OPTIMIZATION OF A MAGNETIC SEPARATOR AIR-GAP

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Abstract The paper describes a method of optimization of a magnetic separator air-gap which serves to separate magnetic particles from volatile power plant dust. The method consists in seeking the air-gap dimensions, assuming that the shape of poles is known on the basis of magnetic force field analysis, or in seeking the shape of poles for the assumed force field distribution. In the second case the problem is reduced to solving a certain inverse boundary problem of the Dirichlet type.

1. INTRODUCTION

In recent years there has been an increasing interest in the separation of magnetic particles from volatile power plants dust. Authors of a previous paper¹ have described a certain laboratory model of magnetic separator and preparatory results of tests. Performances of such a type of separator proved to be so good that an industrial model has been built and has been installed in the power station "Rybnik"². Further investigation into new applications of this type of separator has been carried out in a separation chamber. In another paper³, a method of force field analysis in the separator air-gap has been suggested. Forces were determined on the basis of the magnetic field distribution, which was computed by solving a Laplace equation with Dirichlet boundary conditions by the integral equation method. This method has been found very efficient and the results obtained are correct, which

was confirmed by an experimental investigation⁴. The magnetic forces in the air-gap, calculated numerically and measured with the help of a specially designed sensor, differ from one another at most by a few per cent.

This paper is a continuation of the above-mentioned papers. Its purpose is to formulate a method of optimization of the separator air-gap - an element which has an essential influence on the separation process.

2. OPTIMUM PITCH OF POLES SHAPED LINEARLY

The distribution of magnetic forces in the air-gap is a very important factor which exerts influence on the separator's performance. The volume density of these forces depends on the magnetic field distribution

$$F = \frac{\mu_0(\mu - \mu_0)}{2\mu} \text{grad}|H|^2 \quad (1)$$

where H is the magnetic field.

Thus, in order to determine a force field, we should at first determine a magnetic field. In the paper³, a simplified model of an air-gap shown in Fig. 1 was taken for analysis. It was assumed that the poles are made from an ideal ferromagnetic with permeability $\mu \rightarrow \infty$. Thanks to it, at each point of the pole surface, the scalar magnetic potential Ψ has an identical value. This problem was reduced to solving a Laplace equation with Dirichlet boundary conditions. Next, using a single-layer potential, a Fredholm integral equation of the first kind was obtained. After its solution, it is very easy to determine all the quantities characterising the magnetic field at an arbitrary point in space.

Fig. 2 represents plots of function $f(x) = 4\pi^2 F(x)/\mu_0$ in

the symmetry plane of the air gap $y=0$ for $b/a=0.5$ and different values of angular field of poles, β . The value of angle β has a significant influence on the course of function $f(x)$. For

FIGURE 1 Model of separator air gap taken for analysis

high values of β , maximum $f(x)$ is found near the point $x=0$ and the value of $f(x)$ rapidly decreases for increasing x 's. With decreasing β , the value of $f_{\max}$ increases and the maximum of curve $f(x)$ moves towards the increasing x 's. Beginning from a certain value of angle β in the environment

of point $x=0$, function $f(x)$ assumes negative values. Results of similarly made calculations, carried out for points lying outside the symmetry plane, are shown in Fig. 3. Analysing the

FIGURE 2 Distribution of magnetic forces in the symmetry plane of the air gap for $b/a=0.5$.

results obtained in this way it is possible to determine the optimum value of angle β for each value of the parameter b/a .

From the principle of the separator's work, it follows

FIGURE 3 Distribution of the force field in the whole air gap

FIGURE 4 Dependence of $\tan \beta_{\text{opt}}$ on parameter b/a

that function $f(x)$, describing a component along axis x of the magnetic force in the air gap, should have, conceivably, a high value over a potentially large area of the air-gap. The optimal value of angle β is assumed to be such an angle for which

$$I = \int_c^a f(x) dx$$

is a maximum, where c is the point at which $f(x)=0$.

The result of optimization executed in this way is rather unexpected, because $\tan \beta_{\text{opt}} = f_1(b/a)$ is a linear function to a very high accuracy (Fig. 4).

3. ENERGETISTIC OPTIMIZATION OF THE AIR-GAP SHAPE

On the basis of the results obtained in the previous section, we can state the value of angle β for given b/a . The optimum value of b/a results from the relation of a maximum magnetic force to magnetic field energy accumulated in the air-gap.

The magnetic field energy accumulated in the air-gap amounts to

$$W_m = 0.5 G V_0^2$$

where G is the permeance of the air-gap and V_0 is the magnetic tension between the poles. The ratio, γ , of the maximum of the force F_x (i.e. the useful component) to the magnetic field energy depends only on the air-gap parameters

$$\gamma = \frac{F_{x\text{max}}}{W_m} = k \frac{f_{x\text{max}}}{a^3 G} = k\varepsilon$$

where k is a constant, $f_{x\text{max}}$ is the maximum value of the magnetic force computed for $a=1.0$ and $V_0=1.0$. It is desirable that γ (and consequently ε) be as high as possible. For fixed

FIGURE 5 Plots of parameter ε for different values of angle β .

FIGURE 6 Dependence of parameter ε on b/a for $\beta=\beta_{\text{opt}}$

parameter a , the value of γ rapidly increases when b decreases. But the minimum value of b is, however, frequently delimited by the separator's capacity. Thus, assuming b to be fixed, a may then be optimized.

The plots $\epsilon=f(\beta)$ for different parameters b/a are drawn up in Fig. 5. For high b/a , the curve $\epsilon=f(\beta)$ monotonically decreases. For small b/a there exist a local minimum and maximum on the curve. However, the value of ϵ always increases when b/a increases. Comparing ϵ for β_{opt} - the optimum angle in the sense of the previous section - it becomes also evident that ϵ attains maximum values for high b/a (Fig. 6). Thus, if it is possible, one should tend to design air-gaps with small a or large b .

4. OPTIMIZATION OF THE POLE SHAPE

The results presented so far refer to an air-gap with poles shaped linearly. Optimization of that system consists in a choice of the parameters a/b and β . However, another treatment is also possible. Namely, assumption of the force field distribution and seeking the pole shape.

After applying the integral equation method to the model of the air-gap described in paper 3, we obtain the following equation system

$$\int_0^a J(s) \ln \sqrt{\frac{(x-s)^2 + [g(x)+g(s)]^2}{(x-s)^2 + [g(x)-g(s)]^2}} ds = 2\pi V_0 \quad (4a)$$

$$\int_0^a J(s) \left[\frac{g(s)}{(x-s)^2 + g^2(s)} + \frac{g(s)}{(x-s)^2 + g^2(s)} \right] ds$$

FIGURE 7 Plots of functions describing poles generating homogeneous force distribution in air gap symmetry plane.

$$\int_0^a J(t) (x-t) \left[\frac{g(t)}{[(x-t)^2 + g^2(t)]^2} + \frac{g(t)}{[(x-t)^2 + g^2(t)]^2} \right] dt$$

$$= 4\pi f_0(x) \quad (4b)$$

where $J(s)$ is the magnetic charge density extending over the pole surface, $g(x)$ is the equation of the pole surface, V_0 is the magnetic scalar potential of the pole, and $f_0(x)$ is a function describing the magnetic force distribution in the air-gap symmetry plane.

Eqs. (4a) and (4b) represent a system of two integral equations in which functions $J(s)$ and $g(x)$ are the unknowns to be determined. Considering the unknown $J(s)$, Eq. (4a) is a Fredholm integral equation of the first kind, whereas Eq. (4b) is a nonlinear integral equation. Considering the unknown $g(x)$, both equations are non-linear integral equations. The finite difference method has been applied to solving Eqs. (4a) and (4b), hence this problem is reduced to the nonlinear set of algebraic equations solved by the iteration method⁵.

As functions $f_0(x)$, we can apply constant functions on the segment (d,a) , $/d>0/$ or functions linearly increasing. Such a choice is justified by the principle of the separator's work. Dust containing magnetic particles is transferred through the separation chamber in a rather compact shape. Magnetic particles, pushing through nonmagnetic ones to the conveyor belt, must conquer considerable resistance of friction. Therefore, it is very important that, at points lying far away from the conveyor belt, these forces have to be high.

Fig. 7 shows plots of the pole surface, obtained by solving Eqs. (4a) and (4b), generated on segment (d,a) of the air-gap symmetry plane of a homogeneous force field

$$f_0(x) = f_0 = \text{const.}$$

FIGURE 8 Magnetic forces in air gap symmetry plane generated by poles shown in Fig. 7.

FIGURE 9 Magnetic forces in whole area of air gap generated by poles shaped non-linearly

FIGURE 10 Air gap with linearly-increasing forces
(a) forces in symmetry plane
(b) pole shapes

The results obtained fulfil the requirement with fairly high accuracy (Fig. 8). Improvement in force field homogeneity, in comparison with a force field of the poles shaped linearly, is observed not only on the symmetry plane but in the whole air-gap too. (Fig. 9).

Similarly, computation of the pole shape has been performed assuming that $f_0(x)$ is a linearly-increasing function

$$f_0(x) = m + nx$$

The results, i/e/ the shape of the pole surface and the force density distribution in the air-gap symmetry plane, are shown in Fig. 10.

5. CONCLUSIONS

A method of optimization of the separator air-gap has been suggested in this paper. It consists in optimizing the air-gap dimensions (assuming the pole shape to be known) or in determining the optimum pole geometry. Assumption of the magnetic force distribution has been the criterion for optimization. Integral equations in the calculations are easily reducible to algebraic equations which significantly save on computational time.

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