Design of Indirect Closed-Cycle Cooling Scheme Coupled With a Cryocooler for a 3-MW-Class High-Temperature Superconducting Synchronous Motor

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***Abstract*—The increase in the heat generated from high-temperature superconducting (HTS) rotating components limits the applicability of a cooling method. Hence, a liquid cooling and convection cooling scheme for high-heat-flux applications has gained interest. An indirect closed-cycle cooling scheme coupled with a cryocooler is an alternative cooling technique, in which the heat of vaporization is transferred from an evaporator to a condenser with a relatively small temperature difference. The cooling system of a demonstrative 3-MW-class HTS motor is presented in this paper. A cryogen was used to maintain uniform temperature of the field coil; the maximum temperature of the HTS coils was approximately 30 K during normal operation. The operation process of the cooling system is illustrated, and the main circulation parameters, namely, cryogen flow rate and the heat flux of cooling system, are investigated.**

***Index Terms*—Close-cycle cooling concept, cryogenics cooling system, high-temperature superconducting (HTS) motor, thermal characteristics.**

I. Introduction

In high-temperature superconducting (HTS) rotating machines such as motors and generators, liquid cooling with boiling (thermosyphon) and cooling scheme using gas (convection cooling scheme) coupled with a cryocooler are employed to reduce the temperature of the rotor more effectively than possible by single-phase liquid cooling. Closed-cycle cooling scheme is an alternative cooling technology based on dissipating high local heat fluxes. A closed-cycle cooling scheme loop consists of an evaporator where heat is dissipated from the rotor and a condenser where heat is rejected to the ambient. The goal of this study is to design an effective cryogenic cooling system for a 3-MW-class HTS synchronous motor whose key design parameters are listed in Table I. In this study, first, the thermal design of rotor was performed.

TABLE I
Optimal Parameters for 3.0-MW HTS Motor Design

Number of poles	6
Operating current [A]	150
Coil straight length [mm]	795
Bobbin block length [mm]	1070
Rotor inner radius R_{fi} [mm]	414
Rotor outer radius R_{do} [mm]	460

With the aim of reducing the rotor heat loss, a comparative design of torque tube and torque disk was realized and analyzed. Then, indirect closed-cycle cooling scheme coupled with a Gifford–McMahon (GM) cryocooler was analyzed by comparing the thermodynamic characteristics of two different cryogen liquid neon (LNe) and gas helium (GHe). Finally, other characteristics, namely, the cryogen flow rate and heat flux of cooling system were analyzed to clarify the effects to rotor cooling down process.

II. Total Thermal Loss Estimation

The cryogenic cooling system is a thermal system that can be more appropriately pictured as a collection of heat-leaking material connections (mechanical, electrical, and fluid) linking a rotating superconducting winding with the environment at a stable room temperature. The presence of material links between the cold parts and the external world introduces a permanent, steady-state, heat load on the superconducting winding volume. Technically, the major rotor losses originate from 1) current leads loss, 2) torque tube conduction loss, and 3) radiation loss; the major superconducting coil losses originate from 4) Joule heating loss at mechanical lap joints, 5) superconductor index n-value dissipation loss, and 6) flux flow in an HTS tape

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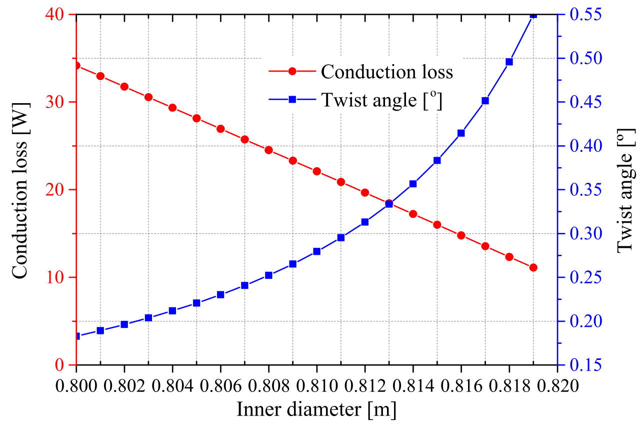

Fig. 1. Relation between conduction loss and twist angle.

exposed to DC transport currents loss and to magnetic fields. The total losses due to the combined action of a DC transport current, an external magnetic field proportional to the transport current, and magnetic field applied to the face of the tape is the sum of the six mentioned losses. These findings delineate the general configuration of the cryogenic cooling system, which is composed of the following major components: current lead loss, torque tube conduction loss, and radiation loss.

Furthermore, superconducting coils must work at temperatures lower than their critical temperature, and the superconducting supporting components must be able to withstand the huge electromagnetic force generated by the extremely large current and magnetic field. These requirements impose contradictory demands on the superconducting rotor supporting components, which must be not only strong enough to bear all the mechanical loads, but also have low heat leakage to reduce the heat load on the cryogenic system [1]. The components should also be capable of maintaining the electromagnetic torque at low rotating speed.

Because of the cooling cost, which accounts for a large portion of the maintenance cost, would then be reduced when we could decrease the thermal losses. Considering the mechanical strength of G-10 material because of its low thermal conductivity ($k = 0.53$ W/m · K), the transmission torque was designed to be 143.3 kNm (3.0 MW, at 200 rpm, direct driven, 6 poles). The conduction heat leak of the torque tube and torque disk can be calculated as follows [2]:

$$Q_t = \frac{kA}{\delta}\Delta T \tag{1}$$

where Q_t is the conduction heat leak of the torque tube, and k is the thermal conductivity of the material; k depends on temperature. ΔT, δ, and A are the temperature difference, the length of the torque tube, and the equivalent cross-sectional area, respectively. Fig. 1 highlights the relative relationship of torque tube conduction loss with the inner diameter and torsion angle σ. For safety, the torsion angle σ must be within 0.2–0.3. The optimal inner diameter was selected as 0.803 m to ensure less conduction heat loss and safer conditions. For the same design configuration for the torque disk, the final stress analysis results and heat loss characteristics of the torque tube and torque disk are summarized in Table II. Correspondingly, the torque disk thermal loss is two-thirds of the torque tube design loss. Although considering that the torque disk is less affected by heat transfer, for the disk to be sufficiently strong to transfer torque from the rotating part and stator part, combination of three disks for each model is strongly recommended, and we need a total of three models, at the two drive-ends and at the center stage.

TABLE II
THERMAL DESIGN OF TORQUE TUBE AND TORQUE DISK

Parameters	Torque tube	Torque disk
Length, l [m]	0.15	0.005
Inner diameter, D_i [m]	0.803	0.3
Outer diameter, D_o [m]	0.828	0.828
Torque, T_q [kN.m]	143.3	143.3
Twist angle, Ø [°]	0.2	0.024
Heat loss [W]	30.5	10.6

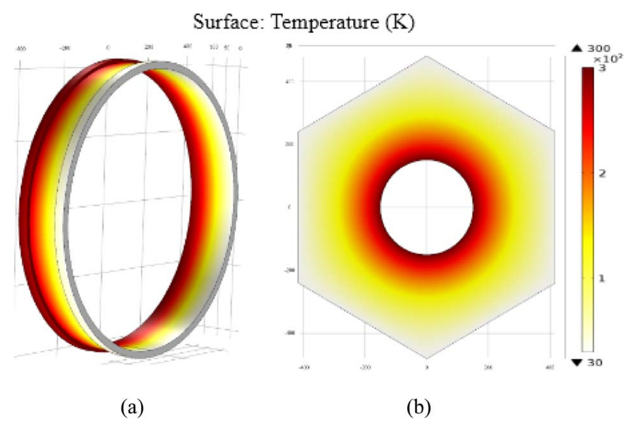

Fig. 2. Temperature distribution of the torque tube and disk. (a) Torque tube. (b) Torque disk.

TABLE III
THERMAL LOSS ESTIMATION [W]

Current leads loss	22.27
Torque tubes conduction loss	61
Radiation loss	11
Mechanical lap joint loss	0.63
Other losses	20.1
Total loss	115

At this time, the total heat loss of the required torque disk is around 95.4 W (10.6 W/disk $\times$ 9 disks $= 95.4$ W), while the total heat loss of two torque tubes is 30% less than the torque disk heat loss at 61 W. Therefore, in this study, torque tube has lower thermal loss. Fig. 2 shows the steady state temperature distribution of the torque tube and torque disk from the room temperature to the operating temperature of 30 K.

Finally, Table III summarizes the total thermal loss estimation of the cooling system for the 3.0-MW-class HTS synchronous motor [2]–[4], where the other losses account for conduction loss through support rods, residual gas, eddy current loss, intrinsic property n-value loss, and flux flow loss. Thus, the total estimated heat loss is 115 W.

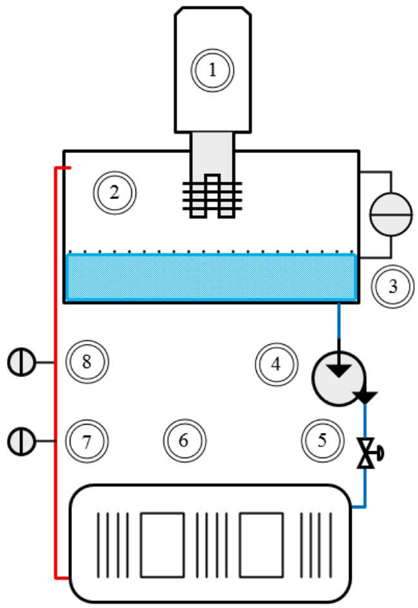

Fig. 3. Schematic of the closed-cycle cooling system.

TABLE IV
PROPERTIES OF CRYOGENIC FLUIDS

Fluid parameter		He	Ne
Triple point temperature	[K]	2.17	24.6
Boiling temperature, T_b	[K]	4.22	27.10
Critical temperature	[K]	5.19	44.4
Thermal cond. liquid at T_b	[W/m·K]	0.027	0.04
Thermal cond. gas at T_b	[W/m ·K]	0.011	0.014
Heat of vaporization, h_L	[kJ/kg]	20.7	85.9
Heat of vaporization, h_l	[J/cm^3]	2.6	104
Density (T_b, liquid)	[kg/cm^3]	125	1206
Density (T_b, vapor)	[kg/cm^3]	16.9	9.37
Density @273 K	[kg/cm^3]	0.179	0.900
Density @293 K	[kg/cm^3]	0.166	0.834
Density (T_b, liquid)/density	(273 K)	700	1340
Density (T_b, liquid)/density	(293 K)	753	1446

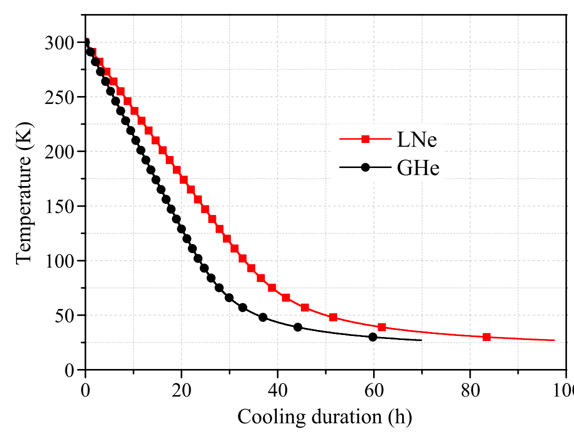

Fig. 4. Simulation results of thermal transient characteristics of the cooling system.

III. CONFIGURATION OF COOLING SYSTEM DESIGN

First, we consider the use of thermosyphon cooling and convection cooling based on gravity difference between the coolant liquid and vapor used for rotating machines, sub-cooler for cables, and small superconducting magnetic energy storage (SMES). The configuration of the cooling system for a 3-MW HTS synchronous generator using cryogens (LNe or GHe) to cool the HTS field coils at 30 K is shown in Fig. 3. It basically consists of a cryogenic refrigerator, heat exchanger, cryostat, and circulation pipe for the flowing cryogen [5].

Then, we consider the choice of a cryogenic liquid. The preferred fluids are gas helium (GHe) and liquid neon (LNe) because these are inert and do not combine with other fluids to create explosive mixtures [6]. The recent costs for each of these are as follows: LN_2 (US$ 0.3–1.5/liter), GHe (US$ 3.5–15/liter), and LNe can cost more than 50 times the price of GHe [7]. However, when selecting the cryogen, the properties of the cryogen must be carefully considered. Based on the details listed in Table IV, LNe is an ideal refrigerant for bath cooling for BSCCO rotating machines operating at 27 K [8], [9]. On the other hand, GHe may also be used to cool SMES and rotating machines operating in the temperature range 20 K to 50 K. In general, heat transfer in a two-phase channel flow depends on the heat flux, pressure level, mass flow, vapor fraction, and thermal properties of the refrigerant and also on the channel geometry. The effect of system pressure, choice of fluid, and evaporator geometry is available in literature [10]–[12].

In the design in this study, a 115-W single-stage G-M cryocooler produced by CRYOMECH and operating at 30 K with optimal thermal loss was used to ensure that the thermal shields were maintained at a temperature of 30 K. The cryocooler is of AL325 type, and its refrigeration capacity of approximately 150 W at 30 K. The parameters listed in Table III indicate that one single-stage AL325 cryocooler can sufficiently remove the heat load with a margin exceeding 23.3%. The redundant cooling capacity can balance any conduction heat leaking from the suspension structures of the thermal shield.

Then, a conductive cooling method is employed. The superconducting coils are cooled indirectly by the cold cryogen stored in the coil former, which holds the coils. The cryogen and coils are held in the interior and surface of the coil former, respectively, and the heat in the coils is dissipated to the coil former through conduction, and the heated coil former is cooled by cryogen. When the cryogen absorbs heat from the coil former, the pipelines collect the heated cryogen and send it into the heat exchanger where it is cooled again by the cold head. The cooled cryogen is pumped into the coil former through the pipelines by cryogen pump, and the next cycle begins. This is a continuous process, and the coolant circulates spontaneously in close-cycle cooling scheme. The cooling process will be simulated by using a 3D finite element analysis (FEA) simulation package. As shown in Fig. 4, we can see that the HTS coil reaches an operating temperature of 30 K after 97.5 h and 69.8 h for LNe and GHe, respectively. The cooling duration of GHe is nearly 50% less than that of LNe

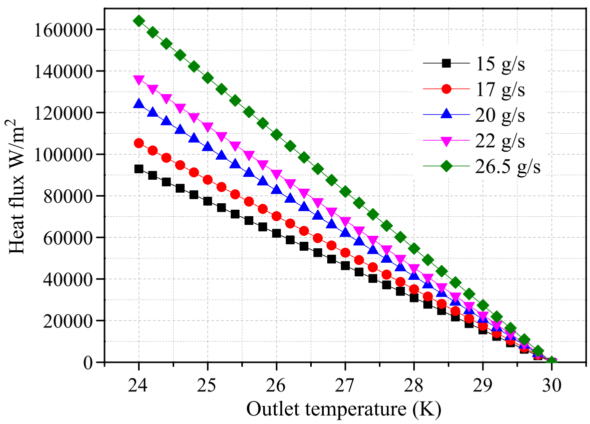

Fig. 5. Heat flux variations at different LNe flow rates.

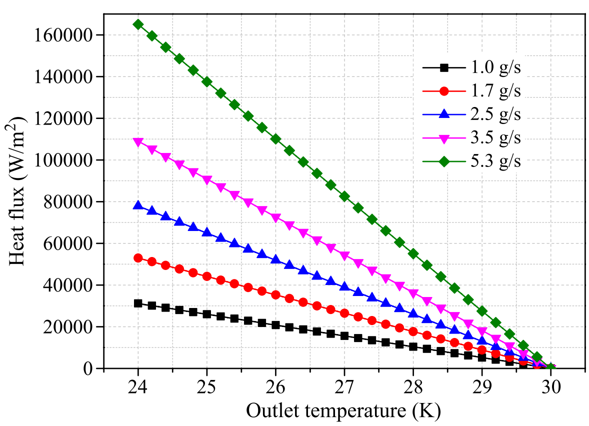

Fig. 6. Heat flux variations at different GHe flow rates.

because the heat capacity of the former (5190 J/kg·K) is much larger than that of the latter (1030 J/kg·K)

$$\dot{m} = \frac{Q_{\text{total}}}{\Delta T \int_{T_i}^{T_f} C_p(T)dT}. \quad (2)$$

When the surface heat flux is constant, the mean fluid temperature changes linearly in the flow direction because the surface area increases linearly in the flow direction (A_s is equal to the perimeter, which is constant, multiplied by the pipe length). Then, the mass flow of used cryogen is numerically estimated as shown in (2), where m is the mass flow; ΔT, the temperature difference; and $C_p(T)$, the heat capacity of the cryogen.

Figs. 5 and 6 show the relation between the flow rates of the cryogen and heat flux generated for LNe and GHe, respectively. It is easily seen that the heat flux is proportional to cryogen flow rate. The heat flux for LNe varies from 0 to 160 kW/m^2 when the flow rate is increased in the range 15 g/s to 26.5 g/s. At the same generated heat flux, the maximum GHe flow rate is 5.3 g/s and decreased to 1.0 g/s.

IV. Conclusion

An optimal cooling system was characterized in this study to cool the integration of 3.0-MW HTS motors. The principle application of the device is to make use of closed-cycle cooling scheme in the range 24.5–30 K. Therefore, it has the benefits of flexibility and availability of cryogen in Dewar systems. To reduce the heat loss, the torque tube and disk were analyzed. On the basis of this analysis, we recommend using the tube to transfer the torque.

For G-M cryocooler AL325, 2.2 L of LNe is used to maintain rotors at the operating temperature; with the total optimum heat leak, the cryocooler at 115 W is cooled to 30 K after 4 days. The mass flow of cryogen is maintained constant at 44.5 g/s by the cryopump. When GHe is used, the total volume is estimated at 22.5 L, and it will take 2.9 days to cool the rotor with the maximum flow rate of 8.8 g/s. In conclusion, this study shows that it is more effective and economical to use GHe as a cryogen because its cooling duration is 30% shorter than that of LNe and also because of its lower cost and greater availability as compared to LNe.

References

[1] D. Laskos, "Design and cavitation performance of contra-rotating propeller," M.S. thesis, Dept. Mech. Eng., Massachusetts Inst. Technol., Cambridge, MA, USA, 2010.

[2] T. D. Le *et al.*, "Thermal design of a cryogenics cooling system for a 10 MW class high-temperature superconducting rotating machine," *IEEE Trans. Appl. Supercond.*, vol. 25, no. 3, Jun. 2015, Art. no. 3800305.

[3] T. D. Le, J. H. Kim, S. I. Park, and H. M. Kim, "Conceptual design of current lead for large scale high temperature superconducting rotating machine," *Progr. Supercond. Cryogenics*, vol. 16, no. 2, pp. 54–58, 2014.

[4] T. D. Le *et al.*, "Transient characteristics of current lead losses for the large scale high-temperature superconducting rotating machine," *Progr. Supercond. Cryogenics*, vol. 16, no. 4, pp. 62–65, 2014.

[5] J. T. Cieslinki and A. Fiuk, "Heat transfer characteristics of a two-phase thermosyphon heat exchanger," *Appl. Thermal Eng.*, vol. 51, no. 1/2, pp. 112–118, Mar. 2013.

[6] R. Radebaugh, "Cryocoolers: The state of the art and recent developments," *J. Phys., Condens. Matter*, vol. 21, pp. 1–9, 2009.

[7] T. Zhang, K. Haran, E. T. Laskaris, and J. W. Bray, "Design and test of a simplified and reliable cryogenic system for high speed superconducting generator applications," *Cryogenics*, vol. 51, no. 7, pp. 380–383, Jul. 2011.

[8] B. Felder *et al.*, "A 100-W grade closed-cycle thermosyphon cooling system used in HTS rotating machines," *Adv. Cryogenic Eng.*, vol. 57, pp. 417–424, 2012.

[9] A. R. Kim *et al.*, "Performance analysis of a 10-kW superconducting synchronous generator," *IEEE Trans. Appl. Supercond.*, vol. 25, no. 3, Jun. 2015, Art. no. 5202004.

[10] R. Khodabandeh, "Pressure drop in riser and evaporator in an advanced two-phase thermosyphon loop," *Int. J. Refrigeration*, vol. 28, no. 5, pp. 725–734, Aug. 2005.

[11] R. Khodabandeh, "Heat transfer in the evaporator of an advanced two-phase thermosyphon loop," *Int. J. Refrigeration*, vol. 28, no. 2, pp. 190–202, Mar. 2005.

[12] R. Khodabandeh, "Thermal performance of a closed advanced two-phase thermosyphon loop for cooling of radio base stations at different operating conditions," *Appl. Thermal Eng.*, vol. 24, no. 17/18, pp. 2643–2655, Dec. 2004.