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High-Power Water-Cooled Magnets in Tohoku University

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Synopsis

Design, fabrication and operating results of water-cooled magnets at High Field Laboratory for Superconducting Materials in the Research Institute for Iron, Steel and Other Metals are described. The four of the eight magnets are used for hybrid magnets, and others are for single operation. Details are shown for the two magnets: one is a combined magnet named WM-4 consisting of an inner polyhelix coil and an outer Bitter-type coil which is designed to produce the magnetic fields up to 20 T in a 32 mm working bore, and the other is a single Bitter magnet named WM-5 which generates the magnetic fields up to 15 T in a 82 mm bore. This is useful for the measurement of AC loss of superconductors because of the large experimental area and the uniformity of field strength. The calculation of field distribution of the water-cooled magnets, including ones for the hybrid magnets, is also described.

I. Introduction

In 1939, a Kapitza-type magnet generating pulsed magnetic fields up to 27.3 T \(^1\) was constructed at the Research Institute for Iron, Steel and Other Metals. The whole installation was destroyed by an air raid in 1945. After the war, the high magnetic field facilities were reconstructed. A mercury rectifier was introduced to be suitable for the power source as it would be usable to produce a continuous magnetic field as well as the pulsed field. The apparatus was installed in 1959 \(^2\). The current capacity of the power source was 10 kA for 2 hours and was capable of overloading for a short time, e.g., 20 kA for 1 minute or 40 kA for 0.1 second. All of the

\(^*\) The 1822th report of the Research Institute for Iron, Steel and Other Metals.
continuous-field magnets were axially cooled Bitter-type coils. The coil was cooled by deionized water of high resistivity more than $10^6$ ohm cm which was stored in a large reservoir of 200 m$^3$ capacity. Because of the insufficient cooling capacity of the secondary cooling system the period of generated maximum field was restricted by the temperature of cooling water at the beginning of experiments. Therefore, a new cooling system was selected on the occasion of the establishment of High Field Laboratory for Superconducting Materials (HFLSM). This cooling system allowed the suitable design and stable operation of water-cooled magnets.

A superconducting magnet for the hybrid magnet has large stored energies (several MJ to over 10 MJ) and also the water-cooled magnet combined in the superconducting magnet is a high-power magnet (about 10 MW). Four water-cooled magnets for the three hybrid magnets are installed in HFLSM and four independent water-cooled magnets are also installed in order to use the systems effectively. For a high-power water-cooled magnet, a Bitter-type coil or a polyhelix coil is used generally. The coils of water-cooled magnets in HFLSM are Bitter-type and polyhelix coils. The present paper describes the design, fabrication and test results of water-cooled magnets installed in HFLSM.

II. Design of the water-cooled magnets

The water-cooled magnets were designed under the following electrical power source and cooling system. Rated output of power source is 8 MW for continuous use. Maximum current is 23 kA and maximum voltage is 350 V. Cooling capacity is 6 MW for continuous use. Maximum flow rate of water through a magnet is 350 m$^3$/h. Hydraulic head loss of magnet is less than 15 kg/cm$^2$. Temperature of inlet water of a magnet has been held between 6 °C and 15 °C.

The characteristics of eight water-cooled magnets in HFLSM were listed in Table 1. WM-1(a and b), WM-2 and WM-3 are the inner magnets for hybrid magnets HM-1, HM-2 and HM-3, respectively; the details were described in the earlier papers. WM-4 and WM-5 will be described in the following sections.

Other water-cooled magnets were named WM-6 and WM-7. In order to obtain a high homogeneity field, WM-6 magnet was designed as a single Bitter-type and slightly splitting magnet. It generates 12.4 T with 4.6 MW in a 62 mm working bore. Figure 1 shows a field distribution along a coil axis (z-axis) and Fig. 2 shows the contour map of field strength of WM-6. As shown in Fig. 2, this magnet has
Table 1 Characteristics of water-cooled magnets in HFLSM

<table>
<thead>
<tr>
<th>Magnet name</th>
<th>Bore (mm)</th>
<th>Field (T)</th>
<th>Power (MW)</th>
<th>Current (kA)</th>
<th>Type of magnet</th>
</tr>
</thead>
<tbody>
<tr>
<td>(for hybrid magnet)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WM-1a</td>
<td>32</td>
<td>19.6</td>
<td>7.4</td>
<td>22.5</td>
<td>polyhelix</td>
</tr>
<tr>
<td>1b</td>
<td>52</td>
<td>17.0</td>
<td>7.0</td>
<td>22.3</td>
<td>polyhelix</td>
</tr>
<tr>
<td>WM-2</td>
<td>52</td>
<td>15.7</td>
<td>6.3</td>
<td>21.4</td>
<td>double Bitter</td>
</tr>
<tr>
<td>WM-3</td>
<td>32</td>
<td>13.0</td>
<td>3.1</td>
<td>11.5</td>
<td>Bitter</td>
</tr>
<tr>
<td>(for single operation)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WM-4</td>
<td>32 (20.1)</td>
<td>6.6</td>
<td>20.8</td>
<td></td>
<td>polyhelix and Bitter</td>
</tr>
<tr>
<td>WM-5</td>
<td>82</td>
<td>15.0</td>
<td>6.7</td>
<td>20.9</td>
<td>Bitter</td>
</tr>
<tr>
<td>WM-6</td>
<td>62</td>
<td>12.4</td>
<td>4.6</td>
<td>13.7</td>
<td>Bitter</td>
</tr>
<tr>
<td>WM-7</td>
<td>52</td>
<td>13.7</td>
<td>4.2</td>
<td>12.6</td>
<td>double Bitter</td>
</tr>
</tbody>
</table>

Figure 1  Field distribution of WM-6 along z-axis.

Figure 2  Contour map of field strength of WM-6.

Figure 3  Calculated field distribution of HM (hybrid magnet) and WM (water-cooled magnet). The fields of HM are calculated by the sum of SM (superconducting magnet) and WM. (SM=12 T and WM=19 T for HM-1a, SM=12 T and WM=17 T for HM-1b. SM=8 T and WM=16 T for HM-2. SM=8 T and WM=13 T for HM-3.)
the field homogeneity of \( 5 \times 10^{-4} \) in a region of sphere of 14 mm diameter. WM-7 magnet is an economized energy type double Bitter magnet. This magnet can generate up to 13.7 T with 4.2 MW in a 52 mm bore. The field distribution of the superconducting and water-cooled magnets installed in HFLSM are calculated and are shown in Fig. 3.

1. WM-5 Bitter-type magnet

Required characteristics of WM-5 are as follows. An outer diameter is less than 380 mm. A required working area for experiments is greater than 55 mm diameter \( \times \) 50 mm height, in which a deviation of field strength from the central field should be less than 2 percent. The maximum operating speed of current increasing form 0 to 23 kA is desired as high as possible because of measurement for characteristics of superconducting materials in transient magnetic fields.

The optimum coil shape is determined by taking account of the mechanical and thermal limitations. The thickness and the cooling holes distribution of a Bitter disk are calculated by Clement's empirical equation \(^8\). According to the equation, effective inner and outer radii of \( i \)-th segment \((r_{i,i}^\prime \) and \( r_{o,i}^\prime \)) divided by adjoining circular lines through the center of cooling holes were expressed as :

\[
\ln(r_{i,i}^\prime) = \ln(r_{i,i}) + [1-\exp(-kn_{i,i}d/\pi r_{i,i})] \ln(1-d/r_{i,i}), \quad (1)
\]

\[
\ln(r_{o,i}^\prime) = \ln(r_{o,i}) + [1-\exp(-kn_{o,i}d/\pi r_{o,i})] \ln(1+d/r_{o,i}), \quad (2)
\]

where \( r_{i,i} \) and \( r_{o,i} \) are the inner and outer radii of the circular lines, \( n_{i,i} \) and \( n_{o,i} \) are the number of holes on these lines, \( d \) is the radius of holes and \( k \) an adjustable constant (see Fig. 4a). According to Clement, the best value for \( k \) is 1.9. Electric current through the \( i \)-th segment is expressed as follows :

\[
I_i = \int_{r_{i,i}}^{r_{o,i}^\prime} j(r) \frac{V_0 t}{2 \pi p} \ln(\frac{r_{o,i}^\prime}{r_{i,i}}), \quad (3)
\]

where \( j(r) \) is a density of current as a function of radial distance \( r \) (inversely proportional to \( r \)), \( V_0 \) the across voltage of a disk, \( p \) the resistivity of material of the disk and \( t \) the thickness of the disk. Dissipated power of the \( i \)-th segment is

\[
W_i = \left( V_0^2 t / 2 \pi p \right) \phi_i, \quad (4)
\]
where \( \phi_i = \ln(r_{0,i}/r_{1,i}) \).

(5)

The temperature rise of the conductor is determined by the balance of Joule heating and cooling through the surface contacting to water. The temperature rise of any segment is uniform if the numbers of holes \( n_{i,i} \) and \( n_{o,i} \) are equal to \( n \) at any line and \( \phi_i \) is constant \((=\phi)\) except for the innermost segment \((\phi_{in})\) and the outermost segment \((\phi_{out})\). Thus total current of the disk, \( I \), is expressed by

\[
I = \frac{V_0 t}{2\pi D} \left[ \phi_{in} + (m - 1)\phi + \phi_{out} \right],
\]

(6)

where \( m \) is the number of the circular lines. When the cooling water flows through the innermost clearance of coil with the same velocity, the relation between \( \phi_{in} \) and \( \phi \) is obtained as

\[
\phi_{in} = \left( \frac{1}{2} + \frac{a_{in}}{nd} \right) \phi,
\]

(7)

where \( a_{in} \) is the inner radius of the disk. \( \phi_{out} \) is also obtained as the same. If the inner and outer radii of the disk \((a_{in} \text{ and } a_{out})\) are given, the optimum distribution of cooling holes is calculated by the equations (5) and (7).

\[ a : \text{circular cooling holes.} \quad b : \text{slender cooling slots.} \]

Figure 4  Distribution of cooling holes in a Bitter disk for design by Clement's equation. \( r_{i,i} \) and \( r_{o,i} \) are inner and outer radii of \( i \)-th segment. Prime means effective radii. \( d \) is radius of cooling holes. \( w_{i,i} \) and \( w_{o,i} \) are width of inner and outer cooling slender slots of \( i \)-th segments. \( g \) is a distance between two neighboring slots. In the case of slender slots, the current density is different from each other in different parts (1), (2) and (3).
Slender cooling slots designed by Weggel 9) are adopted in three inside concentric lines of cooling holes (see Fig. 5). As shown in Fig. 4b, a segment is divided in three parts; (1), (2) and (3). Supposing the current density in part (3) is a half of part (2) and the total current through (1) is equal to the sum of currents through (2) and (3), the resistance of the segment is expressed by combination of the resistance of each part. This assumption is approximately based on the results of analyses for the current density distribution in the conductor disks by means of finite element method 10). The current $I_i$ through the $i$-th segment is roughly obtained as

$$I_i = \frac{V_0 t}{2\pi D} \Phi_i,$$

where

$$\Phi_i = \ln \left( \frac{r_{o,i}'}{r_{i,i}'} \right) \left[ 1 - \frac{ng}{\pi (r_{o,i}'+r_{i,i}')} \right]^{-1} + \frac{2ng \ln(r_{o,i}'/r_{i,i}')}{{\pi}4(r_{o,i}'-r_{i,i}'+w_{o,i}+w_{i,i})} \right]^{-1},$$

where $g$ is a distance between two neighboring slots and $w_{i,i}$ or $w_{o,i}$ is width of a slot at the inner or outer circular line of $i$-th segment. If $\Phi_i$ is fixed to a constant value of $\Phi$, substituting $\Phi_i$ to the equation (5), a correction term of Clement's equation for slender slots is obtained. $\Phi_{in}$ is obtained similarly to equation (7). When the cooling holes on the one side of the segment are round holes and those on the other side are slender slots, the correction can also be made similar to that mentioned above.

Figure 5  Bitter disk of WM-5.
Figure 5 shows the cooling-hole pattern in the Bitter disk of WM-5 determined by computation under the condition that \( n = 36 \), \( m = 18 \), \( d = 1.2 \text{ mm} \), \( a_{\text{in}} = 45 \text{ mm} \), \( a_{\text{out}} = 190 \text{ mm} \) and \( t = 1.2 \text{ mm} \). There are 18 larger holes for bolts to support a stack of the conductor and insulator disks. The conductor disk has a parallel slit of 2.5 mm. The disturbance of the current density due to the bolt hole and the contacted part of adjacent conductor disks are corrected too. Designed coil parameters of WM-5 are listed in Table 2.

<table>
<thead>
<tr>
<th>Table 2 Designed coil parameters of WM-5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner diameter (mm)</td>
</tr>
<tr>
<td>Outer diameter (mm)</td>
</tr>
<tr>
<td>Coil length (mm)</td>
</tr>
<tr>
<td>Thickness of Bitter disk (mm)</td>
</tr>
<tr>
<td>Number of Bitter disks</td>
</tr>
<tr>
<td>Thickness of insulator plate (mm)</td>
</tr>
<tr>
<td>Diameter of cooling hole (mm)</td>
</tr>
<tr>
<td>Number of cooling holes at a line</td>
</tr>
<tr>
<td>Number of circular lines</td>
</tr>
<tr>
<td>Number of bolt holes</td>
</tr>
<tr>
<td>φ</td>
</tr>
</tbody>
</table>

2. WM-4 magnet consisting of polyhelix and Bitter-type coils

In order to construct a high-power intense-field water-cooled magnet, multi-coil magnet is used generally. WM-4 is designed to produce the magnetic fields up to 20 T in a 32 mm working bore. This magnet consists of an inner polyhelix coil and an outer Bitter-type coil. A polyhelix coil is probably better for generation of higher magnetic field than Bitter-type coil. However, the fabrication of polyhelix coil is more difficult than that of the Bitter-type coil. Therefore, only the inner part was fabricated as the polyhelix coil because of more hard operating condition in comparison with the outer part. The procedure of design is as follows.

(1) The optimum coil shape is determined by treating as the continuous model under the thermal limitation 4).

(2) The innermost and outermost radii of the polyhelix coil, flow rate of cooling water, number of concentric thin helical coils and thickness of insulator are given by taking account of the quality of conductor and the difficulty of manufacturing.

(3) Inner and outer radii of each helical coil (helix), number of turns in the helix and current density distribution are determined by computation of optimization under the operating condition.
Figure 6 shows the schema of the polyhelix coil. If the inner radius \( r_i \), the outer radius \( r_o \) and the number of turns \( n \) in each helix are given together with the thickness of conductor \( t \) and thickness of insulator \( t' \), the current \( I \) is given by

\[
I = \frac{Vt}{2\pi np} \ln \frac{r_o}{r_i},
\]

where \( V \) is across voltage of the helix and \( \rho \) the resistivity of conductor.

The thickness and turning pitch of helix are determined by heat removal requirement taking account of the electromagnetic stress. In the steady flow of cooling water, the temperature difference between outlet and inlet, \( \Delta T \) in °C, is expressed as

\[
\Delta T = 860 \frac{W}{F},
\]

where \( W \) is the total power in MW and \( F \) the flow rate in m³/h. The temperature difference between flowing water and conductor surface, \( T_{SW} \), is

\[
T_{SW} = \frac{W}{S_w h_c},
\]
where $S_w$ is the total area of the conductor surfaces in contact with the flowing water and $h_c$ the heat-transfer coefficient. Previously $h_c$ was estimated from the measurement of temperature distribution in a Bitter coil. A similar value is assumed in the present case. If the inlet water temperature is $T_{in}$ °C, the sum of $T_{in}$, $\Delta T$ and $T_{sw}$ should be lower than 100 °C. The clearance between adjacent helices is determined by this condition. The outer Bitter coil of WM-4 is designed by the same as WM-5. The designed coil parameters of WM-4 are shown in Table 3.

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Designed coil parameters of WM-4</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Polyhelix</td>
</tr>
<tr>
<td>Inner diameter (mm)</td>
<td>40.0</td>
</tr>
<tr>
<td>Outer diameter (mm)</td>
<td>158.0</td>
</tr>
<tr>
<td>Dissipated power (MW)</td>
<td>3.4</td>
</tr>
<tr>
<td>Across voltage (V)</td>
<td>165</td>
</tr>
<tr>
<td>Number of helix</td>
<td>12</td>
</tr>
<tr>
<td>Total number of turns</td>
<td>321</td>
</tr>
<tr>
<td>Thickness of Bitter disk (mm)</td>
<td>2.4</td>
</tr>
<tr>
<td>Thickness of insulator plate (mm)</td>
<td>0.1</td>
</tr>
<tr>
<td>Diameter of cooling hole (mm)</td>
<td>3.5</td>
</tr>
<tr>
<td>Number of cooling holes</td>
<td>486</td>
</tr>
<tr>
<td>Number of Bitter disks</td>
<td>103</td>
</tr>
</tbody>
</table>

III. Fabrication of coils

Full-hard pure copper and 0.2 percent silver-copper plates are selected as Bitter disks of WM-4 and WM-5, respectively. Glass-fiber reinforced polyimide sheets are used as insulator plate. Conductor disks and insulator disks are stacked alternately together with upper and lower collector plates. Before the stack of the disks are fastened by nuts, the stack was compressed with a heavy press at 1.8 kg/mm².

Conductor for inner polyhelix coil of WM-4 is full-hard pure copper. The material shaped into cylindrical shell by cold forming has yield strength (0.2 percent offset) of 31 kg/mm² and conductivity of 97 percent IACS. Two kinds of methods for making helices were reported in earlier paper 7). One was the cutting with an electric discharge wire machine (EDM) and the other was the cutting with a numerically controlled lathe (NCL). EDM method is better than NCL method in obtaining the helix with dimensional uniformity and mechanical integrity. The merit of NCL method is to have higher
cutting speed. In the present work NCL was adopted for making seven outer helices. Seven inner helices were cut by a conventional turning lathe. Adjacent turns of each helix were electrically insulated by glass-fiber reinforced semicured epoxy sheet with 0.2 mm thickness. After the turn insulation was performed, outer and inner surfaces of the helix were finished by the turning lathe, and then four key ways (1.0 mm depth and 5.0 mm width) were cut along the z-axis. Rods are inserted into the key ways. The rod is utilized to stop the rotation of helices around on the z-axis. The twelve helices are separated into three blocks with four adjacent helices. In each block, four helices are electrically connected in parallel and three blocks are connected in series. The connecting method of helices is the same as the method by Takano et al [7]. The helices are connected by four comblike inserted plates for electrically connection at upper and lower ends. The inserted comblike plates also play an important role in setting the helices concentrically as shown in Fig. 6. Figure 7 illustrates the cross section of the fabricated polyhelix coil of WM-4. The cooling water flows through the annular clearance among the helices.

Figure 7 An illustrated quadrant cross section of WM-4
IV. Operation and test results

WM-5 coil generated a field of 15.1 T with 6.7 MW power. Table 4 shows a comparison between experimental and calculated values of characteristics. As shown in Table 4, operating results well agree with the designed value. The maximum temperature of conductor was estimated about 120 °C with cooling-water flow rate of 245 m³/h. The uniformity of the field is held within 1.5 percent in available working area. This magnet can be swept up to the maximum field in 10 seconds and the magnetic field can be modulated within two percent of the generated one. The modulating frequencies are not greater than 2.5 Hz. The field distribution along the z-axis is shown in Fig. 8.

Table 4  Operating results and calculated characteristic values of WM-5

<table>
<thead>
<tr>
<th></th>
<th>calculation</th>
<th>operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central field (T)</td>
<td>15.0</td>
<td>15.2</td>
</tr>
<tr>
<td>Dissipated power (MW)</td>
<td>6.69</td>
<td>6.7</td>
</tr>
<tr>
<td>Current (kA)</td>
<td>21.03</td>
<td>21.0</td>
</tr>
<tr>
<td>Voltage (V)</td>
<td>318</td>
<td>318</td>
</tr>
<tr>
<td>Resistance (mΩ, at 10°C)</td>
<td>15.12</td>
<td>15.1</td>
</tr>
<tr>
<td>Flow rate of water (m³/h)</td>
<td>244</td>
<td>245</td>
</tr>
<tr>
<td>Hydraulic head loss (kg/mm²)</td>
<td>14.0</td>
<td>15.0</td>
</tr>
<tr>
<td>Coil constant (T/kA)</td>
<td>0.714</td>
<td>0.723</td>
</tr>
</tbody>
</table>

Figure 8  Field distribution of WM-5 along z-axis.
Figure 9 shows the field strength as a function of current through the coil. The coil constant was obtained from the curve as the value of 0.723 T/kA.

![Graph of WM-5](image)

**Figure 9**  Field strength versus current of WM-5.

<table>
<thead>
<tr>
<th>Table 5</th>
<th>Results of test operation of WM-4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Calculation</td>
</tr>
<tr>
<td>Central field (T)</td>
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</tr>
<tr>
<td>Dissipated power (MW)</td>
<td>6.6</td>
</tr>
<tr>
<td>Current (kA)</td>
<td>20.8</td>
</tr>
<tr>
<td>Voltage (V)</td>
<td>317</td>
</tr>
<tr>
<td>Flow rate of water (m³/h)</td>
<td>230</td>
</tr>
<tr>
<td>Hydraulic head loss (kg/mm²)</td>
<td>15.5</td>
</tr>
<tr>
<td>Coil constant (T/kA)</td>
<td>0.962</td>
</tr>
</tbody>
</table>

![Graph of WM-4](image)

**Figure 10**  Field strength versus current of WM-4.
The polyhelix coil of WM-4 generates a half of the total field of WM-4. Table 5 shows the results of test operation. The calculated values are also listed in Table 5. Figure 10 shows the field strength as a function of current. The curve is straight, the coil constant being 0.967 T/kA. This value is in good agreement with the calculated value. The maximum field obtained up to the present is 17.5 T with 4.3 MW. The magnet is now improving.

V. Conclusions

Eight water-cooled magnets are installed in HFLSM. These are named from WM-1(a and b) to WM-7. WM-1 to WM-3 are the inner magnets for hybrid magnets. WM-4 consisting of an inner polyhelix coil and an outer Bitter coil produced 17.5 T with 4.3 MW in a 32 mm working bore, and will produce more than 20 T. WM-5 is useful for the measurement of AC loss of superconductors because of large available working bore. This was designed at user's desire so that the field could be modulated at fairly high frequencies. WM-6 is a split coil of a high homogeneity type with a field homogeneity of $5 \times 10^{-4}$ in a region of 14 mm diameter. WM-7 is an economized energy type and produced 13.7 T in 52 mm bore with 4.2 MW. Examples of the calculation to design polyhelix and Bitter-type magnets are described. Designed values well agree with operating results.

Acknowledgments

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