Investigation of the subcooled LN2 characteristics in the prototype cryostat for the resistive superconducting fault current limiter

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This paper presents the experimental results of the subcooled liquid nitrogen characteristics in the prototype cryostat. A subcooled liquid nitrogen of 68 K and 1 bar were easily obtained by using cryocooler and helium gas. The temperature and pressure increase during cool down and after quench were measured. Here the quench for the SFCL was simulated by a pulsed power input to a heater in the experiment. The pressure increase due to bubbles generated after quench is measured and compared with the calculated values. They agreed each other reasonably within the range of 35 % on the average.

INTRODUCTION

Liquid nitrogen is an excellent coolant for the cooling of HTS superconducting devices, such as superconducting fault current limiter (SFCL) and power cable system. As subcooled liquid nitrogen has been frequently used for better cooling performance, a subcooled liquid nitrogen cryostat is adopted for the cooling of a 6.6 kV, 200 A resistive type SFCL, which has been developed under a project of the 21st Century Frontier R&D Program started since 2001 in Korea.

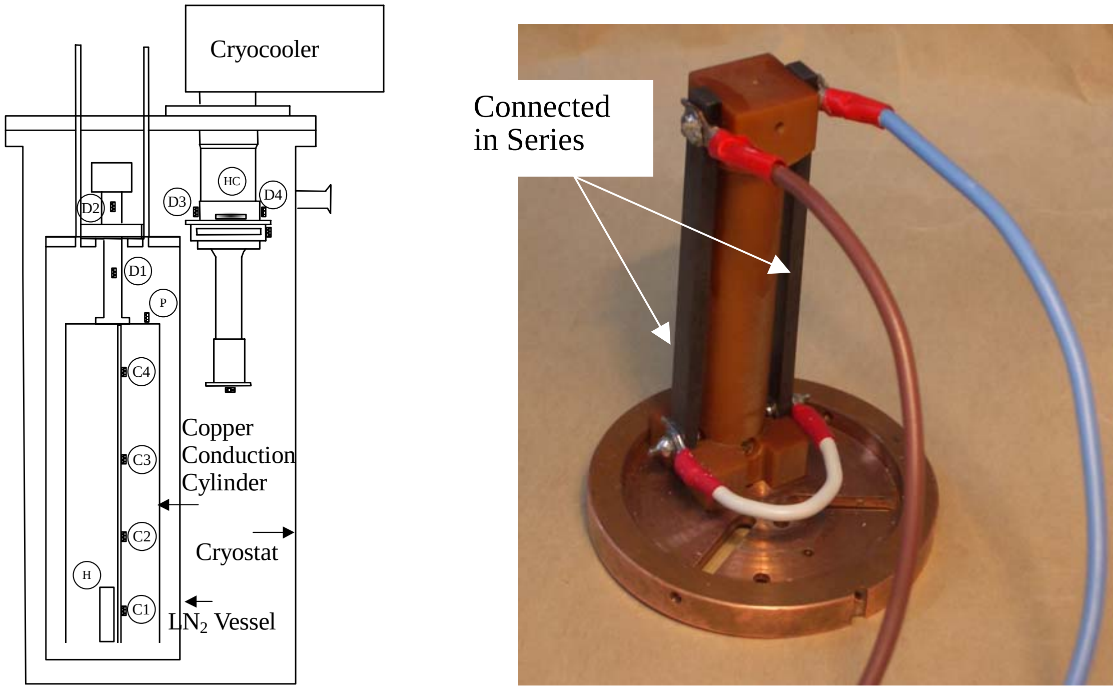
As a method of obtaining subcooled liquid nitrogen of 68 K and 1 bar, a direct cooling using cryocooler is selected. Since bubbles are generated due to quench under a fault condition, the phase change of nitrogen from liquid to gas occurs. So it is important to investigate the effect of the pressure increase due to volumetric expansion of the nitrogen on the cryostat robustness. Also, since the transient and steady state temperature variation of the subcooled liquid nitrogen affects the performance of SFCL, the cryostat needs to be fabricated to provide a uniform temperature and to endure abrupt pressure increase.

To help understand and design a practicable cryostat for investigating the characteristics related to SFCL, a prototype cryostat was fabricated [1]. The capacity of LN_2 Vessel is about 0.02 m^3. The thermal conduction cylinder made of copper connected to the cooling stage of the cryocooler is immersed in the subcooled LN_2 bath to obtain the uniform temperature. The cooling capacity of the cryocooler is controlled by a heater.

In the previous work [1] some similar experiments had been performed. This work, however, expands the scope of the experiments by providing higher input power using different SFCL simulating heater and by measuring the pressure using more accurate sensors. This paper presents the newly obtained experimental results of the subcooled liquid nitrogen characteristics in the prototype cryostat.

EXPERIMENTAL APPRATUS

The cryostat is mainly composed of vacuum vessel, LN_2 vessel, conduction cylinder and a GM cryocooler. The overall configuration of the cryostat is shown in Figure 1. As a method of obtaining subcooled liquid nitrogen, a conductive cooling using GM cryocooler was selected. The cooling load of the cryocooler is controlled by a heater installed at the first stage cold head. Detail specifications are mentioned in Ref. [1] except a ceramic heater used as a substitute for SFCL with the resistance of 20.8 ohm at 77 K, which are shown in Figure 1(b). The dimension of heater is 6 mm x 3 mm x 85 mm. In order to verify the creation of subcooled LN_2 and to investigate the influence of bubbles generated due to quench in the SFCL cryostat, it has to measure the temperature of the liquid nitrogen and the pressure inside LN_2 vessel. The temperature and pressure sensors used in this experiment are also shown in Figure 1(a).



(a) (b)

Figure 1 SFCL prototype cryostat. (a) Location and notation of the temperature and pressure sensors along with heaters, C1 – C4, D1 – D4: temperature sensors; P: pressure sensor; H: SFCL simulating heater; HC: control heater; (b) Ceramic heater simulating SFCL.

CALCULATION OF PRESSURE INSIDE OF LN_2 VESSEL

One of the major SFCL prototype cryostat design parameters is the pressure increase inside of LN_2 vessel after quench. The bubble creation during SFCL quench under fault condition induces a volumetric expansion. LN_2 vessel thickness has to be determined to endure this pressure increase. This pressure increase can be estimated from the following thermodynamic correlation [2]:

$$\frac{P_2}{P_1}\left(1+\frac{V_{LN2}}{V_1}\right)=\left(1+\frac{m_{VN2}}{m_{He}}\frac{M_{He}}{M_{VN2}}\right)\frac{T_2}{T_1} \tag{1}$$

with P_1 and P_2: pressure inside LN_2 vessel before and after quench, V_1: initial gas volume inside LN_2 vessel, V_{LN2}: LN_2 volume equivalent to the evaporated bubble mass due to quench, m_{VN2} and m_{He}: mass of vaporized nitrogen and helium, M_{He} and M_{VN2}: mass molecular weight of helium and nitrogen, T_1 and T_2: temperature of gas region of LN_2 vessel before and after quench.

In order to obtain the pressure required for obtaining subcooled LN_2 during steady state, helium gas was used. The mass of helium gas can be estimated from the following ideal gas equation [2]:

$$m_{He}=\frac{P_1 V_1 M_{He}}{RT_1} \tag{2}$$

with R: universal gas constant. Also the temperature increase, ΔT, after quench can be obtained from the heat transfer equation [3]:

$$\Delta T=\frac{Q}{m_{LN2}\cdot c_p} \tag{3}$$

with Q: input energy, c_p: nitrogen heat capacity, m_{LN2}: mass of LN_2. Using equations (1) through (3), the pressure inside LN_2 vessel after quench, P_2, can be calculated.

GENERATION OF SUBCOOLED LIQUID NITROGEN

A temperature variation representing the process of obtaining subcooled liquid nitrogen during cool down is shown in Figure 2. The temperature increases at each location (see Figure 1) of the cryostat are plotted in this figure. Before LN_2 was injected into the cryostat, the cryocooler was operated first in order to obtain cold atmosphere inside LN_2 vessel. After about 70 min, LN_2 was flowed into the cryostat. Thereafter the temperature (C1-C4) inside LN_2 vessel dropped quickly. When LN_2 was filled about 90% of the vessel, valves were closed keeping the cryocooler running until the temperature of the LN_2 dropped down to 68 K. Then helium gas was injected to obtain the pressure of 1 bar generating subcooled LN_2.

The temperature fluctuation at two sensors, D3 and D4, represents that the contacting surface between cryocooler head and copper block fits tight during cool down. Therefore the thermal contact resistance decreases and the heat is transferred efficiently since then.

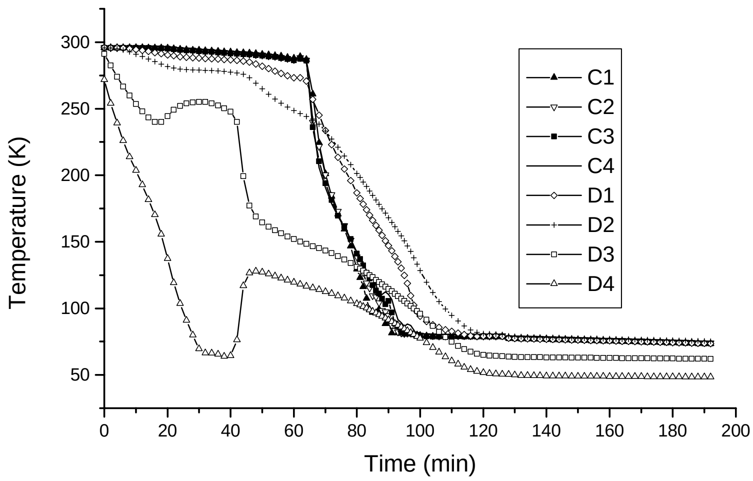


Figure 2 Temperature variation of the prototype cryostat during cool down

SFCL QUENCH TEST RESULTS

When the fault current flows in SFCL the superconductivity is broken up, and then a quench occurs. To investigate the quench phenomenon in the subcooled liquid nitrogen three SFCL quench test runs have been performed using a SFCL simulating heater, as shown in Figure 1(b). Four heat pulse shots were applied to the heater in series with the time period of 0.25 s through 2 s per each test run. The test results for several heat pulse conditions including input energy are summarized in Table 1.

Table 1 Temperature increase of the liquid nitrogen at each temperature sensor and pressure increase inside LN_2 vessel for several heat pulse conditions simulating SFCL quench

Run Number	Pulse Shot Number	Power (W)	Heating Time (ms)	Input Energy (J)	Temperature Increase (K)				Pressure Increase (measured/calculated)	
					C1	C2	C3	C4	(Pa)	|difference| (%)
1	1-a	469	250	117	0	0.028	0.033	0.047	75/61	23
	1-b	470	500	235	0.01	0.001	0.08	0.066	295/122	142
	1-c	466	1000	466	0.005	0.001	0.08	0.120	280/242	16
	1-d	467	2000	935	0.013	0.015	0.174	0.246	431/485	11
2	2-a	1,241	250	310	0.005	0.009	0.081	0.054	185/161	15
	2-b	1,219	500	609	0.007	0.008	0.063	0.167	421/316	33
	2-c	1,252	1000	1,252	0.058	0.086	0.232	0.202	803/650	24
	2-d	1,189	2000	2,378	0.878	0.457	0.6	0.689	1079/1235	13
3	3-a	2,135	250	534	0.006	0.001	0.078	0.144	526/277	90
	3-b	2,029	500	1,014	0.04	0.069	0.207	0.297	557/526	6
	3-c	2,061	1000	2,061	0.527	0.296	0.487	0.517	982/1070	8
	3-d	2,130	2000	4,260	1.239	0.706	0.57	0.544	1124/2217	49

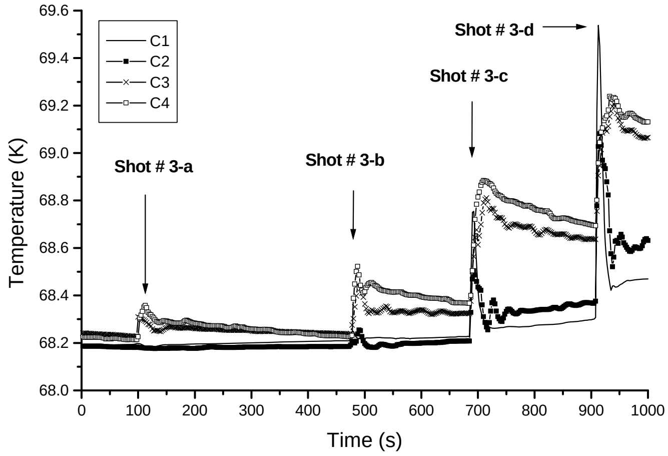


Figure 3 Temperature variation of the liquid nitrogen at each location for the test run #3.

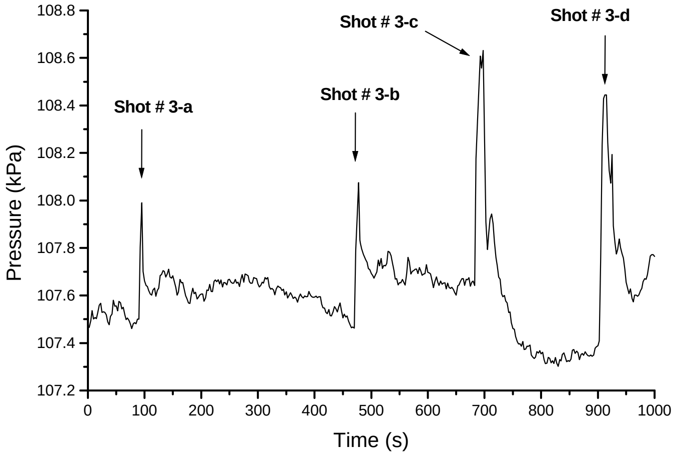


Figure 4 Pressure variation inside liquid nitrogen vessel for the test run #3.

A representative transient temperature variation of the liquid nitrogen at each sensor mentioned in Figure 1(a) for the test run #3 is shown in Figure 3. A temperature peak was found at each heat pulse shot and the values of temperature increase are summarized in Table 1. A higher peak was obtained for high input energy. It is also found that the temperatures at C3 and C4 located relatively in upper position represent the peak phenomena well because the bubble generated during quench moves upwards. However, at very high heat input of 4260 J the temperature at C1 shows the highest peak, because a huge amount of bubbles generated during quench touch the nearest sensor directly.

A representative transient pressure variation inside LN_2 vessel for the test run #3 is shown in Figure 4. The measured peak values of the pressure at each shot and the values calculated from the equation (1) – (3) are summarized in Table 1. Their differences are expressed by percentage. The average of the differences was estimated to be about 35% from the results of 3 sets of test runs. Based on the pressure measurement results, it can be found that the calculated pressure increase during quench agrees with the experimental results reasonably. Therefore the pressure calculation correlation could be used for the design of cryostat for SFCL.

CONCLUSION

To design a practicable cryostat for SFCL, a prototype cryostat was fabricated. The experimental results for the prototype cryostat have been presented. Especially the characteristics of the temperature and pressure inside the cryostat have been investigated. The subcooled liquid nitrogen was obtained by using cryocooler and helium gas. The transient temperature variations before and after pulse heating were obtained. The temperature sensors near SFCL simulating heater showed temperature peaks representing the influence of bubble generated during heat pulse. The pressure increase due to bubbles generated after pulse heating was measured and compared with the calculated values. The calculated pressure increase during quench agrees with the experimental results reasonably. It was found that the pressure calculation correlation could be applied to the design of subcooled liquid nitrogen cryostat for SFCL.

ACKNOWLEDGMENT

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