Effects of the Leakage Flux in the Inhomogeneity of Magnetic Field in a Sectorial Electromagnet

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The difference between magnetic field strengths in the center and in a measuring point in a sector type of a slim electromagnet with ordinary iron pole pieces had been measured under the degree of measuring precision 10^{-4} in such a way as to not cause the eddy-current effect and magnetic after-effect. Important sources producing the inhomogeneities of magnetic fields in the pole pieces with a sharp-cornered profile are the saturation and hysteresis effects in the central ray, and the saturation and magnetic asymmetry of the geometry of pole pieces in the radial direction. The saturation effect is the superimposition of the internal flux and leakage flux from the edges to center in the pole pieces. The hysteresis effect is the difference between leakage fluxes in the magnetization and demagnetization processes because of the saturation in the pole pieces. The magnetic asymmetry of the geometry of pole pieces is the difference between leakage fluxes in pole-piece sides with the small and large curvature radii. The B-constant design of pole pieces has excellent effects in avoiding the inhomogeneities of magnetic fields caused by the above sources, although the small hysteresis effect due to the residual magnetization in the pole pieces remains.

IRON	Carbon Content %	μ_{max}	Pole Piece
IRON 1	0.12	2100	SCOF 1. B-const 1
		2400	SCOF 3
IRON 2	0.03	3200	SCOF 2. B-const 2

μ_{max}=maximum relative permeability

Table 1. Pole pieces and magnetic properties of pole-piece irons.

The magnet has a curvature radius 1000 mm, deflection angle 45° and pole-piece width 240 mm.[1] The thickness of the main air gap is 39.899±0.004 mm. The magnet has the field homogenizers, air-gap spacers machined accurately and pole pieces separated from the yoke. The power supply has a current stability better than $5x10^{-5}$. The magnet has two types of pole pieces with the sharp-cornered (SCOF) and B-constant (B-const) profiles, which are made of a commercial grade of two kinds of low carbon and forged iron plates in table 1. The differential probe consisting of the fixed and search Hall element probes has been used to detect the small differences of field strengths less than 10^{-4}.[1] The analog system can plot the magnetic field difference between the fixed and search probes versus the position of search probe.

<ins>Excitation curves</ins> — Excitation curves in all pole pieces in table 1 split into two different curves SCOF and B-const in fig.1.[1] Curves do not depend on the pole-piece iron, but on the pole-piece profile. The leakage factor in the pole pieces SCOF is derived from the splitting of the excitation curve into two curves, if the pole pieces B-const are assumed to have no leakage.[2] A leakage factor in the pole pieces SCOF is k≅3 in the region of the critical field strength B^*=10.3 kG.

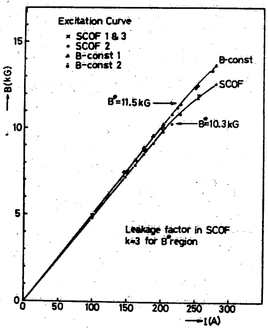

Fig.2. Magnetization curves. Critical field strengths B^* and the leakage factor k in the region of B^* in the pole pieces SCOF are given in the figure.

<ins>Magnetic field distributions</ins> — Fig.2 shows the distributions of the magnetic field difference on the distance along the central ray R with a parameter of the field strength in the SCOF3 (a) and B-const2 (b). The field distributions along the central ray in the pole pieces SCOF change with the field strength in dependence on the magnetization-demagnetization process because of the hysteresis effect. The field distributions along the central ray in the pole pieces SCOF and B-const are summarized in figs.4(a) and (b), respectively.

Fig.3 shows the distributions of the magnetic field inhomogeneity on the distant along the radial direction with two parameters of the field strength and field homogenizers in the SCOF1, SCOF2 and B-const1. The The field strength along the radial direction in the pole pieces SCOF shows the asymmetrical distributions depending on the field strength to the pole-piece center.[3]

<ins>Magnetization curves</ins> — Fig.4 shows the dependences of the magnetic field difference on the field strength along the central ray which are related to the magnetization-demagnetization process. Fig.5 gives the dependence of the magnetic field difference on the field strength along the radial direction.

The field difference is represented by a eq.:[2]

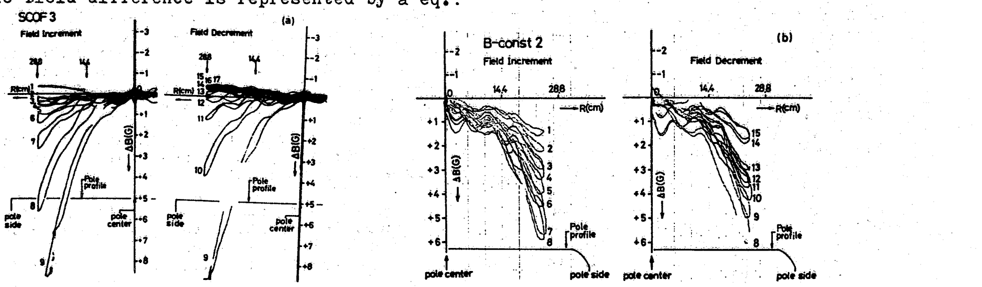

Fig.2. Magnetic field distributions along the central ray in the SCOF3 (a) and B-const2 (b). Numbers on curves denote the order of field setting and also represent field strength corresponding to numbers in fig.4. Distributions are summarized in fig.4.

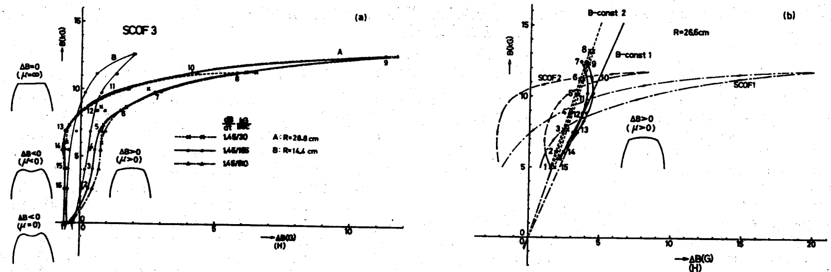

Fig.4. Magnetization curves along the central ray. Arrows and numbers on curves denote the order of field setting.

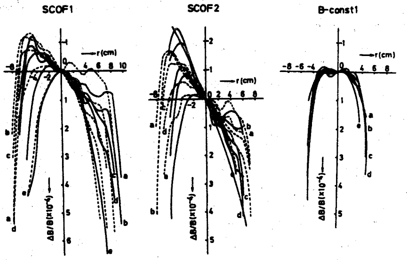

Fig.3. Magnetic field distributions along the radial direction in the SCOF1, SCOF2 and B-const1. Letters (e-a) on curves indicate the order of field setting and also represent field strengths corresponding to letters in fig.5. Solid and dotted curves denote distributions in magnets with and without the field homogenizers.

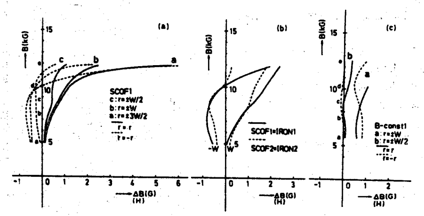

Fig.5. magnetization curves along the radial direction. Curves in positive and negative distances represent those in pole-piece sides with the large and small curvature radii, respectively. The W is a main air-gap thickness distance (W=40 mm).

$$\Delta B \equiv B - B(R \text{ or } r) = (R \text{ or } r/d)\cdot\overline{\sin\theta}\cdot(B/\mu)$$
$$= (R \text{ or } r/d)\cdot\overline{\sin\theta}\cdot\mu_0 H$$

where B and B(R or r) are air-gap field strengths at R or r=0 and R or r, respectively, μ_0 and μ are the permeability of the vacuum and relative permeability of the pole-piece iron, respectively, d is the half air-gap thickness at R or r=0, H is the magnetic field, θ is the inclination of a magnetic induction line in the pole piece and $B\cdot\overline{\sin\theta}$ is the component of the distance along the pole-piece face which is averaged over the half whole of the distance R or r. The dependence of the field difference on the field strength is interpreted to be the B-H curve or magnetization curve in the pole pieces.

The magnetic field in the pole pieces SCOF exhibits the saturation effects depending on the distance, field strength and pole-piece iron. Fig.4 shows the saturations depending on the distance R and field strength in the SCOF3 (a), and on the pole-piece iron and field strength in the SCOF1 and SCOF2 (b). Fig.5 gives the saturations depending on the distance r and field strength in the SCOF1 (a), and on the pole-piece iron and field strength in the SCOF1 and SCOF2 (b). Both pole-piece sides with the small and large curvature radii show a perfectly same saturation.[3)]

The hysteresis effect is the phenomenon which is related to the field-setting procedure of the magnetization-demagnetization and is observed under the degree of measuring precision 10^{-4}.[2)] Different parts along the central ray in the pole pieces SCOF never go through the same fysteresis loop because of the saturation in the pole pieces. Fig.4 shows the hysteresises depending on the field-setting speed dB/dt and distance R in the SCOF3 (a) and on the pole-piece iron in the SCOF1 and SCOF2 (b).

A field distribution before the saturation resulting from the leakage flux in the SCOF3 is shown with a bold solid curve in fig.3.[3)] The asymmetry of the field distribution to the pole-piece center along the radial direction in the pole pieces SCOF will be due to the difference between leakage fluxes in pole-piece sides with the small and large curvature radii, which results from the magnetic asymmetry of the geometry of pole pieces along the radial direction.

B-constant design of pole pieces —— The B-constant design of pole pieces has prominent effects in avoiding many phenomena caused in the pole pieces SCOF.

Hysteresis loop SCOF1 and SCOF2 in the pole pieces SCOF fall into approximately straight lines with the small cycling behaviour B-const1 and B-const2 in the pole pieces B-const, respectively, in fig.4(b). The fact means that the pole pieces B-const exhibits neither the saturation or hysteresis effects and also permeabilities in the pole pieces have finite, positive and constant values over the whole working field region.

Magnetization curves in the pole pieces B-const depend on the distance r, show no any dependence on the field strength and have a perfectly same behaviour in both pole-piece sides with the small and large curvature radii in fig.5(c).

1) Y.Ōkuma, K.Yagi, I.Kumabe and K.Matsuda, Nucl. Instr. and Meth. 102 (1972) 317.
2) Y.Ōkuma, K.Yagi, I.Kumabe and K.Matsuda, Nucl. Instr. and Meth. 160 (1979) 27.
3) Y.Ōkuma, K.Yagi, I.Kumabe and K.Matsuda, present in elsewhere.
2 and 3) Y.Ōkuma, K.Yagi, I.Kumabe and K.Matsuda, to be published in the Intermag Conf. Pros., Boston, (1980).

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