THERMOPHYSICAL AND BIOCHEMICAL CHARACTERISTICS OF BULK WHEAT GRAIN

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This paper recommends ways of determining the coefficients of heat and mass transfer in bulk wheat grain with due regard to molar transfer of moist air.

The unsteady temperature and moisture distributions in a pile are described by a system of nonlinear differential equations [1]. When the system is solved by the electrothermal analog method* relatively simple electric models can be used to investigate the laws of heat and mass transfer in towers, and the optimum conditions of transfer can be chosen.

Solution of the system of equations [1] by the electrothermal analog method requires approximate expressions, which are given below, for the determination of the thermophysical characteristics of bulk wheat from the experimental data available in the literature.

Heat capacity. The heat capacity of free-flowing granular materials is related in a complex manner to the temperature, moisture, mode of cultivation, and variety of the grain. The effects of mode of cultivation and variety of the grain have hardly been investigated at all, but the experimental data on the heat capacity of different crops and varieties of the same plant confirm that these effects are present. The temperature dependence of the heat capacity has not been adequately investigated.

There are fuller experimental data on the effect of moisture content of the grain on the heat capacity. Experimental work in this field by various investigators has been summed up in [2]. An analysis of these and other investigations shows that the heat capacity of the moisture in the grain depends on the mode of binding with the grain. Hence, the relationship between the heat capacity and the moisture content is altered on transition from polymolecular adsorption moisture (the subcritical moisture content of wheat [3]) to capillary moisture (moisture content above the critical level). In the hygroscopic region

$$C = (3U^2 + 4.25U + 1.25)\cdot 10^3 \quad \text{for } U \leqslant 0.18, \tag{1}$$

$$C = (4.19U^2 + 5.22U + 1.03)\cdot 10^3 \quad \text{for } 0.18 \leqslant U \leqslant 0.3. \tag{2}$$

Heat conduction. Heat transfer in granular materials is affected by the heat conduction of the particles, the radiation from particle to particle, and the convection of gas and moisture contained among the particles. The total contribution of convection and radiation at low values of the gradient t and grain diameter d = 3–5 mm does not exceet 3–7% of the total heat transfer, i.e., in these conditions the main heat transfer is due to contact heat conduction, which is given by the well-known expression

$$\lambda = \lambda_d + f(U,\ t). \tag{3}$$

Both components in Eq. (3) depend on the nature of the material, its structure, porosity, state, etc.

An analysis of the experimental data [5–9] does not show the effect of the grain temperature on the heat conduction, since the experimental error and the effect of subsidiary factors (difference in varieties of grain, porosity, size of grains, impurities, etc.) are much greater than the effect of temperature. In the hygroscopic region a satisfactory agreement with the experimental data is obtained from a linear relationship between λ and the grain moisture content

$$\lambda = \lambda_d + 0.1U, \tag{4}$$

where the heat conduction λ_d of the dry wheat mass is given by the expression [4]

$$\lambda_d = (0.0186\gamma_0^2 + 151\gamma_0 + 25600)\cdot 10^{-6}. \tag{5}$$

Expression (4) is valid in the case of local convection of the air in closed pores. If the integral temperature of the grain layer is higher than the ambient temperature then molar transfer of damp air (filtration) due to the different air densities begins to occur in the channels between the grains. In this case the additional heat transfer can be taken into account by an effective thermal conductivity λ_e For a simple model where the grain layer is open on both sides (free access of air to the lower and upper parts of the layer), the value of λ_e by the zonal method of calculation is given by the expression

$$\lambda_e = \lambda \pm c_p' \xi G h, \tag{6}$$

where h is the height of the zone. The value of h is chosen so that the thermophysical characteristics of the grain are practically constant within the region. The moisture precipitation coefficient of the air flow is

$$\xi = 1 + \frac{r}{c_p'} \frac{\Delta\rho}{\Delta t}. \tag{7}$$

Heat and mass transfer between a moving stream of moist air and grain involves an insignificant potential difference due to the large surface of heat and mass transfer and the low flow velocity. Hence, it can be assumed with sufficient accuracy for calculations that the moist air in the spaces among the grains is in thermal and moisture equilibrium with the grain surface. In this case the function $\rho(U, t)$

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* A paper on the method of electric simulation appears on pp. 363–365 of this number of the journal.

can be determined experimentally from the equilibrium moisture content of the material at different U and t.

The experimental data of [14] were used to obtain approximate values of $\rho(U, t)$ in the hygroscopic region (from values of $U \geq 0.07$) and the temperature range 0° C to 50° C.

In the region of subcritical moisture content of wheat the sorption is

$$\rho_s = [(0.257t^2 - 1.05t + 33.5)U - (0.01435t^2 - 0.1045t + 1.95)] \cdot 10^{-3}, \tag{8}$$

the desorption is

$$\rho_d = [(0.205t^2 - 0.41t + 30.8)U - (0.01008t^2 - 0.034t + 1.95)] \cdot 10^{-3}. \tag{9}$$

In the region of subcritical moisture content of wheat the sorption is

$$\rho_s = [(0.06293t^2 + 0.1405t + 7.52)U + (0.00871t^2 + 0.03347t + 1.817)] \cdot 10^{-3}; \tag{10}$$

the desorption

$$\rho_d = [(0.0607t^2 + 0.33t + 8)U + (0.00933t^2 - 0.0127t + 1.68]) \cdot 10^{-3}. \tag{11}$$

Replacing the increase in vapor concentration $\Delta\rho$ in (7) by the total differential of the function $\rho(U, t)$ we obtain

$$\xi = 1 + \frac{r}{c_p'}\left[\left(\frac{\partial\rho}{\partial U}\right)_t \frac{\Delta U}{\Delta t} + \left(\frac{\partial\rho}{\partial t}\right)_U\right]. \tag{12}$$

The weight flowrate G is determined from the condition of equality of the upthrust of the air flow and the aerodynamic resistance of the grain layer. From the experimental data [10] on the aerodynamic resistance of wheat grain for the case of laminar filtration of air

$$G = \frac{\gamma_{0a}\beta_0 g d^2 (1-k)^3}{162\nu\omega^2 k^2}\left(\frac{\Sigma t_i h_i}{\Sigma h_i} - t_{\text{н}}\right). \tag{13}$$

In expression (13)

$$k = \frac{1}{455/\gamma_{\text{b}} + 1.15}, \tag{14}$$

$$d = 0.124\sqrt[3]{mk/\gamma_{\text{b}}}. \tag{15}$$

According to the data of [10], the shape factor for wheat and rye grains is $\omega = 1.55$.

Potential conduction. The laws of mass transfer in moist materials have now been adequately investigated in Lykov's works. The theoretical course of the curve

$$a_m = f(U, t)$$

for typical capillary and colloidal substances is illustrated in [16, 17]. Incomplete experimental data on the mass transfer coefficients for granular materials and food products have been obtained in [5, 11-13] and elsewhere. Yet the available experimental material is still not sufficient to establish the indicated relationship for grain in a wide range of moisture contents and in relation to the way in which the moisture is bound with the material. The data of [13] show that the value of a_m decreases with increase in the moisture content of the grain (from moisture contents corresponding approximately to the start of polymolecular adsorption up to the maximum hygroscopic state). There is a particularly pronounced reduction of a_m in the region of the subcritical moisture content of grain. The coefficient of potential conduction also depends on the temperature and increases with increase in the latter. From the experimental data of [13] we obtain the following empirical relationship connecting the mass transfer coefficient with the moisture content and temperature of the grain:

$$a_m = \frac{0.002125t^2 + 0.366t - 5.9}{100U - 4.2} \cdot 10^{-9}. \tag{16}$$

Formula (16) is valid in the region $0.2 \leq U \leq 0.3$ and $20 \leq t \leq 60°$ C. The determination of a_m for wheat in the region of subcritical moisture content will require further experimental investigations.

Thermal moisture conduction. Thermal moisture conduction in bulk grain, as in hygroscopic materials of inorganic origin, depends on the way in which the moisture is bound with the material. In the region $U = 0-0.03$ (monomolecular adsorption moisture) the thermogradient coefficient is zero. In the region of polymolecular adsorption (approximately up to the critical moisture content) the value of δ is not zero and depends weakly on U:

$$\delta = (U - 0.02)/260. \tag{17}$$

In the region above the critical moisture content of grain there is a sharp increase in δ, which reaches its greatest value at the point of the maximum hygroscopic state. The determination of δ for wheat will require further investigations.

As mentioned above, in bulk wheat grain there is transfer of heat and moisture, which filters through the channels between the grains in the form of a vapor-air mixture. With due regard to the molar transfer of moist air the specific moisture flux is

$$j = -a_m\gamma_0\nabla U - a_m\gamma_0\delta\nabla t \mp Gh\nabla\rho. \tag{18}$$

The value of $\nabla\rho$ is found from the expression [15]

$$\nabla\rho = \left(\frac{\partial\rho}{\partial U}\right)_t \nabla U + \left(\frac{\partial\rho}{\partial t}\right)_U \nabla t. \tag{19}$$

It follows from expression (19) that moisture transfer by a vapor-air mixture conforms to the same law as moisture transfer in hygroscopic materials. Then, on the basis of relationships (18) and (19) we can write

$$j = -a_{m\text{e}}\gamma_0\nabla U - a_m\gamma_0\delta_\text{e}\nabla t, \tag{20}$$

where

$$a_{m\text{e}} = a_m \pm \frac{Gh}{\gamma_0}\left(\frac{\partial\rho}{\partial U}\right)_t, \tag{21}$$

$$\delta_\text{e} = \delta \pm \frac{Gh}{a_m\gamma_0}\left(\frac{\partial\rho}{\partial t}\right)_U. \tag{22}$$

Biochemical processes, particularly the respiration of the grain, have a significant effect on the temperature and moisture distribution in bulk grain. It is known that in resting (nongerminating) seeds the amount of heat released during respiration is almost exactly equal to the total amount of heat produced by the combustion of sugar.

A consideration of this and the experimental data of [18] for the evolution of CO_2 during aerobic respiration gave expressions for the specific rate of heat and moisture release in bulk wheat grain:

$$Q = \gamma_0 (2.24t^3 - 74.4t^2 + 1708t - 7140) \times \times (U/(1+U) - 0.1525) \cdot 10^{-4}, \tag{23}$$

$$D = \gamma_0 (0.856t^3 - 28.52t^2 + 654t - 2740) \times \times (U/(1+U) - 0.1525) \cdot 10^{-11}. \tag{24}$$

Formulas (23) and (24) are valid in the temperature range t = 0°–50° C and for moisture content U = =0.19–0.3.

The proposed analytical relationships give mean errors in comparison with the data of the experiments used in the work in the following range: formulas (1) and (2)—10%; formula (4)—5%; formulas (8) and (11) —1.5%; formula (16)—5%; formula (17)—0.5%; formulas (23) and (24)—4%.

The mean error of formulas (8)-(11) was determined in relation to the mean square values of the experimental figures.

The expressions for the determination of the thermophysical characteristics of grain were used to investigate the temperature and moisture distributions in wheat grain by the electrothermal analog method. The results showed a satisfactory agreement between the electric simulation data and the data of normal experiments.

Example of calculation. We will determine the thermophysical characteristics and the specific heat and moisture release of the surface layer of wheat grain in the following conditions: height of pile l = = 2m; mean integral temperature of pile $t_g = Et_ih_i/ /E_{hi} = 30°$ C; height of surface layer h = 0.1 m; temperature of grain on inner boundary of surface layer $t_{in} = 27°$ C; temperature of grain on outer boundary of surface layer $t_s = 23°$ C; temperature of outer air $t_{ext} = 20°$ C; $\gamma_b = 720$ kg of moist grain / /m^3; moisture content of grain on inner boundary of surface layer $U_{in} = 0.22$ kg of moisture/kg of dry matter; moisture content of grain on outer boundary of surface layer $U_s = 0.18$ kg of moisture /kg of dry matter; shape factor of wheat grain $\omega = 1.55$; weight of 1000 grains m = 0.07 kg; free acess of atmospheric air to bottom of stack.

Solution. In view of the small height of the surface layer (0.1m) we take a linear law for the temperature and moisture distribution over the height of the surface layer. Then the mean integral values of the temperature and moisture content of the surface layer are $t_m = 25$ and $U_m = 0.2$.

The heat capacity of the grain, from (2), is

$$C = [4.19(0.2)^2 + 5.22 \cdot 0.2 + 1.03] \cdot 10^3 = 2241.$$

The density of the dry matter is

$$\gamma_0 = \gamma_b/(1 + U_m) = 720/1.2 = 600.$$

The thermal conductivity of the dry matter is, from (5),

$$\lambda_d = [0.0186 \cdot (600)^2 + 151 \cdot 600 + 25600] \cdot 10^{-6} = 0.1229$$

and of moist grain, from (4), is

$$\lambda = 0.1229 + 0.1 \cdot 0.2 = 0.1429.$$

We determine the equilibrium concentration of moist air in the surface layer from Eq. (10) with $t_m =$ = 25 and $U_m = 0.2$ (sorption at supercritical moisture content). The partial derivatives are

$$\left(\frac{\partial \rho}{\partial U}\right)_t = 10^{-3} [0.06293 (25)^2 + 0.1405 \cdot 25 + 7.52] = 0.0503,$$

$$\left(\frac{\partial \rho}{\partial t}\right)_U = [0.2 (0.06293 \cdot 2 \cdot 25 + 0.1405) + 0.00871 \cdot 2 \cdot 25 + + 0.03347] \cdot 10^{-3} = 1.1264 \cdot 10^{-3}.$$

The coefficient of moisture precipitation of the moist air in the surface layer, from (12), is

$$\xi = 1 + + \frac{2444 \cdot 10^3}{1025} \left[0.0503 \frac{0.22 - 0.18}{27 - 23} + 0.001126\right] = 4.88.$$

The coefficient of packing density of the grain, from (14), is

$$k = \frac{1}{455/720 + 1.15} = 0.56.$$

The equivalent diameter of a single grain, from (15), is

$$d = 0.124 \sqrt[3]{0.07 \cdot 0.56/720} = 0.0047.$$

The weight rate of filtering air, from (13), is

$$G = \frac{1.293 \cdot 9.81 \cdot (0.0047)^2 \cdot (1 - 0.56)^3}{273 \cdot 162 \cdot 15.5 \cdot 10^{-6} \cdot (1.55)^2 (0.56)^2} (30 - 20) = = 46.25 \cdot 10^{-6}.$$

The effective thermal conductivity, from (6), is

$$\lambda_e = 0.1429 + 1025 \cdot 4.88 \cdot 46.25 \cdot 10^{-6} \cdot 0.1 = = 0.1429 + 0.0232 = 0.1661.$$

The moisture diffusion coefficient, from (16), is

$$a_m = \frac{0.002125 (25)^2 + 0.366 \cdot 25 - 5.9}{100 \cdot 0.2 - 4.2} \cdot 10^{-9} = 0.29 \cdot 10^{-9}.$$

The effective moisture diffusion coefficient, from (21), is

$$a_{me} = 0.29 \cdot 10^{-9} + \frac{46.25 \cdot 10^{-6} \cdot 0.1}{600} \cdot 0.0503 = 0.68 \cdot 10^{-9}.$$

We determine the thermogradient coefficient approximately from (17), since the latter is valid only in the region of the subcritical moisture content of wheat (U < 0.18):

$$\delta = (0.2 - 0.02)/260 = 0.692 \cdot 10^{-3}.$$

The effective coefficient of thermal moisture conduction from (22) is

$$\delta_e = 0.692 \cdot 10^{-3} + + 46.25 \cdot 10^{-6} \cdot 0.1 \cdot 1.1264 \cdot 10^{-3}/0.29 \cdot 10^{-9} \cdot 600 = 0.0307.$$

The specific rate of heat release of the grain from (23) is

$$Q = 600 \cdot 10^{-4} [2.24 (25)^3 - 74.4 (25)^2 + 1708 \cdot 25 - 7140] \times \times [0.2/(1 + 0.2) - 0.1525] = 20.45.$$

The specific rate of moisture release of the grain from (24) is

$$D = 600\cdot 10^{-11}\cdot[0.856\,(25)^3 - 28.52\,(25)^2 + 654\cdot 25 - 2740]\times$$
$$\times\,[0.2/(1+0.2) - 0.1525] = 7.83\cdot 10^{-7}.$$

NOTATION

C is the reduced specific weight heat capacity of gain, J/kg of dry matter · deg; c_p' is the reduced specific weight heat capacity of moist air, J/kg of moist air · deg; λ is the thermal conductivity, W/m · deg; γ_0 is the density of dry matter of grain, kg of dry matter/m^3; γ_{0a} is the density of air in normal conditions, kg of moist air/m^3; γ_b is the bulk density of grain, kg of moist grain/m^3; a_m is the moisture diffusion coefficient, m^2/sec; δ is the thermogradient coefficient, kg of moisture/kg of dry matter · deg; ρ is the concentration of vapor in vapor–air mixture, kg of moisture/kg of moist air; r is the heat of phase transition, J/kg; ν is the kinematic viscosity of air, m^2/sec; g is the gravitational constant, m/sec^2; β_0 is the coefficient of bulk expansion of air, 1/deg; d is the equivalent diameter of grain, m; k is the coefficient of packing density of grain; ω is the grain shape factor, m is the weight of 1000 grains, kg; Q is the specific rate of heat release of grain, W/m^3; D is the specific rate of moisture release of grain, kg of moisture/m^3 · sec; G is the weight rate of air filtration, kg of moist air/m^2 · sec; t is the temperature, °C; U is the moisture content of grain, kg of moisture/kg of dry matter. Subscripts: H denotes ambient medium; i denotes regions of grain mass; e e means effective.

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