Study of the features of modeling microwave vacuum evaporation

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Abstract. Evaporation is the most common concentration method. The complete reuse of latent thermal energy by means of mechanical recompression is the most technologically efficient method of operation of evaporators. This method requires much less electricity to compress the secondary steam compared to the heat of the secondary steam. In this scheme, the energy released during steam condensation can be used to heat the initial solution, which makes it possible to achieve the reuse of thermal energy at the level of 95%. Thus, during the the evaporation process implementation, when energy is supplied by electromagnetic microwave radiation, conditions are created for the initiation of vaporization in the entire liquid volume, which will avoid product overheating in the thermal boundary layer due to the absence of such. This allows to get a product of high concentration, without the taste of "cooking", without changing color and flavor. When modeling these processes, boundary conditions of the third kind are replaced by boundary conditions of the second kind. Considering the proposed hypothesis, a process model can be considered, assuming the presence of internal energy sources evenly distributed in the product volume. This opens up the possibility of using deterministic mathematical models, provided that the corresponding initial and boundary conditions are determined. As a result of generalization of the experimental modeling results, a model in a criterion form has been obtained, which allows calculating a microwave vacuum-evaporation apparatus of periodic action for solutions containing polar molecules. The model in the range of dimensionless pressure $2 \leq P \leq 22$, and at the level of dimensionless heat of the phase transition $1 \leq R \leq 4.56$ provides accuracy with a maximum deviation of ± 8%.

1 Introduction

Today there is a problem of choosing healthy foods to strengthen overall health and immunity [1]. Fruits, vegetables, and natural juices are important components of nutrition, rich in vitamins and minerals [2]. Although they are not the main sources of protein and fat, they enrich our diet. These foods also add variety to the diet and provide important components such as vitamin C, provitamin A, calcium, phosphorus, and iron. The dietary fiber contained in them is also essential for a healthy diet. Fruit and vegetable juices

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provide trace elements that contribute to a healthy lifestyle [3]. Studies show that drinking 100% fruit juice is associated with better overall health indicators. Juices contain potassium, magnesium, folic acid, vitamins A and C, as well as polyphenols with antioxidant properties [3]. They also contribute to the normal functioning of the immune system and increase iron absorption. As a result, fruits, vegetables, and juices are easily accessible and useful sources of useful components obtained from nature. In connection with the above, fruits and vegetables have acquired commercial importance, and their growth on a commercial scale has become an important sector of the agricultural industry. Recently, the global production of fruits and vegetables has increased significantly due to advances in agricultural technology. Consequently, the percentage of products requiring suitable post-harvest storage and processing methods to ensure an increase in shelf life is increasing. The production and consumption of processed fruits and vegetables is also increasing.

In 2019, Russian imports of fresh fruits and vegetables amounted to 7 million tons [1]. These imports are mainly represented by fruits that cannot be grown in Russia due to climatic features. Nevertheless, in recent years there has been a decrease in fruit imports as a result of import substitution programs. With this perspective, the safety and efficient processing of domestic products become critically important. Most fruits and vegetables contain more than 80% water and are subject to perishable processes. Rotting plays a big role in losses, especially in developing countries with inadequate handling and storage conditions. These losses include the loss of essential nutrients such as vitamins and minerals. Reducing losses after harvesting products is of paramount importance to increase the availability of products. Nevertheless, restrictions on food production are constantly increasing. Therefore, it is necessary to apply post-harvest conservation methods together with an increase in production [1]. Preservation of products, such as fruits and vegetables, into stabilized products that contribute to reducing post-harvest losses is of great importance [2]. Concentration of the product by removing water is one way. This can be done through evaporation, freezing, and membrane separation methods [4-7]. Nevertheless, membrane methods are often used only for cleaning products. Freezing allows to preserve the original product properties [8]. Block freezing is one of the new directions [7, 9-11]. Evaporation is the most common concentration method [12, 13]. Modern evaporation plants can be compared with cryoconcentration technologies in terms of energy consumption. Some aromatic substances can also be captured in distillation columns. However, the thermal decomposition of some components at high temperature may limit the use of this method [1], which is why vacuum evaporation plants have become widespread. One of the traditional methods of increasing energy efficiency in the evaporation process is the use of multi-stage vacuum-evaporators [14, 15]. This method significantly reduces energy consumption by using secondary steam, which is formed under the action of the primary energy source in the subsequent stages of the apparatus [16]. Nevertheless, with an increase in the number of steps, the temperature difference decreases, which requires an increase in the surface area for heat exchange and, consequently, increases capital costs [1]. To save energy, the secondary steam energy is also used [17], and there are several schemes for organizing the operation of vacuum evaporators with the return of secondary steam as a heat source, such as the use of ejectors [18], the use of compressors or gas blowers [19] and their various variations. The effectiveness of these methods depends on the economic parameters of these devices, their degree of wear and cost. For example, steam ejectors, despite their simplicity and reliability, have a low efficiency, which rarely exceeds 40-50% [1]. The complete reuse of latent thermal energy by means of mechanical recompression is the most technologically efficient method of operation of evaporators [19]. This method requires much less electricity to compress the secondary steam compared to the heat of the secondary steam. In this scheme, the energy released during steam condensation can be used to heat the initial solution, which makes it possible to achieve the reuse of thermal energy at the level of 95%. Nevertheless, it also requires additional investments in equipment [1]. Vacuum evaporation plants with mechanical steam recompression often use high-pressure blowers or turbochargers, which makes them more expensive compared to installations with thermal steam compression. These methods have proven themselves well at a rarefaction of up to 0.4 atmospheres [1].

In recent years, schemes for ensuring the operation of vacuum evaporation plants (VEP) using heat pumps (HP) as heat sources have become popular and promising [18, 19]. Such schemes can effectively solve the problems of heat removal that arise in the air conditioning system due to the condensation of secondary steam formed as a by-product during evaporation. Such devices use two sources (hot and cold) for moisture evaporation and condensation. The built-in heat pump, including a compressor and circulating refrigerant, creates the necessary heat and cold. This reduces energy consumption by about 5 times, since most of the energy (latent heat) is used to form new steam. The level of electricity consumption depends on the compression of the intermediate medium and represents the energy required for reuse. Depending on the temperature of the product undergoing evaporation, both additional heat from a hot source and cold from a cold source are used. Nevertheless, the main problem of evaporators remains an increase in the solution viscosity with a concentration increase, which reduces the intensity of the solution circulation, increases the thermal resistance of the boundary layer and its temperature. In practice, this is limited to the final concentration of the finished product (from 25 to 60%). "The microwave range of electromagnetic energy is used to concentrate solutions with a polar solvent. The microwave field heats the product volumetrically and does not require a heat transfer surface. The energy is directed to the water molecules, avoiding heating of dry substances. Microwave energy supply allows to increase productivity, concentration coefficient, and efficiency. Nevertheless, there are local overheating zones that affect the product quality [20-23]. Vacuum evaporation in traditional devices is limited by metal consumption. Multistage systems and heat pumps increase efficiency, but can cause overheating at high concentrations. Plate devices reduce the heat exchange area, but do not solve the problem. The microwave energy supply prevents local overheating and improves the concentrate quality. For industrial devices with microwave energy supply, methods for determining parameters are required [24, 25]. Thus, the implementation of the evaporation process when energy is supplied by electromagnetic microwave radiation creates conditions for the vaporization initiation in the entire liquid volume, which will avoid product overheating in the thermal boundary layer due to the absence of such. This allows to get a product of high concentration, without the taste of "cooking", without changing color and flavor. When modeling these processes, boundary conditions of the third kind are replaced by boundary conditions of the second kind.

2 Materials and Methods

Considering the proposed hypothesis, a process model can be considered, assuming the presence of internal energy sources evenly distributed in the product volume. This opens up the possibility of using deterministic mathematical models, provided that the corresponding initial and boundary conditions are determined. Probably, the system of differential equations describing this model cannot be solved directly. Nevertheless, the methods of similarity theory allow to transform this model into a criterion form. Already this stage has three important practical applications:

1. Determination of parameters for conducting experimental studies.
2. Generalization of experimental results and creation of an empirical model limited by the range of experiments.

3.Possibility of using empirical models to solve problems of designing and optimizing innovative equipment.

Then it will be possible to conduct correct experimental modeling of transmission processes in an electromagnetic field. The author presented the fundamental differences of this innovative idea from traditional evaporators in his work. [26]

The quality parameters are the final concentration of the solution (Xk) and the specific energy consumption for concentrating 1 kg of the product (j, J/kg). The input parameters, in general, are the thermophysical properties of the raw material, its consumption, initial values of concentration, and temperature. The complexes of parameters that characterize the design of the apparatus and the energy indicators of electromagnetic generators are considered.

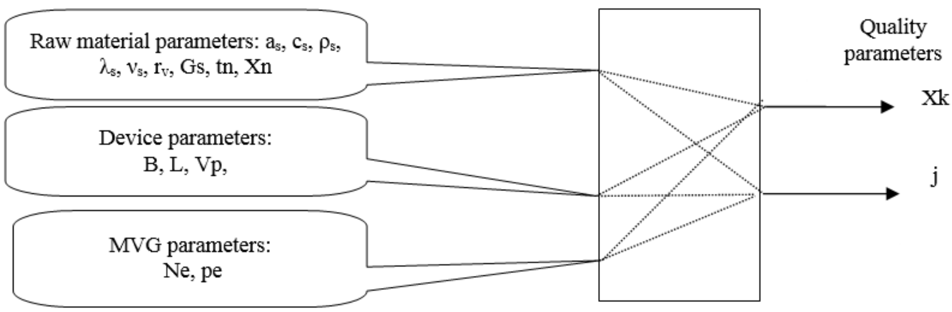

Fig. 1. Parametric model of microwave evaporation apparatus.

Based on the scheme (Fig. 1), a physical model of the apparatus is compiled (Fig. 2), which is the formulation of the problem of a mathematical model formation.

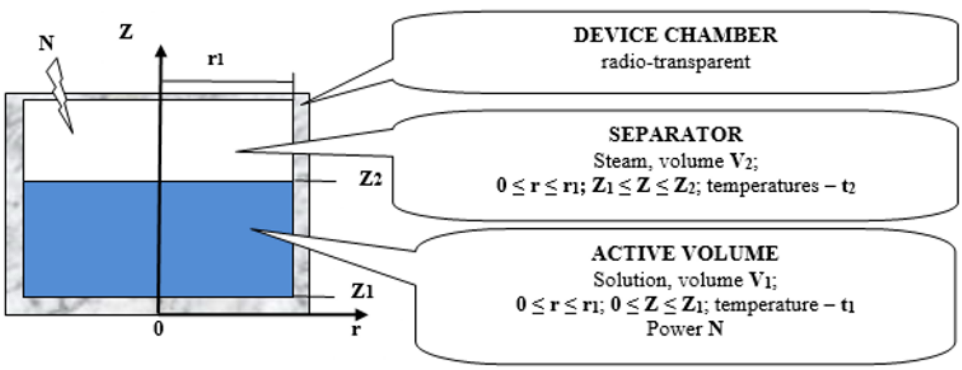

Fig. 2. Physical model of the evaporation process.

The main physical processes unfold in the working volume, where there is a solution exposed to energy from an electromagnetic energy source with a power of N. The energy enters the volume through a radio-transparent case. The energy supply method is volumetric and obeys boundary conditions of the second kind. The separator mechanically separates the solution droplets (if they got there) from the steam, and no energy is absorbed in this separator volume (see Figure 2). The third zone is a radio-transparent body of the device, which is a reaction volume. For these three main zones, it is necessary to develop a mathematical model of a microwave vacuum evaporator.

3 Results and Discussion

The energy interactions between the elements will be considered on the basis of the first law of thermodynamics and the classical Fourier-Kirchhoff equation. No work is done in the system under consideration, so the first law of thermodynamics for this problem will be written as:

$$Q_{st} + Q_V = \Delta U \tag{1}$$

where Q_{st} is the amount of heat transferred through the contact surface (S);
Q_V is the amount of heat that is absorbed by the solution from electromagnetic energy sources;
ΔU – the change in the internal solution energy.
The heat fluxes Q_{st}, Q_V and the change in the internal energy of the body are determined according to the recommendations, for example [27]

$$Q_{st} = \iint\limits_{S\,0}^{\tau} dQd\tau,\ \ Q_V = \iint\limits_{V\,0}^{\tau} q_V dVd\tau,\ \ \Delta U = \iint\limits_{V\,0}^{\tau} c_V \rho \frac{\partial t}{\partial \tau} dVd\tau \tag{2}$$

where q_v is the specific power of internal heat sources (effluents), W/m^3.
Using the Fourier equations, we transform the relations (2), and write in the cylindrical coordinate system:

$$\iint\limits_{S\,0}^{\tau} dQd\tau = \iint\limits_{V\,0}^{\tau} \left[\frac{\partial}{\partial r}\left(\lambda \frac{\partial t}{\partial r}\right) + \frac{\lambda}{r}\frac{\partial t}{\partial r} + \frac{1}{r^2}\frac{\partial}{\partial \varphi}\left(\lambda \frac{\partial t}{\partial \varphi}\right) + \frac{\partial}{\partial z}\left(\lambda \frac{\partial t}{\partial z}\right)\right] dVd\tau \tag{3}$$

Then, substituting (3) into (1), we get:

$$\iint\limits_{V\,0}^{\tau} \left[c_V \rho \frac{\partial t}{\partial \tau} - \frac{\partial}{\partial r}\left(\lambda \frac{\partial t}{\partial r}\right) - \frac{\lambda}{r}\frac{\partial t}{\partial r} - \frac{1}{r^2}\frac{\partial}{\partial \phi}\left(\lambda \frac{\partial t}{\partial \phi}\right) - \frac{\partial}{\partial z}\left(\lambda \frac{\partial t}{\partial z}\right) - q_V \right] dVd\tau = 0 \tag{4}$$

If all the characteristics in (4) are continuous functions of coordinates and time, then the integral is zero when the integrand is equal to zero [33]. Thus:

$$c_V \rho \frac{\partial t}{\partial \tau} = \frac{\partial}{\partial r}\left(\lambda \frac{\partial t}{\partial r}\right) + \frac{\lambda}{r}\frac{\partial}{\partial r} + \frac{1}{r^2}\frac{\partial}{\partial \phi}\left(\lambda \frac{\partial t}{\partial \phi}\right) + \frac{\partial}{\partial z}\left(\lambda \frac{\partial t}{\partial z}\right) + q_V \tag{5}$$

We have established a spatio-temporal relationship between and the temperature change at any point of the body volume. As a rule, the thermal conductivity coefficients are considered constant, and equation (5) is simplified and reduced to a linear partial differential equation of the second parabolic type.

Regularities 5 are common to all 3 zones of the device. Based on them, it is necessary to specify the models for each zone. For zone 1 (Fig. 2), we take the indexes "1". Then in the working volume: the volume of the product $\mathbf{V_1}$; the energy consumed by the product $\mathbf{N\eta\tau}$; temperatures – $\mathbf{t_1}$. Pressure range $\mathbf{P_a \leq P \leq P_i}$ The process proceeds in 2 stages. For stage 1 (heating the product from the initial temperature $t_l = t_n$ to the evaporation temperature $t_l = t_i$) and for stage 2 (evaporation as such). At the first stage, there is no steam output (W = 0), and energy is consumed only to increase the product temperature. For heights $\mathbf{0 \leq Z \leq Z_1}$; radii $\mathbf{0 \leq r \leq r_1}$: Initial conditions ($\tau = 0$): $t_l = t_n$; $V_l = V_{n.}$

$$\frac{\partial t_1}{\partial \tau} = \alpha_1 \left(\frac{\partial^2 t_1}{\partial r^2} + \frac{1}{r}\frac{\partial t_1}{\partial r} + \frac{1}{r^2}\frac{\partial^2 t_1}{\partial \varphi^2} + \frac{\partial^2 t_1}{\partial z^2} \right) + \frac{N\eta}{V_1 c_1 \rho_1} \tag{6}$$

where $\alpha = \frac{\lambda}{(c_1\rho)}$ is the thermal conductivity, m^2/s.

The residue as such is characterized by a constant phase transition temperature (t_i = const). All the energy supplied (**Nητ**) is spent on increasing the internal energy of the solution. There is a change in the heat capacity during the transition of the liquid phase to the vapor phase. The result is an increase in the solution concentration. The energy balance equation will take the following form:

$$N\eta\tau = V_i\, t_i \left(c_1\rho_1 - c_2\rho_2\right) \tag{7}$$

The steam output reduces the liquid volume in the working volume:

$$V_1(\tau) = V_n - V_i(\tau) \tag{8}$$

The hydrodynamic situation in the working volume is reflected by the Navier-Stokes equation. In the conditions of the problem under study (Fig. 2), it is possible to limit one-dimensional recording along the Z axis:

$$\rho_1 \cdot \omega_1 \cdot \frac{\partial \omega_1}{\partial z} = \rho_1 \cdot g - \frac{\partial P_1}{\partial z} + \mu_1 \cdot \frac{\partial^2 \omega_1}{\partial z^2} \tag{9}$$

The second zone (separator) is filled with solvent vapor, the vapor temperature is t_2, the vapor volume is V_2, the energy is not absorbed by steam (N = 0). Thus, for $\mathbf{0 \le r \le r_1; Z_1 \le Z \le Z_2}$, the mathematical model is similar to (6) when replacing t_1 with t_2 and α_1 with α_2. Similarly (9), the hydrodynamic situation in the separator is expressed.

For zone 3, which represents the wall of the reaction volume, the temperature of the material is t_3, the volume is V_3, the energy is not absorbed by the wall (N = 0). Thus, for $\mathbf{r_1 \le r \le r_3; 0 \le Z \le Z_3}$, the model is similar to (6) when replacing t_1 with t_3 and α_1 with α_3, and the hydrodynamic situation is similar to the ratio (9). The resulting system of equations should be supplemented with boundary conditions of interaction between zones. The corresponding boundary conditions are given in Table 3.9.

Table 1. Summary of boundary conditions.

Coordinate according to Fig. 3.17	BC type	BC Model
Z = Zo (the boundary of chamber and environment).	III kind	$\frac{\partial t_3}{\partial \tau} = -\frac{\alpha_c}{\lambda_3}\left(t_3 - t_c\right)$ (10)
Z = Z_1 (the boundary of solution and chamber wall).	III kind	$\frac{\partial t_3}{\partial \tau} = -\frac{\alpha_1}{\lambda_3}\left(t_1 - t_3\right)$ (11)
$Z_1 < Z < Z_2$ (solution volume).	II kind	$q_V = \frac{N}{V_1} = const$ (12)

Z = Z_2 (solution and vapor boundary).	I kind	$t = t_u = const$ (13)
Z > Z_2 (the boundary of chamber and environment).	III kind	$\frac{\partial t_3}{\partial \tau} = -\frac{\alpha_2}{\lambda_3}\left(t_2 - t_3\right)$ (14)

In the ratios (10-14): α – heat transfer coefficient; λ – thermal conductivity coefficient; N – electromagnetic generator power; n – magnetron efficiency; τ – operating time; indices 1 – solution; 2 – steam; 3 – wall of the reaction volume (chamber); c – environment.

The system of equations (6-14) describes a non-stationary temperature field, as well as material and energy balances in the evaporation process. For a more detailed system description, specification is required, including the addition of initial conditions and coupling equations. Nevertheless, despite the simplifications, it is currently almost impossible to solve this system due to the peculiarities of the Navier-Stokes equations. The implementation of the model turns out to be complex and requires the use of similarity theory methods.

The analysis of the above processes led to the formulation of the following hypothesis: "the organization of the vaporization process under the direct influence of energy on the solution polar molecules does not cause the formation of traditional thermal resistances, which can become a prerequisite for stable vapor production, depending only on the solution type and the pressure level in the apparatus." In this formulation, the traditional heat transfer coefficient, which characterizes the thermal resistance of convective heat exchange, loses its value.

For such special evaporation conditions in an electromagnetic, microwave field, the following key process parameters are proposed. These parameters follow from the proposed model (6-14), concretized considering the formulated hypothesis, and are presented in Table 2.

Table 2. Main parameters of the evaporation process in electromagnetic field.

Parameter	**Symbol**	**Dimension**
Specific heat of vaporization	***r***	$m^2 \cdot s^{-2}$
Microwave field power	***N***	$kg \cdot m^2 \cdot s^{-3}$
Pressure	***P***	$kg \cdot m^{-1} \cdot s^{-2}$
Steam output	***W***	$kg \cdot s^{-1}$
Product movement speed	**v**	$m \cdot s$

All these parameters presented in Table 2 contain only three main dimensions: length (***L***), mass (***M***), and time (***τ***). In this case, the number of variables is $n = 5$, the number of measurement units is $m = 3$. Then, according to the π-theorem (the dimension analysis method), the number of dimensionless complexes describing the process should be equal to (***n – m***) = 2. These two complexes are quite simply completed according to Table 2.

$$\frac{Wv}{P} = A\left(\frac{N}{Wr}\right)^m \qquad (15)$$

The first dimensionless complex in (15) is new, it has a technological character. It shows the ratio of the solution inertial forces and the static forces in the apparatus. The second complex is the energy impact number (Bu number), which successfully generalized the results of experimental modeling of mass transfer processes in a microwave field [27].

In practical tasks, another combination of dimensionless complexes can also be used:

$$Bu = A \cdot P^n \cdot R^m \tag{16}$$

In (16) it is accepted: P is the ratio of the current pressure in the apparatus to the base one, and R is the ratio of the heat specific values of the phase transition of the solution under study to the base one. From the obtained value of the Bu number, it is possible to calculate either the required total power (at a given steam capacity), or to make a calibration calculation and determine the performance of the device at a known power of electromagnetic generators.

As a result of processing the entire database of experimental point, the criterion equation is obtained:

$$Bu = 1{,}32 \cdot P^{0{,}35} \cdot R^{-0{,}2} \tag{17}$$

The adequacy of the obtained ratio (17) is carried out by comparing the calculated and experimental values of the *Bu* numbers

4 Conclusions

A comparative analysis of classical dehydration technologies is given and the main problems are highlighted, the solution of which formed the basis of the formulated hypothesis about the possibility of transition from the BC of 3rd kind to the BC of 2nd kind.

Using the methods of similarity theory, models were obtained that allow designing and optimizing installations for obtaining high-quality concentrates of food solutions and installations for drying products with microwave and infrared energy supply.

As a result of generalization of the experimental modeling results, a model in a criterion form has been obtained, which allows calculating a microwave vacuum-evaporation apparatus of periodic action for solutions containing polar molecules. The model in the range of dimensionless pressure $2 \le P \le 22$, and at the level of dimensionless heat of the phase transition $1 \le R \le 4.56$ provides accuracy with a maximum deviation of ± 8%.

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