Development of cooling system for 66/6.9kV-20MVA REBCO superconducting transformers with Ne turbo-Brayton refrigerator and subcooled liquid nitrogen

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Abstract. We developed a turbo-Brayton refrigerator with Ne gas as a working fluid for a 3 φ -66/6.9kV-2MVA superconducting transformer with coated conductors which was bath-cooled with subcooled LN₂. The two-stage compressor and expansion turbine had non-contact magnetic bearings for a long maintenance interval. In the future, we intend to directly install a heat exchanger into the Glass-Fiber-Reinforced-Plastics cryostat of a transformer and make a heat exchange between the working fluid gas and subcooled LN₂. In this paper we investigate the behaviour of subcooled LN₂ in a test cryostat, in which heater coils were arranged side by side with a flat plate finned-tube heat exchanger. Here a He turbo-Brayton refrigerator was used as a substitute for a Ne turbo-Brayton one. The pressure at the surface of LN₂ in the cryostat was one atmosphere. Just under the LN₂ surface, a stationary layer of LN₂ was created over the depth of 20 cm and temperature dropped from 77 K to 65 K with depth while, in the lower level than that, a natural convection flow of LN₂ was formed and temperature was almost uniform over 1 m depth. The boundary plane between the stationary layer and the natural convection region was visible.

1. Introduction
In Japan we have developed 3 φ -66/6.9kV-20MVA RE₄Ba₂Cu₃O₇₋δ (RE: Rare Earth, Y, Gd, Eu, henceforth REBCO) superconducting transformers with a current limiting function as a national project [1]. The subcooling of liquid nitrogen (LN₂) was required from the viewpoint of dielectric strength. We have finished the design of a 20MVA transformer and fabricated a 1/10 model, i.e. 3 φ -66/6.9kV-2MVA one. The superconducting windings were installed in a Glass-Fiber-Reinforced-Plastics (GFRP) cryostat and cooled with subcooled LN₂ at 65 to 77 K. The iron core was located at room temperature. We developed a turbo-Brayton refrigerator with neon gas as a working fluid together with the 2 MVA transformer [1, 2]. The cooling capacity was 2kW at 65K. Here an expansion turbine and a two-stage turbine compressor with non-contact magnetic bearings were adopted for the sake of a long maintenance interval. However in the present 2MVA model, LN₂ was forced-flowed between the GFRP cryostat and an additional cryostat in which a pumping system and a heat...
exchanger between the neon gas and the LN₂ were installed. We adopted a similar subcooled LN₂ circulation system for a 1 φ -22/6.9kV-1MVA transformer with Bi2223 superconducting windings though the cryocooler was Gifford-McMahon-type, which was built in 2000 [3]. The pumping systems were for general use and had long shafts between propellers in LN₂ and motors at room temperature. They naturally had no non-contact magnetic bearing. Therefore, in the present system, the maintenance interval was decide by the pumping system.

For actual transformer systems, we intend to adopt a new cooling system in which a heat exchanger was directly installed into the GFRP cryostat of a transformer. REBCO superconducting windings should be cooled through natural convection of subcooled LN₂ in the same manner as copper windings of conventional transformers are cooled through natural convection of insulation oil [4]. In this study we investigated the behavior of subcooled LN₂ in a test cryostat, in which heater coils as a substitute for superconducting windings were arranged side by side with a flat plate finned-tube heat exchanger. Here a He turbo-Brayton liquefier/refrigerator was used as a substitute for a Ne turbo-Brayton refrigerator for convenience. It was connected with the copper pipe of the heat exchanger.

2. Construction of a cooling test system
The flow diagram of the cooling system which was adopted for a 3 φ -66/6.9kV-2MVA REBCO superconducting transformer system is shown in figure 1 [1].

![Figure 1. The flow diagram of the cooling system which was adopted for 3 φ -66/6.9kV-2MVA REBCO superconducting transformer [1].](image1)

![Figure 2. The flow diagram of the cooling system in the future. In this paper a He turbo-refrigerator was used as a substitute of a Ne turbo-refrigerator one.](image2)
In figure 1, subcooled LN\(_2\) was forced-flowed between the GFRP cryostat in which the transformer windings were installed and the turbo-Brayton refrigerator through a pump unit which was installed into another cryostat. In a new test cooling system in this study, we eliminated the pump unit for circulation inclusive of the cryostat and installed the heat exchanger between the working fluid of turbo-Brayton refrigerator and subcooled LN\(_2\) into a cryostat made of stainless steel (SUS) together with heater coils as a substitute of superconducting windings. The new flow diagram is shown in figure 2. The working fluid of turbo-Brayton refrigerator circulated between the refrigerator itself and the object of cooling, which corresponded to actual superconducting machines and devices. Figure 3 shows the arrangement of the heat exchanger and the heater windings inside the SUS cryostat. We arranged 16 windows on the side of the SUS cryostat as shown in figure 4 so that we can observe the behavior of subcooled LN\(_2\).

![Figure 3](image3.png)  
**Figure 3.** Arrangement inside the test cryostat in which 8 pieces of Manganin heater coils and a heat exchanger made of copper were set up. Blue points indicate the temperature sensor positions.

![Figure 4](image4.png)  
**Figure 4.** Outer view of the test cryostat made of stainless steel. Windows for observation were arranged on each side. LED lamps attached on the windows lightened the inside.

In the present test system, a He turbo-Brayton refrigerator made by Linde Co. with a liquefying capacity of 230 liter/hour was used as a substitute of the developed Ne turbo-Brayton refrigerator for convenience. It had a cooling capacity of over 1.6 kW at 5 to 77 K as shown in figure 5 [4].
For a heat exchanger, a copper pipe with an outer diameter of 12.7 mm, a thickness of 1 mm and a length of about 5 m was bended into a repeated U-shape and many pieces of copper-fin-plates with a thickness of 0.4 mm were attached by silver soldering as shown in figure 6. The dimensions of the completed flat plate finned-tube heat exchanger were 412 mm in width, 40 mm in thickness and 800 mm in height. He gas flowed inside the copper pipe as a working fluid.

Figure 6. Photograph of a flat plate finned-tube heat exchanger made of copper.

Figure 7. Photograph of stacked eight pieces of heater coils with a surrounding glass pipe.
To simulate the ac loss generated in superconducting windings, we wound a Manganin heater wire on a GFRP bobbin into a single-layer solenoid with a diameter of 250 mm and a height of 100 mm and then stacked the eight heater coils in a line as shown in figure 7. We connected every heater coil to a power supply individually so as to simulate the actual ac loss distribution inside a superconducting winding. In addition we arranged a glass pipe with an inner/outer diameter of 290/300 mm and a height of 1050 mm around the heater coils so as to simulate a cooling channel inside the superconducting windings. The width of the cooling channel was 20 mm.

Many temperature sensors were also arranged as indicated in figure 3.

3. Experiment

LN$_2$ at 77 K was first transferred into the SUS cryostat. Just before starting to cool, 500 liter of LN$_2$ was held and the surface level of LN$_2$ was 1.32 m. Operating the He turbo-Brayton refrigerator and flowing He gas as a working fluid into the copper pipe of the heat exchanger, we cooled down LN$_2$ to a subcooled state.

We controlled the temperature of the He gas at the inlet of the heat exchanger so that the temperature of LN$_2$ did not decrease to less than 63.3 K. By overcooling, freezing LN$_2$ clung between the fins of the heat exchanger as shown in figure 8. Before starting to heat LN$_2$ by the heater coils, temperature distribution inside the SUS cryostat became a steady state.

By heating LN$_2$ with heater coils, temperatures of LN$_2$ started to increase. For example, figure 9 shows the temperature rise from around 64 K at the position of respective heater coils in the case of heat power of 200 W per one heater coil. When all the heater coils generated heat evenly and the total heat power was less than 1 kW, no bubble was observed. In that case, a rising current of LN$_2$ in the cooling channel surrounded by a glass pipe became visible even if no bubble appeared.
Figure 9. Temperature variation of LN$_2$ after all of heater coils started to generate heat power of 200 W per each. As for the sensor position, refer to Fig. 3.

On the other hand, when only the uppermost and lowermost heater coils generated a heat power of 200 W per each, bubbles were produced around the uppermost heater coil although the total heat power was only 400 W. At that time, bubbles rose up by several cm from the top of the heater coils and then re-condensed and disappeared by cooling by circumambient subcooled LN$_2$ as shown in figure 10.

Figure 10. Re-condensation and disappearance of N$_2$ bubble at the top of heater coils.
At ten minutes after starting to heat the uppermost and lowermost heater coils, the temperature inside the cryostat became to stable equilibrium. The temperature distribution in the depth direction at that situation is shown in figure 11. Temperature at the surface of LN$_2$ was 77 K since the pressure was one atmosphere and temperature abruptly dropped from 77 K to 66 K with depth from the surface of LN$_2$. The depth where the gradient in temperature was observed was only 20 cm. On the other hand, in the lower level than that, temperature was almost uniform as can be seen from figure 11.

In addition we found out the following interesting phenomenon. LN$_2$ in the cryostat was divide into two layers in the height direction. The boundary plane which was created between them was visible as shown in figure 12. The level was about 8 cm in depth from the LN$_2$ surface. LN$_2$ in the upper layer was almost stationary while LN$_2$ in the lower layer formed a natural convection current whose upper limit was the created boundary plane and lower limit was the bottom of the SUS cryostat. It seems, as the result of the phenomenon, the temperature distribution as shown in figure 11 resulted. Here the top levels of the heat exchanger and the glass pipe around the heater coils were both 1120 mm in height from the bottom of the SUS cryostat whereas the surface of LN$_2$ was 1320 mm in height. The difference in height between them and also the heater power et al might decide the height of stationary layer of subcooled LN$_2$.

4. Conclusion
We built a test system to investigate the behaviour of subcooled LN$_2$ in a cryostat in which a flat plate finned-tube heat exchanger for cooling and heater coils were arranged side by side in the LN$_2$ bath. A He turbo-Brayton refrigerator was connected with the heat exchanger and He gas as a working fluid was introduced into the constituent copper pipe. The pressure at the surface of LN$_2$ was one atmosphere. As a result of a series of experiments, the following interesting phenomena was found out. Just under the LN$_2$ surface, a stationary layer of LN$_2$ was created over the depth of 8 cm and
temperature dropped from 77 K to 70 K with depth while, in the lower level than that, a natural convection current of LN₂ was formed and temperature was almost uniform at 66 K over around 1 m depth. The boundary plane between the stationary layer and the natural convection region was visible. Using the obtained results, we will develop a new cooling system, where a heat exchanger between Ne gas as a working fluid of a turbo-Brayton refrigerator and LN₂ was directly installed into the GFRP cryostat of a transformer and REBCO superconducting windings are cooled through natural convection of subcooled LN₂, so as to realize a long maintenance interval.

References
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