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Development of mathematical model for vacuum cheese drying

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ABSTRACT

On the basis of experimental and analytical studies, a method for calculating and selecting of vacuum drying systems for drying food products wascompiled. Also, a method for calculating the parameters of the process of vacuum cheeses drying has been developed. In addition, there were obtained some regression equations for calculating the duration of the process of vacuum cheeses drying and for organoleptic evaluation of dry cheese products. The cost of the produced dry cheese products by the method of vacuum drying was calculated as well.

Keywords: *vacuum, mathematical model, cheese, dry*.

1. INTRODUCTION

Mainly it is irrational to dry heat-sensitive, expensive and air-oxidized materials by convection at atmospheric pressure [1-4]. Therefore, vacuum drying is used to intensify the process and preserve the quality of the material being dried. Vacuum drying is used for chemical and food products, explosive and heat-sensitive materials. When drying in a vacuum chamber, the main heat is transferred to the material by radiation or conduction from the heating surfaces [5-13].

In practice, vacuum drying of food products is carried out in an air-proof heat-insulated chamber, equipped with heating elements connected to a vacuum line [14-18].

Generally, when drying at a pressure of 1330 Pa and above (vacuum drying), the mechanism of heat and moisture transfer inside the dried material is similar to the equivalent mechanism at contact drying [19-24].

The vapor, formed during the material liquid evaporation process, is removed by a vacuum pump as well as air flowing through the leakages of the chamber. To facilitate the operation of the unit's vacuum pump, it is applied some absorbers for steam or capacitors; the latter partially condense the vapor and turn it into a liquid [25-31].

2. MATERIALS AND METHODS

A food product (cheese) is a thermolabile material, which is placed in a special pan of bulk density and of a certain size for ground particles частиц [32-37].

When considering vacuum methods of drying solid food products, the following methods of heat supply are observed:

- gradual method of heat supply at a constant residual pressure of the medium. In this case, the drying process proceeds at a gradually decreasing heat load and a constant temperature in the chamber;
- pulsed (or "oscillating") method of heat supply at a constant residual pressure of the medium. In this case, the drying process consists of alternating stages of heating and binning at a constant temperature in the chamber;
- multi-stage (multi-level) method of heat supply at a constant temperature in the chamber and alternating values of residual pressure and heat load.

The process of vacuum drying starts with the condenser gaining a temperature mode (minus 20–25 ° C) and the air is pumped out of the working cavity of the apparatus (Fig. 1).

This starting stage excludes the resistance phase, contributes to more intense heat and mass transfer from the wet material to the drying agent. To remove the air environment, the vacuum pump is working; therefore, the duration of this stage is insignificant compared to the duration of the entire drying process.

Heat is applied after achieving the required residual pressure in the vacuum chamber.

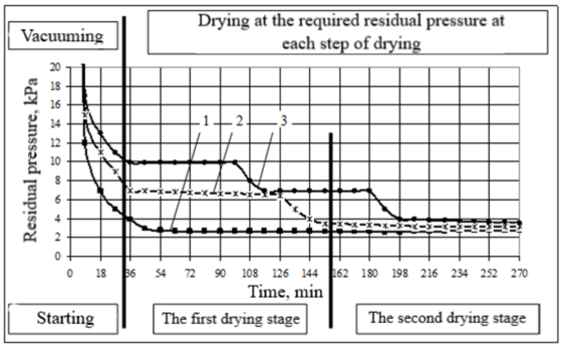

Figure 1. General view of the residual pressure changes during vacuum cheese drying process consisting of: 1 – one stage; 2 – two stages; 3– three stages.

The process of vacuum cheeses drying is divided into two stages:

1) the stage of constant drying rate (the period of material heating);

2) the stage of the falling drying rate.

The energy and substance transfer in the process of drying the material is a subject to the general thermodynamics laws of irreversible heat and mass transfer processes. Until the drying unit gains the mode of residual pressure, the heat is not supplied and the temperature of the surface layers of the product is reduced due to self-evaporation. While this process, a temperature gradient occurs and it coincides in direction with the gradient of moisture content, leading to the intensification of the removing moisture transfer.

The first stage begins when the heaters are turned on and is characterized by a constant drying rate. Due to the fact that the process takes place under reduced pressure, material warming causes intense boiling of moisture throughout the entire cheese volume. The temperature difference between the surface and internal layers is the potential for heat transfer into the product due to thermal conductivity.

The mechanism of the drying process at reduced pressure is based on the well-known laws of the drying theory and of equilibrium between liquid and vapor. A decrease in vapor pressure above the surface of the material shifts the dynamic equilibrium towards the evaporation of moisture, i.e. the driving force of the process is the difference in the partial pressure of the vapor of the removed moisture above the surface of the material and in the medium.

When vacuum drying with infrared heat supplied to the product throughout the whole process, the temperature gradient has a positive effect on the process of moisture removal due to the same direction of the temperature gradient and moisture content.

The kinetics of unbound moisture removal during vacuum cheese drying is determined by the change in water vapor pressure in the vacuum chamber; while at the bound moisture removal this does not occur, since the change in cheese moisture content is determined by the internal processes of heat and mass transfer characterized by various forms of moisture and dry matter.

Having considered the basic laws of moisture removal during vacuum cheese drying with heat supply, it was established the need to develop a mathematical model for calculating the duration of the vacuum cheese drying process.

3. RESULTS

The mathematical description of the real process of food products' vacuum drying is a rather complicated and time-consuming task. Therefore, to describe this process, it is necessary to introduce some basic assumptions:

1) during the process of vacuum drying, the moisture content of the cheese surface is equal to the current value of the partial pressure of water vapor above it, which corresponds to the temperature of its surface;
2) drying cheese has the same temperature and moisture content throughout the whole product volume;
3) during vacuum drying, laws derived for ideal gases can be applied for water vapor;
4) the thermophysical properties of moisture removed from the cheese during vacuum drying are equal to the thermophysical properties of distilled water.

Fig. 2 shows a diagram of vacuum cheese drying with an infrared method of heat supply.

When drying, to intensify the process of evaporation of moisture, heat is supplied to the material. In the process of vacuum drying of cheese with a residual pressure of at least 2 kPa, heat is transferred by convection and radiation. In this case the heat balance equation is the following:

$$c_o \cdot \left(\frac{T_к}{100}\right)^4 + \alpha \cdot F \cdot (t_к - t_c) = r \cdot \left(\frac{du}{d\tau}\right), \quad (1)$$

where $c_o = 5{,}67\ \ \mathrm{kW/(m2 * K4)}$ – black-body coefficient;

α – heat transfer coefficient, W/(m²·K);

$t_к$ – temperature in the chamber, °C;

t_c – temperature of the cheese supplied for drying, °C;

r – specific heat of evaporation, J/kg;

$\frac{du}{d\tau}$ – drying rate, %/min.

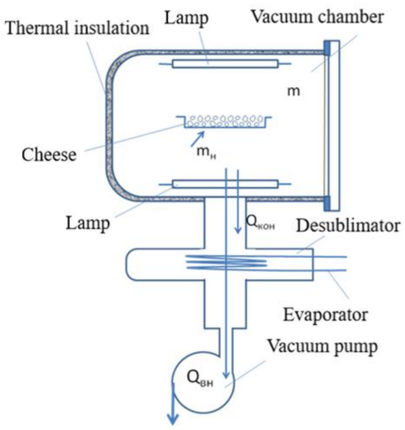

Figure 2. diagram of vacuum cheese drying with an infrared method of heat supply: m – mass of water vapor in the vacuum chamber; m_H – cheese mass; Q_{KOH} – volume capacity of condenser; Q_{BH} – volume capacity of vacuum pump.

The specific heat of vaporization is determined by the formula:

$$r = r_o + (c_П - c_B) \cdot (T_c - 273), \quad (2)$$

where r_o – heat of vaporization at 0 °C, J/kg;

$c_П$ – heat capacity of steam, J/(kg·K);

c_B – heat capacity of evaporated moisture, J/(kg·K).

The convection heat transfer coefficient can be determined by the equation:

$$\alpha = \frac{\lambda}{\delta}, \quad (3)$$

where δ – thickness of the cheese particles, m;

λ – coefficient of thermal conductivity, W/(m·K).

As shown in fig. 2, during the drying process the moisture evaporated from the cheese and the air entering the vacuum system through leakages are pumped from the drying chamber.

It is necessary to obtain an analytical relationship that describes the evaporation of moisture during vacuum drying. The required amount of residual pressure in the vacuum system is supported by a vacuum pump. The equation of material balance during the moisture evaporation in the drying process is::

$$q_{исп} = \rho \cdot Q_H, \qquad (4)$$

where $q_{исп}$ – moisture evaporation rate, kg/h;

ρ – steam density, kg/m³;

Q_H – vacuum pump capacity, м³/ч.

The intensity of moisture evaporation from the material during the drying process is equal to:

$$q_{исп} = \frac{du}{d\tau}. \qquad (5)$$

The density of saturated steam is determined by the equation:

$$\rho = \frac{P \cdot M}{R \cdot T_к}, \qquad (6)$$

where P – gas pressure, Pa;

M – molecular mass of water, kg/mol;

R – molar gas constant, equal to 8314 J/(kg·K).

Applying equations 5 and 6 into formula 4, it is:

$$\frac{du}{d\tau} = \frac{P \cdot M \cdot Q_H}{R \cdot T_к}, \qquad (7)$$

Applying equation 1 into equation 7, the equation of heat and mass transfer is obtained:

$$\frac{d}{d\tau}\left[c_o \cdot \left(\frac{T_к^4}{100}\right) + \alpha \cdot F \cdot (t_к - t_c)\right] = r \cdot \frac{P \cdot M \cdot Q_H}{R \cdot T_к}, \qquad (8)$$

Multiplying equation (8) by dt and integrating, it is obtained:

$$c_o \cdot \left(\frac{T_к^4}{100}\right) + \alpha \cdot F \cdot (t_к - t_c) = r \cdot \frac{P \cdot M \cdot Q_H}{R \cdot T_к} \cdot \tau, \qquad (9)$$

Expressing from the equation 9, the duration of drying τ is:

$$\tau = \frac{\left[c_o \cdot \left(\frac{T_к^4}{100}\right) + \alpha \cdot F \cdot (t_к - t_c)\right] \cdot R \cdot T_к}{r \cdot P \cdot M \cdot Q_H}, \qquad (10)$$

Adequacy of the mathematical model (equation 10) was evaluated by comparing the calculated and experimental drying times. The average error of the calculated model is 6.3%.

4. CONCLUSIONS

Thus, a model to calculate the duration of the cheese vacuum drying process, taking into consideration the drying temperature, the residual pressure and the area of the being dried cheese, has been developed.

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