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A REVIEW : LIQUID COOLING CRYOGENIC TECHNOLOGY OF HTS (HIGH TEMPERATURE SUPERCONDUCTING) TRANSFORMERS

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Abstract: *One of the most critical factors for successful development of any superconducting device is the cryogenic cooling technology. Based upon the availability of cooling media, system configurations and existing cooling technologies, the approach to HTS cooling can be categorized into three large classes: batch cooling, liquid cooling, and conduction cooling. There are two approaches to liquid cooling, natural convection and pump circulation, depending upon whether the circulation pump is employed or not. The cooling using a cryocooler is also an attractive option, allowing lower operating temperature thereby providing improved current capacity in any type of conductor. But there is no back-up cooling in a conduction cooling system if a cryocooler stops suddenly, on the other hand, liquid cryogen can be used for back-up cooling in a liquid cooling system and secondly, the heat transfer is poor in conduction cooling system because of the difficulty in thermal contact between the magnets and a cryocooler.*

Key words: *Liquid cooling, Natural convection cooling, HTS Transformers.*

I. INTRODUCTION

One of the most critical factors for successful development of any superconducting device is the cryogenic cooling technology. Since the first liquefaction of helium and the discovery of the phenomenon of superconductivity in mercury by H. Kamerlingh Onnes in the early 1900s [1], a variety of practical cooling systems for superconducting devices have been developed. For the most part, these systems have utilized the niobium titanium (NbTi) and niobium tin (Nb3Sn), the so called the low temperature superconductors (LTS), which require a helium temperature environment to achieve their specific properties. In the standard cooling of the LTS systems, the low temperature helium is effectively used to maintain the systems at around 4 K [2].

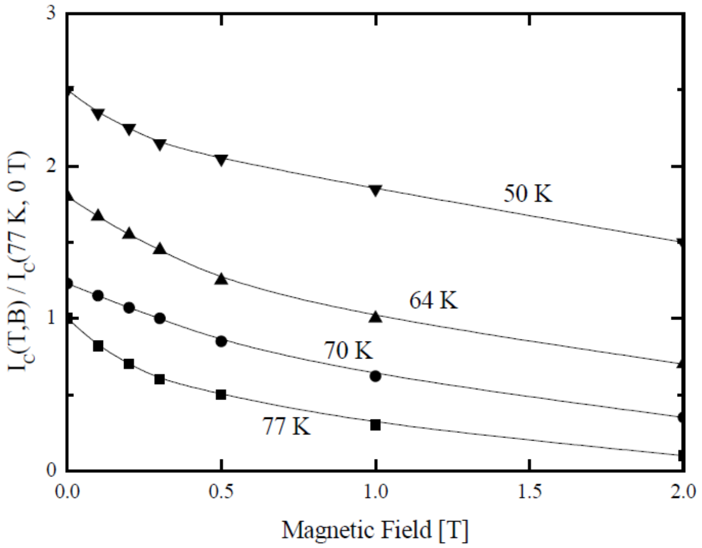

Figure 1. Critical current ratio as a function of temperature when the magnetic flux density parallels to the Bi-2223 tape surface. [3]

The discovery of the high temperature superconductor (HTS) in 1986 by Muller and Bednorz [4] opened new opportunities in the design of several power utility applications, mainly because of the easy and economical cooling with

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liquid nitrogen at considerably higher temperature around 77 K. The high temperature superconductor was initially described as liquid nitrogen superconductor, because liquid nitrogen seemed to be a technically suitable and inexpensive heat transfer fluid. The commercial applications of many HTS magnets, however, requires refrigeration at temperature below 77 K in order to take advantage of a greater critical current density of HTS and reduce considerably the size and weight of the system. Figure 1 shows the critical current ratio as a function of the temperature when the magnetic flux density parallels to the Bi-2223 tape surface [5]. It is obvious that the critical current depends upon the temperature, and the critical current ratio (IC(T)/IC(77 K)) increases with decreasing temperature for a given magnetic field[6]. For example, the critical current at 64 K is approximately three times greater than that at 77 K in a magnetic field of one tesla.

II. CRYOGENIC COOLING TECHNOLOGIES

A wide range of cryogenic cooling technologies is available to HTS magnet applications. The cooling using a cryocooler is an attractive option, allowing lower operating temperature thereby providing improved current capacity in any type of conductor. There are many types of cryocoolers, which are classified according to cycle, the Gifford-McMahon (GM) cryocooler being the most common in use today [7]. The pulse tube cryocooler is a promising candidate for HTS cooling in terms of reliability and efficiency since there are no moving parts in the cold section. However, pulse tube cryocoolers are still under development to increase the cooling capacity [8].

Based upon the availability of cooling media, system configurations and existing cooling technologies, the approach to HTS cooling can be categorized into three large classes: batch cooling, liquid cooling, and conduction cooling. Figure 2 shows the classification of the HTS cooling system.

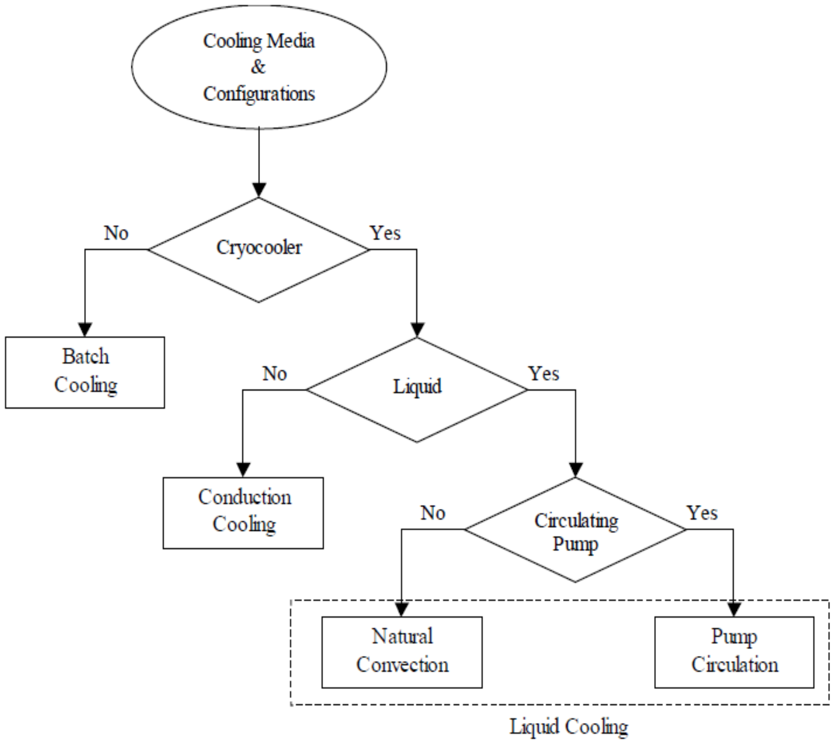

Figure 2. Classification of HTS cooling.

There are two approaches to liquid cooling, natural convection and pump circulation, depending upon whether the circulation pump is employed or not.

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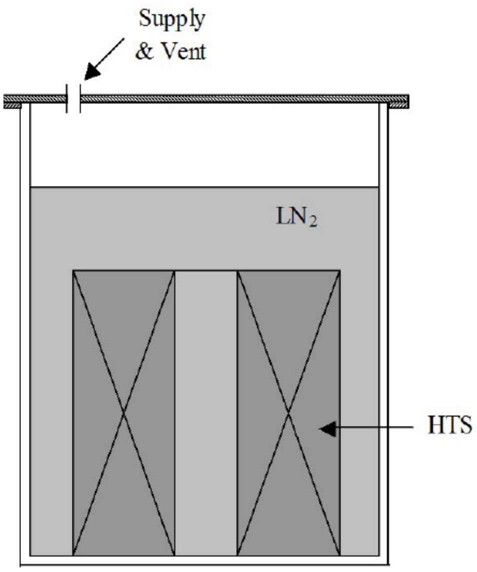

Figure 3. Batch cooling system.

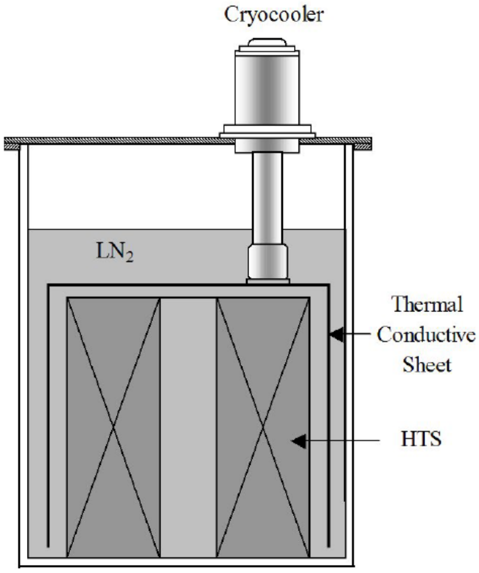

Figure 4. Liquid cooling system by natural convection.

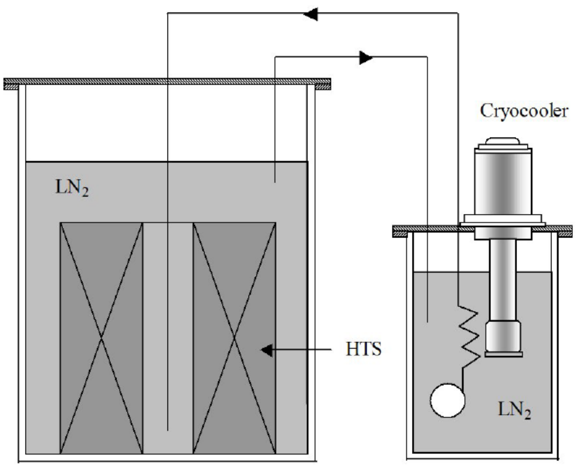

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Figure 5. Liquid cooling system by pump circulation.

In a batch cooling system as shown in Figure 3, the HTS magnet is immersed in a boiling cryogen such as liquid nitrogen where the heat is extracted by the evaporation of the liquid [8]. This cooling system can offer very high availability, however it requires considerable storage capacity of liquid for refill since the liquid is evaporated. Both the restriction of operating temperature and the space requirements may not be acceptable for many of the potential applications.

An attractive system design approach is to look at a combination of liquid cryogens with emerging cryocooler technology, which is called liquid cooling in the present study. The HTS magnet is cooled by the liquid bath, which is subcooled either by thermal conductive sheet connected to a cryocooler through natural convection mechanism as shown in Figure 4, or by forced flow liquid, which is subcooled in a secondary cryostat and circulated by cryogenic pump as shown in Figure 5. Since no pump or transfer line is necessary, the natural convection system can be more compact and efficient than the pump circulation system. However, heat transfer by natural convection is generally much less efficient than in forced convection, which may cause an excessively high temperature of HTS magnets or diminish the essential merits of the low temperature operation.

Since cryocoolers are available for a wide range of operating temperatures, they can lead to innovative HTS cooling systems, in which HTS magnets are cooled only by direct contact with cryocooler. While liquid nitrogen cooling mentioned above can only operates above 64 K in order to avoid freezing, conduction cooling system can be operated over a wider temperature range from 4 to 80 K, which is especially effective for HTS magnets whose optimum operating temperature is typically 30~50 K [9]. However, the stability of the magnet against a thermal disturbance is an important issue in superconducting magnets system [10] and the heat removal in the conduction cooling system is generally less efficient. Therefore, conduction cooling has several disadvantages compared to liquid cooling. First of all, there is no back-up cooling in a conduction cooling system if a cryocooler stops suddenly, on the other hand, liquid cryogen can be used for back-up cooling in a liquid cooling system. Secondly, the heat transfer is poor in conduction cooling system because of the difficulty in thermal contact between the magnets and a cryocooler. Generally liquid nitrogen is used for liquid cooling in cryogenics as it is easily and cheaply available.

III. LIQUID NITROGEN CRYOGENIC HTS TRANSFORMER SYSTEM

A transformer is an electrical device used to convert generation-level voltage to transmission-level voltage, and is usually composed of two conductor coils or windings wound around a magnetic core [11,12]. A current flows into the primary windings and out of the secondary windings by means of electromagnetic induction. In the ideal case, the input power is the same as the output, which is lossless voltage transformation. Since the windings in conventional transformer, however, are made of copper or aluminum wire, the resistance in the windings causes approximately 1 ~ 2 % loss of power. HTS transformers have a variety of potential advantages over conventional units of similar capacity. First of all, they have an improved efficiency and are expected to be lighter. HTS transformer windings, made of high temperature superconductor such as BSCCO or YBCO, have substantially less resistance loss, which can bring the efficiency rate of the transformer closer to the ideal. Also, the higher current density of high temperature superconductor results in reducing weight. Secondary, HTS transformers do not suffer from the insulation degradation when run at full capacity and can even tolerate being operated at up to twice rated capacity without reducing lifetime. Finally, oil and its potential hazard are eliminated in the HTS transformers since they are cooled by an environmentally friendly medium such as liquid nitrogen or helium gas [13,14]. One of the key techniques to realize these advantages in practice is the cryogenic design, as the cooling system of HTS windings determines to a large extent the size, weight, power consumption, and even the reliability of the entire transformer unit. Once the initial efforts have successfully demonstrated the feasibility of HTS transformers [15], a few different configurations of cryogenic system have been designed and tested. Zueger [16] reported the first prototype of HTS transformer with batch cooling. The HTS windings were immersed in boiling liquid nitrogen at 77 K under atmospheric pressure contained in a vacuum insulated epoxy cryostat.

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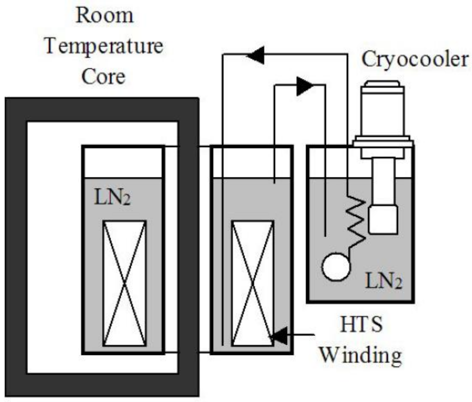

Figure 6. Schematic configuration of HTS cooling system by LN2 subcooling [Funaki et al.(17-20)]

Funaki et al. [17-20] presented forced circulation liquid cooling system for a HTS single-phase transformer. The HTS windings were contained in a main GFRP cryostat filled with subcooled liquid nitrogen at around 65 K, with an iron core located through room temperature bore of the cryostat. As shown in Figure 6, the subcooled liquid was continuously chilled by two sets of GM cryocoolers in a secondary cryostat and circulated through transfer lines to the main cryostat by a pump. Recently, they redesigned the secondary cryostat with the cryocooler located at the bottom of cryostat and the inner vessel suspended by narrow supports in order to reduce heat leak through the neck tube [21].

IV. CRYOGENIC HTS TRANSFORMER SYSTEM WITH SUBCOOLED LIQUID NITROGEN

Materials exist in three phases, solid, liquid, and vapor. Shown in Figure 7 is a phase diagram for low temperature nitrogen [22]. Subcooled liquid refers to liquid that is below its saturation temperature for a given pressure or above its saturation pressure for a given temperature. In other words, subcooled liquid is a liquid that is not in equilibrium its saturated vapor, as indicated in Figure 7. Any liquid at constant temperature is subcooled somewhat by the hydrostatic head, so that the only liquid is truly saturated is at the liquid surface. Sub cooling moves the thermodynamic state off the saturation line into the pure liquid region [23]. For pressure above the critical pressure, the fluid is in the supercritical region.

The common method to make sub cooled liquid is evacuation by a vacuum pump and then pressurization [21,24]. A temperature of liquid nitrogen around 65 K can be achieved by controlling the vacuum pump at a level of 17.4 kPa. Another approach to subcooling is achieved by employing a cryocooler and heat exchanger. Since the coldhead of a cryocooler has a limited surface area, the thermal conductive metal such as copper plate is attached to the coldhead in order to extend the heat transfer area.

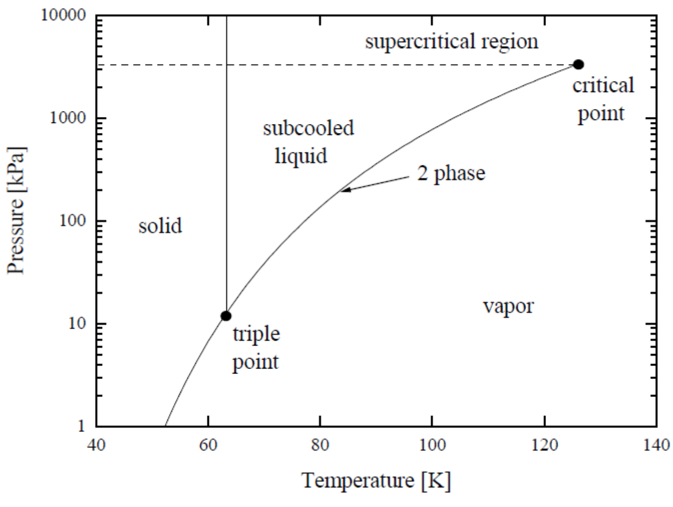

Figure 7. Phase diagram for low temperature nitrogen.

In cooling for HTS magnet application, subcooled liquid nitrogen has several advantages over saturated liquid [21,25,26]. First of all, the temperature of subcooled liquid is lower than that of saturated liquid for a given pressure, which results in increased critical current of HTS tape as described in Figure 7. Another advantage of sub cooling is augmentation of the electric insulation characteristics. The main reason for the augmentation is that the probability of bubble generation on the heated surface decreases when the liquid is cooled well below its saturation temperature.

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V. CONCLUSION

Natural convection in a cavity where each vertical surface has a uniform temperature has been studied extensively. However, natural convection in a cavity whose surface temperature decreases upwards was an unexplored problem. Through the present experimental investigation, the heat transfer between two vertical plates whose surface temperature decrease upwards turned out to have quite different behavior resulting from the onset of multi-cellular flow. Thus, the present experimental data contributes to understanding the natural convection phenomena between two plates whose surface temperature decrease upwards.

REFERENCES

1. Rose-innes AC and Rhoderick EH. Introduction to Superconductivity, Pergamon Press, 1978.
2. Van Sciver SW, Helium Cryogenics, Plenum Press, 1986.
3. American superconductor, High Temperature Superconducting Wire, ASC/HTS-FS-0004, American Superconductor Corp., Westborough, MA, January 2002.
4. Muller KA, and Bednorz JG, "The discovery of a class of high-temperature superconductors," Science, 237, 1133-1139, 1987.
5. Fleck U, Vogel D, and Ziegler B, "Cooling of HTS applications in the temperature range of 66 K to 80 K," Advances in Cryogenic Engineering, 47, 188-195, 2002.
6. Ter Brake HJM, and Wiegerinck CFM, "Low-power cryocooler survey," Cryogenics, 42, 705-718, 2002.
7. A.T.A.M. de Waele, "Pulse-tube refrigerators: principle, recent developments, and prospects," Physica B, 280, 479-482, 2000.
8. Van Sciver SW, "Cryogenic system for superconducting devices," Physica C, 354, 129-135, 2001.
9. Rey CM, Hoffman WC, Cantrell K, Eyssa YM, Van Sciver SW, Richards D, and Boehm, "Design and Fabrication of an HTS Reciprocating Magnetic Separator," IEEE Trans Appl Supercond, 12, 971-974, 2002.
10. Dresner L, Stability of Superconductors, Plenum Press, 1995.
11. Erickson RW, Fundamentals of power electronics, Kluwer Academic Publishers, 2001.
12. Del Vecchio RM, Transformer design principles, Gordon and Breach Science Publishers, 2001.
13. Kummeth P, Schlosser R, Massek P, Schmidt H, Albrecht C, Breitfelder D, and Neumuller HW, "Development and test of a 100 kVA superconducting transformer operated at 77 K," Supercond Sci. Technol, 13, 503-505, 2000.
14. Donnier-Valentin G, Tixador P, and Vinot E, "Consideration about HTS superconducting transformer," IEEE Trans Appl Supercond, 11, 1498-1501, 2001.
15. Wolsky AM, "Cooling for future power sector equipment incorporating ceramic superconductors," Argonne National Laboratory Report, Paper #2001-1, April 2002.
16. Zueger H, "630 kVA high temperature superconducting transformer," Cryogenics, 38, 1169-1172, 1998
17. Funaki K, Iwakuma M, Kajikawa K, et al., "Development of a 500 kVA-class oxide superconducting power transformer operated at liquid-nitrogen temperature," Cryogenics, 38, 211-220, 1998.
18. Funaki K and Iwakuma M, "Recent activities for applications to HTS transformers in Japan," Supercond Sci. Technol, 13, 60-67, 2000.
19. Funaki K, Iwakuma M, Kajikawa K, et al., "Development of a 22kV/6.9kV Single-phase Model for a 3 MVA HTS Power Transformer," IEEE Trans Appl Supercond, 11, 1578-1581, 2001.
20. Iwakuma M, Funaki K, Kajikawa K, et al., "Ac Loss Properties of a 1 MVA Single-phase HTS Power Transformer," IEEE Trans Appl Supercond, 11, 1482-1485, 2001.
21. Suzuki Y, Yoshida S, and Kamioka Y, "Subcooled liquid nitrogen refrigerator for HTS power systems," Cryogenics, 43, 597-602, 2003.
22. NIST, "NIST Thermophysical Properties of Pure Fluids," NIST, 1992.
23. Bejan, A, Advanced Engineering Thermodynamics, John Wiley & Sons, 1988.
24. Richardson RN, Scurlock RG, and Tavner ACR, "Cryogenic engineering of high temperature superconductors below 77 K," Cryogenics, 35, 387-391, 1995.
25. Furuse, M, Fuchino S, and Higuchi N, "Investigation of structure of superconducting power transmission cables with LN2 counter-flow cooling," Physica C, 386, 474-479, 2003.
26. Yazawa, T, Ohtani Y, Kuriyama T, et al., "66kV-calss Superconducting Fault Current Limiter Magnet – Subcooled Nitrogen Cryostat," International Cryogenic Engineering **19**, 261-264, 2002

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