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A WATER-COOLED, COMPENSATED SOLENOID FOR HIGH GRADIENT MAGNETIC FILTRATION TESTS

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Résumé - Un solénôide compensé refroidi à l'eau a été étudié et construit dans le but de produire un champ magnétique uniforme pour une expérience de filtration magnétique à haut gradient. Le bobinage utilise un conducteur creux en cuivre de section carrée 6,35 x 6,35 mm². Le solénôide a un alèseage de 113 mm et une longueur de 317 mm. Les composantes axiale et radiale du champ magnétique ont été mesurées à l'aide de sondes de Hall respectivement axiale et transverse. La distribution du champ axial montre une bonne homogénéité, se traduisant par une variation du champ sur l'axe de seulement 1,6 % sur une longueur de 150 mm dans la région centrale. Les champs radiaux sont très faibles dans cette région.

Abstract - A water-cooled, compensated solenoid was designed and constructed to produce a uniform magnetic field for an HGMF investigation. Coils were wound from 6.35 mm square, hollow copper tubes. The solenoid has a 113 mm bore and is 317 mm long. Axial and radial magnetic fields were determined with an axial and a transverse Hall effect field probes respectively. The axial field distribution of the compensated solenoid shows good homogeneity, giving an on-axis field variation of only 1.6% over a 150 mm length of the central region. Radial fields are very weak in this region.

INTRODUCTION

For controlled High Gradient Magnetic Filtration (HGMF) investigations, it is highly desirable that the magnetic field throughout the matrix be uni-directional and homogeneous everywhere. By incorporating an inside notched coil at the middle section of the solenoid, the field uniformity can be improved. The water-cooled compensated solenoid described herein was developed for an HGMF process for capturing basic oxygen furnace dust in air streams. It was designed to provide an homogeneous axial field of up to 0.8 Tesla throughout the bore. The bore has to accommodate a filter canister of external diameter 102 mm and filter lengths of up to 0.25 m.

SOLENOID DESIGN

The central axial magnetic field $H_0$ (amps-turns/m) of a simple solenoid (Fig. 1) of length $2b$ (m) is given by [1]:

$$H_0 = \left\{10/\pi\right\}[NI/a_1]\left\{1/2\beta\right\}\left\{1/(\alpha-1)\right\}\left\{F(\alpha,\beta)\right\}$$

and $F(\alpha,\beta) = \frac{4\pi\beta}{10} \ln\left\{\frac{\alpha + \sqrt{\alpha^2 + \beta^2}}{1 + \sqrt{\alpha^2 + \beta^2}}\right\}$

where N=total number of turns; I=current (amps); $a_1,a_2=$inside and outside radii respectively (m); $\alpha = a_2/a_1$, $\beta = b/a_1$. It can be shown that a solenoid of $\alpha = 3, \beta = 2$ produces the most field for the least power. The axial field $H_z$ along the z axis is also given by [1]:

$$H_z = H_0\left\{1 + E_2(z/a_1)^2 + E_4(z/a_1)^4 + E_6(z/a_1)^6 + \ldots\right\}$$

where $E_n$ are coefficients in a Taylor expansion. One of the methods of increasing the field homogeneity of a simple solenoid is by superimposing a suitable inside notched compensated coil on the main coil (Fig. 2). The axial field of this solenoid with a compensated coil (suffix c) then becomes:
When $F_{E2}(a,\beta) \neq F_{E4}(a,\beta)$ and $F_{0}E_{4}(a,\beta) = F_{E4}(a,\beta)$, the original $E_{2}$ and $E_{4}$ terms are cancelled, thus compensating the solenoid to sixth order.

Design values of $a=2.18$ and $\beta=2.81$ were used for the main coil in order to satisfy the specified solenoid dimensions, maximum field required, size of conductors used, output from the power supply unit, etc. For $a=2.18$ and $\beta=2.81$, values of $F_{E2}(a,\beta)$ and $F_{E4}(a,\beta)$ are obtained by interpolations from tabulated values of $F_{E2}(a,\beta)$, $F_{E4}(a,\beta)$ versus $a,\beta$ in Table 1, giving $F_{E2}(a,\beta)=-0.043$ and $F_{E4}(a,\beta)=-0.0038$. All values of $a,\beta$ that also satisfy $F_{E2}(a_{c},\beta_{c})=-0.043$ and $F_{E4}(a_{c},\beta_{c})=-0.0038$ are obtained from Figs. 3 and 4 respectively. The two loci of $(a,\beta)$ points are then plotted in Fig. 5 and their intersection locates the values of $\alpha_{c}=1.15$ and $\beta_{c}=1.08$ for the compensated coil.

Table 1. Values of $F_{E2}(a,\beta)$ and $F_{E4}(a,\beta)$ versus $a,\beta$ (after Montgomery ref. 1)

<table>
<thead>
<tr>
<th>$a$</th>
<th>$\beta$</th>
<th>$F_{E2}(a,\beta)$</th>
<th>$F_{E4}(a,\beta)$</th>
<th>$a$</th>
<th>$\beta$</th>
<th>$F_{E2}(a,\beta)$</th>
<th>$F_{E4}(a,\beta)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.00</td>
<td>2.80</td>
<td>-0.0355263</td>
<td>-0.00345390</td>
<td>2.20</td>
<td>2.80</td>
<td>-0.0443812</td>
<td>-0.00390020</td>
</tr>
<tr>
<td>2.00</td>
<td>2.90</td>
<td>-0.0321415</td>
<td>-0.00305147</td>
<td>2.20</td>
<td>2.90</td>
<td>-0.0403270</td>
<td>-0.00347537</td>
</tr>
<tr>
<td>2.18</td>
<td>2.81</td>
<td>-0.0430727</td>
<td>-0.00382249</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The solenoid was built by combining a series of pancake coils together. Each was wound from a square hollow copper tubes (6.35 mm square and 1.63 mm wall thickness) in the form of a double-layered coil as shown in Fig. 6. The cross-over of the two layers is at the innermost diameter, leaving the two water terminals accessible on the outside.

Fig. 5. Contours of $F_{E2} = -0.0431$ and $F_{E4} = -0.00382$. Fig. 6. A typical pancake coil
A winding rig (Fig. 7) was designed and constructed. Briefly, it consisted of a winding platform which was slowly rotated by a d.c. motor via reduction gearboxes. The first layer of a pancake coil was wound from half of the copper tube length, starting from the cross-over point and winding outwards around a steel former. Epoxy impregnated glass fibre tape was used for inter-turn insulation. The epoxy was cured by shining four infra-red light bulbs at the completed layer, forming it into a rigid coil. Glass backed micapaper was used for inter-layer insulation. With the rotation reversed, the above procedures were repeated for the second layer.

All the pancake coils, stacked side by side and insulated from each other by micapaper, were clamped together between two cast iron plates by four cast iron tie bars (Fig. 8). Copper flags which were brazed onto the two rims of each pancake coil (Fig. 6) provided series electrical connections between adjacent pancake coils by surface contact. Due to the limited voltage output from the d.c. power source (maximum 1200 amps at 45 volts), the series connections were broken off at the mid-plane to split the solenoid into two identical and parallel electrical circuits. This allows the full 45 volts to be applied equally across each half length of the solenoid, thereby reducing the maximum possible solenoid current to 600 amps. All the gaps between the two copper flags within each pancake coil and that at the mid-plane were filled with a hard material, Tuffnol, for packing and insulation. The flags and Tuffnol packings were clamped together in line by two long bolts.

The compensated coil at the middle section of the solenoid is made up of 8 double-layered pancake coils which have 9 turns per layer. They make up to a length of 116 mm, resulting in a value of $\Phi_0 = 1.03$ instead of 1.08. The main coil is made up of 1/4 pancake coils, split equally at each end of the solenoid, and having 10 turns per layer. The compensated solenoid, overall dimensions given in Fig.2, consists of 22 parallel water paths. Using plastic tubes, one terminal of each pancake coil is connected to a common water inlet manifold whilst the other terminal to a common outlet manifold (Fig. 8). The water flowrate through the solenoid is 28 l/min which limits the bulk water temperature rise to less than 30°C at full power.

Magnetic stresses in the coils were calculated using expressions given in ref. [1]. Even at maximum field, they were found to be small in comparison to the yield strength of copper.

MAGNETIC FIELD MEASUREMENTS AND PROFILES

Using a Bell gaussmeter (Model 615), the axial and radial magnetic flux densities were measured with an axial (Type SAB1-1802) and a transverse (Type STG1-0204) Hall effect field probes respectively. Each probe was mounted on a jig (Fig. 8) and could be slided along the length of the solenoid bore. The compensated solenoid produced a maximum central axial flux density of 0.855 Tesla for a current of 580 amps. Using eqns. (1) and (4), the same current would give a theoretical flux density of only 0.790 Tesla. The measured value shows an improvement of 8.2% over the theoretical one. This must most probably be due to the presence of a magnetic return path.
provided by the cast iron end plates and tie bars, thus reducing stray fields. The difference in the current flowing through the two solenoid circuits is only 0.86%, hence this should produce good symmetry of field profile about the mid-plane.

Figure 9 shows the axial field profiles along the principal axis of the solenoid and at different radii up to $r/a_1=0.885$. The flat profiles within the central region indicate good field homogeneity. An overall field symmetry about the mid-point is also shown. Over a length of 150 mm of the central region, the field variation along the principal axis is 1.6%. Within this same length, the maximum difference in the flux density from $r/a_1=0$ to 0.885 is 3.6%. The flux densities decrease rapidly towards the two solenoid ends as the $E_6$ and higher order terms in eqn. (4) would then become increasingly significant. Figure 10 shows two axial field measurements compared to the principal axis profile of a simple solenoid as calculated from eqn. (3). It shows a parabolic profile for the simple solenoid. Again, over the 150 mm length of the central region, the on-axis axial field of the compensated solenoid has decreased to only 0.99 of its central axial field whilst for the simple solenoid, it has decreased to 0.93. The relative magnitudes of the radial to the axial fields at different radii ($r/a_1$) are shown in Fig. 11. Over the same 150 mm length of the central region, the maximum ratio of the radial to the axial fields is 0.016.

CONCLUSIONS

Good homogeneity of the axial magnetic field of the compensated solenoid was obtained. The on-axis field variation over a 150 mm length of the central region is 1.6%. Radial flux density is negligible when compared to the axial flux density over the working length of the compensated solenoid.

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REFERENCE