Journal of Engineering and Applied Sciences 12 (Special Issue 1): 5754-5760, 2017
ISSN: 1816-949X

Experimental and Analytical Study of the Beet Pulp Drying Process by Overheated Steam in Active Hydrodynamic Conditions

A.A. Shevtsov, A.V. Drannikov, A.A. Derkanosova, A.S. Muravev and A.V. Kvasov
Voronezh State University of Engineering Technologies, Voronezh, Russia

Abstract: Experimental studies were performed, during which kinetic regularities of the beet pulp drying process by overheated steam at atmospheric pressure in active hydrodynamic conditions were studied. A mathematical model of the pulp drying process was developed in the form of a differential equations system of second order heat and mass transfer with allowance for the phase transformation under the following simplifying assumptions: the particle of pulp is represented as an indefinite plate; heat and mass transfer at the interface between the particle and the coolant was considered by one spatial coordinate with boundary conditions of the third form for a given initial distribution of temperature and moisture content by volume of the product to be dried. A zonal method is used to calculate the moisture content and temperature fields. Within each time zone, the density, thermophysical and mass-exchange parameters of the product were averaged. Identification of model parameters from experimental data was carried out. The numerical-analytical solution of the mathematical model in the criterial form is obtained by the method of Fourier and Laplace integral transformations joint application. The adequacy of the model to the actual experiment was estimated. The maximum error in the simulation was 8.5%.

Key words: Beet pulp, overheated steam, drying, modeling of the drying process, heat exchange, transformations

INTRODUCTION

Recently, the use of high-temperature inert coolants in particular overheated steam has become widespread in the technology of drying food plant raw materials (Ostrikov *et al*., 2015; Shevtsov *et al*., 2013). This is due to the fact that overheated steam has significant advantages over other heat carriers used in heat treatment:

- High energy efficiency of the drying process, due to the possibility of recycling the secondary steam, the uniformity of the used coolant and the evaporated moisture
- Decrease in the required amount of steam in the circulation circuit due to the higher specific heat of the steam compared to the heat capacity of the hot air
- More intensive drying, provided by an increase in the heat transfer coefficient from overheated steam to the product
- Increase in the temperature of the drying process without a significant deterioration in the quality of the product due to the lack of oxygen in the overheated steam
- Improving the quality of the product because the gradients of moisture content decrease and the plasticity of the product increases

Insufficient information on the process of drying beet pulp with overheated steam, unjustified fear for the safety of its quality prevent the development of a general calculation methodology and makes it difficult to select the optimal conditions of process and restrain the introduction of drying technology in industry.

The current level of computer technology development as well as progress in the theory of heat and mass transfer during the drying of colloidal capillary-porous materials, make it possible to study the drying process by mathematical modeling methods that ensure high accuracy of calculations and the possibility of verifying simulation results in practice.

Heat and moister transfer during the drying of food plant raw materials complies with the general laws of heat and mass transfer and it is its special case. Theoretical basis for them is a unified theory of heat and mass transfer. On the basis of this theory, the processes of heat transfer and moisture transfer in a product can be described analytically. This description allows to

Corresponding Author: A.V. Drannikov, Voronezh State University of Engineering Technologies, Voronezh, Russia

determine the temperature and moisture content in the product at any time, find their gradients and time variation, calculate the density of heat and moisture fluxes, predict the further development of these processes (Chryat *et al*., 2017; Hamawand, 2013; Jokic *et al*., 2013; Romdhana *et al*., 2015).

Drying the beet pulp with overheated steam is an energy-intensive process (Alfy *et al*., 2016; Devahastin and Mujumdar, 2014; Mujumdar, 2014; Romdhana *et al*., 2015). In this regard, the solution of energy saving problems in the process of drying beet pulp by overheated steam by methods of mathematical modeling becomes urgent.

Object of study: Beet pulp was used as an object of study which is a de-sugared beet chips (80-82% of the processed sugar beet weight with a dry matter content of about 6.5-7.0%). The chemical composition of fresh beet pulp contains (in dry matter) about 45-47% of cellulose and up to 50% of pectin substances, 2% of protein, 0.6-0.7% of sugar and about 1% of mineral substances, vitamins and organic acids. Beet pulp has a complex colloidal capillary-porous body. After the desaccharifying in the hot water of the diffusion apparatus, the beet chips still retains the cellular structure and the intracellular space is filled with a weak (0.2%) solution of sugar. According to, the particle size (length 20-70 mm, thickness 1-2 mm, width 2-4 mm), the pulp refers to the coarsely dispersed medium.

MATERIALS AND METHODS

Experimental part: Since, the beet pulp is liable to clumping, it is possible to obtain a stable fluidization only by the simultaneous action of lattice vibrations and the gas flow blown through the material layer (Ko and Fascetti, 2016; Wang *et al*., 2016). The structure of the vibrated fluidized bed differs by uniformity and drying under such a hydrodynamic condition is of high intensity. When drying in the vibrated fluidized bed, the product particles are heated very rapidly due to the contact of the coolant with the product throughout the surface. This results in intensive mixing of the particles which contributes to their uniform heating. This allows to reduce the drying time due to the use of a coolant with a higher temperature without losing in quality of the product (Huang *et al*., 2017).

Taking these features into account, the study of the pulp drying process was carried out on an experimental setup at atmospheric pressure of overheated steam in active hydrodynamic conditions. The pulp was on a horizontal air distribution plate which

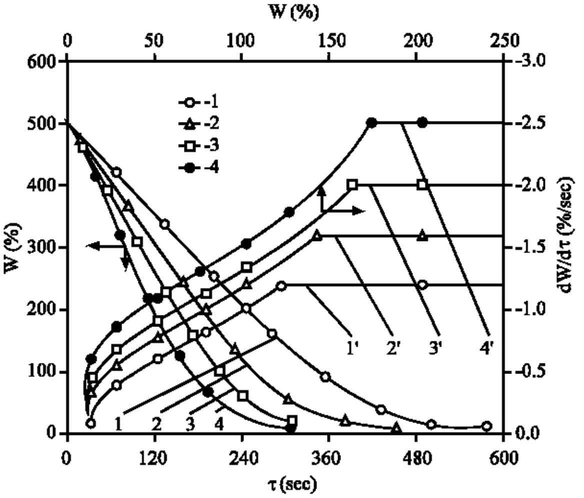

Fig. 1: Drying curves (1-4) and drying speed (1'-4') of the pulp under the different temperatures of overheated steam, K: 1-393; 2-413; 3-433; 4-453; A = 7 mm; f =12.5 Hz; u = 2 m/sec; $f_{p.g.}$ = 0.017 Hz

made vertically-directed vibrations. The amplitude and frequency of oscillations of the air distribution plate were A = 7 mm and f = 12.5 Hz, respectively. The duration of a single pulsation (the effect of the lattice on the layer) was τ_p = 3 sec. The specific load on the air distribution plate in all the experiments was q = 25 kg/m^2.

Drying curves and drying speeds of beet pulp in pulsed vibrated fluidized bed at various process parameters are shown in Fig. 1-4 heating curves for beet pulp at various temperatures of overheated steam at the inlet to the drying chamber. The axes on figures signify: τ, drying time sec; W, moisture content of pulp in DM, %; dW/τ, speed of drying, %/sec; T_{beet}, temperature of pulp, K.

The analysis of the curves (Fig. 1-3) in the period of constant drying speed shows that the temperature of the coolant has the greatest influence on the drying intensity. So, an increase in the overheated steam temperature T_s at the inlet to the drying chamber from 393-453 K leads to a double increase in the drying speed.

A minor effect on the drying intensity is caused by a change in the speed of the coolant u. When the steam speed is increased by 3 times (from 1-3 m/sec), the drying speed increases by 25%. An increase in the frequency of plate pulsations $f_{p.g.}$ from 0.0083 (one pulsation in 2 min) to 0.04 Hz (one pulsation in 25 sec) leads to an increase in the drying speed by 1.8 times.

The period of the drying speed decrease is not uniform. This period is characterized by the removal of moisture from the material with different types of binding energy and therefore, there are several bends on the

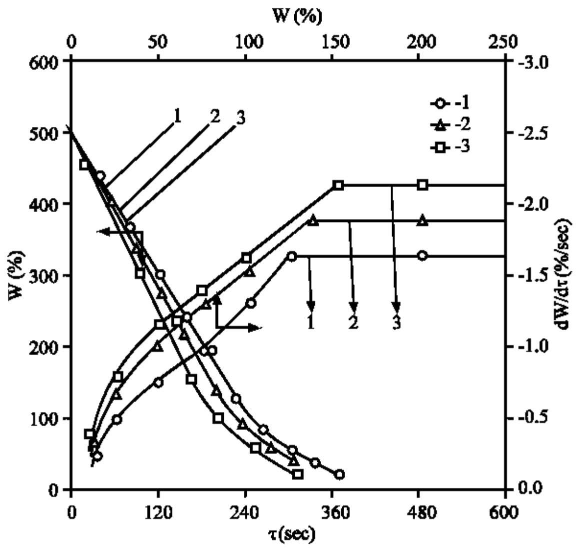

Fig. 2: Drying curves (1-3) and drying speed(1'-3') of the pulp under the different speeds of overheated steam, m/sec: 1-1; 2-2; 3-3; T_s = 423 K; A = 7 mm; f = 12.5 Hz; $f_{p.g.}$ = 0.017 Hz

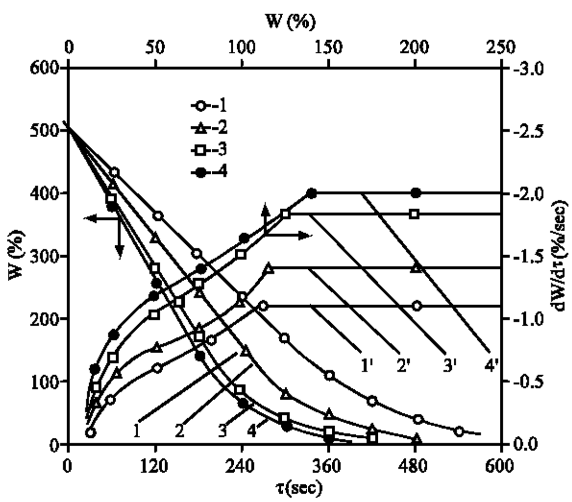

Fig. 3: Drying curves (1-4) and drying speed (1'-4') of the pulp under the different frequencies of plate vibrations, Hz: 1-0.0083; 2-0.017; 3-0.033; 4-0.04; T_s = 403 κ; A = 7 mm; f = 12.5 Hz, ν = 2 m/sec

drying speed curves. The effect of individual conditions on the drying intensity in this period in comparison with the same effect in the period of constant speed does not change on the whole.

The nature of the temperature change in the beet pulp, observed on the heating curves (Fig. 4), corresponds to the periods of constant and decreasing drying speed. As can be seen from the graphs, the

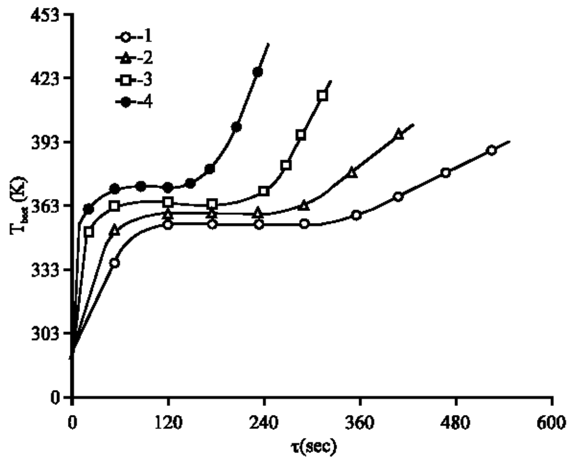

Fig. 4: Heating curves of the beet pulp under the different temperatures of overheated steam, K: 1-393; 2-413; 3-433; 4-453; A = 7 mm; f = 12.5 Hz; v_s = 2 m/sec; $f_{p.g.}$ = 0.017 Hz

material is heated to a constant temperature very quickly. This is due to the fact that drying is carried out in an active hydrodynamic conditions, small particle size of the drying object as well as high heat transfer coefficients.

The warm-up time of the material in the overheated steam environment is much faster than in the air environment. The presence of constant temperature period indicates that the intensity of moisture diffusion exceeds the intensity of moisture exchange. At the same time as can be seen from the graphs (Fig. 4), during this drying period the temperature inside the particles of pulp in the studied intervals of overheated steam temperature, does not exceed 373 K. This fact can be explained by the peculiarity of the beet pulp structure that has developed pore structure and high initial moisture content of the material. This suggests that the moisture inside the particles of beet pulp in the period of constant drying speed, moves mainly in the form of a liquid.

A granulometric composition of dry beet pulp (humidity 12-13%) was compared which was obtained with constant and periodic impact of the air distribution plate on the product layer under the same condition parameters of the drying process. The studies were carried out by sieving with a standard set of sieves. As shown by the experiments carried out under the constant impact of the palte, the amount of fine dry pulp fractions (sieve size 1.5 mm) is much higher than when the plate is periodically applied to the layer. In addition with constant vibration there is an increase in the amount of medium pulp fraction (sieves sizes 3.5-4.5 mm) and a reduction in coarse fraction (sieves size 5.0-5.5 mm).

The increase in the number of fine fractions is observed practically throughout the process, since with constant impact of the plate to the layer, the particles move more intensely as a result small particles are wore off as well as larger ones that have already dried on the surface (the end of first, the beginning of the second drying period). At the same time an increase in the number of middle fractions due to breakage of large fractions occurs only in the second half of the decreasing drying speed period. This is caused by the fact that the large factions during this period have already dried up sufficiently became fragile and being at the bottom of the material layer, contacted with a constantly vibrating air distribution plate that facilitates their fragmentation.

Theoretical part: The mathematical model of the drying process of pulp is formulated on the basis of moisture transfer general law taking in to account the moisture flow, both in the form of steam and in the form of a liquid, caused by moisture gradient and temperature gradient in the wet material (Hamawand, 2013). The distribution of the temperature and moisture content fields in a single particle was considered which was represented as an unbounded plate with the thickness 2 R and coordinates (x, τ), i.e., t = (x, τ), u = u (x, τ).

The associated heat and mass transfer in the drying process was described by a system of second-order differential Eq. 1 and 2:

$$c_m \rho_0 \frac{\partial t}{\partial \tau} = \lambda \frac{\partial^2 t}{\partial x^2} + \varepsilon r \rho_0 \frac{\partial u}{\partial \tau} \tag{1}$$

$$\frac{\partial u}{\partial \tau} = a_m \frac{\partial^2 t}{\partial x^2} + a_m \delta \frac{\partial^2 t}{\partial x^2} \tag{2}$$

with boundary conditions of the third form:

$$-\lambda \left(\frac{\partial t}{\partial x} \right)_{x=R} + q_n(\tau) = 0 \tag{3}$$

$$a_m \rho_0 \left(\frac{\partial t}{\partial x} \right)_{x=R} + a_m \rho_0 \delta \left(\frac{\partial t}{\partial x} \right)_{x=R} + j_n(t) = 0 \tag{4}$$

Initial conditions:

$$t(x,0) = f_1(x), u(x,0) = f_2(x) \tag{5}$$

And symmetry conditions:

$$\left. \frac{\partial t}{\partial x} \right|_{x=0} = \left. \frac{\partial u}{\partial x} \right|_{x=0} \tag{6}$$

Where:

τ	= Current time (sec)
x	= Current coordinate (m)
u (x, τ)	= Moisture of product (kg/kg)
t (x, τ)	= Temperature of product (K)
c_m	= Specific heat of product (kJ/kg.K)
p_0	= The density of the absolutely dry matter of the product (kg drymat./m^3)
λ	= Heat-conductivity factor of dry product (W/(m·K)
$\alpha = \lambda / c_m \rho_0$	= Coefficient of thermal diffusivity (m^2/sec)
r	= Heat of phase transition (specific heat of steam formation) (kJ/kg)
ε	= Phase transformation criterion
a_m	= Moisture diffusion coefficient (potential conductivitycoefficient of moisture transfer) (m^2/sec)
$\delta = (\Delta u/\Delta t)\, q_m = 0$	= Thermal diffusion relative coefficient of wet material (kgmoist./kg. drymat) K
q_n (τ)	= Heat exchange rate or the specific heat flux at the surface (W/m^2)
j_n (τ)	= Specific moisture flux or intensity of moisture exchange (kg/(m^2·sec))
f_1(x) and f_2(x)	= Functions

By means of which the initial distribution of the temperature and moisture content of the product is set along the coordinate x and which have the same dimension as the temperature and moisture content, respectively.

Equation system (1-6) was transformed to the criterial form using the following dimensionless variables: X = x/R dimensionless coordinate; T = $t\text{-}t_n/t_k\text{-}t_n$ dimensionless temperature; U = $u_n\text{-}u/u_n\text{-}u_p$ dimensionless moisture content where, t_k, u_p fixed values of temperature and moisture content, corresponding to a certain final value of temperature and the equilibrium value of moisture content; R characteristic dimension (half the thickness of the plate), m.

Since, $\partial t = \partial t \Delta T$, $\partial u = \partial u \Delta U$ and $\partial x = R \partial x$, where, $\Delta T = t_k\text{-}t_n$; $\Delta U = u_n\text{-}u_p$, then Eq. 1 and 2 has the following view:

$$\frac{\partial T(X,Fo)}{\partial Fo} = (1+\varepsilon KoLuPn) \frac{\partial^2 T(X,Fo)}{\partial X^2} - \varepsilon KoLu \frac{\partial^2 U(X,Fo)}{\partial X^2} \tag{7}$$

$$\frac{\partial U(X,Fo)}{\partial Fo} = Lu\frac{\partial^2 U(X,Fo)}{\partial X^2} - LuPn\frac{\partial^2 T(X,Fo)}{\partial X^2} \quad (8)$$

Where:

$Ko = r\Delta u/c_m\Delta T$ = Kossovich criterion
$Lu = a_m/a$ = Lykov criterion
$pn = \partial\Delta T/\Delta u$ = Posnov criterion for diffusion transfer
$Fo = a_\tau/R^2$ = Fourier number

Substituend Lu ∂^2U (X, Fo)/∂X^2 from to Eq. 7 and 8 transforming into a dimensionless form the initial conditions, the boundary conditions and the symmetry conditions (Eq. 1-6), б we obtained a system of criterial differential equations describing heat and mass transfer in an unbounded plate:

$$\frac{\partial T(X,Fo)}{\partial Fo} = \frac{\partial^2 T(X,Fo)}{\partial X^2} - Ko^*\frac{\partial U(X,Fo)}{\partial Fo} \quad (9)$$

$$\frac{\partial U(X,Fo)}{\partial Fo} = Lu\frac{\partial^2 U(X,Fo)}{\partial X^2} - LuPn\frac{\partial^2 T(X,Fo)}{\partial X^2} \quad (10)$$

$$T(X,0) = \frac{f_1(x,0)-t_n}{t_k-t_n} = F_1(X) \quad (11)$$

$$U(X,0) = \frac{u_n - f2(x,0)}{u_n-u_p} = F_2(X) \quad (12)$$

$$-\left.\frac{\partial T}{\partial X}\right|_{X=1} + Ki_q = 0 \quad (13)$$

$$-\left.\frac{\partial U}{\partial X}\right|_{X=1} + Pn\left.\frac{\partial T}{\partial X}\right|_{X=1} + Ki_m = 0 \quad (14)$$

$$\left.\frac{\partial T}{\partial X}\right|_{X=0} = \left.\frac{\partial U}{\partial X}\right|_{X=0} \quad (15)$$

Where:

Ki_q = $q(\tau)R/ac_m\rho_0\Delta T$ Kirpichev number heat
Ki_m = $j(\tau)R/a_m\rho_0\Delta u$, mass transfer

To solve the task Eq. 9-15 the method of integral transformations by Fourier and Laplace was used. With respect to the variable X, the finite Fourier transformation was used in the following form:

$$\{\phi(\mu,Fo)\}_c = \int_0^1 \phi(X,Fo)\cos\mu X dX \quad (16)$$

where, $\mu = n\pi$, (n = 0, 1, 2-). The second-order derivatives were transformed by the relation:

$$\int_0^1 \frac{\partial^2\phi(X,Fo)}{\partial X^2}\cos\mu X dX = (-1)^n \frac{\partial\phi(1,Fo)}{\partial X} - \mu^2\{\phi(\mu,Fo)\}_c \quad (17)$$

Transfer from $\{\phi(\mu, Fo)\}_c$ to the original is carried out by expression:

$$\phi(X,Fo) = \{\phi(0,Fo)\}_c + 2\sum_{n=1}^{\infty}\{\phi(\mu_n \times Fo)\}_c \cos\mu_n X \quad (18)$$

Applying the Fourier cosine transformation and taking in to account the boundary conditions of Eq. 13 and 14 and the symmetry conditions (Eq. 15) to second-order derivatives also assuming that the Fourier transformation operator is commutative with the differentiation operator, $\partial/\partial Fo$, after multiplying all the equation terms (Eq. 9 and 10) to cos $\mu_n X$ and integration along X from 0-1, the initial system of partial differential equations was reduced to a system of two ordinary differential equation:

$$\begin{cases} \dfrac{dT_c}{dFo} = (-1)^n Ki_q(Fo) - \mu^2 T_c - \varepsilon Ko\dfrac{dU_c}{dFo}; \\ \dfrac{dU_c}{dFo} = (-1)^n LuKi_m(Fo) - Lu\mu^2 U_c + LuPn\mu^2 T_c \end{cases} \quad (19)$$

Initial conditions (Eq. 11 and 12), after applying the transformations (Eq. 16) has the following view:

$$T_{oc} = T_c(\mu,0) = \int_0^1 F_1(X)\cos\mu X dX \quad (20)$$

$$U_{oc} = U_c(\mu,0) = \int_0^1 F_2(X)\cos\mu X dX \quad (21)$$

The integral Laplace transformation is used in the following view:

$$\{\phi(X,s)\}_L = \int_{\infty}^{0} \phi(X,Fo)\exp(-sFo)dFo \quad (22)$$

Then taking in to account (Eq. 19-21), from an algebraic system of equations is obtained:

$$\begin{cases} (s+\mu^2)T_{cL} + sKoU_{cL} = (-1)^n\{Ki_q(Fo)\}_L + T_{oc} + KoU_{oc}; \\ -LuPn\mu^2 T_{cL} + (s+Lu\mu^2)U_{cL} = (-1)^n Lu\{Ki_m(Fo)\}_L + U_{oc} \end{cases}$$

Where:

$$\{Ki_k\}_L = \int_0^{\infty} Ki_k(Fo)\exp(-sFo)dFo; \left(k = \begin{cases} 1 & \text{or} \quad q; \\ 2 & \text{or} \quad m \end{cases}\right)$$

Solving the system with respect to T_{cL} (μ, s) and U_{cL} (μ, s) and moving to the originals of these potentials with respect to the parameter s, we obtain:

$$T_c(\mu,Fo)=\sum_{k,i=1}^{2}\left[A_{ki}^{q}\{P_{ki}\}_c+B_{ki}^{q}\{Q_{ki}\}_c\right] \tag{23}$$

$$U_c(\mu,Fo)=\sum_{k,i=1}^{2}\left[A_{ki}^{m}\{P_{ki}\}_c+B_{ki}^{m}\{Q_{ki}\}_c\right] \tag{24}$$

Where:

$$\left.\begin{aligned}
&A_{1i}^{q}=(-1)^i\frac{1-v_i^2}{v_1^2-v_2^2}; && A_{1i}^{m}=(-1)^i\frac{Pn}{v_1^2-v_2^2};\\
&A_{2i}^{q}=(-1)^i\frac{Ko^*}{v_1^2-v_2^2}; && A_{2i}^{m}=(-1)^i\frac{1/Lu-v_i^2+Ko^*Pn}{v_1^2-v_2^2};\\
&B_{1i}^{q}=(-1)^i\frac{1-v_i^2}{v_1^2-v_2^2}; && B_{1i}^{m}=(-1)^i\frac{Pn}{v_1^2-v_2^2};\\
&B_{2i}^{q}=(-1)^i\frac{Ko^*Luv_i^2}{v_1^2-v_2^2}; && B_{2i}^{m}=(-1)^i\frac{Lu\left(1/Lu-v_i^2\right)}{v_1^2-v_2^2}
\end{aligned}\right\} \tag{25}$$

$$\left.\begin{aligned}
&\{P_{1i}\}_c=T_{oc}\exp[-\mu^2v_i^2LuFo]\\
&\{P_{2i}\}_c=U_{oc}\exp[-\mu^2v_i^2LuFo]\\
&\{Q_{1i}\}_c=(-1)^n\int_0^{Fo}Ki_q(Fo^*)\exp\left[-\mu^2v_i^2Lu(Fo-Fo^*)\right]dFo^*;\\
&\{Q_{2i}\}_c=(-1)^n\int_0^{Fo}Ki_m(Fo^*)\exp\left[-\mu^2v_i^2Lu(Fo-Fo^*)\right]dFo^*
\end{aligned}\right\} \tag{26}$$

$$v_i^2=\frac{1}{2}\left[\left(1+Ko^*Pn+\frac{1}{Lu}\right)+(-1)^i\sqrt{\left(1+Ko^*Pn+\frac{1}{Lu}\right)^2-\frac{4}{Lu}}\right] \tag{27}$$

$$\left(k=\begin{cases}1 & \text{or } q;\\ 2 & \text{or } m\end{cases}\right)(i=1.2)$$

T_c (μ, Fo) and U (μ, Fo), defined by Eq. 23 and 24, satisfy the initial conditions (Eq. 20). Using Eq. 18 after the transformations their originals were found:

$$T(X,Fo)=\sum_{k=1}^{2}\sum_{i=1}^{2}\left[A_{ki}^{q}P_{ki}+B_{ki}^{q}Q_{ki}\right] \tag{28}$$

$$U(X,Fo)=\sum_{k=1}^{2}\sum_{i=1}^{2}\left[A_{ki}^{m}P_{ki}+B_{ki}^{m}Q_{ki}\right] \tag{29}$$

Where:

$$\begin{gathered}P_{ki}=\int_0^1Fo_k(X)dX+2\sum_{n=1}^{\infty}\cos\mu_nX\\ \exp\left[-\mu_n^2v_i^2LuFo\right]\int_0^1Fo_k(X)\cos\mu_nXdX\end{gathered} \tag{30}$$

$$\begin{gathered}Q_{ki}=\int_0^{Fo}Ki_k(Fo^*)dFo^*+2\sum_{2}^{\infty}(-1)^n\cos\mu_nX\exp\left[-\mu_n^2v_i^2LuFo\right]\times\\ \int_0^{Fo}Ki_k(Fo^*)\exp\left[-\mu_n^2v_i^2LuFo^*\right]dFo^*\\ k=\begin{cases}1\text{ for F and q for Ki}\\ 2\text{ for F and m for Ki}\end{cases}\end{gathered} \tag{31}$$

$\mu_n = n_\pi$, n = 1.2; i = 1.2

Since, it was believed that the initial distribution of transfer potentials is constant across the material cross-section and correspondingly equal to the value of the fixed potentials (t_H, u_H), then:

$$F_1(X)=F_2(X)=0 \tag{32}$$

Assuming that the specific fluxes of heat and matter on the surface of the material are constant within a short time interval, i.e.:

$$Ki_q=\text{const and }Ki_m=\text{const} \tag{33}$$

Then finally we obtained:

$$\begin{gathered}T(X,Fo)=\left(Ki_q-Ko^*LuKi_m\right)Fo-\frac{1}{6}\left(1-3X^2\right)Ki_q-\\ \sum_{n=1}^{\infty}\sum_{i=1}^{2}(-1)^n\frac{2}{\mu_n^2}C_i^q\cos\mu_nX\exp\left(-\mu_n^2v_i^2LuFo\right)\end{gathered} \tag{34}$$

$$\begin{gathered}U(X,Fo)=Ki_mLuFo-\frac{1}{6}\left(1-3X^2\right)\left(PnKi_q+Ki_m\right)-\\ \sum_{n=1}^{\infty}\sum_{i=1}^{2}(-1)^n\frac{2}{\mu_n^2}C_i^q\cos\mu_nX\exp\left(-\mu_n^2v_i^2LuFo\right)\end{gathered} \tag{35}$$

Where:

$$C_1^q=\frac{Ki_q\left(v_2^2-1/Lu\right)+Ko^*Ki_m}{v_2^2-v_1^2};\quad C_2^q=\frac{Ki_q\left(v_1^2-1/Lu\right)+Ko^*Ki_m}{v_2^2-v_1^2};$$

$$C_1^m=\frac{PnKi_qv_2^2-\left(1-v_2^2\right)Ki_m}{v_2^2-v_1^2};\qquad C_1^m=\frac{PnKi_qv_1^2-\left(1-v_1^2\right)Ki_m}{v_2^2-v_1^2}$$

$$v_i^2=\frac{1}{2}\left[\begin{gathered}\left(1+Ko^*Pn+\frac{1}{Lu}\right)+\\ (-1)^i\sqrt{\left(1+Ko^*Pn+\frac{1}{Lu}\right)^2-\frac{4}{Lu}}\end{gathered}\right],(i=1.2)$$

RESULTS AND DISCUSSION

Calculation of the heat and mass transfer processes was complicated by the fact that the properties of the medium and beet pulp that participate in the exchange of heat and mass are not constant. As the product was dried, the intensity of heat and mass transfer changed and accordingly the heat and mass transfer coefficients in different zones of the drying apparatus.

Therefore, calculations were carried out by zones using the zonal method of calculation. A certain time interval was set $\Delta\tau_j = \tau_j - \tau_{j-1}$ ($\tau_{j-1} < \tau_j$, $j = \overline{0, k}$, $\tau_0 = 0$, τ_k dryingtime), during which heat andmass process took place.

The method of computer experiment was used to identify the model parameters from the experimental data. The following coefficients were subjected to identification: mass conductivity (a_m), heat-transmission capacity (λ), thermal diffusion (δ) and transformation (ε). For the average values of $\overline{a_m} = 22\times10^{-8}$ m^2/sec; $\overline{\lambda} = 0.385$ W/(m·K); $\overline{\delta} = 0.1\times10^{-3}$ kg/(kg·K); $\overline{\varepsilon} = 0.018$ sufficient repeatabilityof the results is ensured at which the error of the calculated and experimental data did not exceed the absolute value of 8.5%.

CONCLUSION

The conducted studies let us to conclude that the process of drying beet pulp by overheated steam at atmospheric pressure in a pulsed vibrated fluidized bed was a high-intensity process due to high heat exchange coefficients and an active hydrodynamic conditions. In addition, the pulsed vibrated fluidized conditions ensured the gentle drying process, contributing to the preservation of the dry pulp high quality, reducing the load on the cleaning equipment and the costs per mass unit of dried pulp.

The results of modeling confirm the character of the beet pulp dry in process by over heated steam at atmospheric pressure and can be used to design the process for a scale transition from experimental to commercial prototype and it is advisable to use a Mathematical model during the micro process or control of drying process technological parameters in the condition of radom perturbations.

REFERENCES

Alfy, A., B.V. Kiran, G.C. Jeevitha and H.U. Hebbar, 2016. Recent developments in superheated steam processing of foods a review. Crit. Rev. Food Sci. Nutr., 56: 2191-2208.

Chryat, Y., H. Romdhana and M. Esteban-Decloux, 2017. Reducing energy requirement for drying of beet-pulp: Simulation of energy integration between superheated steam and air drying systems. Drying Technol., 35: 838-848.

Devahastin, S. and A.S. Mujumdar, 2014. Superheated steam drying of foods and biomaterials. Mod. Drying Technol., 5: 57-84.

Hamawand, I., 2013. Drying steps under superheated steam: A review and modeling. Energy Environ. Res., 3: 107-125.

Huang, X., D. Li, L.J. Wang, B. Adhikari and X.D. Chen, 2017. Effect of drying methods on the rheological properties of sugar beet pulp pectin. Intl. J. Food Eng., 13: 1-10.

Jokic, A., Z. Zavargo, N. Lukic, B. Ikonic and J. Markovic *et al*., 2013. Thin-layer modeling of the convective and microwave drying of sugar beet pulp. J. Proc. Energy Agric., 17: 24-28.

Ko, K.S. and A.J. Fascetti, 2016. Dietary beet pulp decreases taurine status in dogs fed low protein diet. J. Anim. Sci. Technol., 58: 1-10.

Mujumdar, A.S., 2014. Superheated Steam Drying. In: Handbook of Industrial Drying, Mujumdar, A.S. (Ed.). CRC Press, Boca Raton, Florida, USA., ISBN:9781466596658, pp: 421-432.

Ostrikov, A.N., S.A. Shevtsov and S.V. Kutsov, 2015. The study of the kinetics of drying food rawmaterial of plant origin in the active hydrodynamic regimes and development of dryer engineering calculation methods. Proc. Voronezh State Univ. Eng. Technol., 1: 42-50.

Romdhana, H., C. Bonazzi and M. Esteban-Decloux, 2015. Superheated steam drying: An overview of pilot and industrial dryers with a focus on energy efficiency. Drying Technol., 33: 1255-1274.

Shevtsov, A.A., A.A. Derkanosova, A.A. Korotaeva and S.A. Dyatlova, 2013. Kinetics and optimization of redclover pulp drying. Proc. Voronezh State Univ. Eng. Technol., 4: 41-46.

Wang, L.F., E. Beltranena and R.T. Zijlstra, 2016. Diet nutrient digestibility and growth performance of weaned pigs fed sugar beet pulp. Anim. Feed Sci. Technol., 211: 145-152.