# Cool-down test of cryogenic cooling system for superconducting fault current limiter

**Yong-Ju Hong[*,a], Sehwan In[a], Han-Kil Yeom[a], Heesun Kim[b], and Hye-Rim Kim[b]**

[a] *Korea Institute of Machinery & Materials, Daejeon, Korea*
[b] *KEPCO Research Institute, Daejeon, Korea*

### Abstract

A Superconducting Fault Current Limiter is an electric power device which limits the fault current immediately in a power grid. The SFCL must be cooled to below the critical temperature of high temperature superconductor modules. In general, they are submerged in sub-cooled liquid nitrogen for their stable thermal characteristics. To cool and maintain the target temperature and pressure of the sub-cooled liquid nitrogen, the cryogenic cooling system should be designed well with a cryocooler and coolant circulation devices. The pressure of the cryostat for the SFCL should be pressurized to suppress the generation of nitrogen bubbles in quench mode of the SFCL. In this study, we tested the performance of the cooling system for the prototype 154 kV SFCL, which consist of a Stirling cryocooler, a subcooling cryostat, a pressure builder and a main cryostat for the SFCL module, to verify the design of the cooling system and the electric performance of the SFCL. The normal operation condition of the main cryostat is 71 K and 500 kPa. This paper presents tests results of the overall cooling system.

*Keywords*: Superconducting Fault Current Limiter, Cryogenic Cooling, Cool-down

## 1. INTRODUCTION

Fault current limiter is concept of an electric power device to protect electric power system from unexpected occurrence of fault current. With progresses of superconducting technologies and developments of large scale power grid, superconducting fault current limiter (SFCL) will take place as a new alternative in fault current limiting technology in electric power grid [1].

The SFCL is a device that limits quickly the fault current by using the impedance characteristics of the superconductor in normal operation condition. A large amount of heat is generated by outbreak of the fault current in the SFCL. A cryogenic cooling of the SFCL is an essential prerequisite to safely protect superconducting elements from the heat generation and to promptly recover them to the normal operation condition.

When the fault current occurs, the heat is generated in a short time but the amount is very large. Typical cryocoolers cannot remove the heat generated within the recovery time required by the power grid. Consequently, liquid cooling using subcooled $LN_2$ are widely used for the cryogenic cooling of the SFCL. In general, SFCL modules are submerged in sub-cooled liquid nitrogen for their stable thermal characteristics.

Cooling superconducting elements in subcooled $LN_2$ at below the normal boiling point (77 K) and elevated pressure is a good choice in many respects.

The critical current of the SFCL is increased at low temperature, so the size of the superconducting elements

and the cryogenic system can be reduced.

The heat dissipation during the fault current-limiting process generates bubbles by vaporization of the liquid nitrogen, resulting in the deterioration of the electric insulation. The use of the subcooled $LN_2$ at elevated pressure can suppress the generation of bubble and evade the occurrence of the cavitation in the cooling system [2-5].

However, the use of the subcooled $LN_2$ at the elevated pressure leads to drawbacks in the design of the pressure vessel and the cooling capacity of the cryocooler.

Several cryogenic cooling systems have been successfully developed for the distribution class SFCL in the subcooled $LN_2$ [6, 7]. On the other hand, transmission class SFCL has not been developed.

Recently, due to higher demand in a transmission level, 154 kV / 2 kA SFCL has been developed in Korea. The SFCL is resistive type and uses quench phenomena in HTS tapes to limit the fault current. The normal operation condition of the 154 kV SFCL is 71 K and 500 kPa. This paper reports the performance of the cooling system for the 154 kV class SFCL during the cool-down period.

## 2. COOLING SYSTEM CONFIGURATION

The cooling system for the 154 kV single phase SFCL consists of a Main Cryostat (MC), a Subcooling Cryostat (SC), a Pressure builder (PB) and a cryocooler as shown in Fig. 1. The MC is responsible for the cooling of SFCL modules below the critical temperature by removing the dissipated heat by the circulation of the subcooled $LN_2$.
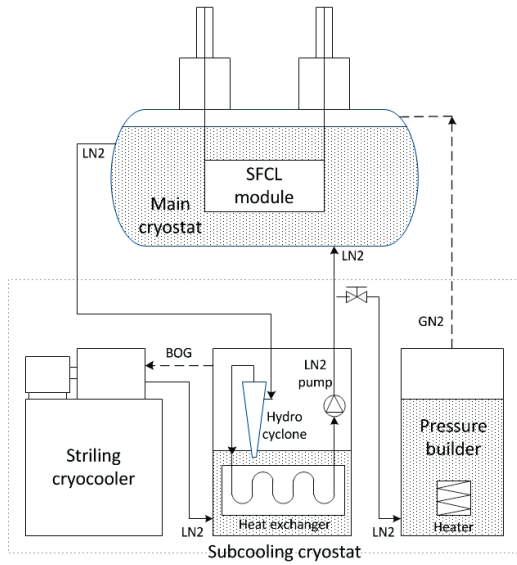
* Corresponding author: yjhong@kimm.re.kr

Fig. 1. Schematic diagram of cooling system for the 154 kV SFCL.

The volume of the MC is 30 m$^3$, and it was filled with approximately 23 ton of the subcooled LN$_2$. The LN$_2$ is supplied from the bottom of the MC, and returned at the height of 85 % of the MC, so that the LN$_2$ should be filled with the LN$_2$ up to above 85 % height of the MC.

The SC, which is consisting of a heat exchanger, a hydro cyclone and a LN$_2$ circulation pump, is responsible for the subcooling of the LN$_2$. The hydrocyclone is used to filter out particles with diameter of 50 $\mu$m or more to prevent partial discharge under high electric voltage in the MC. The heat exchanger with the capacity of 4 kW and the LN$_2$ circulation pump (Barber-Nichols Inc., BNCP-64C), which are used to cool the LN$_2$ down to 71 K, were installed.

The PB is responsible for the maintaining the pressure of the MC at 500 kPa. It is automatically controlled by the set pressure using a 2 kW heater and a solenoid valve.

A Stirling cryocooler (Stirling Cryogenics, SPC-04) is responsible for the re-liquefaction (RL) of the evaporated nitrogen due to the heat duty of the heat exchanger. Table 1 shows the detailed specifications of the cooling system.

TABLE I
SPECIFICATION OF THE COOLING SYSTEM.

| component | Specification |
|---|---|
| SFCL Module | 154 kV / 2000 A, 2G YBCO AC loss(estimated) 1.4 kW |
| Main cryostat (MC) | 71 K (500 kPa), Heat load < 800 W |
| Coolant | Subcooled LN$_2$ (500 kPa, 71 K, 23 Ton) |
| Pressure Builder (PB) | Automatic pressure control (500 kPa), Heater 2 kW |
| Subcooling Cryostat (SC) | LN$_2$ circulation pump (5700 RPM, 450 W) / Hydrocyclone (50 $\mu$m) / Heat exchanger (4 kW) |
| Cryocooler | Stirling cryocooler, RL type (4.0 kW@77 K/48 kWmax) |
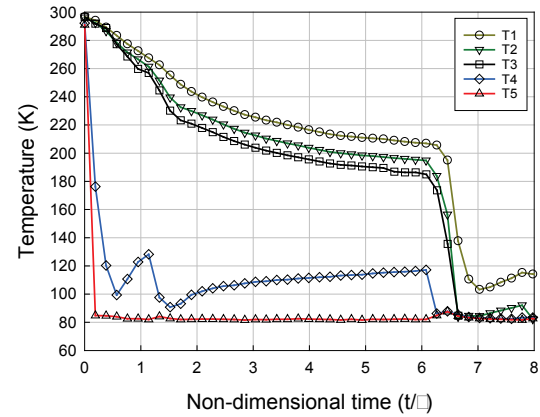


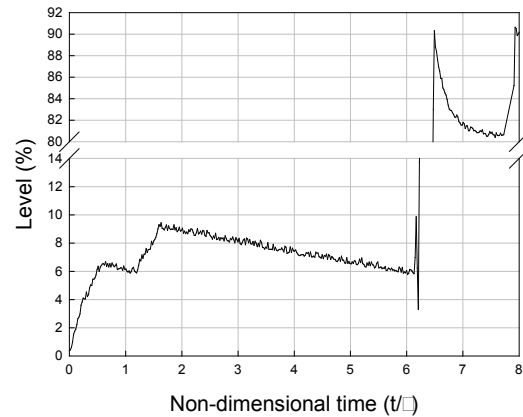Fig. 2. Temperature changes on the surface of the MC during the precooling and LN$_2$ filing process.



Fig. 3. Level of the LN$_2$ in the MC during the precooling and LN$_2$ filling process.

## 3. PERFORMANCE OF THE COOLING SYSTEM

To demonstrate the performance of components of the MC, the PB, the SC and the cryocooler, component tests were performed [8]. Then, performance tests of the cooling system for the 154 kV SFCL were carried out. Cooling processes are composed of a purging process, a cleaning and precooling process, a LN$_2$ filling process, a subcooling process and a pressurizing process.

First, all of cryostats were purged with nitrogen gas to remove impurities. Then, small amount of the LN$_2$ was filled to the cryostat for the precooling.

Fig. 2 shows temperature changes of the surface of the MC. To monitor the change of temperatures, five E-type thermocouples are attached to the surface of the MC. Attached locations (T1, T2, T3, T4, T5) are the top, the height of 90 %, 80 %, 12 % of the MC and the bottom of MC, respectively. Fig. 3 shows the level of the LN$_2$ in the MC. In the figure, a reference time ($\tau$= 14.6 hrs) denotes a time to replace the whole subcooled LN$_2$ in the MC by the operation of the circulation pump.

In the experiment, a small portion of the MC was initially filled with the LN$_2$, and the MC was to be cooled by the evaporation of the LN$_2$ during a certain amount of

time. This process is to suppress the generation of excessive thermal stress in the wall of the MC and electric bushings.

After the time of 6 $\tau$, the residual LN$_2$ in the MC was discharged for the cleaning of the cryostat, and the MC was filled with the LN2 up to the height of 90 % of the MC. For thermal stabilization, the evaporated nitrogen was vented during about 1.0 $\tau$, during that period the level of the LN$_2$ in the MC was decreased to the height of 81 % of the MC. So, the MC was refilled up to the height of 90 % of the MC. At the same time, the PB and the SC were filled with the LN$_2$. Heat loads of the MC and the PB were measured as about 722 W by using boil-off calorimetry. The heat load of the LN$_2$ pipe estimated at about 15 W, this value was based on the typical value of the heat leak of vacuum insulated pipes.

And then the vent valve of the MC was closed at the time of 8 $\tau$, and the subcooling process was carried out by turning on the cryocooler and the LN$_2$ circulation pump. Fig. 4 shows temperature changes of the surface of the MC during the subcooling process. During the cool-down, since the LN$_2$ was supplied to the bottom of the MC, the cooling was conducted sequentially in the order from bottom to top of the MC. As the temperature of the LN$_2$ was decreased, the level of the LN$_2$ in the MC was decreased as shown in Fig. 5. These phenomena come
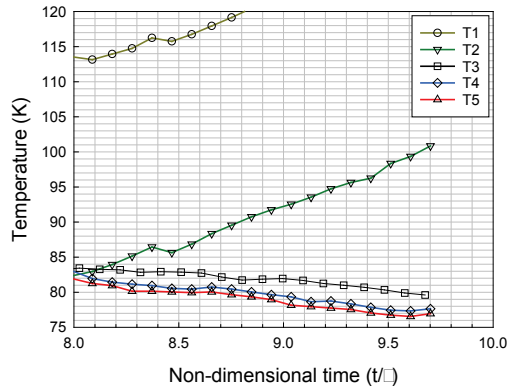
from the densification of the LN$_2$.

The subcooling process is a cooling process of the LN$_2$ from temperature of the saturated liquid to the temperature of 71 K. Fig. 6 shows temperatures of the cryocooler, the saturated LN$_2$ in the PB, the supplying LN$_2$ to the MC and the returning LN$_2$ from the MC, respectively. Silicon Diode temperature sensors were installed on the inlet and outlet pipe, and in the LN$_2$ of the SC.

From the estimated thermal masses of the inner vessel of the MC, superconducting module and LN$_2$, cool-down time is estimated at about 2.26 $\tau$ by using (1).

$$t_{CD} = \frac{\int_{71}^{77}\left[\{MC_p\}_{LN_2} + \{MC_p\}_{SFCL} + \{MC_p\}_{VESSEL}\right]dT}{Q_{ref} - Q_{loss}} \quad (1)$$

Where M is mass, C$_p$ is specific heat capacity, Q$_{ref}$ is the cooling capacity of the cryocooler, Q$_{loss}$ is the loss of the cooling system.

In the experiment, the cool-down time was approximately 3 $\tau$. This difference is believed to be caused from the turn-down operation of the cryocooler during cool-down time.

As shown in Fig. 6, the temperature difference at steady state between the cryocooler and the LN$_2$ in the SC was about 1 K, and the temperature of the LN$_2$ in the SC was over 70 K. But the calculated temperature from the vapor



Fig. 4. Temperature changes on the surface of the MC during the subcooling pressurizing process.



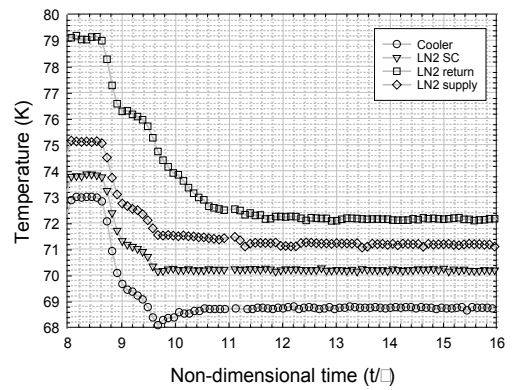Fig. 6. Temperature variation during subcooling and pressurizing process.



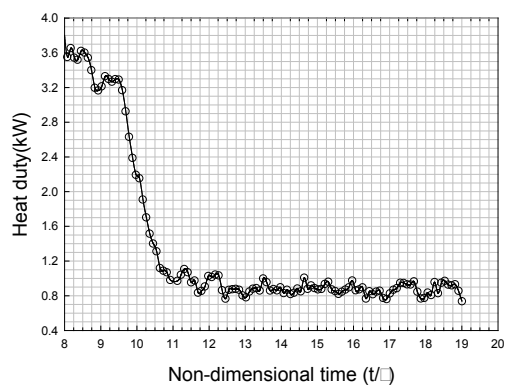Fig. 5. Level of the LN$_2$ in the PB and the MC during the subcooling and pressurizing process.



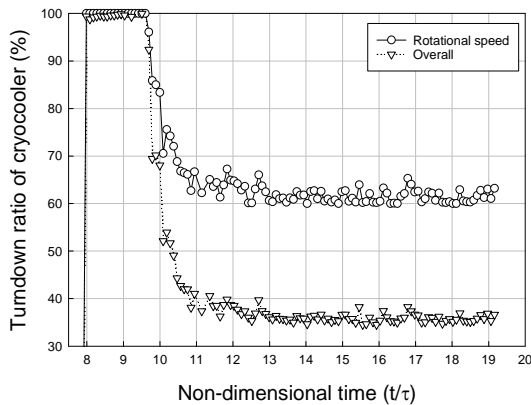Fig. 7. Heat duty varation during the subcooling and pressurizing process.

Fig. 8. Capacity control of the Stirling cryocooler during the subcooling and pressurizing process.
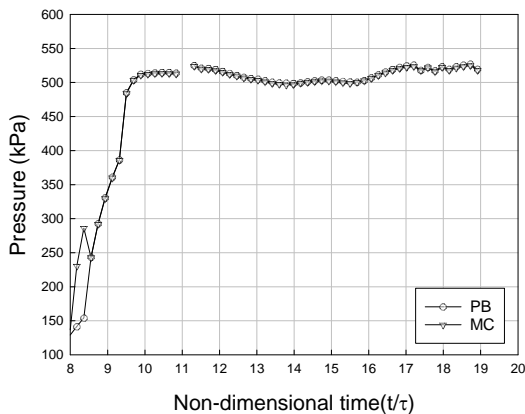


Fig. 9. Pressure variation of the PB and the MC during the subcooling and pressurizing process.

pressure was about 69.4 K. These results indicate that the temperature gradient in the $LN_2$ of the SC due to the heat dissipation from the immerged heat exchanger.

The temperature difference between the supplying and returning $LN_2$ of the MC was reduced to 1 K in the steady state. Therefore temperature variations of the $LN_2$ in the MC were determined to be maintained at less than 1 K without the operation of the SFCL. In normal operation of the 154 kV SFCL, since the heat dissipation by the superconducting element does not exceed the cooling capacity of the cryocooler, it is expected that significant changes will not occur.

Fig. 7 shows the heat duty based on the temperature difference between the supplying and returning $LN_2$. The heat load of the MC was reduced to 880 W in steady state. The heat load comes from the MC, the PB, the $LN_2$ pipe and the $GN_2$ pipe. This value was higher than the expected value of the heat loads. It is considered to have been mainly caused from the large heat load of the $GN_2$ pipe.

Fig. 8 shows the performance of the Stirling cryocooler during the subcooling and pressurizing process. The Stirling cryocooler could modulate the cooling capacity with the control of the rotational speed or the pressure of the helium gas. In early stage of operation, the Stirling cryocooler was operated at maximum load condition.

According to the reduction of the heat load as shown in Fig. 7, the Stirling cryocooler turned the cooling capacity down to the 36 % of the full capacity.

Fig. 9 shows the change of the pressure in the PB and the MC. The initial pressurization was carried out by the charging of the nitrogen gas to the gas space of the PB and the MC. Pressure control was achieved by the operation of the submerged 2 kW electric heater in the PB to evaporate the $LN_2$ and by the operation of the relief valve. As shown in Fig. 9, at the time of 10 $\tau$, the pressure of the MC and the PB approached to a set value of pressure. And then, during the period of $\tau$, the pressure was maintained to a set value without the operation of the relief valve. As shown in Fig. 5, continuous evaporations of the $LN_2$ in the PB resulted in the decrease of the level of the $LN_2$. So, at the time of 11$\tau$, it was carried out to supply the $LN_2$ from the MC to the PB until the level of $LN_2$ reached the level of 88%. At this time, there were no significant changes in the level of the $LN_2$ in the MC. After the replenishment of the $LN_2$ to the PB, in the PB and MC the pressure and the level of the $LN_2$ were slowly changing during the period of 6 $\tau$. Due to the continuous evaporation of the $LN_2$ in the PB and the condensation of the $GN_2$ in the MC, the level of the $LN_2$ in the MC was gradually increased.

In conclusion, the $LN_2$ and the SFCL module in the MC were maintained at the operation condition of 71 K, 500 kPa during more than 9 $\tau$.

## 4. SUMMARY

In this study, we tested the cool-down performance of the cooling system for the prototype single phase 154 kV SFCL, which consist of the stirling cryocooler, the SC, the PB and the MC for the SFCL module, to verify the design of the cooling system and the cool-down procedure.

Cooling processes are composed of a purging process, a cleaning and precooling process, a $LN_2$ filling process, a subcooling process and a pressurizing process.

Results confirm that the cooling system and process are designed to ensure the normal operation condition of 71 K, 500 kPa. And temperature variations of the $LN_2$ and the SFCL module in the MC are less than 1 K after the cool-down

## REFERENCES

[1] H. P. Kraemer, W. Schmidt, H. Cai and B. Gamble, "Superconducting fault current limiter for transmission voltage*,*" *Physics Procedia*, vol. 36, pp. 921-926, 2012.

[2]  K. Nam, B.-Y. Seok, J. Byun, H.-M. Chang, "Suppression of bubbles in subcooled liquid nitrogen under heat impulse," *Cryogenics,* vol. 47, pp. 442-449, 2007.

[3]  J. Ko, H. Yeom, Y. J. Hong, H. Kim, S. J. Park, D. Y. Koh and H. R. Kim, "Study on thermal response to instantaneous heat generation in LN2 chamber for HTS-FCL," *IEEE Trans. Applied. Superconductivity,* vol.23, 2013, Art. ID. 5603204.

[4]  S. In, H. Yeom, J. Ko, Y. J. Hong, H. Kim, S. J. Park, D. Y. Koh and H. R. Kim, "Experimental study on vaporization of subcooled liquid nitrogen by instantaneous heat generation in LN2 chamber for HTS-FCL," *IEEE Trans. Applied. Superconductivity,* vol.25, 2015, Art. ID. 3800204.

[5]  Y. Ohtani, T. Yazawa, S. Kurita, T. Kuriyama, S. Nomura, T. Ohkuma, N. Hobara, Y. Takahashi and K. Inoue, "Cryostat for 66 kV/750 A high-Tc superconducting fault current limiter magnet," *IEEE Trans. Applied. Superconductivity,* vol. 14, pp. 855-858, 2004.

[6]  L. H. Gong, Z. C. Fang, X. D. Xu, X. D. Jiao, L. F. Li and L. Y. Xiao, "The cryogenic system of the 10.5 kV/1.5 kA high Tc superconducting fault current limiter," *Cryogenics,* vol. 47, pp. 450-454, 2007.

[7]  J. F. Maguire and J. Yuan, "Status of high temperature superconductor cable and fault current limiter projects at American Superconductor," *Physica C,* vol.469, pp. 874-880, 2009.

[8]  H. Yeom, Y. J. Hong, S. In, J. Ko, H. B. Kim, S. J. Park, H. Kim and H. R. Kim, "Cooling performance test of the superconducting fault current limiter," *Progress in Superconductivity and Cryogenics,* vol.16, pp. 66-70, 2014.