Experimental Set-up for Evaluation of Electro-magnetic characteristics of High-Tc Superconductors Cooled by Liquid Hydrogen

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***Abstract*— Liquid hydrogen (LH_2) has excellent properties as a coolant, such as large latent heat, low viscosity coefficient and so on. Not only MgB_2 but also other high-Tc superconductors are expected to have excellent properties with being cooled by LH_2. It is necessary for a stability design of a high-Tc superconductor cooled by LH_2 to make an electro-magnetic characteristic clear. However, due to the handling difficulties of LH_2, there are only few papers on the properties of LH_2 cooled superconductors, especially under the external magnetic field. In this paper, an experimental set-up, which was designed and fabricated for evaluation of electro-magnetic characteristics of high-Tc superconductors cooled by LH_2, is described. The LH_2 cryostat of 309 mm inner diameter was set co-axially with vacuum layer in the LHe cryostat in which the LHe cooled superconducting magnet for external magnetic field (up to 7 T) was set. The LH_2 cryostat has three power leads for feeding up to 500 A to the test high-Tc superconductors.**

***Index Terms*— liquid hydrogen, heat transfer, magnetic field, high-Tc superconductor**

I. INTRODUCTION

LIQUID hydrogen (LH_2) has excellent properties as a coolant, such as large latent heat, low viscosity coefficient and so on [1]-[3]. Generally, the high-Tc superconductors, such as YBCO and BSCCO are cooled by liquid nitrogen (77K). However, it is considered that the excellent electro-magnetic properties of such materials are achieved with temperature of 20 – 40 K. There are many application studies with this temperature region using cryo-coolers. The characteristics of Jc-B (critical current density and critical magnetic flux density) of high-Tc superconductors cooled by LH_2 are not so degraded from those with LHe temperature (4.2 K), but the heat capacity of the materials in LH_2 becomes much larger than that in LHe. While MgB_2 superconductor has been developing years by years, LH_2 is expected to be the coolant for that material whose critical temperature is 39 K.

However there are many difficulties to handle gas and liquid hydrogen because of its explosive nature. For the first step, we have developed a thermal-hydraulics experimental system for liquid hydrogen in order to investigate heat transfer characteristics for wide ranges of subcoolings, pressures up to supercritical and flow velocities in forced flow cooling. Basic data on immersion cooling and forced flow cooling of liquid hydrogen are especially required for the design of applied superconductivity apparatus. Details on the experimental system and preliminary operation results have been already reported [4]-[6].

In addition to the cooling properties of liquid hydrogen, it is necessary to evaluate electro-magnetic properties of superconductors cooled by liquid hydrogen. Cooling stability in steady state and transient state of superconductors and their coils cooled by LH_2 in a certain magnetic field is important issue for design LH_2 cooled superconducting power apparatus. In this paper, an additional experimental set-up, which was designed and fabricated for the above purpose, and experimental results of cooling test, basic operation test are described. Remote control systems and interlock systems were also designed to carry out the experiment safely.

II. CRYOSTAT

A. *Design Criteria*

Purposes of the experimental setup are for evaluation of electro-magnetic properties of high-Tc superconductors cooled by LH_2. The set-up provides circumstances that not only short sample of a test superconductor but a small superconducting coil (~300 mm diameter) cooled by LH_2 can be tested with excitation of various current patterns (~500 A) in a certain magnetic field (~7 T). Test conditions are the pressure of ~2.0 MPa (up to supercritical critical pressure of LH_2 whose critical pressure is 1.293 MPa) and the temperature of 14 K~32 K (subcooled condition under several pressures).

B. *General Configuration*

Experimental setup was designed and made as shown in Fig.1 (photo view) and Fig.2 (cross-sectional view). Main components of the setup are a LHe cryostat equipped with a superconducting magnet, and a main LH_2 cryostat inside the LHe cryostat with concentric arrangement, thermally insulated by vacuum layer. Major specification of the test facility is listed in Table I.

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TABLE I

SPECIFICATION OF CRYOSTAT AND MAGNET

Liquid Hydrogen Cryostat	
Inner diameter	309.5 mm
Height (bottom to top flange)	2218 mm
Volumetric capacity for LH_2	61 L max
Liquid Helium Cryostat	
Inner diameter	350 mm
Outer diameter	630 mm
Height (bottom to top flange)	1625 mm
Volumetric capacity for LHe	175 L max
Superconducting Magnet	
Material	NbTi
Inductance	112.36 H
Rated current	175A
Max. magnetic field (center)	7 T

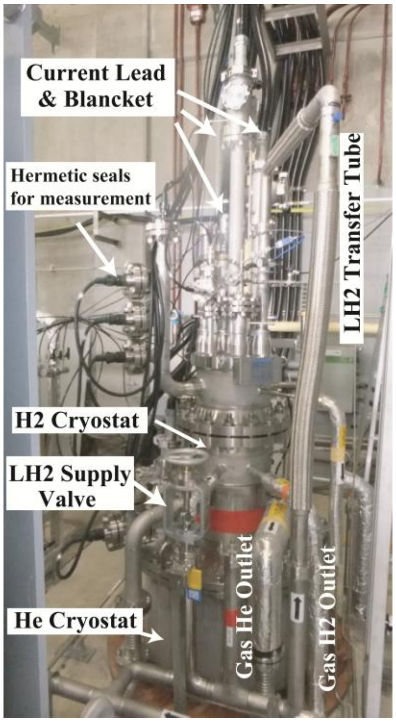

Fig. 1. Photo view of test facility (manufactured by JeccTorisha, Japan). The cryostats were set about 1 m under the ground level.

C. Liquid Hydrogen Cryostat

The LH_2 cryostat is a vacuum insulated cylindrical stainless steel vessel whose inner diameter is 309 mm and height is 2218 mm. Its inner filling capacity is 61 L. The cryostat is designed for pressures up to 2.0 MPa available for tests with supercritical condition.

Test temperature of LH_2 can be set from 14 K to 32 K according to the pressures. Sheath heater (~500 W) is set undermost area of the LH_2 cryostat. It is used for setting subcooling of the LH_2 under a certain pressures. A LHe forced flow line was set in the LH_2 area for heat exchange with LH_2 to obtain subcooling below 20 K. A gas hydrogen feeding port was set at the bottom of the cryostat to scramble up LH_2 for avoiding thermal stratification.

Five temperature sensors (Cernox) were set at LH_2 level of 50, 40, 20, 16 and 13 L. The sensors are used for monitoring not only the temperature but also the LH_2 level. A LH_2 level sensor using MgB_2 wire was also equipped

The LH_2 cryostat has three power lead terminals for test sample (superconductors) excitation. The power leads (up to 500 A) are covered with blankets pressurized by nitrogen gas kept slightly higher (5 kPa) than the atmospheric pressure for explosion-protection.

Total conductive heat was estimated to be 14.7 W without feeding current to test samples.

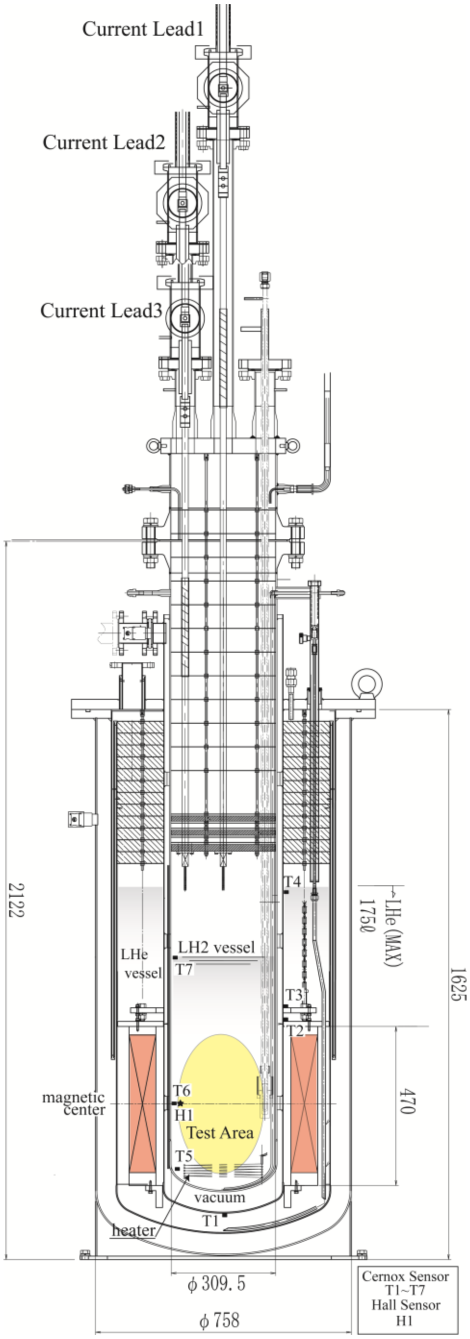

Fig. 2. Cross-sectional view of cryostats for electro-magnetic property tests of liquid hydrogen cooled superconductors.

D. *Superconducting Magnet*

The superconducting magnet is of 406.4 mm height, 400.1 mm inner diameter and 558.8 mm outer diameter. Inductance is 112.36 H and rated current is 175 A (7 T). The LH_2 cryostat is equipped though the bore area of the magnet. Maximum current sweep rate is 0.09 A/s. It takes about one hour to excite the magnet up to 7 T of test area field.

E. *Liquid Helium Cryostat*

There are three major problems in LHe Cryostat design.

First, LHe cryostat has superconducting magnet and two 200 A class power leads for magnet excitation which are covered with blankets filled with pressurized nitrogen gas for explosion-protection especially at the quench of the magnet.

Second, even if the quench occurs at the 7 T (175 A) operation, the stored energy of 1.71 MJ is dissipated in shunt diodes connected parallel to the magnet and is used to evaporate the liquid helium and to raise the material (154 kg) temperature. Temperature rise of the magnet wire at the quench was roughly estimated to be less than 105 K.

The blow-off rate and the pressure are estimated 400 g/s and 0.04 MPa, respectively using blow-off valve whose nominal diameter is 50A.

Third, to keep the test time (including magnetization and demagnetization) more than 5 hours, the conductive heat through LH_2 and LHe cryostats walls and the current leads made of copper should be reduced less than 18 W, which is calculated from the capacity 100 L of LHe overhead the magnet. Total conductive heat was designed 14.5 W at 175 A by cooling the current leads by evaporating He gas.

F. *Stray Magnetic Field and Electro-magnetic Shield*

Because of restriction on layout space, many valves and instruments must be set near the magnet. There was a concern that stray magnetic field may affect the performance of the valve control, the measuring system and so on.

The stray magnetic field analysis was carried out with 7 T excitation of the magnet. It is more than 25 Gauss within 3 m from the center of the magnet. As a result, some of the control valves and measuring instruments would be affected by the field as it was. In order to reduce the stray field at the key components less than 20 Gauss, the electro-magnetic shielding panels and boxes made of iron were equipped for control valves, weight scale, control panels based on the analytical results.

G. *Measurement, Control and Interlock Systems*

All the control valves, the excitation control and the measuring system were remote-operated through optical fiber connected computer controls. The control and measurement site is 71 m away from the facility site.

Excitation powers delivered to one of test samples and the superconducting magnet are given by the remote-controlled power supplies set next room to the main facility room.

At the event of emergency or accessing the experimental setup, the interlock system immediately shutdown all the heating power and open the vent valves for safety. As for the superconducting magnet, the stored energy will be discharged to the power supply at the maximum rate. The events of emergency are as follows; 1: LH_2 cryostat pressure exceeds 2.0 MPa, 2:GH_2 feed line pressure exceeds 2.0 MPa, 3: GN_2 pressure of the blanket for current leads exceeds 0.15 MPa and falls below 0.105MPa.

III. FUNCTIONAL TESTS

A. *Insert for LH_2 Cryostat and Test Section*

Test section is inner-bottom area (309 mm diameter and 400 mm height) of the LH_2 cryostat where the external magnetic field is generated by the superconducting magnet immersed in LHe (see Fig. 2). Fig. 3 shows the photo view of the insert for the LH_2 cryostat. The upside area of the bottom FRP flange, we have set a test sample, that is, small test coil wound by Bi2223 wire (Sumitomo DI-BSCCO wire Type ACT).

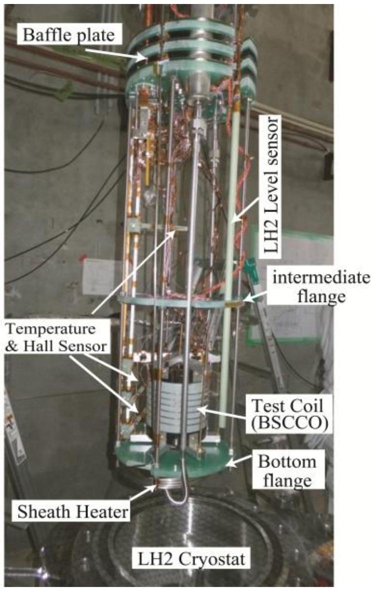

Fig. 3. Photo view of the insert for the LH_2 cryostat and test samples set in the test section.

B. *Cooling Test*

At first, the LHe cryostat was pre-cooled by liquid nitrogen.

Secondly, liquid hydrogen was transferred from LH_2 container (2000 L) through flexible transfer tube. Temperature change inside the LH_2 cryostat was measured by Cernox sensors (T5, T6 and T7; see Fig.2) as shown in Fig. 4 (left). At the time of 2 min., LH_2 transfer started, however, due to small trouble, the operation was suspended for about 8 min. The transfer operation re-started at 11 min. The temperature sensor T7 (set at 50 L level) touched liquid hydrogen at about 22 min. It took about 11 min to fill up the main cryostat. Temperature change during LH_2 re-filling is shown in Fig.4 (right) together with LH_2 level measured by the level meter using MgB_2 wire.

Then the liquid nitrogen in the outer (LHe) cryostat was purged out. LHe cryostat was filled with helium gas. Next, the liquid helium was transferred to the outer cryostat from LHe container. Temperature trends measured by Cernox sensors are shown in Fig.5. Setting location of the Cernox temperature sensors (T1 ~ T4) was shown in Fig. 2. Liquid helium was filled up within one hour.

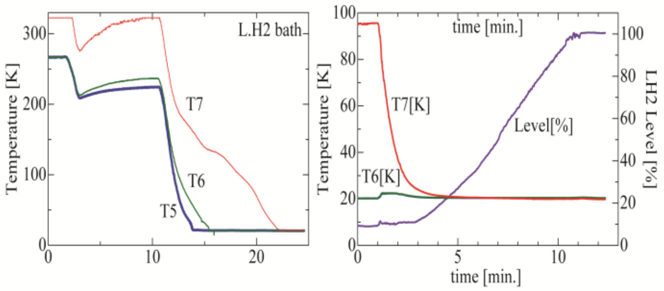

Fig. 4. Cooling down characteristics of LH_2 cryostat (left) and re-filling LH_2 (right).

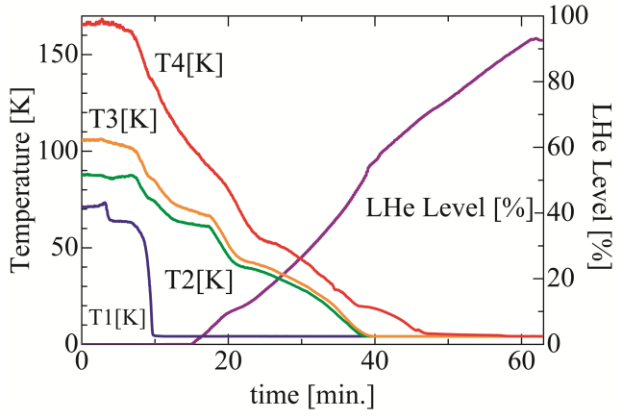

Fig. 5. Cooling down characteristics of LHe cryostat.

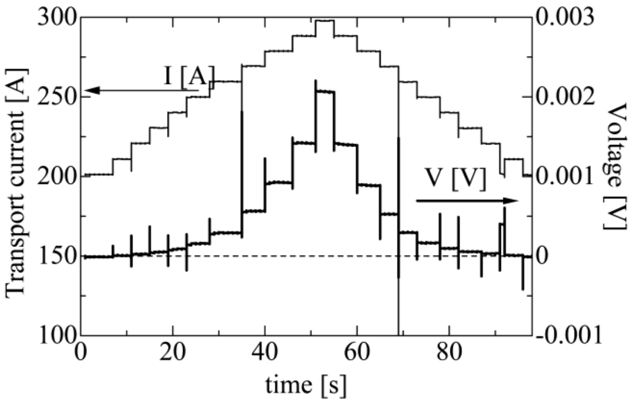

Fig. 6. Current through the Bi2223 small coil and tap voltage of the coil near the critical current.

C. *Superconductor Excitation Test*

The test Bi2223 small coil was energized by the remote-controlled power supply up to its critical current as shown in Fig. 6. The sample coil was excited up to 300 A with 10 A step by the current source. The coil tap voltage appeared above 200 A of transfer current. The current was successfully introduced to the sample set in the LH_2 cryostat.

D. *Magnetic Field at Test Section*

The superconducting magnet excitation test was carried out. The voltage range of the power source was -10 ~ 10 V. As the magnet inductance is 112.36 H, the current increasing or decreasing rate is less than 0.089 A/s. Moreover, there is voltage drop along the power lead cables to the magnet, therefore the rate becomes smaller.

Fig. 7 shows one of the sample result of the magnetic field (Hall sensor H1: see Fig.2) change test. The magnet current was ramped up to 50 A (2.1 T) and kept for 20 min. Then it was ramped up again to 100 A (4.2 T), and after 20 min., the magnet was discharged once. The magnet was charged again up to 150 A (6.3 T) and then discharged.

During the whole test, the LHe level was also plotted on the same figure. At the beginning of the charging, LHe was almost filled up full. LHe level was decreased to 55 % (level at the top flange of the magnet) with about 5 hours operation.

The stray field distribution around the cryostat was measured at every magnet current (50, 100 and 150 A). The stray field near the valves and measuring instruments was sufficiently reduced by the shielding panels and boxes. There was no degradation in performances of the valves and measuring instruments.

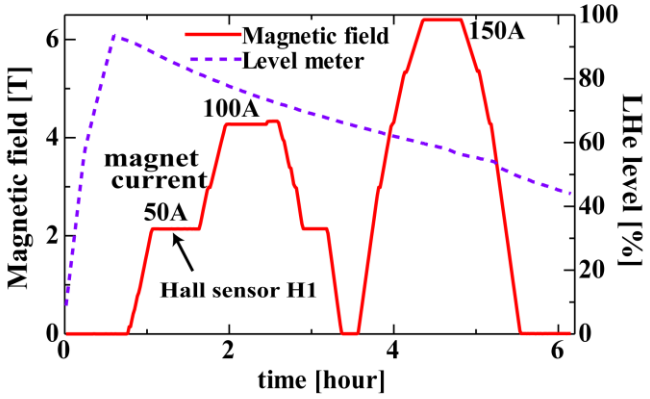

Fig. 7. Magnet excitation pattern and trend of LHe level.

IV. CONCLUSION

In order to clear the cooling properties of the LH_2, we have developed the thermal-hydraulics experimental system for wide ranges of subcoolings, pressures up to supercritical and flow velocities in forced flow cooling.

In addition, the new experimental set-up to evaluate the electro-magnetic properties of superconductors cooled by liquid hydrogen was designed and fabricated.

The cryostat of LH_2 of 309 mm inner diameter was set co-axially with vacuum layer in the LHe cryostat in which the LHe cooled superconducting magnet for external magnetic field (up to 7 T) was set. The LH_2 cryostat has three power leads for feeding up to 500 A to the test high-Tc superconductors.

The fundamental functional test results of cooling test, basic operation test were successfully performed. Remote control systems and interlock systems were also designed to carry out the experiment safely.

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