Measurement of Metallic Weight of The Pulp By The Electromagnetic Method

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Abstract: In the paper, two methods are considered of exact measurement of the metal containing pulp mass. The first one consists in the continuous measuring of the pulp magnetic susceptibility and subsequent automatic correction when calculating the dry solid matter of the metal containing product. The second one provides for use of the special electromagnetic mass flow meters insensitive to the variations of the magnetic properties of the medium measured. The paper presents the technical solutions providing an additional electric signal characterizing the pulp magnetic susceptibility. Presence of such signal makes it possible not only to exclude the volumetric mass flow measurement uncertainty caused by the influence of the pulp magnetic constituent but also to measure the metal containing product mass. Use of such electromagnetic mass flow meters is the most prospective method of solution of the problem posed.

Keywords: Magnetic Pulp, Magnetic Susceptibility, Metal Containing Mass.

1. Introduction

Facing the needs from the Measuring of the metal containing mass in the pulps is an urgent question for the metallurgy industry. Here considered are the pulps containing magnetite, copper, nickel, gravitational concentrates, recrements, etc. Here, the technological parameters of the pulp products obtained and dispatch by the metallurgy plants are the objects to be measured.

The pulp products are the two-phase or the three-phase substance, that is, the mixture of the solid and the fluid phases; sometimes, the gaseous phase is also present.

The pulp may be referred to as a non-stable suspension because it contains the particles from 0.05mm (90-92%) up to 0.28mm (about 0.2%) in size; in the steady or laminar flowing suspension, these particles precipitate, under the action of gravity, to form the immobile sediment.

Such pulps flow in the turbulent regimes because the processes of dredging and transfer of relatively large particles with negative floatage are only possible under the presence of pulsations of the velocity and the pressure in the carrying fluid. For such mixtures, the flow pattern becomes more complicated by presence of the phase boundary surface playing the role of mobile boundaries with respect to the carrying fluid and causes the additional interphase forces that are external for each individual phase but internal for the mixture as a whole. Besides, due to the difference in the physical properties of the fluid and the dredge particles it carries, the latter ones may influence significantly on the kinematic, dynamic, and energy parameters of movement of the carrying fluid itself.

As a rule, the pulp contains a concentrate with the particles up to 0.2 mm in size; such pulps may be referred to as the flows with "light" solid particles. Practically uniform distribution of the particles over the flow cross-section and the symmetrical profile of the averaged longitudinal velocity are the characteristics of such flows. For the light particles, the energy losses are predominantly caused by the momentum transfer, similarly to the energy losses in the carrying fluid due to its turbulent agitation. From the hydraulic standpoint, such flows may be considered as the conventionally uniform fluids with the density differing from that of the carrying medium.

As a rule, the dry solid matter of the metal containing product (MCP) in the pulp is automatically calculated within the frame of the automatic systems of technological parameter control using the algorithm:

$$M = \frac{V \cdot \rho_s(\rho_p - \rho_f)}{(\rho_s - \rho_f)}, \qquad (1)$$

where V is the pulp volume, ρ_s – the density of the solid pulp phase (the proper density), ρ_p – the pulp density, ρ_f - the density of the fluid pulp phase.

The pulp density is measured using the radioisotope densitometer with the fractional error of ±1.0%. The pulp volume is determined using the industrial electromagnetic mass flow meter. The density of water is usually taken to equal to 1 g/cm^3 with the fractional error of ±1.0%.

The density of the pulp solid phase is selectively determined from the laboratory test samples with the fractional error of ±(0.3…1.0)%. The measurement and the calculation results obtained for the pulp product parameters are used in business as well as in the areas of the state metrological control and supervision.

The disadvantages of the techniques used at the metallurgy plants are as follows:

1. The algorithm (1) of the MCP calculations does not account for the gaseous phase being a constituent of many pulps. The gaseous phase presence may increase the MCP measurement error up to several percents.
2. The algorithm doesn't provide the reasonable accuracy of the low concentration pulp MCP measurements when the values of the pulp density, ρ_p, and the fluid phase density, ρ_f, are close to each other. The error of the MCP value for the low concentration pulps may reach several percent.
3. The metal containing mass of the considered pulps always contains significant amount of ferromagnetic elements (nickel, cobalt, and, predominantly, iron). The known fact is that the industrial electromagnetic mass flow meters are not aimed at measuring the pulps with the magnetic properties. For those cases, the measurement error may also reach several percent.

In this paper, the solution of the MCP measurement problem, based on the account for the pulp magnetic properties, is considered [1].

2. Algorithm of the MCP calculation

If one should evaluate the mineralogical composition of the pulps from the magnetic properties of the components than each pulp composition may be divided into two characteristic groups. The fluid phase and the gas are in fact non-magnetic, with the negligible magnetic susceptibility, χ, as compared to the same of the solid phase. The solid phase composition includes ferromagnetics (Fe and, in many pulps, Ni and Co). To measure the volume flow rate and the magnetic susceptibility of the considered pulps, the electromagnetic methods are the most reliable.

Consider the concept of the specific magnetic susceptibility of the dry solid matter of the metal containing product; designate it as χ_d. The magnetic susceptibility, χ_s, is the dimensionless value whereas the χ_d is the dimensional value, its dimension being cm^3/g.

Thus, the density of the dry solid matter of the solid phase (the proper density), ρ_s, may be expressed in the form

$$\rho_s = \frac{\chi_s}{\chi_d}. \qquad (2)$$

Note that each dry metal containing product includes, in some ratio, both ferromagnetics and dia- and paramagnetic elements (Cu, S, C, etc.). Thus, for the particular pulp, the mineralogical composition of the metal containing product mass may be characterized by its averaged equivalents: ρ_s, χ_s, and χ_d; then, the magnetic properties of the product will in fact be governed by the ferromagnetic constituents.

Consider the concepts of the conventional density of the fluid phase, ρ_f^*, and the conventional density of the pulp, ρ_p^*, in the form

$$\rho_p^* = \frac{\chi_p}{\chi_d}, \qquad \rho_f^* = \frac{\chi_f}{\chi_d}. \tag{3}$$

Note that the conventional densities of the fluid phase and the pulp absolutely don't correspond to their proper density. As the fluid phase consists totally of diamagnetics and the pulp contains a significant proportion of the fluid phase, the values of their conventional densities are essentially lower than those proper. The magnetic susceptibility of the diamagnetic is lower than the same of the ferromagnetic by five-six orders of magnitude; thus, the conventional density ρ_f^* is in fact equal to zero whereas the proportion of the pulp ferromagnetic constituents characterizes its conventional density. Thus, by measuring the magnetic susceptibility of the pulp components, the fluid and the gaseous phases may be easily detached from the solid phase. Then, the algorithm of the MCP calculation takes the form

$$M = V\frac{\chi_p}{\chi_d}. \tag{4}$$

To measure the magnetic permeability of the product is much easier than to measure its magnetic susceptibility; thus, the equation (4) should be expressed via the magnetic permeabilities of the pulp, μ_p, and of the MCP, μ_d. Thus,

$$M = V\frac{\mu_p - 1}{\mu_d}. \tag{5}$$

To use the expression (5), it is necessary to measure the volume, *V*, by the electromagnetic mass flow meter; its readings shouldn't depend on the magnetic permeability of the pulp. Usually, the industrial type mass flow meters are engaged which readings are proportional to the magnetic permeability of the media measured. These mass flow meters may be used if the correction will be introduced to the MCP calculation algorithm (5). Thus, the algorithm becomes

$$M = \frac{V^*}{\mu_d}\left(1 - \frac{1}{\mu_p}\right), \tag{6}$$

where V^* are the readings for the magnetic pulp volume from the industrial electromagnetic mass flow meter preliminary graduated against water.

The algorithm under consideration has the following advantages as compared to (1):

- the algorithm makes it possible to determine the MCP for all the above mentioned pulps including those containing the non-specified gaseous phase;

- the necessity vanishes to measure the densities of the pulp, its fluid and gas constituents and to calculate the difference of those densities, (ρ_p - ρ_f);

- variation in the physical properties of the fluid and gaseous phases of the pulp don't practically influence on the accuracy of calculation of the solid phase mass using the above algorithm;

- the necessity vanishes to measure the pulp density and thus the radioisotope densitometer is excluded from the process.

Yet, to realize the above algorithm, special measuring means are needed to measure the volume flow rate of the pulp and its magnetic properties. We claim that these measuring means may be established on the base of the electromagnetic methods of measurements.

3. Solid Phase Influence on the Flowmeter Signal

To select the measurement mode of the electromagnetic mass flow meter where the useful component proportional to the volume flow rate may be easily detached from the pulp magnetic permeability is one of the main tasks when designing the special-purpose device for the pulps. In other words, the two-channel electromagnetic mass flow meter should be designed with one channel measuring the volume flow rate independently of the magnetic properties of the measured medium and the other channel measuring the magnetic permeability or the magnetic susceptibility of the pulp.

The pulps are characterized by the non-uniformity of the distributions of the electrical conductivity and the magnetic permeability. Yet, in the considered pulps, the size of the solid particle is small and the flow velocity is high – thus, the above distributions may be referred to as uniform.

So, one may expect that the mass flow meter signal depends weakly on the non-uniformity of the distributions of the electrical conductivity and of the magnetic permeability of the ferromagnetic pulps.

The pattern of the signal dependence on the ferromagnetic concentration in the pulp is the predominant question.

The solid phase influence on the mass flow meter readings may be estimated from the analysis of the equation

$$U = \int_{\tau} \left\{ \left[\mathbf{V} \times \mathbf{B} \right] - \frac{\partial \mathbf{A}}{\partial t} \right\} \mathbf{G}_{\delta} d\tau , \tag{7}$$

where G_{δ} is the vector weight function, V – the flow velocity, **B** – the magnetic induction, **A** – the vector magnetic potential, t – the time, τ - the work volume of the channel.

The weight function, G_{δ}, depends on the distribution of the non-uniformity over the pulp electrical conductivity whereas B – on the distribution of its magnetic permeability.

Variations in the distributions of the weight function and the magnetic induction may cause drift of the mass flow meter readings.

The electric field inside the mass flow meter channel is described by the Maxwell equation system:

$$\mathrm{rot}\,\mathbf{H} = \sigma \left\{ \mathbf{E} + \left[\mathbf{V} \times \mathbf{B} \right] \right\}, \tag{8}$$

$$\mathrm{rot}\,\mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}, \tag{9}$$

$$\mathrm{div}\,\mathbf{B} = 0 . \tag{10}$$

Now, enter the vector magnetic potential, **A**, such as

$$\mathbf{B} = \mathrm{rot}\,\mathbf{A} . \tag{11}$$

From the equation (9), it follows that

$$\mathbf{E} = -\frac{\partial \mathbf{A}}{\partial t} + \mathrm{grad}\,\varphi, \tag{12}$$

where φ is an arbitrary function.

Apply the "div" operation to the equation (8):

$$\nabla^2 \varphi - \mathrm{div}\frac{\partial \mathbf{A}}{\partial \tau} + \mathrm{div}\left[\mathbf{V} \times \mathbf{B} \right] - \frac{1}{\sigma}\frac{\partial \sigma}{\partial \mathbf{r}} \mathbf{A} + \frac{1}{\sigma}\frac{\partial \sigma}{\partial \mathbf{r}} \left[\mathbf{V} \times \mathbf{B} \right] + \frac{1}{\sigma}\frac{\partial \sigma}{\partial \mathbf{r}}\frac{\partial \varphi}{\partial \mathbf{r}} = 0, \tag{13}$$

where **r** is the radius-vector.
Next, take the cylindrical coordinate system where the z-axis coincides with the pipe axis, ρ is the distance from the z-axis, θ - the anticlockwise angular displacement around the z-axis, $x = \rho\cos\theta$, $y = \rho\cos\theta$. Take the electrodes to be placed at the internal pipe surface in the points with the coordinates $\rho = R$, $z = 0$, $\theta = \pm\pi/2$.
From the vector A definition, it follows that the magnetic potential **A** is defined ambiguously.
To obtain unambiguity, apply the condition to the vector potential **A**:

$$\operatorname{div}\mathbf{A} = 0, \quad \mathbf{A}_r\Big|_{\rho=R} = 0 . \tag{14}$$

Here, $\mathbf{A}_r$ is the magnetic potential projection over the radial direction.
To determine the φ function, the equation should be solved

$$\nabla^2\varphi = F, \tag{15}$$

where

$$F = \operatorname{div}\left[\mathbf{V}\times\mathbf{B}\right] - \frac{1}{\sigma}\frac{\partial\sigma}{\partial\mathbf{r}}\left[-\frac{\partial\mathbf{A}}{\partial t} + \left[\mathbf{V}\times\mathbf{B}\right]\right] + \frac{1}{\sigma}\frac{\partial\sigma}{\partial\mathbf{r}}\frac{\partial\varphi}{\partial\mathbf{r}}, \tag{16}$$

with the boundary condition $\frac{\partial\varphi}{\partial\rho}\Big|_{\rho=R} = 0$ resulting from the fact that the normal current through the internal wall surface equals to zero. The potential distribution may be written in the form

$$\varphi(z,\rho,\theta) = \int_\tau \partial\tau \tilde{G}\left(z-\tilde{z},\rho,\tilde{\rho},\theta-\tilde{\theta}\right) F\left(\tilde{z},\tilde{\rho},\tilde{\theta}\right), \tag{17}$$

where $\partial\tau = \tilde{\rho}d\tilde{\rho}d\tilde{z}d\tilde{\theta}$; $\tilde{G}\left(z-\tilde{z},\rho,\tilde{\rho},\theta-\tilde{\theta}\right)$ is the Green function for the potential distribution in the cylindrical channel

$$\begin{aligned}\tilde{G}\left(z-\tilde{z},\rho,\tilde{\rho},\theta-\tilde{\theta}\right) &= \frac{1}{\pi}\int_{-\infty}^{+\infty} dk \sum_{n=0}^{\infty}\cos n\left(\theta-\tilde{\theta}\right)e^{ik(z-\tilde{z})} \times \\ &\times\left\{\mathrm{K}_n(k\rho)\mathrm{I}_n(k\tilde{\rho})\sigma(\rho-\tilde{\rho}) + \mathrm{I}_n(k\rho)\mathrm{K}_n(k\tilde{\rho})\sigma(\rho-\tilde{\rho}) - \mathrm{I}_n(k\rho)\frac{\mathrm{K}_n'(kr)}{\mathrm{I}_n'(kr)}\mathrm{I}_n(k\tilde{\rho}),\right\}\end{aligned} \tag{18}$$

The function $\sigma(x) = \begin{cases}1, x \ge 0\\ 0, x < 0\end{cases}$. The value

$$U = r\int_{-\pi/2}^{+\pi/2} d\theta\left(-\frac{\partial A_0}{\partial t} + \frac{1}{r}\frac{\partial\varphi}{\partial\theta}\right), \tag{19}$$

or

$$U = \int_\tau d\tau\left\{-\frac{\partial\mathbf{A}}{\partial t} + \left[\mathbf{V}\times\mathbf{B}\right]\mathbf{G}_\sigma + \frac{1}{\sigma}\frac{\partial\sigma}{\partial\mathbf{r}}\frac{\partial\varphi}{\partial\mathbf{r}}G(z,\rho,\theta)\right\} + \int_s dS\frac{\partial B_u(S)}{\partial t}W(S), \tag{20}$$

is the mass flow meter signal. Here, S is the channel surface, $dS = r d\theta dz$;

$$\mathbf{G}_\sigma = \frac{\partial G}{\partial\mathbf{r}} - \frac{1}{\sigma}\frac{\partial\sigma}{\partial\mathbf{r}}G, \tag{21}$$

$$W(S) = \int_{-\infty}^{+\infty} dre^{ikz}\sum_{n=0}^{\infty}\frac{1}{ik}\left[\frac{1}{r^2}\frac{n^2\,\mathrm{I}_n(kr)}{\mathrm{I}_n'(kr)} - \frac{\mathrm{I}_n'(kr)}{\mathrm{I}_n(kr)}\right]\frac{\mathrm{I}_n(kr)}{r\,\mathrm{I}_n'(kr)}. \tag{22}$$

From the analysis of the equation (20), it follows that the signal may be written as the sum of the two terms

$$U = U_1 + U_2, \tag{23}$$

where U_1 is the mass flow meter signal when only pure water is the working fluid; U_2 – the signal variation caused by the solid phase of the magnetic pulp.

$$U_1 = \int_\tau d\tau \left\{ \left[\frac{\partial \mathbf{A}_0}{\partial t} + M_n \left[\mathbf{V} \times \mathbf{H} \right] \right] \frac{\partial G}{\partial \mathbf{r}} \right\} + M_n \int_S dS \frac{\partial H_n(S)}{\partial t} W(S). \quad (24)$$

If the signal is measured under the pseudo-constant magnetic field produced by the pulsed low frequency inductor supply current than the signal U_1 takes the form

$$U_1 = \int_\tau d\tau M_n \left[\mathbf{V} \times \mathbf{H} \right] \frac{\partial G}{\partial \mathbf{r}}, \quad (25)$$

and the signal U_2

$$U_2 = \left\{ \int_\tau d\tau 4\pi \left[\mathbf{V} \times \mathbf{M} \right] \frac{\partial G}{\partial \mathbf{r}} + \frac{1}{\sigma} \frac{\partial \sigma}{\partial \mathbf{r}} G + \left[\mathbf{V} \times \mathbf{B} \right] + \frac{1}{\sigma} \frac{\partial \sigma}{\partial \mathbf{r}} \frac{\partial \phi}{\partial \mathbf{r}} G(z, \rho, \theta) \right\} + 4\pi \int_S dS \frac{\partial M(S)}{\partial t} W(S). \quad (26)$$

Under the absence of evident distribution of the fluid conductivity over the channel cross-section, all the terms proportional to the conductivity gradients in the equation (26) are negligible. Thus, the two first terms play the main role in the U_2 signal, thus

$$U_2 = \int_\tau d\tau \left\{ -\frac{\partial (\mathbf{A} - \mathbf{A}_0)}{\partial t} + 4\pi \left[\mathbf{V} \times \mathbf{M} \right] \frac{\partial G}{\partial \mathbf{r}} \right\}. \quad (27)$$

The pulps are usually measured in the magnetic fields where the magnetization reaches the saturation [2] and the magnetization is proportional to the volume concentration of the solid phase. The difference of the magnetic potentials, $A - A_0$, governs the fluid magnetization:

$$\mathbf{M} = \frac{1}{4\pi} \operatorname{rot}\left(\mathbf{A} - \mathbf{A}_0 \right), \quad (28)$$

so the value ($\mathbf{A} - \mathbf{A}_0$) is also proportional to the volume concentration of the pulp.
All other terms in the expression (26) don't depend on the ferromagnetic pulp concentration. Thus, the signal U_2 is proportional to the volume concentration of the solid phase. The term in the expression (27) proportional to $\frac{\partial}{\partial t}$ produces additional noise background hampering the signal measuring. Thus, the signal on the electrodes depend linearly on the magnetic field strength in the mass flow meter channel and on the magnetic concentration of the solid phase, that is, on its magnetic permeability. In other words, the industrial electromagnetic mass flow meter is sensible to the variation of the magnetic properties of the medium measured. Practically, its readings are linearly proportional to the magnetic permeability of the pulp.

5. Results

In the industrial electromagnetic mass flow meters, the compensation is only provided of the influence of the magnetic field strength variation in the channel; it is performed as follows. Besides the signal on the electrodes, the inductor supply current is measured which is proportional to the magnetic field strength, H, in the channel. If the inductor supply current is produced by the stabilized current supply than its value resides constant with sufficiently high accuracy and needs not to be measured. Then, the ratio of the signal between the electrodes to the inductor supply current may be taken to be a measure of the volume flow rate. As the signal induced between the electrodes depends on the pulp magnetic permeability, the variations of the pulp magnetic permeability is not compensated. The experience in use of the electromagnetic mass flow meter at the metallurgy plants confirms this conclusion. At some plants, the pulp product mass flow meters are at regular intervals (e.g. twice a year) verified, more exactly, calibrated against the pulps by the spill method, using a volumetric tank or a pool. During the next calibration, the pulp possibly has the magnetic permeability differing from the same during the previous one (the magnetic permeability is not controlled) and thus the divergence takes place between the mass flow meter readings and the volume measure. The reading divergence may be eliminated by adjustment of the mass flow meter calibration curve to the magnetic parameters of the pulp used for the regular calibration.

The mass flow meter calibration curve displacement is caused by the device sensibility to the magnetic permeability variations of the measured medium.

We, in collaboration with the “Vzlet” company, St.-Petersberg, design the EMR-KM electromagnetic mass flow meter with the nominal bore of 300 mm aimed specially at the ferromagnetic pulps. The device measures the two parameters: the mass flow rate, independently of the magnetic permeability of the measured medium, and the pulp magnetic permeability itself. To enhance the reliability when working with the medium having the higher abrasive properties, the insulating coating of the channel is made of polyurethane. The mass flow meter peculiarity consists in the fact that, when measuring the mass flow rate, the device is insensitive to the magnetic permeability variations of the measured medium and, besides, makes it possible to measure the pulp magnetic permeability itself.

Here, the pulp mass flow rate measure is:

$$Q_p = \frac{kU}{\int Edt} = K\frac{U}{B}, \qquad (29)$$

whereas the magnetic permeability measure:

$$\mu = k_\mu \frac{\int Bdt}{I}, \qquad (30)$$

where K and k_μ are the calibration coefficients, U – the voltage between the electrodes, I – the mass flow meter inductor supply current. As the inductor supply current is stabilized by the power supply within the accuracy of 0.15%, it isn’t measured.

References

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