MOISTURE DISTRIBUTION IN GRANULAR MATERIAL DURING DRYING IN A FLUIDIZED BED

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This paper gives the results of a determination of the moisture content gradient and an investigation of the moisture distribution in a granular material during drying in a fluidized bed.

It was shown earlier [2] that an important factor in the case of a moisture-inert granular material ($Lu \sim \sim 1.0 \cdot 10^{-3}$) is internal moisture transfer, which is responsible for the specific nature of the moisture distribution in the material during drying.

In this work we used the experimental data of [9] for the drying of wheat grain in a fluidized bed and our own data for the moisture diffusion coefficient a_m. According to [1, 9], the drying of moist grain in a fluidized bed occurs during the constant rate period. According to [4], in the constant drying rate period with the temperature of the material and the coefficient a_m constant the moisture distribution in the material is of a parabolic nature. However, the moisture distribution in grain during drying in a fluidized bed is not parabolic. The absence of a parabolic moisture distribution in the material in the initial phase of drying is confirmed by analytical solutions [5, 6] and experimental investigations [3, 8].

Hence, as a first approximation we suggest that the moisture distribution in the grain in the constant drying rate period is described by the equation

$$u = u_{0,\tau} - m\,(r/R)^n \quad (n > 2) \tag{1}$$

or

$$\frac{du}{dr} = -\frac{mnr^{n-1}}{R^n}, \tag{1a}$$

where du/dr is the scalar value of the moisture content gradient, which can be found graphically.

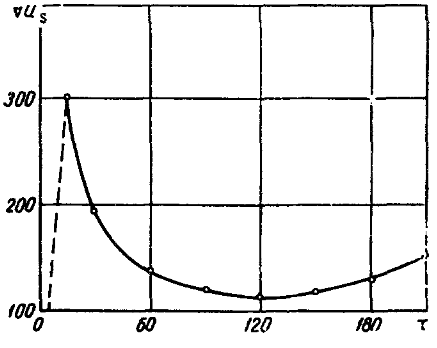

Fig. 1. Change in moisture content gradient ∇u_S on grain surface during drying (τ in sec), calculated from formula (3).

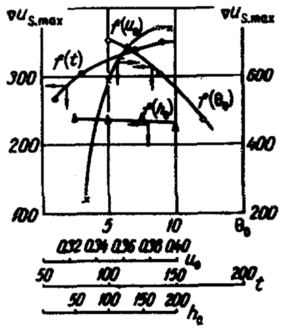

Fig. 2. Maximum moisture content gradient on grain surface $\nabla u_{S,max}$ as a function of initial grain content u_0 (kg/kg), initial grain temperature Θ_0(°C), temperature of drying agent t(°C), and height of bed h_0(mm).

The moisture content gradient on the surface, determined from the equation for the moisture flux, can be put in the form

$$\nabla u_n = -\mathrm{Ki}_m \frac{u_0}{R} - \delta \nabla T. \tag{2}$$

As our calculations showed, for a sphere of radius R and an ellipsoid of revolution (which a grain of equivalent volume most closely resembles in shape) with semi-axes a and b (a = 2.1 b) the difference in surface area does not exceed 3%. Hence, we can regard the grain as a sphere of equivalent volume and can calculate the characteristic radius R from the formula

$$R = 0.5\sqrt[3]{6M/\pi n \rho}.$$

If shrinkage of the material is neglected, R = const. The first term on the right side of Eq. (2) is the moisture content gradient, which depends on the moisture diffusion coefficient a_m and the drying regime parameters. The second term characterizes the thermal moisture condition. The thermogradient coefficient δ depends on the moisture content and, according to [4], for grain δ_{max} = 0.0005 kg/kg × deg for U = 0.333 kg/kg.

Research workers [10, 11, etc.] have determined the temperature gradient ∇T which is produced during the drying of grain and have obtained different results. The maximum difference in the temperatures at the surface and the center of the grain was obtained in [10] in the case of drying of single seeds with moisture content u_0 = 0.25 kg/kg by a drying agent with temperature

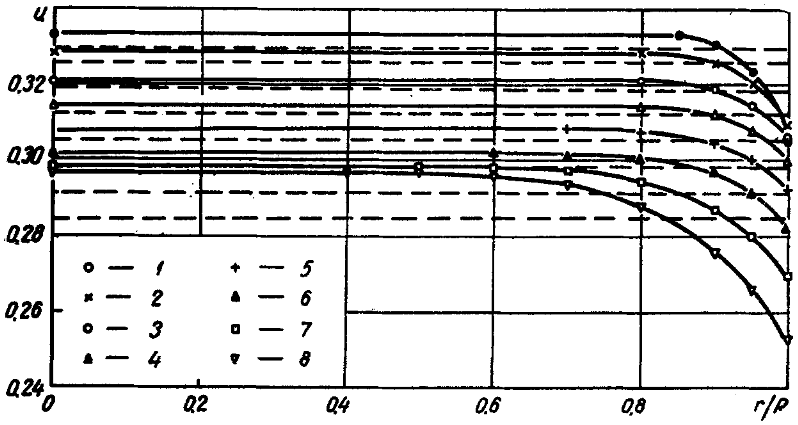

Fig. 3. Change in local moisture content u (kg/kg) in relation to local coordinate for different τ = const (broken lines show mean moisture content for corresponding τ): 1) τ = 15; 2) 30; 3) 60; 4) 90; 5) 120; 6) 150; 7) 180; 8) 210 sec.

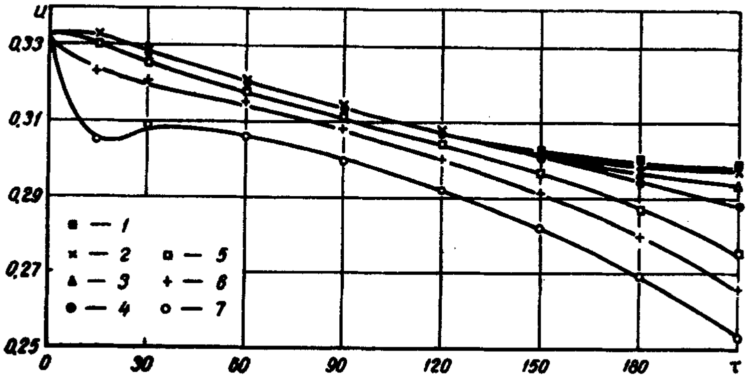

Fig. 4. Change in local moisture content u (kg/kg) with time τ (sec) for different r/R = const: 1) r/R = 0; 2) 0.6; 3) 0.7; 4) 0.8; 5) 0.9; 6) 0.95; 7) 1.0.

$t = 110°$ C and a flow velocity $v = 3.8$ m/sec. The maximum temperature difference of 14°, observed 1–1.5 sec after the start of the experiment, corresponded to $\nabla T \sim 14\ 000$ deg/m (in the case of a parabolic temperature distribution). Then, as an exploratory estimate $\delta\nabla T \sim 7$ kg/kg · m. (At this instant, obviously, the value of $\mathrm{Ki}_m u_0/R$ is also low and thermogradient transfer plays a definite part). According to our calculations, the maximum value of the first term, observed 15 sec after the start of the experiment, was $\mathrm{Ki}_m u_0/R > 100$ kg/kg · m. Then the thermogradient component of ∇u_s can be neglected and for $\tau \geq 15$ sec we can write

$$\nabla u_s = -\mathrm{Ki}_m u_0/R. \qquad (3)$$

Figure 1 shows that the moisture content gradient on the grain surface, as is to be expected, has a maximum at the start of the process and then begins to decrease appreciably owing to the sharp increase in the moisture diffusion coefficient a_m with increase in the temperature of the material [2, 7]. Subsequently, owing to the reduction of the coefficient a_m with reduction in moisture content of the grain ∇u_s increases.

Figure 2 shows that the value of $\nabla u_{s\max}$ is most affected by the initial moisture content and initial grain temperature. The value of $\nabla u_{s\max}$ is less affected by the change in the temperature of the drying agent and, finally, the change in the height of the bed has least effect on the maximum value of this gradient. For instance, the maximum surface moisture content gradient formed in the drying of grain with initial moisture content $u_0 = 0.396$ kg/kg in a fluidized bed is more than three times the value of ∇u_s for grain with $u_0 = 0.333$. A reduction of the initial temperature of the grain by only 4.5° increases ∇u_s by 25% (other conditions being equal).

The moisture content gradient in certain conditions affects the structural and mechanical properties of the grain and, hence, excessively high moisture content gradients are undesirable. For instance, we found that drying of grain with an initial moisture content $\omega_0 \geq$ $\geq 33\%$ and low initial temperature (5–10° C) by a drying agent with a temperature of more than 150° C led to some reduction in the sorption capacity of the grain and this was accompanied by a deterioration in its milling quality (the ash content of the flour was increased). This can be attributed to a reduction in the elasticity of the husk, which is penetrated by a dense network of capillaries, and an increase in its brittleness, so that some of the husk material is found in the flour after milling.

Hence, the drying conditions for grain must be chosen with due regard to its mass-transfer characteristics. To preserve the processing qualities of grain its rapid drying must obviously, entail prior heating of the grain in highly saturated air (high φ).

From (1a) and (3)

$$m = \mathrm{Ki}_m u_0/n. \qquad (4)$$

Regarding a grain as a sphere we can find the moisture content $u_{0,\tau}$ in the center of the material at time τ by integrating Eq. (1) and using Eq. (4):

$$u_{0,\tau} = \bar{u}_\tau + 3\mathrm{Ki}_m u_0/(n^2 + 3n). \qquad (5)$$

In Eq. (5) u_0, $\bar{u}_\tau$, and Ki_m are known from experiment. The unknown quantities are $u_{0,\tau}$ and $n = f(\tau)$.

Assuming that in the course of $\tau = 15$ sec the moisture content in the center of the grain is constant and is approximately equal to the initial moisture content ($u_{0.15} \cong u_0$), we find from (5) the corresponding value of n and plot the moisture distribution curve for this instant.

To plot the moisture content curve at subsequent periods we must know how $u_{0,\tau}$ or n vary with time. As mentioned above, the drying of grain in a fluidized bed at $t \geq 80°$ C and $\Theta \leq 65°$ occurs in the first drying period. We can infer from the foregoing that a parabolic moisture distribution is set up when the moisture content of the grain reaches its first critical value. After determining the latter, we find the value of τ_{cr1}, for which $n = 2$. Thus, n is an inverse linear function of the time τ and decreases from an initial, relatively high value to 2 at the end of the first drying period.

Hence, to find the moisture content $u_{r,\tau}$ of any point of the grain at time τ during drying in a fluidized bed we need to know u_0, $\bar{u}_\tau$ and Ki_m. Then, putting $u_{0.15} = u_0$, we determine n_{15} for $\tau = 15$ sec and marking the value $n = 2$, corresponding to τ_{cr1}, on the graph $n = f(\tau)$, we connect points n_{15} and $n = 2$ by a straight line and determine n_τ. Then, from (5) and from the known Ki_m, $\bar{u}_\tau$, u_0, n_τ we determine $u_{0,\tau}$, and from (1) we find $u_{r,\tau}$.

The graphs in Figs. 3 and 4 show the curves $u = f(r)$ for τ = const and $u = f(\tau)$ for r = const for one of the experiments.

The experimental and analytical investigation of moisture transfer within the material enables us to select efficient drying conditions for grain with due regard to its mass-transfer characteristics and its structural and mechanical properties.

NOTATION

t is the temperature of drying agent; Θ is the temperature of heating of grain; Γ, χ_Γ are form factors.

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