hydrogen. In order to validate the proposed principle of operation, numerical calculations are carried out based on a one-dimensional heat balance equation. Experiments with the proposed type of superconducting level sensor composed of an MgB$_2$ wire and its non-heat-treated wire are also carried out during refill and discharge of the liquid hydrogen.

2. Proposal

Fig. 1 shows a new configuration of superconducting (SC) level sensor proposed here. The level sensor is composed of two thin wires, SC wire A and non-SC wire B. The non-SC wire B is located close and parallel to the SC wire A, and they are electrically connected in series. If a current $I$ is applied to these wires located vertically inside a cryostat containing a cryogenic liquid, the SC wire A operates in the same manner as a conventional type of SC level sensor. That is, the upper part of the SC wire A in gas generates a voltage drop $V_G$, whereas the lower part of the SC wire A in liquid is in the SC state and then the voltage drop becomes zero. 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 $V_G$ under the condition that both the wires have the temperature dependence of resistance identical to each other. On the other hand, the lower part of the non-SC wire B in liquid generates a voltage drop $V_L = R(T_b)I$ if the non-SC wire B is in a resistive state and has a resistance $R$ at the temperature $T_b$ of liquid, so that the terminal voltage $V_B$ of the non-SC wire B is given by $V_B = V_G + V_L$. Therefore, the difference voltage $\Delta V = V_B - V_A$ becomes equal to the voltage drop for the part of non-SC wire B in liquid, $V_L$. Finally, the liquid level can be obtained from the difference voltage $\Delta V$ proportional to the wire length of non-SC wire B placed in liquid.

The non-SC wire B with a normal resistance same as the SC wire A can be realized as follows:

1. The non-SC wire B may be composed of only sheath materials in the SC wire A
2. A non-heat-treated wire just after drawing for the SC wire A may be used as the non-SC wire B
3. The non-SC wire B may be obtained from an additional heat treatment of the SC wire A
4. Mechanical disconnection between crystal grains in the SC wire A may lead to the non-SC wire B

3. Numerical simulation

In order to confirm the validity of the proposed configuration of level sensor, numerical calculations are carried out. Since the wires are straight and very thin, the temperature profiles along them can be computed numerically.
Table 1. Parameters for numerical calculation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structure of wire</td>
<td>MgB$_2$/Fe/Stainless steel</td>
</tr>
<tr>
<td>Diameter of wire</td>
<td>0.1 mm</td>
</tr>
<tr>
<td>Ratio of cross-sectional area</td>
<td>1/1/2</td>
</tr>
<tr>
<td>Length of wire</td>
<td>300 mm</td>
</tr>
<tr>
<td>Critical temperature</td>
<td>33 K</td>
</tr>
<tr>
<td>Boiling temperature of liquid hydrogen</td>
<td>20.4 K</td>
</tr>
<tr>
<td>Heat transfer coefficient of gaseous hydrogen</td>
<td>0.01 W/cm$^2$·K</td>
</tr>
<tr>
<td>Temperature gradient in gaseous hydrogen</td>
<td>0.2 K/mm</td>
</tr>
<tr>
<td>Applied current, $I$</td>
<td>0.35 A</td>
</tr>
</tbody>
</table>

Fig. 2. (a) Resistances per unit length of SC wire A and non-SC wire B as a function of temperature for numerical simulation; (b) Time evolution of liquid level and applied current for numerical simulation

obtained from a one-dimensional heat balance equation. The numerical code to solve the one-dimensional heat balance equation for the conventional type of SC level sensor has already been established [5, 6], and it is used here. The numerical parameters are listed in Table 1. The mono-cored MgB$_2$ superconductor is located in a stainless steel sheath with a barrier layer of iron for an SC wire A. The diameter and length of the wire is 0.1 mm and 300 mm, respectively. The critical temperature is 33 K. Fig. 2(a) shows the resistances per unit length of the SC wire A and a non-SC wire B as a function of temperature for numerical simulation. The temperature dependence of resistance for the SC wire A is estimated according to the amounts of all the materials constituting the wire [5, 6]. The specific heat and thermal conductivity as a function of temperature for the SC wire A have also been formulated in the same manner as the literatures [5, 6]. The specifications for the non-SC wire B are identical to those for the SC wire A except for a finite resistance below the critical temperature. Moreover, the boiling temperature of liquid hydrogen is 20.4 K. The heat transfer coefficient of gaseous hydrogen is also fixed at 0.01 W/cm$^2$·K [5, 6], and the temperature gradient is assumed to be 0.2 K/mm above the liquid level. Fig. 2(b) shows the time evolution of liquid level and applied current for numerical simulation. The level of liquid hydrogen varies from 250 mm to 50 mm in the first step between 100 s and 200 s and then from 50 mm to 250 mm in the second step between 300 s and 400 s under a constant current of 0.35 A applied to the wires, where the position of 0 mm is set at the lowermost end of the wire and 300 mm is for the uppermost end.

Fig. 3 shows the numerical results of temperature profiles along the SC wire A and non-SC wire B during decrease in the liquid level from 250 mm to 50 mm between 100 s and 200 s. The dotted lines represent the temperature profiles just before applying the transport current. The temperature profiles for the non-SC wire
Fig. 3. Numerical results of temperature profiles during decrease in liquid level for (a) SC wire A and (b) non-SC wire B

Fig. 4. Numerical results of temperature profiles during increase in liquid level for (a) SC wire A and (b) non-SC wire B

B are almost identical to those for the SC wire A except for slight temperature rise in the part immersed in the liquid. The temperature profiles during increase in the liquid level from 50 mm to 250 mm between 300 s and 400 s are also drawn in Fig. 4, where the discrepancy between the numerical results for the SC wire A and non-SC wire B is scarcely found as well. Furthermore, it can be seen from the comparison between Fig. 3 and Fig. 4 that there is no hysteresis for the temperature profiles and the almost similar distribution of temperature is obtained for the fixed liquid level. Fig. 5(a) shows the numerical results of output voltages for the SC wire A and non-SC wire B, $V_A$ and $V_B$. The difference voltage between them, $\Delta V = V_B - V_A$, is also evaluated. It is found that the output voltage $V_B$ for the non-SC wire B is always larger than that for the SC wire A due to the existence of the voltage drop in the part immersed in the liquid. The output voltages in Fig. 5(a) are redrawn for the liquid level as shown in Fig. 5(b), where the lower horizontal axis represents the wire length immersed in the liquid and the upper axis is for the wire length in the gas. It can be seen that the output voltage $V_A$ for the SC wire A drawn by a dotted line has a one-to-one relation with the liquid level and is a function of the wire length in the gas. However, the output voltage $V_A$ is nonlinear due to the strong dependence of resistance on temperature as shown in Fig. 2(a), which is mainly caused by containing iron.
Voltages (V)

0 1 2

Time (s)

(a)

(b)

Fig. 5. (a) Time evolution of output voltages for SC wire A and non-SC wire B and their difference voltage; (b) Dependence of output voltages on liquid level

in the wire. On the other hand, it is found that the difference voltage $\Delta V = V_B - V_A$ has a linear relationship with the wire length in the liquid. This is because the difference voltage $\Delta V$ is almost equal to the voltage drop in the part of the non-SC wire B immersed in the liquid, which is given by the product of the resistance at the temperature of liquid and the applied current as already mentioned in the section 2.

4. Experiments

In order to evaluate the proposed principle of operation experimentally, a level sensor for liquid hydrogen is fabricated. An MgB$_2$ monofilamentary wire with only a stainless-steel sheath is prepared by means of an in-site powder-in-tube (PIT) method to suppress the temperature dependence of resistance in the normal state as low as possible [9]. The diameter of the wire is 0.14 mm, and the effective length is 200 mm. The ratio of stainless-steel sheath to the MgB$_2$ core is 2.81. The critical temperature is also estimated as 33 K. A non-heat-treated wire just after the drawing is used as the non-SC wire B.

Fig. 6 shows an example of the time evolution of sensor output and pressure during refill and discharge of liquid hydrogen. The constant transport current of 300 mA is applied to the fabricated sensor. In order to compensate the sensor output, the difference voltage between the output voltages for the SC wire A and non-SC wire B is cancelled out in advance in a situation without liquid hydrogen in the tank. Fig. 6(a) represents the experimental results for the refill of liquid hydrogen. After that, the liquid hydrogen is discharged by pressurizing the tank with gaseous hydrogen as shown in Fig. 6(b). In both the processes, it is confirmed that the amounts of liquid hydrogen in the tank almost vary in constant rates. When the liquid hydrogen is refilled into the tank as shown in Fig. 6(a), the output of the fabricated sensor increases with the liquid hydrogen. The sensor output also becomes smaller just after refilling the liquid hydrogen. This is because the volume of liquid hydrogen usually becomes small for decrease in the pressure. After waiting for a few minutes, the liquid hydrogen in the tank is discharged outwards as shown in Fig. 6(b). The sensor output seems to be very reasonable until the tank becomes empty.

5. Conclusions

The new type of superconducting level sensor for liquid hydrogen with an MgB$_2$ superconducting wire and another wire not to present a zero-resistivity at the boiling temperature was proposed. The output voltage
of the sensor is determined by only the part in the non-superconducting wire immersed in the liquid, so that various conditions of gas such as temperature, pressure and object scarcely affect the sensor operation and therefore it is expected that the reproducibility of sensor output becomes very good. The numerical simulation was also carried out by evaluating the time evolution of temperature profiles along the wires to validate the proposed principle of sensor operation. Furthermore, the proposed type of sensor was fabricated with the in-site processed MgB$_2$ wire and its non-heat-treated wire, and the expected operation of sensor was confirmed experimentally.

References