Journal of Engineering Physics and Thermophysics, Vol. 80, No. 1, 2007

CONTROL OF MOISTURE CONTENT IN CAPILLARY-POROUS MATERIALS BY MICROWAVE METHODS

V. V. Lisovskii

UDC 621.317.39

Based on a linear model of a moist capillary-porous material that is located in an electromagnetic microwave field, basic relations between the measured parameters and moisture content been obtained for amplitude and resonator methods. Calculated and experimental dependences of the attenuation of the microwave energy on moisture content and variants of application of moisture meters of the Microradar series are presented.

The choice of the microwave range of electromagnetic waves is dictated by the dielectric properties of the water itself that ensure a high accuracy and sensitivity of the method used to measure moisture content in capillary-porous materials with a minimum influence of various disturbing factors. At the same time, to raise the accuracy of this measurement it is necessary to take into account the influence of density and temperature (or their stabilization or automatic correction), which is typical of all indirect methods [1].

The dielectric properties of the majority of capillary-porous materials as a function of moisture content $\varepsilon^*(W)$ can be rather accurately described on the basis of a linear model [1], from which it follows that the real, $\varepsilon'(t)$, and imaginary, $\varepsilon''(t)$, parts of the complex dielectric permittivity ε^* (as well as $\alpha = \frac{\pi}{\lambda}\frac{\varepsilon''}{\sqrt{\varepsilon'}}$ and $\beta = \frac{2\pi}{\lambda}\sqrt{\varepsilon'}$) depend not only on the moisture content W, but also on the density of the material under study ρ. In view of this, we will consider two variants of using microwave moisture meters in the technological processes of drying and processing of agricultural products.

The technological process of drying grain allows one to rather simply stabilize the flow of the material controlled. In the given case, it is sufficient to measure only one parameter, e.g., the net coefficient of attenuation of an electromagnetic wave in a moisture-containing material $\alpha_{\rm w}$ (provided there is an automatic temperature correction). Thus, the relationship between the attenuation of an electromagnetic wave N in a sample of thickness d and moisture content W has the form

$$N = 8.686\alpha_{\rm w} W\rho d\,. \tag{1}$$

Within the framework of the linear model, the attenuation coefficient $\alpha_{\rm w}$ will be defined by the expression

$$\alpha_{\rm w} = \alpha_{\rm w,c} q_{\rm w,c} + \alpha_{\rm w,p} q_{\rm w,p} + \alpha_{\rm w0} q_{\rm w0}\,, \tag{2}$$

from which we obtain

$$\alpha_{\rm w} = \Phi \frac{\rho_{\rm a}}{\rho_{\rm w}}\left[\frac{W}{1-W}\alpha_{\rm w0} + \frac{\mu S}{N_{\rm A}\sigma} a_{\max}\varphi\,(W, S, a_{\max})\,(\alpha_{\rm w,p} - \alpha_{\rm w0}) + \frac{W_{\rm cr}}{1-W_{\rm cr}}\,(\alpha_{\rm w,c} - \alpha_{\rm w0})\right]. \tag{3}$$

The function $\varphi(W, S, a_{\max})$ can be found in conformity with the Evens–Busker model [2], in which it is assumed that the rate of change in the given form of moisture with increase in wetting is directly proportional to the portion of the sorption volume not occupied by this moisture. Consequently,

---

Belarusian State Agrarian Technical University, 99 Nezavisimost' Ave., Minsk, 220023, Belarus; email: meridian2738e@mail.ru. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 80, No. 1, pp. 22–26, January–February, 2007. Original article submitted December 22, 2005.

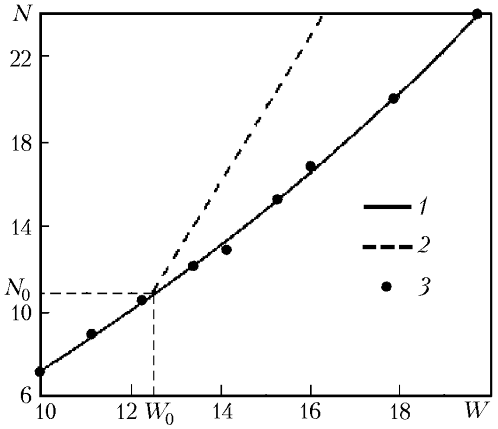

Fig. 1. Calculated dependence of the attenuation of microwave energy N for microwave probes as a function of moisture content W: 1) probe No. 1; 2) probe No. 2; 3) experimental values for wheat of natural moisture content. W, %; N, dB.

$$\frac{dq_{\mathrm{w,p}}}{d\Theta} = 1 - \frac{q_{\mathrm{w,p}}}{q_{\mathrm{w,p,max}}}, \quad \Theta = \frac{P_{\mathrm{w}}}{\rho_{\mathrm{w}} V}. \tag{4}$$

Integrating (4) and taking into account that at $\Theta = \Theta_{\mathrm{w,p}}$ the bulk concentration $q_{\mathrm{w,p}} = 0$, we obtain

$$q_{\mathrm{w,p}} = q_{\mathrm{w,p,max}} \left(1 - \exp \frac{\Theta_{\mathrm{cr}} - \Theta}{q_{\mathrm{w,p,max}}} \right). \tag{5}$$

It is inconvenient to use Eq. (5) in such a form, since all the bulk concentrations of water in this expression depend on the volume efficiency Φ. Knowing the specific surface of the material S and the maximum number of polysorption water monolayers a_{max}, we can find the bulk concentration $q_{\mathrm{w,p,max}}$ as follows:

$$q_{\mathrm{w,p,max}} = \frac{\mu \rho_{\mathrm{a}} S}{N_{\mathrm{A}} \rho_{\mathrm{w}} \sigma} a_{\mathrm{max}} \Phi,$$

then

$$q_{\mathrm{w,p}} = \Phi \frac{\rho_{\mathrm{a}} \mu S}{\rho_{\mathrm{w}} N_{\mathrm{A}} \sigma} a_{\mathrm{max}} \left[1 - \exp \frac{(W_{\mathrm{cr}} - W)\, \sigma N_{\mathrm{A}}}{(1 - W_{\mathrm{cr}})(1 - W)\, \mu S a_{\mathrm{max}}} \right]. \tag{6}$$

Consequently, the function $\varphi(W, S, a_{\mathrm{max}})$ that characterizes the relationship between the polysorption moisture and free moisture is independent of the volume efficiency Φ and will be defined by the expression

$$\varphi\,(W, S, a_{\mathrm{max}}) = 1 - \exp \frac{(W_{\mathrm{cr}} - W)\, \sigma N_{\mathrm{A}}}{(1 - W_{\mathrm{cr}})(1 - W)\, \mu S a_{\mathrm{max}}}. \tag{7}$$

The results of calculation by relation (1), with account for the fact that the volume efficiency Φ is a function of the moisture content, show that the theoretical dependence $N(W)$ differs from the calibrated characteristic for the Microradar-113 microwave moisture meter by not more than 10% (Fig. 1).

However, in flour production, in connection with the technology of rapid additional wetting of grain from 12–14% to 15.5–16%, it is necessary to take into account the influence of the free water present in the surface layer, i.e., to pass to another calculation algorithm which takes into account scattering and absorption of the microwave energy in a thin water film. For this purpose, a new modification of the moisture meter with two microwave sensors (at the inlet and outlet of the wetting machine) and one computational block operating by two algorithms has been developed. The

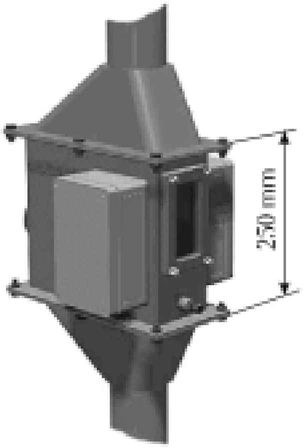

Fig. 2. Appearance of the block of primary transformers of the Microradar-113 microwave moisture meter.

first algorithm is based on dependence (1), where α_w is determined from Eq. (3). The second algorithm is also based on Eq. (1), but $\alpha_w = \alpha(W)$ is determined computationally from the well-known dielectric characteristics of free water:

$$N = N_0 + \alpha(W)\, k\, (W - W_0)\,. \tag{8}$$

The results of calculation for grain (wheat) made by the adopted model for the temperature $t = 20^{\circ}$C and wavelength $\lambda = 3.2$ cm are presented in Fig. 1 (the dashed line presents the values for $N(W)$ of free water or a theoretical calibrating dependence for probe No. 2). In this figure, N_0 is the initial reduction in the energy of the electromagnetic wave introduced by the mass of grain with the initial moisture content W_0 which is present in probe No. 1.

The results of experimental investigations, as well as the experience of industrial operation of automatic systems of additional wetting on the basis of the Microradar-113 microwave moisture meter with two identical blocks of primary transducers (Fig. 2) prove the possibility of sustaining a finite moisture content of grain with a high accuracy (±0.2%) [3].

The technological processes of the production of sugar, dried milk, casein, and some other loose capillary-porous materials require precise control of the moisture content of the initial raw material and the final product in a range of small and supersmall moisture contents, which becomes possible by applying resonator methods of microwave moisture metering. Usually, resonator transducers are based on measuring the quality factor Q or frequency departure Δf of a resonator partially filled with a wet material (method of small perturbations).

In order to measure moisture content by resonator methods, we will obtain basic relations that couple the resonator parameters of transformation and the complex dielectric permittivity of the moisture-content material ε^*. A change in the resonance frequency of a cavity resonator is defined by the well-known expression [1]

$$\frac{\omega - \omega_0}{\omega_0} \approx -\frac{\int\limits_V (\varepsilon^* - 1)\, |\mathbf{E}_0|^2\, dV}{2\int\limits_V (\mathbf{E}_0)^2\, dV}\,. \tag{9}$$

It is also known [1] that

$$\omega'' = \frac{\omega'}{2Q_{0\mathrm{d}}}\,. \tag{10}$$

For resonators with a high quality factor, $\omega_0'' << \omega_0'$. Moreover, in the method of small perturbations, $\frac{\omega' - \omega_0'}{\omega_0'} << 1$. With allowance for the remarks made, we will obtain expressions for ε'' and ε':

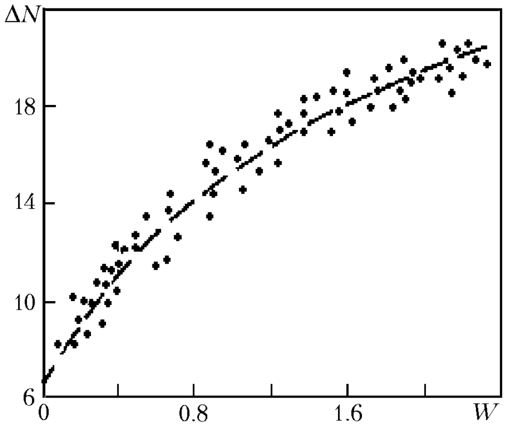

Fig. 3. Dependence of the transient attenuation ΔN of the cavity resonator at the E_{010}-type wave on the moisture content of quartz sand W at a frequency of 1.4 GHz; curve, calculation. W, %.

$$\varepsilon' = 1 + \frac{\Delta\omega}{\omega_0} \frac{\int_V |\mathbf{E}_0|^2 dV}{\int_{\Delta V} |\mathbf{E}_0|^2 dV}, \quad \varepsilon'' = \frac{1}{2}\left[\frac{1}{Q_{0\mathrm{d}}} - \frac{1}{Q_0}\right] \frac{\int_V |\mathbf{E}_0|^2 dV}{\int_{\Delta V} |\mathbf{E}_0|^2 dV}. \tag{11}$$

Under real conditions, the cavity resonator is always connected with the feeder system of the microwave circuit of the moisture meter, the quality factor of which is Q_{out}; therefore, usually the loaded Q_{e} factor of the resonator is controlled. With allowance for the fact that $Q_{\mathrm{e}}^{-1} = Q_0^{-1} - Q_{\mathrm{out}}^{-1}$, for ε'' we obtain

$$\varepsilon'' = \frac{1}{2}\left[\frac{1}{Q_{\mathrm{d}}} - \frac{1}{Q_{\mathrm{e}}}\right] \frac{\int_V |\mathbf{E}_0|^2 dV}{\int_{\Delta V} |\mathbf{E}_0|^2 dV}. \tag{12}$$

For cylindrical resonators with excitation at the wave E_{010} the foregoing relations will have the form [3]

$$\varepsilon' = 1 + 0.27 \frac{\Delta\omega}{\omega_0} \frac{a^2}{d^2\left[1 + \frac{1.2d^2}{a^2}\right]}, \quad \varepsilon'' = \frac{0.135\,(Q_{\mathrm{d}}^{-1} - Q_{\mathrm{e}}^{-1})\,a^2}{d^2\left[1 + \frac{1.2d^2}{a^2}\right]}. \tag{13}$$

We will consider the transformation parameter when the resonator is in transfer connection. The resonator then has two coupling elements (at the inlet and outlet), and its transition attenuation will be prescribed by the expression [3]

$$\Delta N = N_1 - N_0 = 20 \log \frac{Q}{Q_{\mathrm{d}}} = 8.686 \ln\left(1 + \frac{2Q}{B}\varepsilon''\right). \tag{14}$$

In order to find the coupling between ΔN and W, we will avail ourselves of a linear model and take into account that in a range of small and supersmall moisture contents the $\varepsilon''_{\mathrm{a}}$ of the dry material proper may turn out to be comparable with the value of $\varepsilon''_{\mathrm{w}}$ attributable to the presence of water in a sample; then, within the framework of the linear model, we may write

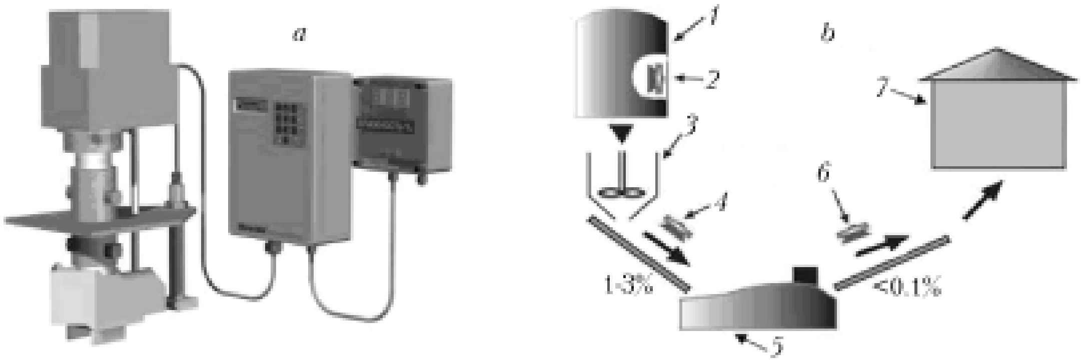

Fig. 4. Appearance of the Microradar-114 microwave moisture meter (a) and variants of its mounting in the production line in sugar production (b): 1) evaporator-crystallizer; 2, 4, 6) moisture meter (variants of mounting); 3) centrifuge; 5) line of sugar drying; 7) storehouse of finished products.

$$\frac{\pi}{\lambda}\frac{\varepsilon''_{\mathrm{w}}}{\sqrt{\varepsilon'_{\mathrm{w}}}}\Phi\frac{\rho_{\mathrm{a}}}{\rho_{\mathrm{w}}}W+\frac{\pi}{\lambda}\frac{\varepsilon''_{\mathrm{a}}}{\sqrt{\varepsilon'_{\mathrm{a}}}}\Phi=\frac{\pi}{\lambda}\frac{\varepsilon''}{\sqrt{\varepsilon'}}, \tag{15}$$

whence

$$\varepsilon''=\Phi\left(\frac{\rho_{\mathrm{a}}}{\rho_{\mathrm{w}}}\frac{\varepsilon''_{\mathrm{w}}}{\sqrt{\varepsilon'_{\mathrm{w}}}}W+\frac{\varepsilon''_{\mathrm{a}}}{\sqrt{\varepsilon'_{\mathrm{a}}}}\right)\left[\Phi\left(\sqrt{\varepsilon'_{\mathrm{a}}}-1\right)+1\right]. \tag{16}$$

When $W << 1$,

$$1+\Phi\left(\sqrt{\varepsilon'_{\mathrm{a}}}-1\right)>>\Phi\frac{\rho_0}{\rho_{\mathrm{w}}}\frac{W}{1-W}\left(\sqrt{\varepsilon'}-1\right).$$

By combining (14) and (16) we obtain the following relation for the transformation parameter ΔN:

$$\Delta N=8.686\ \ln\left[1+\frac{2Q}{B}\Phi\left(\frac{\rho_{\mathrm{a}}}{\rho_{\mathrm{w}}}\frac{\varepsilon''_{\mathrm{w}}}{\sqrt{\varepsilon'_{\mathrm{w}}}}W+\frac{\varepsilon''_{\mathrm{a}}}{\sqrt{\varepsilon'_{\mathrm{a}}}}\right)\right]\left[\Phi\left(\sqrt{\varepsilon'_{\mathrm{a}}}+1\right)\right]. \tag{17}$$

Figure 3 presents experimental dependences $\Delta N(W)$ for quartz sand within a range of small moisture contents. Given here is also the theoretical dependence constructed by Eq. (17). The experimental values for $\Delta N(W)$ were obtained in a resonator with dimensions a = 84 mm and d = 8.2 m at a frequency of 1.4 GHz. In the nonperturbed resonator, the loaded factor Q measured by the well-known technique turned out to be equal to 2400 and the initial attenuation N_0 to be equal to 23 dB. The dependences given point to the good agreement between the experimental and theoretical data.

Resonator moisture meters find practical application in those technological processes where control of moisture content in a range of small and supersmall moisture contents is required. By the way, the Microradar-114 resonator-type microwave moisture meter for continuously controlling moisture content in sugar production can be installed at any points of the production line (Fig. 4).

The absolute error of measuring moisture content in finished sugar within the range 0–3% is within ±0.03%. A variant of the use of the Microradar-114 moisture meter for automatization of the technological processes in production of dried milk and casein is considered in detail in [4]. Given there are also the specifications of the Microradar-101-2 universal laboratory resonator moisture meter for a range of small moisture contents.

The above-given examples of application of microwave moisture meters of high-precision class do not exhaust all the possible areas of their application in agricultural production and industry. More detailed information on this topic can be gained from [3].

NOTATION

a, radius of a resonator, cm; $a_{\max} = 100$, maximum number of the water monolayers occupied by the polysorption moisture in the given material; B, coefficient depending on the type of resonator; d, sample thickness (diameter for the resonator method), cm; $\mathbf{E}_0$, vector of the electric-field strength, V/m; E_{010}, type of wave in the resonator; f, frequency of the resonator, Hz; k, coefficient depending on the type of material; N, attenuation of electromagnetic energy in a wet material, dB; $N_A = 6.022 \cdot 10^{23}$, Avogadro number; P_w, mass of a wet material, g; Q_0 and Q_{0d}, loaded quality factors of an undisturbed and of a disturbed resonator; Q and Q_d, loaded quality factor of an undisturbed and of a disturbed resonator; Q_{out} and Q_e, outer and loaded quality factors; $q_{w,c}$, $q_{w,p}$, and q_{w0}, bulk concentration of water with a high coupling energy, polysorption water, and free water; S, specific surface of pores in grain (wheat), cm^2/g; t, temperature of a sample, ^{o}C; V, volume of a resonator, cm^3; W, moisture content of the material, %; $W_{cr} = 0.1(10\%)$, critical moisture content corresponding to transition from a monosorption water to a polysorption one; α and α_w, coefficient of attenuation of an electromagnetic wave and the same in a moisture-containing material, dB/cm; $\alpha_{w,c}$, $\alpha_{w,p}$, and α_{w0}, coefficients of attenuation of an electromagnetic wave in water having a high coupling energy, polysorption water, and free water, dB/cm; β, phase constant, rad/cm; Δ, difference between final and initial values; $\varepsilon^* = \varepsilon' + i\varepsilon''$, complex dielectric permittivity of the material; μ, grammolecular weight of water; Θ, relative volumetric moisture content of the material; ρ, ρ_a, and ρ_w, relative density of a moist and arid material and of water; λ, wavelength, cm; $\sigma = 3 \cdot 10^{-8}$, seat of one water molecule on the solid-phase surface, cm^2; $\varphi(W, S, a_{\max})$, function characterizing the relationship between free and bound water; Φ, volume efficiency; $\omega = \omega' + i\omega''$, complex angular frequency, sec^{-1}. Subscripts: a, arid; c, monosorption water; cr, critical moisture content; d, disturbed; max, maximum; out, outer; p, polysorption water; w, water; 0, initial value (for water — free water); e, equivalent.

REFERENCES

1. V. K. Benzar', *The Technique of Microwave Moisture Metering* [in Russian], Vysheishaya Shkola, Minsk (1974).
2. L. H. Busker, Microwave moisture measurement, *Inst. Control Syst.*, **12**, 72–79 (1968).
3. V. V. Lisovskii, *Theory and Practice of Microwave Control of the Moisture Content of Agricultural Materials* [in Russian], BGATU, Minsk (2005).
4. I. Renhart, The control of moisture of rocks by methods of microwave aquametry, in: *Proc. 4th Int. Conf. "Electromagnetic Wave Interaction with Water and Moist Substances,"* Weimar (2001), pp. 372–379.