THE RESEARCH OF THE MAGNETOHYDROSTATIC JIGGING SEPARATION①

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ABSTRACT

The Magnetohydrostatic Jigging Separation (MHSJS) is a method which makes use of the vibration of the solid particles obtained by applying a periodically changing magnetic field to cause a periodically changing magnetic bouyancy to achieve an efficient separation of materials.

KEY WORD: Megnetic Fluid, Jigging Separation, Vibration

1 INTRODUCTION

Since the first magnetohydrostatic separator was made by Andress[1] in the 1960s, great advance has been made in Magnetohydrostatic Separation (MHSS) which has been applicated in lab and industry[2-5]. Through years of study here, on the basis of the characteristics of the magnetic fluid, we present the idea of the MHSJS, the separating principle, the structure of the separator and the jigging curve in this paper.

2 THE BASIC PRINCIPLE OF MHSJS

As the magnetic bouyancy is closely related to the outside magenetic field, by applying a periodical changing magnetic field , a periodical changing magnetic buoyancy can be achieved to make the solid particles vibrate vertically in the fluid, thus a better separation effect by specific gravity can be achieved.

When a solid particle of one unit volume is set in a magnetic fluid (Fig. 1) , the resultant of forces acting on it in the vertical di- rection is

$$F=F_1+F_2-F_3-F_4 \qquad (1)$$

Where F_1—gravity;

F_2—magneetic force;

F_3—buoyancy;

F_4—magnetic buoyancy.

or

$$F=\rho_1 g+\mu_0 x F S_1 HgradH-\rho_0 g-\mu_0 x_0 HgradH \qquad (2)$$

Where ρ_1—density of the particle;

g—acceleration of gravity;

μ_0—magnetic conductivity of vacuum;

x_1—specific magnetic susceptibility of the particle;

HgradH—magnetic force of the field;

ρ_0—density of the fluid;

x_0—specific magnetic susceptibility of the fluid.

When the particle is at the static equilibrium, $F=0$, therefore

$$(\rho_1-\rho_0)g / \mu_0(X_0-X_1)=C=HgradH \qquad (3)$$

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Where C—a constant

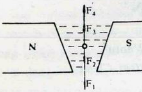

Fig.1 The forces acting on a particle

It can be seen from equation (3) that the C only related to the characteristics (density and magnetism) of the fluid and the particles is only a function of HgradH.This means when magnetic fluid and solid particles are given, the position of the suspended particle in the fluid is only related to HgradH, i.e. when (HgradH)> C, the particles move upwards, and when (HgradH) < C, the particles move downwards. Thus the particles will periodically vibrate once the imhomogeneous magneltic field is periodically changed. This vibration which is similar to the jigging action in the gravity separation can better separate the materials.

3 THE STRUCTURE OF MHSJS

The separator(Fig. 2) mainly consists of three parts: a magnet exciting system, a separation system and a fluid cycling system.

The magnet exciting system includes iron core, coils and an electric power. The core is made from the engineering soft iron. The shape of the magnetic poles can decide the characteristics of the field, which could be calculated through the shape of the equalmagnetic-potential face of a magnetic field in certain condition. In the plane static magnetic field, the potentical (v) between the poles is close to Laplace's equation v= 0, when adopting the pole-coordinate. the solution with actual meaning is:

$$\left.\begin{array}{ll} V=A\theta & k=0 \\ V=Ar^{k}\sin k\theta & k\neq 0 \end{array}\right\} \quad (4)$$

where r—the vector of the pland pole coordinate

θ—the pole-angle;

A and k—constants

By meas of the limit conditions, k can be calculated:

when $k=0$, $\theta=\theta_0$, the cuneate poles are available.

when $k=3/2$,

$$r=r_0\sin^{-2/3}(3\theta/2)$$

the equal-magnetic-foce-shape poles is availble.

when $k=2$, $r=r_0\sin^{-1/2}2\theta$, the equal-axis-hyperbola is availble.

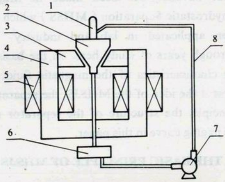

Fig.2 The schematic of MHSJS machine

1—a supplier 2—a separating cell
3—magnetic poles 4—iron core
5—coils 6—a trough
7—a pump 8—tubes

The cuneate poles with an angle of 78 ° is used in MHSJS. When the magnet is excited by the direct current, the HgradH along the centre axis y is show in Fig. 3. Since its curve of HgradH-y is very steep, the poles suit with the separation of materials which have larger specific gravity of ores and less specific gravity of gangues.

The coil has 2,527 circles in total which are decided by means of total magnetic potential of the coil, i.e. the sum of each part magnetic potential is equal to the total magne- tic potential.

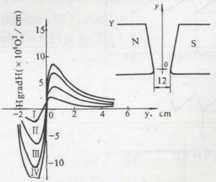

Fig.3 The HgradH-y of the cuneate poles

MHSJS uses the pulse-power which consists of a silicon-controlled rectifier and a extra-low-frequency signal generator. The power can transmit the D C as well as AC.

The separating system consists of a supplier, a separating cell and a trough. There are separating plates in the cell, the exits for light products and heavy products are set in the bottom of the cell.

The cycling system, made up of a pump and cycling tubes, serves to control the separating speed, to increase the productive capacity and to ensure the liquid surface in the cell.

4 THE JIGGING CURVE OF MHSJS

In MHSJS, the periodically changing of the magnetic buoyancy makes solid particles in the fluid vibrate periodically. Since the buoyancy is determined by the value of the apparent density, therefore, we define the relation of the apparent density against time as the jigging curve of the separator.

4.1 The Characteristic of the Exciting Current.

The solid lines in Fig. 4 show the current-waves measured by an oscillograph in each frequency.

By"the analysing method of pulse-array"[6], the waves in Fig. 4 can be expressed by the following function:

$$I(t) = k_2 - (k_2 - I_1)e^{(-K_1 t)} \qquad 0 \leqslant t \leqslant T' \qquad (5)$$

$$I(t) = I_2 e^{(-(t-T')K_1)} \qquad T' \leqslant t \leqslant t \qquad (6)$$

where t—time;

$I(t)$—the functiom of the current;

I_1, I_2, T′ and T shown in Fig. 4;

K_1 and K_2— constants, their values shown in table 1.

The imaginary lines in Fig. 4 show I(t) $-t$ of the equations (5) and (6) , the period of the curves is T, that conforms to the measured results.

4.2 *The Characteristics of the Magnetic Field*

The cuneate poles (Fig. 5) are used in the separator. To make analysis easy, assume the poles in the vertical direction to the paper surface be infinite, the edge effect of the magnetic field can be neglected and the magnetic field in horizontal direction is approximatly constant.

Table 1 The values of K_1 and K_2

Frequency, Hz	2.0	3.0	4.0	5.0	6.0	7.0
Constant, K_1	2.01	2.402	2.145	2.614	2.273	2.649
Constant, K_2	19.95	18.05	32.258	36.618	52.317	64.083

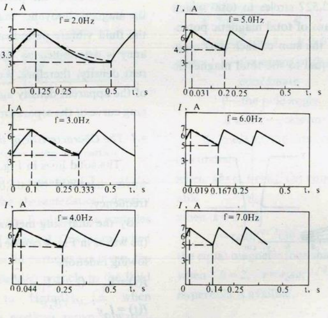

Fig.4 The current waves

— — measured; - - - —calculated

Therefore, HgradH is considered only as a function of coordinate z. At any instant, the equation of HgradH$-z$ can be calculated by equal magnetic potential on surfaces between different media[7]:

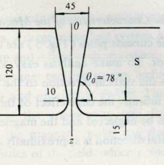

Fig.5 The cuneate poles

$$\mathrm{HgradH} = \left(\frac{V_0}{\pi - 2\theta_0}\right)^2 \left(\frac{1}{10.6 \times 10^{-2} - z}\right)^3 \quad (7)$$

$$V_0 = (nI/2)/(1 + \mu_0 s_2 l_1 / \mu_1 s_1 l_2) \quad (8)$$

Where I—current;

n—circle numbers of coils;

θ_0—angle (see Fig. 5) ;

l_1 and s_1—the length of the centre line of the magnetic yoke and its cross area;

l_2 and s_2—the length of the centre line of the air gap between poles and its cross area;

z—vertical coordinate, ($0 < z < 10.6^{-2}$ m);

μ_1— magnetic susceptibility of DT_2-typesoft iron.

Because the greatest relative magnetic susceptibility of DT_2 soft iron is $\mu_m > 4000$ [8], and it is difficult to make the magnetic field saturation in the separating process, if $\mu_1 = 200\ \mu_0$ and the following parameters are put into (8), such as $l_1 = 1.54$ m, $s_1 = 0.24 \times 0.12$ m^2,

$l_2 = 0.02$ m, $n = 2{,}527$, $s_2 = (1.22 \times 0.24) \times (1.22 \times 1.2) \text{m}^2$.

the equation (9) can be obtained.

$$V_0 = 1{,}195.02\ I \qquad (9)$$

When the equation (9) and $\theta_0 = 78 \times \pi / 180$ are put into the equation (7), we get

$$\text{HgradH} = [8.15 \times 10^6 / (10.6/100 - z)^3] I^2 \qquad (10)$$

Put the coupled equation (5) and (6) into equation (10), then

$$\left.\begin{aligned} \text{HgradH} &= 8.15 \times 10^6 [k_2 - (k_2 - I_1) e^{-k_1 t}]^2 / (10.6 \times 10^{-2} - z)^3 \\ &0 \leqslant t \leqslant T' \end{aligned}\right\} \qquad (11)$$

$$\left.\begin{aligned} \text{HgradH} &= 8.15 \times 10^6 I_2^2 e^{-2(t - T')k_1} / (10.6 \times 10^{-2} - z)^3 \\ &T' \leqslant t \leqslant T \end{aligned}\right\} \qquad (12)$$

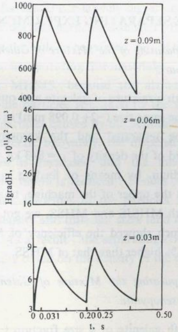

Fig.6 The curve of HgradH

Equations (11) and (12) are the function of HgradH-t of the separator. When the frequancy is 5.0 Hz, the greatest exciting current is 7A and z is 3×10^{-2}, 6×10^{-2} and 9×10^{-2}m respectively, the curve of HgradH-t can be expressed as Fig. 6. Therefore HgradH-t is a periodical function and the volume of HgradH will increase and its changing will become more intensive as the value of z increases because of the upper–weak and lower-strong distribution of the magnetic field produced by the cuneate poles.

4 · 3 *The Jigging Curve*

Set in the inhomogeheous magnetic field produced by the poles as shown in Fig. 5, the magnetic fluid will be influenced by the gravity and the magnetic force. Their resultant force can be expressed as

$$F = F_5 + F_6 \qquad (13)$$

where F—the resultant force;

F_5—the gravity;

F_6—the magnetic force.

Since the directions of f_5 and f_6 are both downwards, equation (13) can be turned into

$$F = F_5 + F_6 = \rho_0 g + \mu_0 x_0 HgradH \qquad (14)$$

or

$$\rho_s = F / g = \rho_0 + \mu_0 x_0 \text{HgradH} / g \qquad (15)$$

ρ_s is defined as the apparent density (the separating density) of the fluid. From equation (15) it can be reasoned that the ρ_s is only a function of HgradH when the density of the fluid is a constant.

Put the equation (10) into equation (15), we have

$$\left.\begin{aligned} \rho_s &= \rho_o + \frac{8.15 \times 10^6 \mu_o x_o}{(10.6 \times 10^{-2} - z)^3 g} [k_2 - (k_1 - I_1) e^{-k_1 t}]^2 \\ &0 \leqslant t \leqslant T' \end{aligned}\right\} \qquad (16)$$

Put the eqyations (5) and (6) into

equations(17), then

$$\left.\begin{array}{l}\rho_s = \rho_o + \dfrac{8.15\times 10^6 \mu_o x_o I_2^2}{(10.6\times 10^{-2} - z)^3 g} \times \\ e^{-2(t-T')k_1} \\ T' \leqslant t \leqslant T\end{array}\right\} \quad (17)$$

Equations (17) is the function expression of the jigging curve . When the density of the fluid is $\rho_0 = 864$ kg / m^3, its magnetic susceptibility is $x_0 = 7.5\times 10^{-6}$m^2 / kg , and of the current frequency is 5. 0Hz and the greatest volume is 7A, the jigging curve can be shown as Fig. 7.

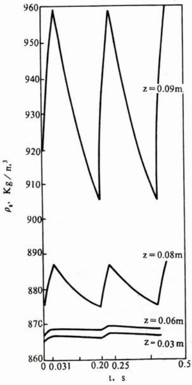

Fig. 7 The jigging curve

Obviously jigging curve is of a saw-tooth shape , similar to that of Bird's hypothesis[5]. Because of the existence of magnetic buoyancy, the fluid can be taken as a heavy-medium, with its separating density in accordance with the density of the materials to be separated. Therefore, the jigging curve of MHSJS fits fairly well with the characteristics of the precipitating materials in the fluid, thus enabling the sepatator to separate materials of wider and finer size-fraction. On the other hand, the value and amplitude of ρ_s will increase if z increases. For this reason , materials should be fed through the lower part of this machine . By doing so, the material will be in a fully loose state because of the violent changes of the magnetic buoyancy, hence the particles of different densities and the magnetic susceptiability will respectively get into the regions where the separating density is similar to their own . As a result , the mix degree between lagers is decreased , the separating size can be degraded and the separating precision is upgraded.

5 THE SEPARATING EXPERIMENTS

5.1 *Separating of the Mixture of Galenite and Quartz*

With a mixture of galenite and quartz (9: 10) of the same size (−2+ 0.098 mm) as material to be separated and the kerosene-basic ferrofluid of the density of $\rho = 843$ kg / m^3 as the medium, by means of feeding materials through the upper of the machine, treating in turn with MHSJS and MHSS, we got the results which showed the efficiency of MHSJS was 7. 5% higher than that of MHSS.

5.2 *Separating the Mixture of Galenite and Arsenopynite.*

With galenite of 4 size fraction (−0.18+ 0.145, −0.11+0.09, −0.09+0.055, −0.18+0.11, −0.11+0.055) and arsenopynite of 4 size fraction (− 0.45+ 0.28, − 0.28+ 0.18, − 0.18+0.11, −0.11+0.055) respectively mixed as the materials and with water-basic ferrofluid of a density of P = 1,030 kg / m^3 as the medium, by means of feeding materials through the upper of the machine , treating each mixture in turn with MHSJS and MHSS, we got the results and found the efficiency of MHSJS was 11. 18% higher than that of MHSS.

5.3 *Discussion*

MHSJS is superior to MHSS. In the direction of the magnetic induction, non-magnetic particles in the fluid attract each other, and in the direction vertical to the magnetic induction, they repel each other[9]. In the course of MHSS , on one hand , only gravity and constant magnetic buoyancy act on particles of different materials, difficult to break down the attraction. On the other hand, as the viscosity of the ferrofluid is relatively bigger and the inertia of the fine particles is smaller , fine particles are difficult to separated. So, MHSS is in efficient in separating fine materials.

In MHSJS, because the attraction between the particles is broken by the vibration of the particles caused by the periodical changing magnetic buoyancy, the dispersity of the particles is increased and the mix degree betweeen layers is reduced . Besides , the precipitation velocities of the particles with the same density and different sizes tend to be the same . As a result , the separating course can be mainly based on the density of the particles, the viscocity of the medium and the separating density. Therefore, MHSJS can be used to separate fine− fraction and wide-size-fraction materials with efficiency.

6 CONCLUSION

MHSJS as a new separating method, has overcome some of the shortcomings of MHSS which is able to separate finer and wider-size-fraction meterials, and its unique jigging curve in saw-tooth-shape better fits the characteristics of the preciptation of the materials in the fluid, thus enable to reduce the mix degree between layers and increase the separating efficiency. In a word, MHSJS can be used for separating nonmagnetic materials, such as precious and nonferrous metal etc.

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