Heat and mass transfer modeling during keeping bulk food raw materials in ferroconcrete storages

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Abstract. The quality of finished and semi-finished food products, as well as the possibility of deep processing of secondary raw materials, largely depends on the storage conditions of raw materials coming for processing. Excessive overheating or overcooling of bulk food raw materials (for example, grain, potatoes, Jerusalem artichoke and other types of agricultural products) often leads to bacterial contamination and another type of damage. It causes unwanted costs due to extra sorting. Besides, the damaged raw material cannot be recycled to extract additional useful substances such as starch from the cleaned surface of the pulp or food fibers during the processing of Jerusalem artichoke, so additional losses occur. Thus, the processes should be closely attended both in the storage themselves and directly in the stored bulks of food products. It is necessary to take into account this external environment impact on set mode storage to maintain the required temperature and humidity conditions, providing safe prolonged storage regimes for the bulk food raw materials.

1. Introduction
[1] provided an analytical description of the non-stationary temperature field of a limited volume of grain mass (in metal silos of cylindrical shape) in the function of outdoor air temperature. However, the most common way to store agricultural raw materials is to store them in ferroconcrete elevators. In this method of storage, the effect of atmospheric conditions on the storage mode (especially humidity) of the bulk of food raw materials varies significantly.

2. Problem statement
The present work considers more general solutions than the solution investigated in [1] because the thermal conducting properties of the ferroconcrete wall are taken into account and the problem of joint heat and mass transfer is considered, not just the net thermal conductivity of the bulk. Besides, the heat of respiration of food raw materials is also taken into account.

If we consider the bulk of food raw materials as a homogeneous and isotropic medium and assume that the wall is moistureless (outer and inner insulation are made) and that the outer temperature of the side (outer) cylindrical surface of the elevator changes depending on time in accordance with the periodic law (as in [1-3,6-8]), then mathematically the problem of joint heat and mass transfer in a bulk of
food raw materials stored in a ferroconcrete elevator can be formulated as follows: it is required to solve a system of second-order partial differential equations:

\[
\begin{align*}
\frac{\partial t_1(r, \tau)}{\partial \tau} &= a_{q_1} \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial t_1(r, \tau)}{\partial r} \right) + \frac{\varepsilon \rho}{c_{q_1}} \frac{\partial u(r, \tau)}{\partial \tau} + \frac{q}{c_q}; \\
\frac{\partial u(r, \tau)}{\partial \tau} &= a_m \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial u(r, \tau)}{\partial r} \right) + a_m \delta \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial t_1(r, \tau)}{\partial \tau} \right); \\
(t > 0, \tau > 0 < \tau < R_1) \\
\frac{\partial t_2(r, \tau)}{\partial \tau} &= a_{q_2} \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial t_2(r, \tau)}{\partial r} \right), \\
(t > 0, \tau > 0 < \tau < R_2)
\end{align*}
\]

Under the following boundary conditions:

\[
\begin{align*}
t_1(r, 0) &= t_2(r, 0) = t_0 = \text{const}; \\
\frac{\partial u(0, \tau)}{\partial r} &= \frac{\partial t_1(0, \tau)}{\partial r} = 0; \\
t_1(0, \tau) &< \infty; \ u(0, \tau) < \infty; \\
t_1(R_1, \tau) &= t_2(R_1, \tau); \\
\lambda_{q_1} \frac{\partial t_1(R_1, \tau)}{\partial r} &= \lambda_{q_2} \frac{\partial t_2(R_1, \tau)}{\partial r}; \\
u(r, 0) &= u_0 = \text{const}; \\
\frac{\partial u(R_1, \tau)}{\partial r} &= \delta \frac{\partial t_1(R_1, \tau)}{\partial r} = 0; \\
t_2(R_2, \tau) &= t_{\text{environment}} = t_0 + t_m \cos(\omega(\tau + \tau_0)); \\
q &= q_{\pm} \pm q_2 \exp(-k\tau), \quad k = \text{const} > 0.
\end{align*}
\]

Here (1) and (3) are equations of the heat transfer in the bulk of food raw materials and in the ferroconcrete wall, respectively.

Equation (2) is the equation of moisture transfer in the bulk of food raw materials.

Equalities (4) and (8) are the conditions of the uniformity of temperature and humidity fields in the bulk of food raw materials and in the wall at the beginning time of the process (\(\tau=0\)).

Expressions (5) are the conditions of symmetry and physical limitation of the transfer potentials in the bulk of food raw materials.

Equalities (6) and (7) are the boundary conditions of the fourth kind, which express the equality of temperature and heat flows given good contact on the inner surface of the cylinder wall.

Equation (9) is the condition of moisture insulation on the inner surface of a ferroconcrete wall.

Equation (10) is a condition of the dependence of the temperature of the outer surface of the wall on seasonal change in atmospheric air temperature [1].

The dependence of the specific heat of respiration of the bulk of food raw materials on time is given by equation (11), where the lower sign refers to oilseeds such as flax[2,7], the upper sign refers to Jerusalem artichoke, potatoes, etc. [3-5, 9-11].

Index \(i=1\) refers to the bulk of food raw materials, index \(i=2\) - to the wall.

3. Discussion of results

The thermal conductivity equation (3) is written for a hollow cylinder. However, considering that the outer casing - ferroconcrete wall - is thin in comparison with the radius of the inner cylinder, in the
first approximation it can be considered flat. So, equation (3) can be replaced by an equation of thermal conductivity for an unlimited plate:

$$\frac{\partial \theta_2(r, \tau)}{\partial \tau} = a_{q_2} \frac{\partial^2 \theta_2(r, \tau)}{\partial r^2}, \quad (\tau > 0, \ R_1 < r < R_2).$$  \hspace{1cm} (12)

The boundary value problem (1) - (2), (4) - (12) is solved by integral transformation methods. Due to the fact that the expressions for the fields of the desired transfer potentials are heavy, we present only the solution for the temperature field inside the food raw material volume:

$$T_1(X, F_0) = \frac{t_1(\tau, \tau) - t_0}{t_m - t_0} = \pm \frac{P_{\alpha_0}}{Pd} \exp(-Pf F_0) \times$$

$$\times \left[ 1 + \frac{1}{\phi_k} \left( J_0(\sqrt{Pd} v_1 X) - J_1(\sqrt{Pd} v_2 X) \right) \cos \left( \sqrt{k_a Pd} (k_R - 1) \right) - \right]$$

$$- \frac{1}{4} \frac{P_{\alpha_1}}{Pd} \left( 2k_a (k_R - 1)^2 + \frac{N v_2^2 - v_2^2}{N + 1} (2k_a (k_R - 1) + 1) \right) -$$

$$- \frac{1}{\phi_{\omega}} \left[ \left( ber(\sqrt{Pd} v_1 X) - N ber(\sqrt{Pd} v_2 X) \right) \cos \beta - \right]$$

$$- \left( bei(\sqrt{Pd} v_1 X) - N bei(\sqrt{Pd} v_2 X) \right) \sin \beta -$$

$$- \sum_{n=1}^{\infty} \frac{A_{nT} \left[ N J_0(v_1 \mu_a X) - J_1(v_1 \mu_a X) \right] \exp(-\mu_a^2 F_0)}{\mu_a^2 \mu_n \left( 1 - \mu_n^2 \right)}. \hspace{1cm} (13)$$

Here

$$v_i^2 = \frac{1}{2} \left[ \chi + (-1)^{i-1} \sqrt{\chi^2 - \frac{4}{L_u}} \right], \quad (i = 1, 2)$$

$$\chi = 1 + \varepsilon Ko Pn + \frac{1}{L_u}; \quad N = \frac{v_1 (1 - v_2^2)}{v_2 (1 - v_1^2)};$$

$$L_u = \frac{a_{m_1}}{a_{m_2}} \text{ Lykov number;}$$

$$Ko = \frac{\rho u_0}{c_{q_1} \Delta t} \text{ Kossovich number, } \Delta t = t_m - t_0;$$

$$Pn = \frac{\delta \Delta t}{a_0} \text{ Posnov number;}$$

$$FO = \frac{a_{q_2} \tau}{R_1^2}; \quad FO_0 = \frac{a_{q_2} \tau_0}{R_1^2} \text{ Fourier numbers;}$$

$$Pd = \frac{k R_1^2}{a_{q_1}}, Pd_1 = \frac{a_{q_1} \tau_1}{R_1^2}, Pd_2 = k Pd_1 \text{ - Predvodielev numbers;}$$

$$k_R = \frac{R_2}{R_1}; \quad k_e = \frac{k_a}{\sqrt{k_a}}; \quad k_\lambda = \frac{\lambda d_1}{\lambda d_2};$$

$$PO = \frac{a_{q_1} R_1^3}{a_{q_1} c_{q_1} \Delta t} \text{ - Pomerantsev number;}$$

$$\lambda_{q_1} \text{ coefficients of thermal conductivity;}$$

$$\phi_k = \left[ J_0(\sqrt{Pd} v_2 - N J_0(\sqrt{Pd} v_1)) \right] \cos \left( \sqrt{k_a Pd} (k_R - 1) \right) +$$

$$+ k_\varepsilon \left[ v_2 J_1(\sqrt{Pd} v_2 - N v_1 J_1(\sqrt{Pd} v_1)) \right] \sin \left( \sqrt{k_a Pd} (k_R - 1) \right);$$
\[ \phi_{\omega} = \phi_1^2 + \phi_2^2; \]
\[ \phi_1 = \left( \text{ber}\left(\sqrt{P_{d1}}v_2\right) - N\text{ber}\left(\sqrt{P_{d1}}v_1\right)\text{ch}p\cos \rho + \left(N\text{bei}\left(\sqrt{P_{d1}}v_1\right) - \text{bei}\left(\sqrt{P_{d1}}v_2\right)\right)\text{sh}p\sin \rho + k_e \left(v_2\text{bei}_1\left(\sqrt{P_{d1}}v_2\right) - Nv_1\text{bei}_1\left(\sqrt{P_{d1}}v_1\right)\right)\text{ch}p\cos \rho + \left(v_2\text{ber}_1\left(\sqrt{P_{d1}}v_2\right) - Nv_1\text{ber}_1\left(\sqrt{P_{d1}}v_1\right)\right)\text{sh}p\sin \rho \right); \]
\[ \phi_2 = -\left(N\text{bei}\left(\sqrt{P_{d1}}v_1\right) - \text{bei}\left(\sqrt{P_{d1}}v_2\right)\right)\text{ch}p\cos \rho + \left(N\text{ber}\left(\sqrt{P_{d1}}v_1\right) - \text{ber}\left(\sqrt{P_{d1}}v_2\right)\right)\text{sh}p\sin \rho + k_e \left(v_2\text{be}_1\left(\sqrt{P_{d1}}v_2\right) - v_2\text{be}_1\left(\sqrt{P_{d1}}v_1\right)\right)\text{ch}p\sin \rho - \left(Nv_1\text{ber}_1\left(\sqrt{P_{d1}}v_1\right) - v_2\text{ber}_1\left(\sqrt{P_{d1}}v_2\right)\right)\text{sh}p\cos \rho \right); \]
\[ \phi_n = \left[1 + k_\lambda(k_R - 1)\right]V_{I1}(V_1\mu_n) - NV_{I1}(V_1\mu_n) \right] \times \cos\left(\sqrt{k_\alpha}(k_R - 1)\mu_n\right) - \left(N\left(k_\alpha(k_R - 1) + k_e v_2\right)\right)J_0(V_1\mu_n) - \left(\sqrt{k_\alpha}(k_R - 1) + k_e v_2\right)J_0(V_2\mu_n) - \frac{k_e}{\mu_n} \left[NV_{I1}(V_1\mu_n) - v_2J_1(v_2\mu_H)\right] \sin\left(\sqrt{k_\alpha}(k_R - 1)\mu_H\right); \]
\[ \mu_n - \text{consecutive positive roots of the characteristic equation}; \]
\[ \frac{[N\cos\left(\sqrt{k_\alpha}(k_R - 1)\mu\right) - \left(N\left(k_\alpha(k_R - 1) + k_e v_2\right)\right)J_0(V_1\mu) - \left(\sqrt{k_\alpha}(k_R - 1) + k_e v_2\right)J_0(V_2\mu_H) - \frac{k_e}{\mu} \left[NV_{I1}(V_1\mu) - v_2J_1(v_2\mu_H)\right] \sin\left(\sqrt{k_\alpha}(k_R - 1)\mu_H\right) = 0} \]
\[ \beta = P_{d1}(\text{Fo} + F_{a0}) - \arctg \frac{\phi_2}{\phi_1}; \]
\[ \rho = \sqrt{\frac{k_e P_{d1}}{2}} (k_R - 1) = \sqrt{\frac{P_{d2}}{2}} (k_R - 1); \]
\[ A_{nR} = 2T_m \cos\left(\frac{P_{d1}F_{o0} + \arctg \frac{P_{d1}}{\mu_H}}{\mu_H}\right) + \frac{P_{oH}^2}{\mu_H} \left(1 + \frac{P_{oH}}{\mu_H}\right); \]
\[ T_m = \frac{t_m}{\Delta t}; \quad X = \frac{r}{R_1}, \quad 0 < X < 1. \]

\[ J_n(y) - \text{the Bessel function of the first kind of } n\text{-th order of the argument } y; \]
\[ J_n(y\sqrt{\pm i}) = \text{ber}_n y \pm i\text{bei}_n y, \quad (n = 0, 1, 2, \ldots), \quad i = \sqrt{-1}; \]

\[ \text{ber}_n y \text{ and } \text{bei}_n y - \text{Thomson functions, the real and imaginary parts of the power series decomposition of the complex argument of Bessel function } J_n(y\sqrt{\pm i}), \text{with this } \text{ber}_0 y = \text{ber} y, \text{bei}_0 y = \text{bei} y [12-14]; \]
\[ J_n(y) = \sum_{m=0}^{\infty} \frac{(-1)^m (y/2)^{4m}}{(2m)!}; \quad \text{bei} y = \sum_{m=0}^{\infty} \frac{(-1)^m (y/2)^{4m-2}}{(2m-1)!}. \]

Thus, it can be seen, that the temperature distribution field inside the bulk of food raw materials is a function of a large number of similarity numbers:
For the quasi-stationary state ($Fo > Fo_c$) we obtain an expression from solution (13), that is convenient for engineering calculations of the temperature of a food raw material bulk stored in a cylindrical ferroconcrete elevator:

\[
t_1(r, \tau) = t_0 + \frac{q_1 R_1^2}{\alpha q_1} \left[ 2K_a(k_R - 1)^2 + \frac{N v_2^2 - v_2^2}{N - 1} (2k_a(k_R - 1) + 1) \right] - \frac{t_m - t_0}{\Phi_w} \left( \left( \text{ber} \left( \sqrt{\frac{P}{D_1}} v_2 x \right) - N \text{ber} \left( \sqrt{\frac{P}{D_1}} v_2 x \right) \cos \beta \right) - \left( \text{bei} \left( \sqrt{\frac{P}{D_1}} v_2 x \right) - N \text{bei} \left( \sqrt{\frac{P}{D_1}} v_2 x \right) \sin \beta \right) \right).
\]

The solution may have significant errors in comparison with the actual distribution of the temperature field for storage modes that do not meet taken assumptions, therefore the solution must be modified if we need to use it in practice [5-6].

For example, for storing a bulk product, taken as a homogeneous and isotropic medium, in a cylindrical storage, it can be assumed that the side surface is thermally insulated, and the temperatures of the base and top surfaces are change randomly. Then the heat transfer problem can be formulated as follows: it is necessary to solve heterogeneous thermal conductivity equation for an unlimited plate (the height of the product bulk is less than the storage diameter), or a limited rod (the height of the product bulk is much larger than the storage diameter).

\[
\frac{\partial t(z, \tau)}{\partial \tau} = a \frac{\partial^2 t(z, \tau)}{\partial z^2} + \frac{q_0}{c} \exp(k_1 \tau - k_z z)
\]

(0 < z < h, \ \tau > 0)

under the initial condition:

\[
t(z, 0) = t_0 = \text{const}
\]

and boundary conditions:

\[
t(0, \tau) = f_1(\tau);
\]
\[
t(h, \tau) = f_2(\tau)
\]

where $a$ - thermal diffusivity, $h$ - the height of the bulk, $t_0$ - product temperature at the beginning of the storage process, $c$ - specific heat capacity of the product bulk, $f_1(\tau)$, $f_2(\tau)$ - given bounded and continuous functions. Substituting [7]:

\[
t(z, \tau) = \psi(z, \tau) + \frac{q_0}{c} \exp \left( k_1 \tau - k_z z \right)
\]

where $\psi(z, \tau)$ is the new search function.

We bring equation (2) to a homogeneous one, that is, without a heat source:

\[
\frac{\partial \psi(z, \tau)}{\partial \tau} = a \frac{\partial^2 \psi(z, \tau)}{\partial z^2}
\]

but with new initial and boundary conditions:

\[
\psi(z, 0) = t_0 - \frac{q_0}{c} \exp(-k_z z) = \varphi(z)
\]
\[
\begin{align*}
\nu(0, \tau) &= f_1(\tau) - \frac{q_0}{c(k_1 - ak_2^2)} \exp(k_1 \tau) = \varphi_1(\tau) \\
\nu(h, \tau) &= f_2(\tau) - \frac{q_0}{c(k_1 - ak_2^2)} \exp(k_1 \tau - k_2 h) = \varphi_2(\tau)
\end{align*}
\]

The analytical solution of the recorded boundary value problem for the distribution of the temperature field in the product bulk was obtained by the integral finite sine transformation method.

The solution is obtained in the following form for the particular case of constant temperatures of the bulk bases, that is when \(t(0, \tau) = t_1 = \text{const} \), \(t(h, \tau) = t_2 = \text{const} \), and taking into account the known ratios [8-9]:

\[
t(z, \tau) = \frac{q_0}{c(k_1 - ak_2^2)} \exp(k_1 - k_2 z) + t_1 + (t_2 - t_1) \frac{z}{h} + \\
+ \left( \frac{2}{\pi} \sum_{n=1} \frac{t_0 - t_1 - (1)^n (t_0 - t_2)}{n \pi} \sin \frac{n \pi z}{h} \exp \left( \frac{an^2 \pi^2 \tau}{h^2} \right) - \frac{2q_0}{c(k_1 - ak_2^2)} \sum_{n=1} [1 - (1)^n \exp(- k_2 h) \sin \frac{n \pi z}{h} \times \right) \\
\left[ \exp \left( \frac{an^2 \pi^2 \tau}{h^2} \right) - \frac{k_2 h^2}{a} + (n \pi)^2 \right] \\
\left( \frac{k_2 h^2}{(k_2 h)^2 + (n \pi)^2} \right)
\]

The obtained dependence was used to model the storage process in the bulk.

Data of storage of sunflower seeds in the warehouse were used as experimental data. Due to the fact that the humidity difference between the layers when laying the batch (\(x=0\)) fluctuated slightly (±0.2%), the value of \(k_2\) was taken equal to zero. The moisture content of the seeds in the layer at the beginning - \(U(Z,0) = 8.4\%\), temperature value - \(t_0 = 16^\circ C\), \(k_1 = 0.8 \times 10^{-7} c^{-1}\) \(q_0 = 0.013 W/kg\). This corresponds to the estimates of seed allocation heat with appropriate humidity and temperature, obtained from the data of the paper [10].

The results of calculations for a bulk with a height of 3 m are shown in table 1.

| Table 1 - Experimental and calculated values of temperatures during storage of sunflower seed (\(t_1 = 24^\circ C; t_2 = 22^\circ C\)) |
|---|---|---|---|---|
| \(Fo, 10^3\) | \(X=0.17\) | \(X=0.5\) | \(X=0.83\) |
| The experimental temperature values | The calculated temperature values | The experimental temperature values | The calculated temperature values | The experimental temperature values | The calculated temperature values |
| 1 | - | 20.6 | - | 20.1 | - | 19.2 |
| 3 | 22 | 21.4 | 20 | 21.2 | 13 | 20.8 |
| 6 | - | 21.9 | - | 21.5 | - | 21.0 |
| 9 | - | 22.3 | - | 21.8 | - | 21.3 |
| 13 | 23 | 22.6 | 21 | 22.0 | 20 | 21.5 |
| 17 | - | 23.0 | - | 22.2 | - | 21.7 |
| 20 | 23 | 23.2 | 31 | 22.3 | 29 | 21.9 |
| 25 | - | 23.4 | - | 22.4 | - | 21.9 |
| 30 | - | 23.5 | - | 22.5 | - | 21.9 |
Here $F_0 = \frac{a \tau}{h^2}$ - Fourier number, $X = \frac{z}{h}$ - the dimensionless coordinate.

4. Conclusion

It is evident that a more complex model is more relevant for describing the real process at low heights of the seed bulk and Fourier number $F_0 < 0.02$. In other cases, discrepancies between the calculated and experimental values are observed which can be explained by several reasons. On the one hand, the change in humidity during storage is not taken into account in the function of the heat source which amounted to (0.6 - 1.0% as a result of storage). Besides, accelerating effect of temperature on the intensity of heat generation is not taken into account. The temperature difference at the beginning and end of storage reached 15 °C for the middle layer. It can be concluded that it is necessary to switch to models that take into account both the heat and moisture transfer coefficient and the non-linearity in temperature. The proposed mathematical models make it possible to predict and control temperature fields of product bulks and thus influence their quality and storage duration.

At the same time, the general solutions considered in this paper take into account thermal conductivity of ferroconcrete storage walls for the problem of joint heat and mass transfer and allow taking into account the heat of respiration inside the bulk of food raw materials. The mathematical solution of the problem allows getting a general picture of the joint heat and mass transfer in the bulk of food raw materials stored in a ferroconcrete elevator, also when the uniformity and isotropy of the bulk of food raw materials are assumed. Moreover, the expression for the quasistationary state ($F_0 > F_{0c}$) is obtained which is necessary for engineering calculations of the temperature of the bulk of food raw materials stored under the indicated conditions.

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