DRYING OF MATERIALS IN MAGNETIC HIGH-FREQUENCY FIELD

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A theoretical analysis is made of energy relations which determine the efficiency of drying granular materials in a magnetic high-frequency field.

Most studies dealing with problems of intensification of drying processes with high-frequency heating have been concerned with drying in an alternating electric field [1, 2]. Meanwhile, there are several materials for which it is expedient to use drying in a magnetic high-frequency field.

Application of this method is based foremost on such materials having a sufficiently high feed through electrical conductivity, which depends on the moisture content and reaches levels of the order of 10^4 (ohm•m)$^{-1}$. It is also necessary that the high-frequency energy be transferred to the load at a high efficiency.

It must be noted that high-frequency drying is, as a rule, several times more expensive than convective drying. It therefore is of primary importance in the development of its technology to analyze the energy relations which determine the most favorable conditions for this process. One can add to this that at the present time there are hardly any data available, experimental or theoretical, on the laws governing the kinetics of this process, as well as on the attendant heat and mass transfer.

In this study theoretical relations will be derived which determine the conditions for drying granular materials in a magnetic high-frequency field.

For specificity we will consider heating and drying of a moist spherical granule of a nonmagnetic material and a cluster of spherical granules in a uniform alternating magnetic field produced by an inductor.

Let us formulate the conditions which determine the efficiency of heating and drying of materials in a magnetic high-frequency field. The first such condition is the requirement that within the operating range of frequencies the modulus of the through-conduction current density $\bar{j}_c$ in the dried material be much larger than the modulus of the displacement current density $\bar{j}_d$. In the case of an electromagnetic field with parameters varying sinusoidally in time, these two current densities are, respectively,

$$\bar{j}_c = \gamma_c \bar{E},\ \bar{j}_d = (\gamma_d^a + i\gamma_d^r)\cdot\bar{E}. \tag{1}$$

The inequality $|\bar{j}_c| \gg |\bar{j}_d|$ constitutes a necessary condition for efficient drying and is equivalent to the inequality

$$\gamma_c \gg \sqrt{(\gamma_d^a)^2 + (\gamma_d^r)^2}. \tag{2}$$

However, fulfillment of inequality (2) does not yet mean that electromagnetic energy is transmitted to the load at a high efficiency. Condition (2) is therefore a necessary but not a sufficient one. Maximum efficiency is attainable only with a developed effect, i.e., when the granule has a radius much larger than the depth of field penetration in the material: $R \gg \delta$. The expression for the field penetration depth is [3]:

$$\delta = \frac{1}{\omega\sqrt{\frac{\mu_0\varepsilon_0\varepsilon}{2}\left(\sqrt{\left(\frac{\gamma_c + \gamma_d^a}{\gamma_d^r}\right)^2 + 1} - 1\right)}}. \tag{3}$$

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With inequality (2) fulfilled, expression (3) becomes

$$\delta = \frac{1}{\omega} \sqrt{\frac{2\gamma_d^r}{\mu_0 \varepsilon_0 \varepsilon \gamma_c}}. \tag{4}$$

Considering that $\gamma_d^r = \omega\varepsilon_0\varepsilon$, we obtain

$$R \gg \sqrt{\frac{2}{\mu_0 \omega \gamma_c}}. \tag{5}$$

In this way, fulfillment of inequalities (2) and (5) are the necessary and sufficient conditions for efficient drying in a magnetic high-frequency field. We note that these inequalities must be satisfied during the entire drying time. In some cases the feedthrough electrical conductivity of the material depends strongly on the moisture content and decreases as the material dries. Then conditions (2) and (5) cannot be satisfied. It will be found then that drying in a magnetic high-frequency field is efficient only during the initial stage of the process. Final "finish drying" of the material must be effected by some other method.

For deriving the energy relations which determine the conditions for drying granular materials in an alternating magnetic field, we will use points in the theory of induction heating of metals [4, 5].

The power generated in a unit volume of a spherical particle of a moist material upon placement of the latter in a uniform alternating magnetic field of intensity $\overline{H} = \overline{H}_0 \exp(i\omega\tau)$ is

$$P = \frac{3}{4} \mu_0 \omega H_0^2 \operatorname{Im}(F(z)). \tag{6}$$

The function F(z) of the complex argument $z = \frac{R}{\delta}(1 - i)$ can be expressed through Bessel functions of orders 1/2 and 3/2 of the same argument:

$$F(z) = \frac{zJ_{1/2}(z) - 3J_{3/2}(z)}{zJ_{1/2}(z)}. \tag{7}$$

An analysis of expression (7) will reveal that the function Im F(z) becomes maximum at $R = 2.4\delta$ in the extreme cases, when $R \ll \delta$ or $R \gg \delta$, becoming

$$\operatorname{Im}(F(z)) = \begin{cases} \frac{2}{15}\left(\frac{R}{\delta}\right)^2, & R \ll \delta, \\ \frac{3}{2}\left(\frac{R}{\delta} - 1\right)\left(\frac{\delta}{R}\right)^2, & R \gg \delta. \end{cases} \tag{8}$$

While clusters of spherical particles of radius R not making electrical contact with one another are dried in an alternating magnetic field, each of them finds itself generally in a magnetic field of an intensity $\overline{H}'$ not equal to $\overline{H}$. When the entire cluster of particles is also a sphere or nearly one, however, then $\overline{H}' \simeq \overline{H}$. The power per unit volume of a layer of moist material can in this case be determined from the relation

$$P_l \simeq \frac{3}{4} \mu_0 \omega (1 - \nu_0) H_0^2 \operatorname{Im}(F(z)). \tag{9}$$

The theoretical relations derived here can serve as a basis for correct selection of the source of electromagnetic energy, in terms of power and frequency, necessary in the design of drying equipment with high-frequency heating.

The obtained results can also be used to describe the kinetics of drying and heating materials in a high-frequency magnetic field. We introduce the expression for heating kinetics.

The high-frequency energy transmitted to the material heats it and dries it. The amount of heat expended on heating a unit mass of perfectly dry solid-phase material, together with the moisture it contains and the amount of heat expended on drying, are, respectively,

$$Q_1 = \frac{dT}{d\tau}(c_s + uc_m), \quad Q_2 = -r\frac{du}{d\tau}. \tag{10}$$

The equation of heating kinetics for a material in a magnetic high-frequency field will then be

$$\frac{dT}{d\tau} = \frac{1}{c_s + uc_m}\left(\frac{P}{\rho} + r\frac{du}{d\tau}\right). \tag{11}$$

NOTATION

$\bar{j}_c$, vector of through-conduction current density; $\bar{j}_d$, vector of displacement current density; $\bar{E}$, vector of electric field intensity; γ_c, feedthrough electrical conductivity; γ_d^a, γ_d^r, active and reactive components due to polarization; R, radius of a granule; δ, field penetration depth; ω, radian frequency; μ_0, magnetic constant; ε_0, dielectric constant; ε, relative dielectric permittivity; $\bar{H}$, $\bar{H}'$, vectors of magnetic field intensity; H_0, amplitude of magnetic field intensity; i, imaginary unity; τ, time; P; power density generated in a granule; F, auxiliary function; $J_{1/2}$, $J_{3/2}$, Bessel functions of orders 1/2 and 3/2, respectively; P_l, power density generated in a layer of particles; ν_0, porosity of a layer of particles; c_m, c_s, specific heat of water (moisture) and of the solid phase material respectively; r, heat of evaporation of water; T, mean temperature of a granule; u, mean moisture content in a granule; ρ, density of the material; Q_1, Q_2, amounts of heat.

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