Modeling of heat and mass transfer processes at frying barley grain with superheated steam

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Abstract. The use of high-temperature inert heat carriers, in particular superheated steam, has become widespread in the technology of frying food products. This process is because superheated steam has significant advantages over other heat carriers used in thermal treatment. Insufficient study of the process of frying barley grain with overloaded steam, unjustified fear for preservation of the quality of the finished product prevent the development of a general method of calculating the process of frying, makes it challenging to choose optimal processing modes and prevents the introduction of frying techniques and technologies into the feed industry. In this connection, it is very relevant to study the mechanism of heat and mass when frying barley grain with overheated steam using mathematical modelling methods. The spatial coordinates and time were taken as the independent coordinates of any point of the wet body. The model of the process of heat and mass transfer in frying barley grain presented by the system of differential equations of the second order in partial derivatives has been developed and solved by numerical methods. Good convergence of calculated and experimental data confirmed the expediency of using a mathematical model for process calculation and analysis of physical and chemical phenomena, development of high-efficiency roasting machines and program-logic algorithms for controlling technological parameters.

1. Introduction
In the structure of the feed balance barley grain takes up to 50 – 80 %, so the increase in the nutritional value of grain raw materials directly affects the assimilability of mixed feed.

It is known [1] that heat treatment of grain increases its nutritional value. For animals where the activity of amyloolytic enzymes is poorly developed in the gastrointestinal tract, it is advisable to convert starch into easily digestible carbohydrates – dextrins, maltose, thereby improving its digestion. Thermal hydrolysis in the process of grain heat treatment makes it possible to convert part of complex high-molecular substances into pure out-of-stomach fat-and-fat substances, which is a necessary condition in increasing assimilability of mixed feed.
Recently, the use of high-temperature inert heat carriers, in particular superheated steam, has become widespread in the technology of frying food products [2, 3]. This process is because superheated steam has significant advantages over other heat carriers used in thermal treatment:

- The high energy efficiency of the frying process due to the possibility of recycling secondary steam and uniformity of the used heat carrier and evaporated moisture;
- Reduction of the required amount of steam in the circulation circuit due to higher specific heat capacity of steam compared to the heat capacity of hot air;
- More intensive frying, provided by increasing the heat transfer pressure from superheated steam to grain;
- Increasing the temperature of the frying process without significant deterioration of grain quality due to the absence of oxygen in the superheated steam;
- Improvement of grain quality, as moisture-holding gradients are reduced, and product plasticity is increased.

2. The purpose of the study
Insufficient study of the process of frying barley grain with overcharged steam, unjustified fear for preservation of the quality of the finished product prevent the development of a general method of calculating the process of frying, makes it challenging to choose optimal processing modes and prevents the introduction of frying techniques and technologies into the feed industry. In this connection, it is very relevant to study the mechanism of heat and mass when frying barley grain with superheated steam using mathematical modelling methods.

3. The object of the study
Barley grain has a geometric shape close to the cylinder (Figure 1). The ratio of the height $h$ to the radius $R$ of the cylinder averages 8, which gives the basis for barley grain to be considered as an infinite cylinder bounded by surface $S$ and in a cylindrical coordinate system $(r, h, \phi)$.

![Figure 1. Barley Grain](image)

In this case, heat and moisture exchange during heat treatment of barley with superheated steam under conditions of forced convection is carried out in the direction of the external average vector $n$ to surface $S$ (Figure 2).
Figure 2. Model of heat and mass transfer process when frying barley grain with superheated steam

4. Materials and methods

The process of roasting barley is accompanied by the formation of a peel grain on the surface, which is characterized by a peel formation coefficient.

$$\zeta = \frac{\zeta}{(u_{\text{start}} - u_{\text{final}}) - \zeta \cdot u_{\text{start}}}$$

(1)

where $\zeta$ - relative peel formation:

$$\zeta = \frac{d}{R}$$

(2)

where $d$ is the thickness of the peel, m

$$d = R - r_s$$

(3)

where $R$ and $r_s$ – respectively the radius of the grain and the radius of the surface of heat and mass transfer, $u_{\text{start}}$, $u_{\text{final}}$ – accordingly, the moisture content of barley grain at the beginning and end of the roasting process.
For barley during the roasting process $\xi = 240...310 \%$, while relative peel formation $\zeta = 23...28 \%$.

The mathematical model of the roasting process is based on the generalized law of moisture movement, taking into account its the material flows both in the form of steam and in the form of liquid, caused by the presence of humidity and temperature gradients in the material

$$q' = -a_m \rho_0 (\nabla u + \delta \nabla t),$$  

(4)

where $a_m$ – coefficient of potential conductivity of material, m$^2$/s; $\delta$ – thermogradient coefficient, 1/K; $\rho_0$ – density of the dry material, kg/m$^3$;

and the law of thermal conductivity for wet materials, taking into account the transfer of heat in the grain due to the temperature gradient and heat transferred from the moisture evaporated from the grain

$$q = -\lambda \nabla t + I q',$$  

(5)

where $\lambda$ – coefficient of thermal conductivity, W/(m·K), $(a = \lambda / c_m \rho_0)$; $I$ – fluid enthalpy, kJ/kg.

The distribution of temperature and moisture content in barley grain was considered in a cylindrical coordinate system. The spatial coordinates $r$, $h$, $\varphi$ and time $\tau$ were taken as the independent coordinates of any point M of the wet body.

It was assumed that the desired temperature field $t = t (r, \tau)$ and moisture field $u = u (r, \tau)$ were symmetric about the axis of the cylinder and were independent of height $h$ and angle $\varphi$ [4, 5].

Moisture loss rate $q_m$ depends on the concentration of moisture on the surface of the product and in the environment:

$$q_m = \alpha_{mu} \rho_0 (u(M, \tau)|_{M \in S} - u_e),$$  

(6)

where $\alpha_{mu} = D_s / \delta_u$ – moisture loss coefficient, m/s, or diffusion rate constant $k_D$, $\rho_0$ – density of absolutely dry material, kg s. things./m$^3$; $u_e$ – equilibrium moisture content of the product, kg ow./kg from things; $u(M, \tau)|_{M \in S}$ – moisture content of the product on the surface $S$; $D_s = f(u)$ – steam diffusion coefficient, m$^2$/s; $\delta_u$ – conventional thickness of the boundary layer, m;

For setting the intensity of the heat transfer process, the Newton – Richmann law [6] was used:

$$q = \alpha (T(M, t)|_{M \in S} - T_c),$$  

(7)

where $q$ – heat flux density, W/m$^2$; $\alpha$ – heat transfer coefficient, W/(m$^2$·K); $T_s = T(M, t)|_{M \in S}$ – surface temperature, K; $M$ – point on the surface S heat transfer; $T_c$ – temperature in the center of the heat transfer fluid flow, K.

Under these conditions, the process of frying a product particle is represented by a system of partial differential equations in a cylindrical coordinate system

$$\frac{\partial t}{\partial \tau} = \frac{\lambda}{\rho_0 c} \left( \frac{\partial^2 t}{\partial r^2} + \frac{1}{r} \frac{\partial t}{\partial r} \right) + \frac{1}{\rho_0 c} \frac{\partial \lambda}{\partial r} \frac{\partial t}{\partial r} + \frac{\varepsilon}{c} \frac{\partial u}{\partial \tau},$$  

$$\frac{\partial u}{\partial \tau} = a_m \left( \frac{\partial^2 u}{\partial r^2} + \frac{1}{r} \frac{\partial u}{\partial r} \right) + \frac{\partial a_m}{\partial \tau} \frac{\partial u}{\partial r} + a_m \delta \left( \frac{\partial^2 t}{\partial r^2} + \frac{1}{r} \frac{\partial t}{\partial r} \right) +$$  

(8)
\[
+ \left( \delta \frac{\partial a_m}{\partial r} + a_m \frac{\partial \delta}{\partial r} \right) \frac{\partial t}{\partial r},
\]
(9)

\[
t(r,0) = \begin{cases} T_c, & \text{on condition } r \geq R \\ t_{\text{start}}, & \text{on condition } r < R \end{cases},
\]
(10)

with initial conditions

\[
u(r,0) = \begin{cases} u_\varepsilon, & \text{on condition } r \geq R \\ u_{\text{start}}, & \text{on condition } r < R \end{cases},
\]
(11)

boundary conditions of the third kind, reflecting heat transfer between the peel and the heat transfer fluid

\[
- \lambda_p \left( \frac{\partial t_p}{\partial r} \right)_{r=R} + \alpha_p \left[ T_c - t_p(\tau) \right] - r_c (1-\varepsilon) \beta \rho_0 \left[ u_p(\tau) - u_\varepsilon \right] = 0,
\]
(12)

and mass transfer between the peel and the heat transfer fluid

\[
- a_{mp} \left( \frac{\partial u_p}{\partial r} \right)_{r=R} + a_{mp} \delta \left( \frac{\partial t_p}{\partial r} \right)_{r=R} + \beta \left[ u_p(\tau) - u_\varepsilon \right] = 0,
\]
(13)

boundary conditions of the fourth kind, reflecting heat transfer between the product and the peel

\[
\lambda_p \left( \frac{\partial t_p}{\partial r} \right)_{r=r_s} = \lambda_t \left( \frac{\partial t_t}{\partial r} \right)_{r=r_s},
\]
(14)

and mass transfer between product and peel

\[
a_{mp} \left( \frac{\partial u_p}{\partial r} \right)_{r=r_s} = a_{mm} \left( \frac{\partial u_m}{\partial r} \right)_{r=r_s},
\]
(15)

and symmetry conditions

\[
\left. \frac{\partial t}{\partial r} \right|_{r=0} = 0, \quad \left. \frac{\partial u}{\partial r} \right|_{r=0} = 0.
\]
(16)

Problem (4) – (16) was solved under the condition that the boundary between the product and the peel is mobile and its displacement was specified by the function \(d(\tau)\):

\[
d(\tau) = \xi \tau, \quad 0 \leq r \leq R - d(\tau), \quad [R - d(0) = r], \quad \tau > 0.
\]
(17)

In the equations (6) – (17), the following notation is accepted:

\(t(\tau), t_p(\tau)\) – respectively the temperature of the product particle and the peel, \(K; u(\tau), u_p(\tau)\) – respectively, the moisture content of the product particles and the peel, kg/kg; \(t_{\text{start}}, T_c, t_p\) – accordingly, the initial temperature of the product, the temperature of the heat transfer fluid (superheated steam) and the temperature of the peel, \(K; u_{\text{start}}, u_\varepsilon, u_p\) – accordingly, the initial moisture
content of the product, the moisture content of the heat transfer fluid and the moisture content of the peel, kg/kg; \( c, c_p \) – accordingly, the specific heat of the product and peel, kJ/(kg·K); \( \rho_0 \) – the density of the dried product, kg/m³; \( r_c \) – specific heat of vaporization, kJ/kg; \( \varepsilon \) – phase transformation criterion; \( \varepsilon = \frac{D_1}{(D_1 + D_2)} \) – the ratio of the flows of the vapour phase (index 1) and the liquid phase (index 2); \( \lambda, \lambda_p \) – respectively, the thermal conductivity of the dry product and peel, W/(m·K); \( a, a_p \) – respectively, thermal diffusivity (coefficient of potential conductivity of heat transfer) of the product and peel, m²/s; \( \alpha, \alpha_p \) – accordingly, the diffusion coefficient of moisture in the product and the peel, m²/s; \( \beta \) – mass transfer coefficient, m/s; \( \tau \) – time, s.

Problem (8) - (17) is a boundary-value problem of heat and mass conductivity with one static and one moving boundary [4, 6, 7] and is solved using functional transformations by the finite difference method [8]. A software module for calculating the process of roasting barley with superheated steam in the system has been developed Maple 9.5.

5. Discussion of the results

A comparative analysis of the results of approximation of the calculated and experimental data (Figure 3) showed that their deviation in absolute value did not exceed 8.7 % for temperature and 10.3 % for moisture content. From the kinetic curves of roasting barley (Figure 3), obtained experimentally, it is seen that the product reaches the final moisture \( W = 4 \% \) (\( u = 0,04123 \ kg/kg \)) after 850 s. From the solution of the mathematical model by the numerical method, the time value is obtained at which the product reaches a final moisture content of \( W = 4 \% \), equal to 855 s. During roasting, barley reaches a temperature of protein denaturation of 70 °C after 80 s, and according to calculated data, the grain temperature is 70 °C after 82 s.

![Figure 3. Comparison of calculated (1) and experimental (2) data when frying with superheated steam, \( T_s = 383 \ K; q_n = 25 \ kg/m^2; v = 2.3 \ m/s \):](image-url)

1 – the curve of roasting barley grain; 2 – thermogram of heat and mass transfer during the roasting of barley grain
6. Conclusion
Thus, the obtained simulation results with sufficient accuracy for engineering calculations reflect
the kinetic regularities of the barley frying process with superheated steam as an object with
distributed parameters and can be used for analyzing the ongoing physicochemical changes,
process calculation, design of the frying apparatus and development of program-logic algorithms
for controlling technological parameters.

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