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Abstract: An electric pump composed of an MgB2 motor is combined with superconducting level sensors using thin CuNi-sheathed MgB2 wires to transfer liquid hydrogen. An impeller is attached to the lower end of a rotating shaft on the MgB2 motor and covered with an outer casing to form a centrifugal pump. Then, the MgB2 motor and impeller are placed vertically inside a cryostat with an infill of liquid hydrogen. A glass Dewar vessel is prepared to receive the liquid hydrogen transferred from the cryostat containing the MgB2 motor. The MgB2 sensors are used not only to detect the level of liquid hydrogen but also to control the electric pump on the basis of their pre-estimated calibration curves. By using the assembled pump system, the liquid hydrogen is successfully transferred from the cryostat to the glass Dewar vessel via a transfer tube.

Highlights:

- A pump system composed of an MgB_2 motor and MgB_2 level sensors was constructed.
- The centrifugal pump was formed by attaching an aluminum impeller to the motor.
- A glass Dewar vessel receives the liquid hydrogen from a cryostat for the pump.
- The MgB_2 sensors were used to detect the liquid level and to control the motor.
- Transfer of liquid hydrogen was successfully carried out with the pump system.

Title:

Development of a liquid hydrogen transfer pump system with MgB_2 wires

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An electric pump composed of an MgB_2 motor is combined with superconducting level sensors using thin CuNi-sheathed MgB_2 wires to transfer liquid hydrogen. An impeller is attached to the lower end of a rotating shaft on the MgB_2 motor and covered with an outer casing to form a centrifugal pump. Then, the MgB_2 motor and impeller are placed vertically inside a cryostat with an infill of liquid hydrogen. A glass Dewar vessel is prepared to receive the liquid hydrogen transferred from the cryostat containing the MgB_2 motor. The MgB_2 sensors are used not only to detect the level of liquid hydrogen but also to control the electric pump on the basis of their pre-estimated calibration curves. By using the assembled pump system, the liquid hydrogen is successfully transferred from the cryostat to the glass Dewar vessel via a transfer tube.

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1. Introduction

The hydrogen economy has been investigated as one of the advanced technologies necessary for improvement in the energy and environmental problems of recent decades [1,2]. In order to effectively obtain energy by oxidizing hydrogen with a fuel cell, for example, it will be necessary to produce, transport, store, and transfer hydrogen safely and stably. In such situations, it may be essential to use hydrogen not only as a compressed gas but also as a liquefied gas, especially during transportation and storage, because the mass density of compressed gaseous hydrogen is lower than that of liquid hydrogen [3]. A candidate material for this purpose is magnesium diboride (MgB_2), a new metallic superconductor discovered in the beginning of the 21st century and having a transition temperature of 39 K [4]. This material can maintain a superconducting state with zero resistivity at 20 K, which is the boiling temperature of liquid hydrogen at atmospheric pressure. Thus, the applications of MgB_2 superconducting wires operating at the liquid hydrogen temperature are very promising in the near future [5–11].

A fully superconducting motor that drives an electric pump has been proposed for the circulation or transfer of liquid hydrogen [9]. The motor composed of an MgB_2 rotor winding enables us to suppress the operating loss in a cryogenic environment due to its synchronous rotation mode and, furthermore, to increase the synchronous torque and output power [12]. In addition, at liquid hydrogen temperature, the MgB_2 stator winding affords a greater decrease in the primary power consumption than a copper winding [13]. Furthermore, a superconducting level sensor with a CuNi-sheathed MgB_2 wire has been fabricated and tested using liquid hydrogen [8]. It has been found that decreases in both wire diameter and critical temperature are quite effective in suppressing the input power to the cryogenic environment and realizing level sensors for liquid hydrogen using

MgB_2 wires [14]. Furthermore, the physical mechanism for the automatic development of a normal zone in the MgB_2 wires with a CuNi sheath has been understood experimentally to achieve a superconducting level sensor without any heater input [15].

In this paper, a pump system developed to transfer liquid hydrogen is presented. MgB_2 level sensors are used not only to detect the liquid level but also to control the MgB_2 motor. The successful transfer of liquid hydrogen is also carried out.

2. Calibrations of superconducting level sensors

Two kinds of CuNi-sheathed MgB_2 wires with diameters of 0.0925 mm and 0.155 mm are used to detect the level of liquid hydrogen. The initial total lengths of the wires are about 300 mm. The critical temperatures of the wires are estimated at 30 K for 0.0925 mm and 33 K for 0.155 mm. Using these wires, superconducting level sensors are assembled. Two copper wires are soldered to both ends of each MgB_2 wire in advance, and they are located on the central axis of a hollow Bakelite tube. The copper wires are used to keep the MgB_2 wire straight and to facilitate its attachment to the current terminals. The effective lengths of the wires after the sensor assemblage are 260 mm for the 0.0925-mm wire and 280 mm for the 0.155-mm wire. Additional heater wire is not wound around the upper part of the current terminal because a normal zone automatically develops in the MgB_2 wire with CuNi sheath if a transport current is applied to the wire [15]. A PtCo temperature sensor is installed at the same level as the lowermost end of the sensing part in each MgB_2 wire to detect when the liquid level passes through the corresponding position.

Figs. 1(a) and (b) show the experimental results of output voltages during the repeated infill of liquid hydrogen for the fabricated level sensors with MgB_2 wires of

0.0925-mm and 0.155-mm diameters, respectively. The levels of the liquid hydrogen are estimated using a commercially available capacitance-type level sensor, the lowermost end of which is placed several tens of millimeters higher than that of each MgB_2 level sensor. After several measurements, the optimum currents for the present MgB_2 wires with the diameters of 0.0925 mm and 0.155 mm are determined as 150 mA and 300 mA, respectively. It can be seen that the reproducibility is very good. The solid lines in Fig. 1 represent calibration curves for the fabricated level sensors. The extrapolation of the calibration curve for each MgB_2 level sensor based on the capacitance-type level sensor is in good agreement with the signal from the PtCo temperature sensor.

3. Rotation tests of superconducting motor

In order to fabricate a high-temperature superconducting induction/synchronous motor [16–18], the rotor winding in a commercially available induction motor is replaced by an MgB_2 squirrel-cage-type winding. The MgB_2 wire used for the rotor winding has the three-layer structure of a mono-cored MgB_2 superconductor surrounded by inner niobium and outer copper sheaths. The MgB_2 wires are imbedded inside oxygen-free copper housings by soldering to form rotor bars and end rings. The wires have a critical current of 336 A at 20 K in a self-field. The details of the MgB_2 winding have already been published [12]. A stator composed of a copper winding and an iron core in a conventional induction motor is also used in this study. The conventional motor has a rated output power, voltage, and frequency of 1.5 kW, 200 V, and 60 Hz, respectively. The numbers of phases and poles are three and four, respectively; consequently, the synchronous rotating speed is 1800 rpm.

Fig. 2 shows the experimental results of a no-load test using the MgB_2 motor immersed in liquid hydrogen. The input voltage is increased with a constant sweep rate from 0 V to 200 V, and after a short interval, it is decreased from 200 V to 0 V. The frequency is fixed at 60 Hz. It can be seen that, initially, the motor does not rotate with increasing input voltage, and the input current increases monotonically. Then, the motor begins to rotate slowly at an input voltage of about 50 V. At an input voltage of about 70 V, the rotation speed of the motor suddenly approaches 1800 rpm and the input current also decreases sharply from an RMS value of about 10 A. Since the turn number of the stator windings per phase is 26.7, this maximum primary current corresponds to a secondary current of about 270 A, which is roughly close to the critical current of a single MgB_2 wire used for the rotor windings. A torque of about 0.4 N·m is also observed, but only during the rapid increase in rotation speed, as shown in the inset of Fig. 2. Subsequently, the motor rotates at an almost constant speed of 1800 rpm up to an input voltage of 200 V, and the input current begins to increase slightly again. With decreasing input voltage, the motor maintains a rotation speed of about 1800 rpm down to several tens of volts, after which it gradually decreases to zero. The final rotation speed of about 100 rpm in Fig. 2 is an apparent output from the tachometer used in this study, so that the actual rotation speed in the corresponding period is zero.

4. Transfer of liquid hydrogen with pump system

In order to demonstrate the transfer of liquid hydrogen using the MgB_2 motor in combination with the MgB_2 level sensors, a pump system is constructed as shown in Fig. 3. An aluminum impeller is attached to the lower end of a rotating shaft of the MgB_2 motor and covered with an outer casing to form a kind of centrifugal pump. Then, the MgB_2 motor with the impeller is placed vertically inside a metal cryostat with an infill of liquid hydrogen. The upper end of the motor's rotating shaft is extended outside the cryostat to measure rotation speed and torque. The level sensor composed of the MgB_2 wire with 0.155-mm diameter is used to determine the liquid level inside the metal cryostat. A glass Dewar vessel is prepared to receive liquid hydrogen transferred from the cryostat containing the MgB_2 motor. The MgB_2 level sensor with 0.0925-mm wire is placed vertically inside the glass Dewar vessel to measure the level of liquid hydrogen. A network video camera is installed to record the status of the liquid level through a vertical narrow slit between silver coatings; this arrangement prevents the thermal radiation from entering the glass Dewar vessel. The metal cryostat and glass Dewar vessel are connected to each other using a transfer tube with an inner diameter of 10 mm. The evaporation gases from both the metal cryostat and glass Dewar vessel flow directly to a vent line in which the pressure is almost equal to the atmospheric pressure.

Fig. 4 shows the experimental flow rates of liquid hydrogen for different rotation speeds of the MgB_2 motor. In the case without a shaft, the rotation speeds cannot be observed directly, and therefore, the speeds are obtained by conversion from input frequencies. It can be seen that the liquid hydrogen cannot be transferred at a rotation speed less than 750 rpm, whereas the flow rates increase with a rotation speed of more than 900 rpm. There is slight discrepancy between the experimental results for both cases. A maximum flow rate of 6.5 L/min is obtained at 1800 rpm. It should also be pointed out that the flow rates seem to be sensitive to several experimental conditions, such as pressure and the remaining amount of liquid hydrogen.

An example of automatic transfer of liquid hydrogen is shown in Fig. 5, where a self-produced LabVIEW® program is used to control the MgB_2 motor on the basis of the output signals from the MgB_2 level sensors. Fig. 5(a) represents the time evolution of the liquid level in the glass Dewar vessel measured by the MgB_2 level sensor with 0.0925-mm wire, whereas Fig. 5(b) is the temporal dependence of the input voltage and current of the MgB_2 motor inside the metal cryostat. A typical sequence of the motor's operation is shown in the inset of Fig. 5(a), where the motor rotates at 30 Hz if the difference between a pre-determined target value and the present liquid level is less than 20% of the effective length of level sensor (260 mm) and at 40 Hz if this difference is more than the 20%. In the case of a poor liquid level and if the difference is larger than 100%, the motor always rotates if the liquid hydrogen remaining in the metal cryostat is sufficient for cooling the motor. On the other hand, the motor does not rotate at all if the liquid level becomes higher than the target value and the difference is smaller than zero. The MgB_2 motor is operated with a pulse width modulation inverter by means of V/f control. The constant ratio of voltage V to frequency f is set at 200 V/60 Hz. This means that the frequencies of 30 Hz and 40 Hz correspond to the input voltages of 100 V and 133 V, respectively. The liquid level in the glass Dewar vessel is about 34% initially. The motor begins to rotate at $t = 0$ at a speed of 1200 rpm for the pre-determined target value at a 90% liquid level. Then, the liquid level decreases slightly with time from the flow of warm gaseous hydrogen in the transfer tube. When the transfer tube is cooled, however, the liquid level begins to increase at an almost constant rate. When the liquid level reaches 70% and the difference from the target becomes less than 20%, the rotation speed automatically changes from 1200 rpm to 900 rpm, as per the sequence. This causes a sharp reduction in the flow rate. When the liquid level finally approaches 90% of target value, the rotation of the motor is automatically stopped. After the rotation halts, the liquid level becomes constant at around 90%. In order to establish a practical pump system, more complicated sequences for the control of the motor would be required. The input current during the rotation is almost constant at 2.35 A.

5. Conclusions

A pump system composed of an MgB_2 motor and MgB_2 level sensors was constructed to transfer liquid hydrogen. The main part of centrifugal pump was formed by attaching an aluminum impeller with casing to the lower end of the rotating shaft of the MgB_2 motor. The MgB_2 level sensors were used not only to detect the liquid level but also to control the MgB_2 motor. Transfer of liquid hydrogen was successfully carried out with the prepared pump system.

Acknowledgements

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Figure captions:

Fig. 1 Dependence of output voltages from liquid hydrogen level sensors with MgB_2 wires of diameter (a) 0.0925 mm and (b) 0.155 mm. The calibration curves are drawn as solid lines.

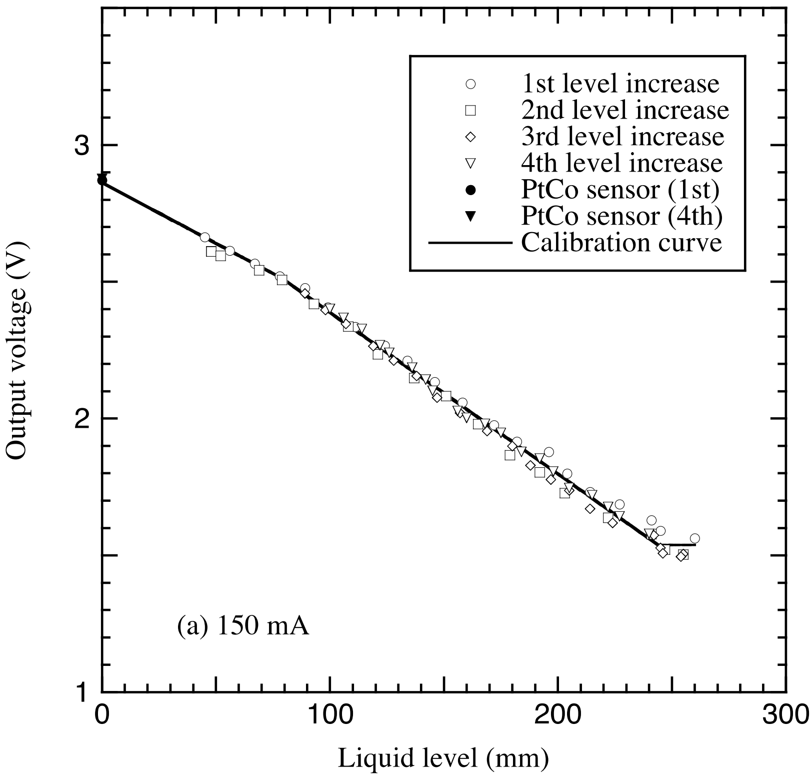
Fig. 2 Experimental results of no-load test of MgB_2 motor in liquid hydrogen. The frequency is fixed at 60 Hz. The inset shows the torque for input voltage.

Fig. 3 (a) Photograph of pump system for demonstration of liquid hydrogen transfer and (b) schematic diagram of pump system with MgB_2 motor and MgB_2 level sensors.

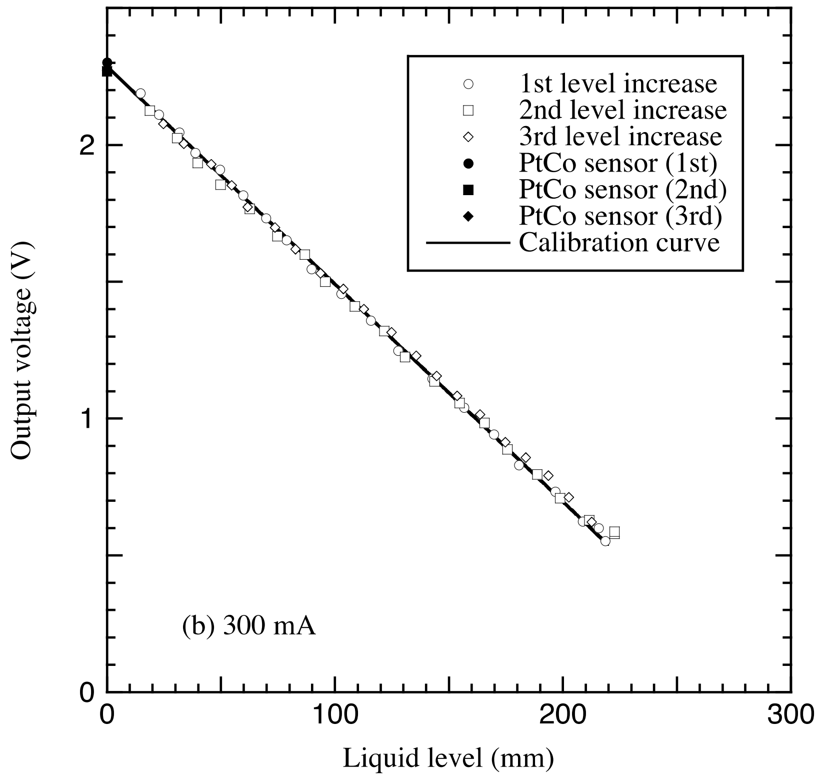
Fig. 4 Experimental flow rates of liquid hydrogen for fixed rotation speeds. Flow rates are observed for the cases with and without the shaft extended outside of the cryostat.

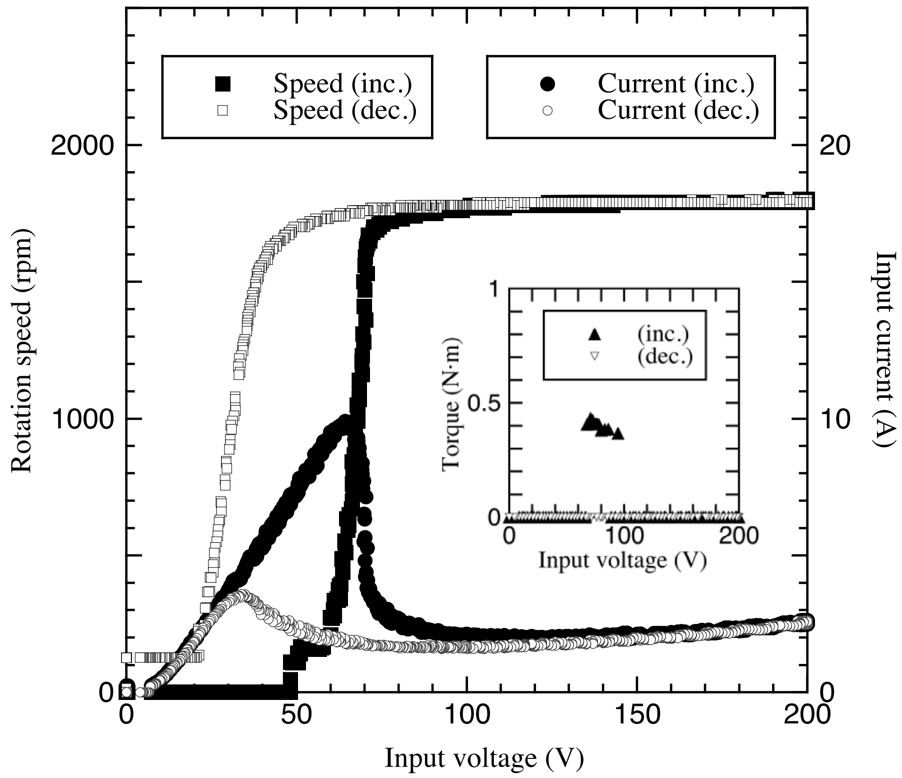
Fig. 5 Examples of automatic transfer of liquid hydrogen. (a) represents the time evolution of the liquid level in the glass Dewar vessel measured by the MgB_2 level sensor with 0.0925-mm wire, whereas (b) shows the temporal dependence of input voltage and current of the MgB_2 motor inside the metal cryostat. The vertical dashed lines represent the times when the motor's rotation speeds begin to vary.

Cryogenics, K. Kajikawa et al., Fig. 1(a)



Cryogenics, K. Kajikawa et al., Fig. 1(b)

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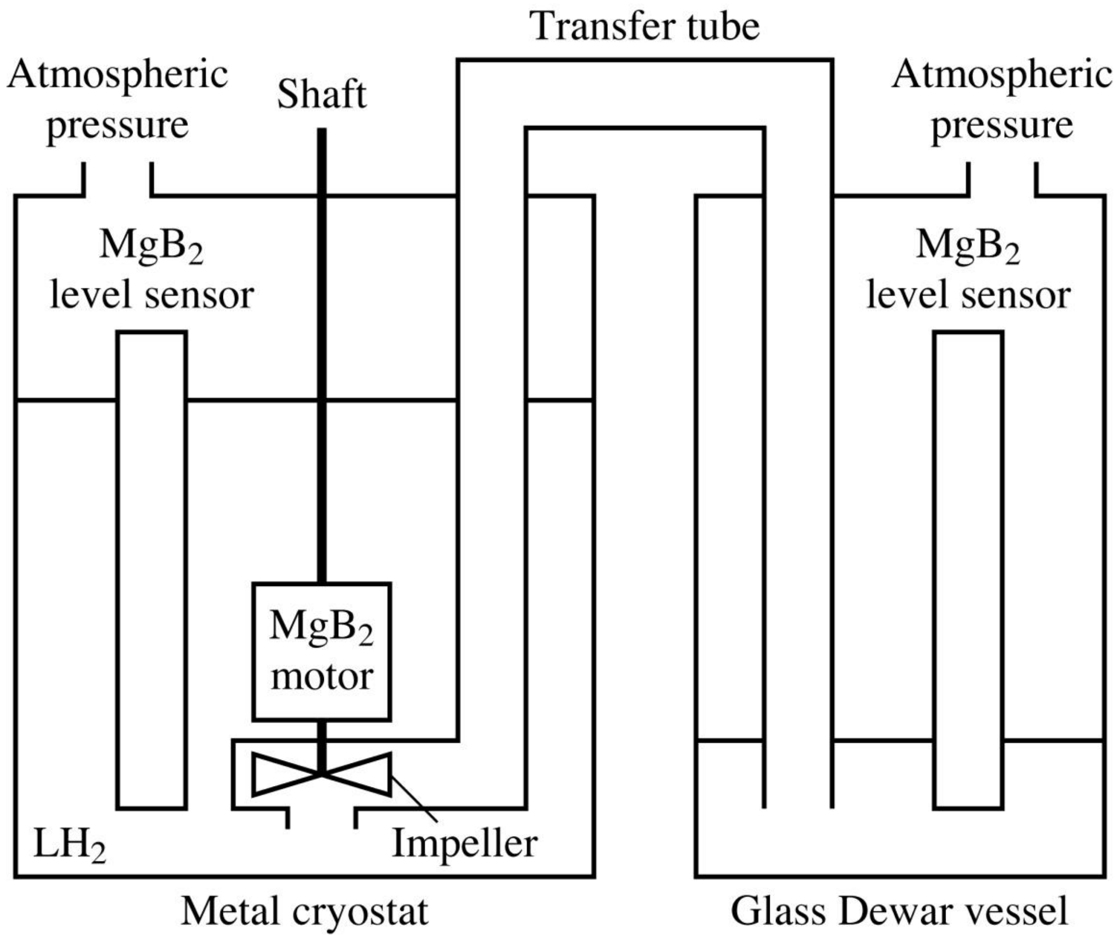
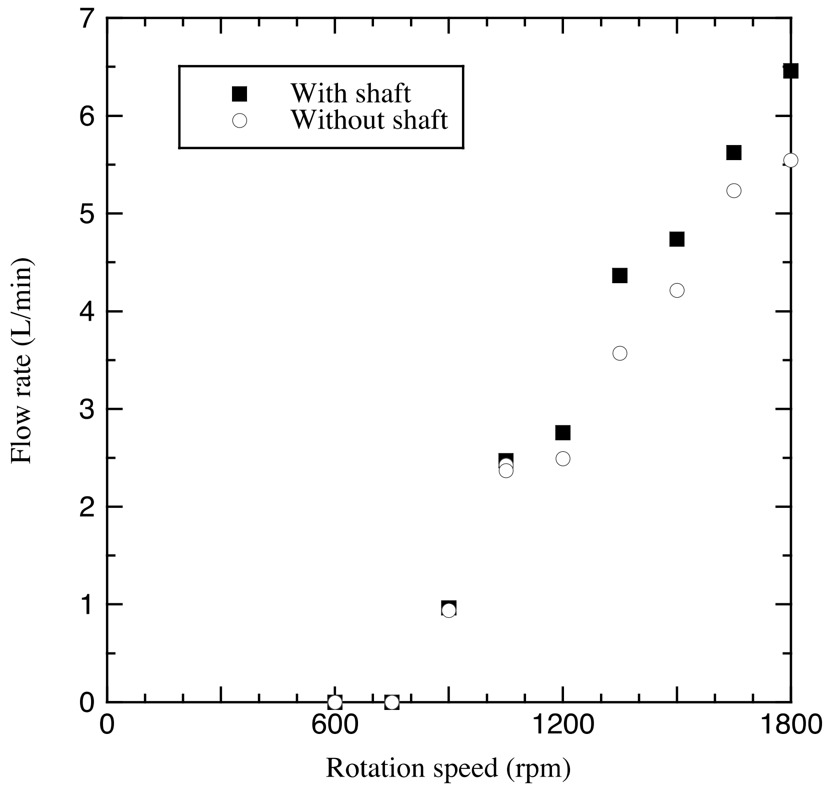
Speed (dec.)
Current (inc.)
Current (dec.)
Rotation speed (rpm)
Input current (A)
Input voltage (V)
0
1000
2000
0
10
20
0
50
100
150
200
Torque (N·m)
(inc.)
(dec.)
0
0.5
1
0
100
200
Input voltage (V)

Cryogenics, K. Kajikawa et al., Fig. 3(a)

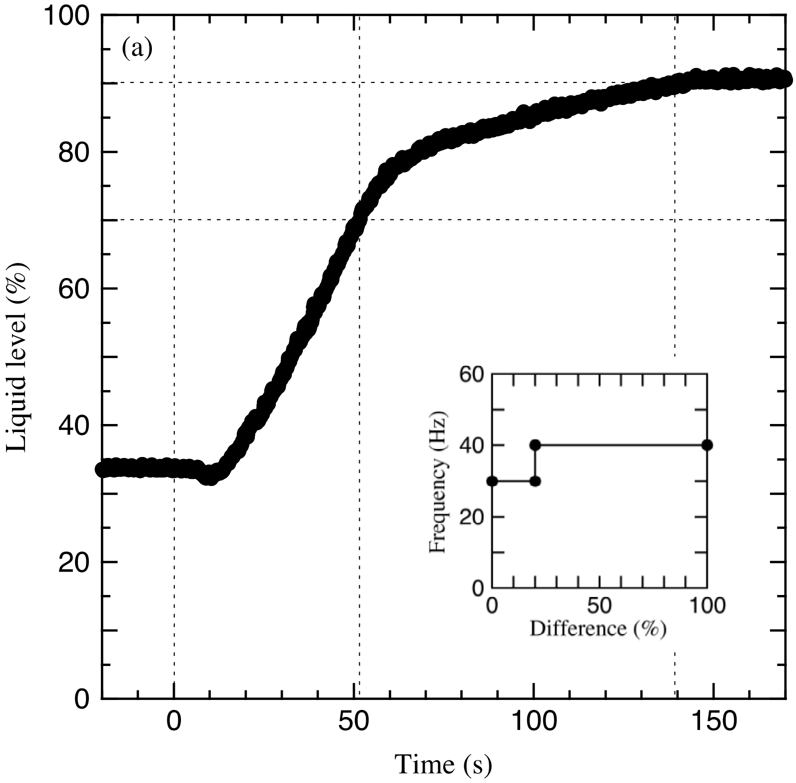
Cryogenics, K. Kajikawa et al., Fig. 3(b)



Cryogenics, K. Kajikawa et al., Fig. 4



Cryogenics, K. Kajikawa et al., Fig. 5(a)



Cryogenics, K. Kajikawa et al., Fig. 5(b)