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The investigation of low temperature vacuum drying processes of agricultural materials

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Abstract

The low-temperature vacuum drying processes for different kinds of floral agriculture products have been researched both theoretically and experimentally. Infrared ceramic radiators were used in experiments. The analytic dependences were obtained on the basis of experimental results for determination of efficient radiator power to provide optimal drying conditions such as drying duration, energy consumption and final product quality. The results facilitate the optimization of the technological approaches and the low temperature drying technology itself.

Keywords: Infrared drying; Vacuum; Low-temperature

1. Introduction

The problem of conservation and most complete retention of the useful properties of products during storage is of importance both for foodstuff manufacturers and for consumers. The list of agricultural crop products requiring further processing becomes more and more wide. As the result, this increases demand for drying equipment.

There are a lot of known ways of drying in world food engineering practice: convective, conductive sublimation and UHF-drying and these can be compared using the following indices (Rogov & Gorbatov, 1990; Skripnikov, 1988):

- specific energy consumption for evaporation of 1 kg of moisture;
- complexity and metal intensity of the drying equipment;
- quality of output product;
- ecological safety of the technology.

Convective drying is based on heat transfer to the drying product of energy from the heated drying agent (air or gas/vapor mixture). This drying method is used widely for drying food products. The drying facilities based on this method are simple and have average metal intensity indexes. These facilities have high specific energy consumption per unit mass of the drying material, which can reach up to 1.6– 2.5 kW h/kg. Nevertheless, the abovementioned method has disadvantages, resulting in significant reduction in final product quality (loss of nutritious properties). During this type of drying the water evaporates from the surface only, and this feature

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Nomenclature

i	specific heat content (J/kg)
k	coefficient (kg/s^2)
l	specific work (J/kg)
$\dot{m}$	mass flow rate (kg/s)
p	pressure (Pa)
r	specific heat (J/kg)
t	time (s)
D	constant (J/kg s)
M	mass (kg)
R	gas constant (J/kg K)
N	power (W)
T	temperature (K)
W	specific power (W/kg)
Greek symbol	
ρ	fluid density (kg/m^3)
Subscripts	
0	initial conditions
bm	bounded moisture
iv	internal vapor
fm	free moisture
lq	liquid phase
m	moisture
pr	product
sv	saturated vapor
v	vapor phase
Superscripts	
*	average feature
1, 2	coefficient numbers

may form a film during the drying process which reduces some of the quality properties of the dried product, namely the restoration of the product after soaking decreases while the color, taste and natural aroma of product are changed. High temperature and long duration of drying promotes oxidation, loss of vitamins and other bioactive substances in the dried product, and does not facilitate suppression of the initial micro-flora.

Conductive drying is based on heat transfer to the drying product due to contact with a hot surface. The drying facilities using this technology have a high metal intensity and are classified in the middle complexity class of food engineering. The specific energy consumption per unit mass of drying material is equal to 1.5–1.7 kW h/kg. The conductive technology is usually used for processing of paste like and foam like products. There is no opportunity to achieve a high quality in the final product because of irregularities in moisture distribution. The product layer in contact with the hot surface becomes over dried and the oxidation processes may be non-reversible.

Sublimation drying is based on moisture removal from a frozen product under deep vacuum conditions. Sublimation drying facilities are complicated from a technical point of view, and they require a combination of deep vacuum technology and cryogenic technology. This class of equipment is classified in the highest complexity class of foodstuff machinery. The facilities have high indices of energy consumption per unit mass of the drying product: 2.5–3 kW h/kg, high metal intensity and are not ecologically safe. The facilities must be operated by highly qualified personnel. As to biochemical indexes, one may stress that the process preserves most nutritive and bioactive substances, color and aroma. Nevertheless, the cell membranes are destroyed due to the freezing procedure and the product becomes of porous during the drying, and that reduces some organoleptic properties after product reconstitution.

Drying by high and ultrahigh frequency electric current. The processed product is placed in a high frequency (HF) or ultrahigh frequency (UHF) electro-magnetic field and therefore the molecular dipoles start vibrating and the electro-magnetic energy transforms into the heat form. HF and UHF dryers are classified in the middle complexity class of food machinery, they have average metal intensity indexes and they are ecologically unfriendly due to the microwave influence on personnel. They require service by qualified personnel and constant monitoring of UHF irradiation. The specific energy consumption per unit mass of the drying product is between 2 and 3 kW h/kg. The HF and UHF technology have significant advantages in comparison with convective and conductive ones concerning rate of drying. However, adoption of this drying method is limited because of the unknown influence of UHF drying on humans.

The ecologically safe drying technologies based on *infrared irradiation* are the most promising. The infrared irradiation is harmless for the environment and humans. It is common knowledge, that the possibilities of energy transfer to products using thermal irradiation drying are significant, and drying rate is controlled mainly by moisture transport in the product, but not by the rate of heat transfer. At the same time, the maximum achievable temperature in the product during the drying does not result in any changes in product molecular structure.

Infrared drying has also another distinctive feature. It is possible to form selective IR irradiation in specific bands using specific types of ceramics. This method allows the generation of specific IR irradiation that can significantly penetrate into the dried product and most efficiently affect the water on a molecular level. This facilitates the drying process and saves useful elements of the dried product.

Selection of IR-rays in the middle and long waves bands is favorable both for uniform energy distribution over the product surface and for long-term operation of the irradiators.

As a consequence, layer-by-layer drying of the stuff takes place. This method prevents transfer of soluble substances beyond the product surface and formation of surface films and the relatively high rate of drying suppresses oxidation and prevents vitamins and other bioactive substances being lost from the product during the processing. Preserving the integrity of the product cell membranes allows recreation of product cell structure after rehydration and then re-creation of the original shape, elasticity, natural color, aroma and flavor. Moreover, the irradiation generated by the specific functional ceramic has disinfection properties and significantly suppresses the original micro-flora on the product during the drying procedure. The simultaneous affecting of above-mentioned factors facilitates production of dried products with a quality that cannot be reached by other known technologies. However, the application of infrared irradiation for fruits and berries drying will only be effective in combination with other methods of drying (Rogov & Gorbatov, 1990).

Within the frameworks of STCU Project #Gr-14j "Creation of ecologically pure drying plants and development of power-saving technologies for agricultural production processing and preservation" research on low temperature vacuum drying technology with use of infrared irradiation has been carried out. The experiments were conducted using the drying facility of the National Aerospace University "Kharkov Aviation Institute" (KhAI). The results of theoretical and experimental researches are presented in this paper, and these results allow optimization of technological approaches and processes of low temperature vacuum drying.

2. Description of experimental facility

The KhAI experimental drying facility (see Fig. 1) consists of a vacuum chamber with a volume of about 200 l. The vacuum pump provides pressure in the chamber ≈10 mm Hg. The chamber is equipped with the condensate collector. The trays are fixed in a special frame and they allow loading of 5 kg of product for drying. The frame and the trays are connected to a balance and the change in product weight is registered automatically during the drying process. The drying procedure control system registers all working parameters (pressure in vacuum chamber, temperature on the radiators surfaces, temperature of dried product internal layers and surface) and the system controls the level of electric power supplied to the radiators to provide a product temperature not more than 55–65 °C.

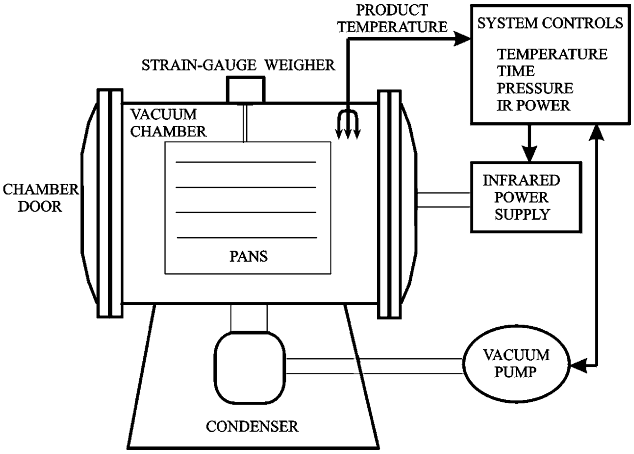

Fig. 1. Schematic drawing of laboratory infrared vacuum unit.

The special ceramic coating on the heaters generates the infrared irradiation. The specially designed screen system provides rapid and uniform drying of the product. High intensity of the infrared irradiation (≈0.4 W/cm^2) actively suppresses harmful micro-flora within the product and the product could be stored for a long time without quality reduction.

The peculiarity of drying using selective IR irradiation of middle and low bands of frequency conserves vitamins and other bioactive substances in the dried products at a level of 80–90% of the initial contents. After short-term soaking the product regains all its natural properties: color, initial aroma, flavor and could be consumed both as fresh or cooked. The resulting product does not contain any preservers or other additives.

The duration of drying in the experimental KhAI facility lies in the interval from 50 to 200 min depending from the product initial properties, i.e. weight and required final moisture (5–15%).

3. Mathematical modeling of the processes in the drying product

3.1. The mass balance equations

The parametric analysis of the processes taking place in the drying product and beyond it (Guskov, Bazyma, Basteev, Lyashenko, & Kutovoy, 2003) yielded the analytical solution of the basic equations, describing non-stationary parametric situations within the dried product. This can also lead to simplification of the mathematical model. The changes of parameters in the drying product and in the adjacent environment could be estimated using integrally averaged approaches. We will assume that there is uniform heating of the sliced product along its thickness and over the tray. The stated assumption is well founded since we are using the selective infrared radiators and this assumption is confirmed by quasi-isothermal conditions of vapor generation within the product. The uniform heat transfer to each tray of drying product is provided by the lateral infrared rays reflectors. These reflectors exclude excess dissipation of heat irradiation to the free working volume of the vacuum chamber.

As a first approximation the mass balance equation could be written as

$$-\frac{\mathrm{d}(\overline{M}_{\mathrm{pr}})}{\mathrm{d}\bar{t}} = -\frac{\mathrm{d}(\overline{M}_{\mathrm{sr}} + \overline{M}_{\mathrm{m}})}{\mathrm{d}\bar{t}} \cong \frac{\mathrm{d}(\overline{M}_{\mathrm{v}})}{\mathrm{d}\bar{t}} \equiv \dot{\bar{m}}_{\mathrm{v}}, \qquad (1)$$

where M_{pr}, M_{sr} = constant, M_{m} and M_{v} are the drying product mass, mass of residual solid, moisture mass and the mass of vapor, which are divided by the product initial mass M_{pr0}, and current time t related to some characteristic time t^* (see below). The term $\dot{m}_{\mathrm{v}}$ is the discharge rate of the vapor mass extracted from the drying product.

On the basis of experimental data (Gr-14j STCU Project Annual Report, 2002) the dependences of product mass change (apples, bananas, melon, beet root, etc.) versus drying duration have been obtained. The generalized dependence of product mass change versus time is shown in Fig. 2, which has been obtained for bananas on the basis of numerous experimental data processing. The moisture mass M_{m} divided by the solid residual level M_{sr} and shown on Fig. 2 is divided conditionally on the mass of liquid phase $M_{\mathrm{lq}} = M_{\mathrm{fm}} + M_{\mathrm{bm}}$ (free and bonded) and vapor mass M_{iv} (generated within the product) $M_{\mathrm{m}} = M_{\mathrm{lq}} + M_{\mathrm{iv}}$. It was assumed that while the product is heated, part of the vapor phase tends to increase up to some point A (see Fig. 2), and this is connected with the fact that some vapor has not been removed from the internal structure of the product. We assumed that the moment of completion of the first drying stage (the stage of product heating) coincides with point A. Let us denote this moment as $\bar{t} = t/t^* = 0$, since we will not consider this stage during the further analysis. At the end of the first stage of drying the vapor mass discharge from the product reaches its maximum value.

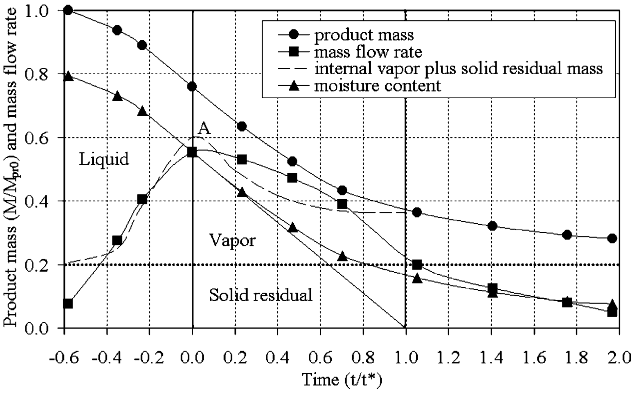

Fig. 2. The product mass and mass flow rate changing versus time.

The character time t^* (see above) is determined as the value of moisture mass M_{m} divided by the value of vapor mass discharge from the drying product $\dot{m}_{\mathrm{v}}$ that is reached at the end of the first stage of drying $t^* = M_{\mathrm{m}}/\dot{m}_{\mathrm{v}}$.

The time t^* determines the duration of the next stage of drying $\bar{t} = t/t^* = 1$. This is the stage of bubble-drop (two phase mixture) transport of moisture out from the product (the main stage of moisture removal).

The vapor phase is dominant within the product at $\bar{t} \geqslant 1$. This stage may be called as pressure-diffusion stage (the stage of finishing drying).

Taking this statement into account Eq. (1) may be rewritten as

$$-\frac{\mathrm{d}(\overline{M}_{\mathrm{pr}})}{\mathrm{d}\bar{t}} = \begin{cases} -\frac{\mathrm{d}(\overline{M}_{\mathrm{fm}}+\overline{M}_{\mathrm{bm}}+\overline{M}_{\mathrm{iv}})}{\mathrm{d}\bar{t}} \simeq -\frac{\mathrm{d}(\overline{M}_{\mathrm{lq}})}{\mathrm{d}\bar{t}} + \left(k^1_{\mathrm{iv}} - 2k^2_{\mathrm{iv}}\bar{t}\right) \\ \qquad\qquad\qquad \simeq \dot{\bar{m}}_{\mathrm{v}}, \quad \bar{t} = 0\text{–}1, \\ -\frac{\mathrm{d}(\overline{M}_{\mathrm{iv}})}{\mathrm{d}\bar{t}} \simeq \dot{\bar{m}}_{\mathrm{v}}, \quad \bar{t} \geqslant 1, \end{cases} \qquad (2)$$

at k^1_{iv}, k^2_{iv} are the coefficients of polynomial dependence of vapor phase change within the product.

On the basis of experimental data processing the polynomial dependences for mass changes and mass consumption upon time were obtained for different drying products for the main stage of moisture removal as well for the stage of finishing-drying.

3.2. The energy balance equation

The energy balance equation could be written as

$$\overline{N} = \frac{\mathrm{d}(\overline{M}_{\mathrm{lq}}\bar{i}_{\mathrm{lq}})}{\mathrm{d}\bar{t}} + \frac{\mathrm{d}(\overline{M}_{\mathrm{iv}}\bar{r}_{\mathrm{w}} + \overline{M}_{\mathrm{iv}}\bar{l}_{\mathrm{iv}})}{\mathrm{d}\bar{t}} + \overline{M}_{\mathrm{sr}}\frac{\mathrm{d}\bar{i}_{\mathrm{sr}}}{\mathrm{d}\bar{t}} + \dot{\bar{m}}_{\mathrm{v}}\bar{i}_{\mathrm{sv}}, \qquad (3)$$

where $\overline{N}$ is the heat power directly supplied to the drying product (divided on the maximal electric power of infrared radiators N_{e}). The terms $\bar{i}_{\mathrm{lq}}$, $\bar{i}_{\mathrm{sv}}$, $\bar{i}_{\mathrm{sr}}$, $\bar{r}_{\mathrm{w}}$ and $\bar{l}_{\mathrm{iv}}$ are specific heat of drop moisture, saturated vapor, solid residual, the specific heat of vapor formation and specific work of vapor transport outside the drying product structures (are divided on $N_{\mathrm{e}}/M_{\mathrm{pr0}}$).

The dividing of the drying process into stages $\bar{t} = 0$–1 (the main stage of moisture removal) and $\bar{t} > 1$ (finishing drying) allows significant simplification of further parametric analysis. It is obvious that we may ignore the heat power expenses for moisture transport within the product at the first stage of drying due to the significant differences between the vapor pressure within the product and outside of it in the vacuum volume. Moreover, we will not take into account the heat power expenses for heating of the residual solid product

$$\frac{\mathrm{d}(\overline{M}_{\mathrm{iv}}\bar{l}_{\mathrm{iv}})}{\mathrm{d}\bar{t}} \to 0, \quad \overline{M}_{\mathrm{sr}}\frac{\mathrm{d}\bar{i}_{\mathrm{sr}}}{\mathrm{d}\bar{t}}\bigg|_{\overline{M}_{\mathrm{sr}} \ll \overline{M}_{\mathrm{m}}} \to 0, \quad \bar{t} = 0\text{–}1,$$
$$\overline{M}_{\mathrm{sr}}\frac{\mathrm{d}\bar{i}_{\mathrm{sr}}}{\mathrm{d}\bar{t}}\bigg|_{T \leqslant T_{\max}} \to 0, \quad \bar{t} > 1. \tag{4}$$

The reason for the above assumptions is the significant difference between the solid residual mass and the moisture mass during the main stage of moisture removal and the limits for the maximum temperature of product heating (no more than 55 °C) during the stage of finishing drying.

Since $\bar{i}_{\mathrm{sv}} - \bar{i}_{\mathrm{lq}} = \bar{r}_{\mathrm{w}}$ and, therefore $\bar{r}_{\mathrm{w}} - \bar{i}_{\mathrm{lq}} = 2\bar{r}_{\mathrm{w}} - \bar{i}_{\mathrm{sv}}$, after transformation of Eq. (3) taking into consideration Eq. (2) we will obtain for the main stage of moisture removal ($\bar{t} = 0$–1):

$$\overline{N} = \overline{M}_{\mathrm{lq}}\frac{\mathrm{d}(\bar{i}_{\mathrm{lq}})}{\mathrm{d}\bar{t}} + \overline{M}_{\mathrm{iv}}\frac{\mathrm{d}(\bar{r}_{\mathrm{w}})}{\mathrm{d}\bar{t}} + (2\bar{r}_{\mathrm{w}} - \bar{i}_{\mathrm{sv}})\frac{\mathrm{d}(\overline{M}_{\mathrm{iv}})}{\mathrm{d}\bar{t}} + \bar{r}_{\mathrm{w}}\dot{\bar{m}}_{\mathrm{v}}. \tag{5}$$

Within the considered temperature band in the drying product (30–55 °C) we may make changes for current values of $\bar{r}_{\mathrm{w}}$ and $\bar{i}_{\mathrm{sv}}$ on their averaged ones $\bar{r}^*_{\mathrm{w}} = \text{constant}$ and $\bar{r}^*_{\mathrm{sv}} = \text{constant}$ without significant inaccuracy (±2%). Then Eq. (5) with the assumption $\bar{r}^*_{\mathrm{w}} \approx \bar{r}^*_{\mathrm{sv}}$ could be rewritten as

$$\overline{N} \simeq \overline{M}_{\mathrm{lq}}\frac{\mathrm{d}(\bar{i}_{\mathrm{lq}})}{\mathrm{d}\bar{t}} + \bar{r}^*_{\mathrm{w}}\left(\dot{\bar{m}}_{\mathrm{v}} - k^1_{\mathrm{iv}} + 2k^2_{\mathrm{iv}}\bar{t}\right). \tag{6}$$

Here we used the assumption (see above) about the parabolic law of vapor content change in the product. Since the main component of product moisture is water, after linear temperature increase within the product during the main stage of moisture removal we will obtain:

$$\overline{N} \simeq (\overline{M}_{\mathrm{pr}} - \overline{M}_{\mathrm{sr}} - \overline{M}_{\mathrm{iv}})D + \bar{r}^*_{\mathrm{w}}\left(\dot{\bar{m}}_{\mathrm{v}} - k^1_{\mathrm{iv}} + 2k^2_{\mathrm{iv}}\bar{t}\right), \tag{7}$$

where D is some small constant that can be neglected in our consideration.

During the finishing drying ($\bar{t} > 1$), Eq. (3) could be presented in the following form, taking into account Eqs. (2) and (4):

$$\overline{N} = \frac{\mathrm{d}(\overline{M}_{\mathrm{iv}}\bar{l}_{\mathrm{iv}})}{\mathrm{d}\bar{t}} + \dot{\bar{m}}_{\mathrm{v}}\bar{i}_{\mathrm{sv}} = \left(\frac{p_{\mathrm{sv}} - p}{\rho_{\mathrm{sv}}} + \bar{i}_{\mathrm{sv}}\right)\dot{\bar{m}}_{\mathrm{v}}. \tag{8}$$

At this stage of drying all product layers are heated up to the maximum allowable temperatures. Nevertheless, the mass discharge of vapor from the product surface reduces since the vapor diffusion phenomena are dominating and the bound product liquid phase moves to the surface from the inside layers. Taking into account that $p \ll p_{\mathrm{sv}}$ and assuming the average value $\bar{r}^*_{\mathrm{sv}} = \text{constant}$, we obtain the following for the second drying stage

$$\overline{N} = \left((RT)^*_{\mathrm{sv}} + \bar{i}^*_{\mathrm{sv}}\right)\dot{\bar{m}}_{\mathrm{v}}. \tag{9}$$

The estimations of heat power supplied to the drying product at the stages of main moisture removal and finishing drying were made with the use of Eqs. (7), (9) and also polynomial dependencies for mass and mass discharge change versus time that were obtained on the basis of experimental data processing.

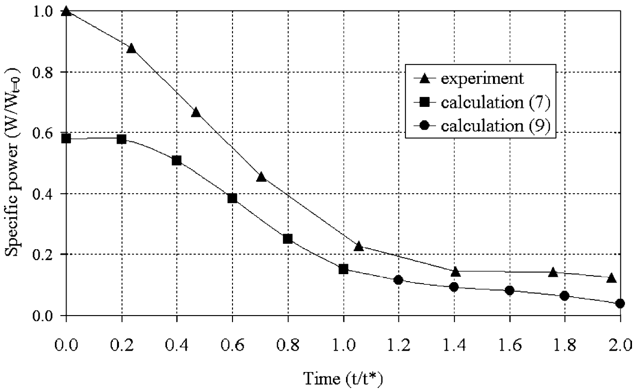

Fig. 3. The specific power change as a function of drying time.

The changes of specific electric power of the infrared radiators $\overline{W}_{\mathrm{e}} = W_{\mathrm{e}}/(W_{\mathrm{e}})|_{t=0}$, $\overline{W}_{\mathrm{e}} = (N_{\mathrm{e}}/M_{\mathrm{pr}})/(N_{\mathrm{e}}/M_{\mathrm{pr}})|_{t=0}$ experimentally obtained (bananas drying) and changes in the heat power supplied to the drying product $\overline{W} = W/(W_{\mathrm{e}})|_{t=0}$, $\overline{W} = (N/M_{\mathrm{pr}})/(N_{\mathrm{e}}/M_{\mathrm{pr}})|_{t=0}$ calculated due to Eqs. (7) and (9) are presented on Fig. 3. The thermo-physical parameters for saturated steam: specific heat of vaporization $\bar{r}_{\mathrm{w}}$, and heat content of saturated steam $\bar{i}_{\mathrm{sv}}$ were used for these calculations. For convenience the power values in the Fig. 3 are related not to the product start mass and maximal electric power of infrared radiators but to the product mass and electric power at time $\bar{t} = t/t^* = 0$. Approximately 90% of electric power supplied to the infrared radiators (during the main stage of moisture removal and the stage of finishing drying) are transformed into heat power, transferred to the drying product at the constant temperature of the drying product surface.

4. Conclusions

The dependence between the energy irradiated by infrared radiators and the duration of processing at a fixed drying temperature and final product humidity have been determined experimentally. Polynomial relationships for mass and mass discharge changes versus time were obtained for different drying products on the basis of experimental data both for the main stage of moisture removal and for the stage of finishing drying. The obtained relations for the two stages of drying (7) and (9) allow estimation of the power level needed both for the main stage of moisture removal and for the stage of finishing drying. The obtained data can be used for programming of the vacuum drying facility control system.

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