Kinetics laws as the base for mathematical simulation of microwave vacuum drying process

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Abstract. The process of drying food is extremely complex. Therefore, the mathematical modeling of the process needs high requirements. The combination of approaches in modeling is of practical interest. On the one hand, analytical solutions based on the application of physical laws or phenomenological equations are used. On the other hand, experimental identification of the relationship between temperature and body moisture, which is considered as a peculiar characteristic of heat and mass transfer for each material. It is proposed to consider vacuum microwave drying from the standpoint of physical chemistry as a quasitopochemical heterogeneous reaction and perform mathematical modeling of this process based on the laws of chemical kinetics.

Ключевые слова: modeling, microwave drying, heat and mass transfer, chemical kinetics, black currant.

1. Introduction
An analysis of existing approaches to the mathematical description of microwave drying of blackcurrant shows that, based on only one approach to modeling complex interrelated phenomena occurring during drying, it is not possible to satisfactorily describe in whole with a single model all drying periods - constant and falling speed. During the drying process, the fruits decrease in volume by 3–4 times, the physical characteristics (some by several orders of magnitude) of both the individual fruit and the fruit layer in the dryer significantly change. Many well-known models of the drying process use the approximation of the constancy of the geometric parameters of the drying object and the constancy of its physical properties [1,2,3,4]. However, when describing microwave drying of blackcurrant fruits, such models have low reliability. In addition, in the mathematical description of convective drying with an additional microwave energy supply, additional errors arise. The occurrence of such factors is due to the complexity of the mathematical description of the amount of energy that is absorbed by a multicomponent substance, which is black currant.

For the practical implementation and development of the idea of applying the laws of chemical kinetics to mathematical modeling of microwave drying processes, drying should be considered broadly as some heterogeneous reaction due to a whole complex of chemical, physico-chemical, biochemical and...
rheological processes, the kinetics of which, along with the kinetics of energy transfer and substances determines the mechanism and rate of drying processes. In our opinion, all these processes during drying can be described by the equations of chemical kinetics [5, 6, 7, 8].

2. Methods

The methodological basis of the study includes a complex of analysis and synthesis, verification of the truth of the theory by resorting to practice. The theoretical and methodological basis of research is the work of domestic and foreign authors in the field of drying, in particular, the work by Lykov A.V., Rebinder P.A., Ginzburg A.S., Lebedev P.D. and others.

The object of the study was the kinetics of the process of vacuum microwave drying of black currant. The subject of the research is the methodology of applying the laws of chemical kinetics to the modeling of microwave drying processes.

The apparatus for researching vacuum microwave drying of black currant consists (Figure 1) of a sealed vacuum chamber with a lid equipped with an inspection window, a control panel, a microwave energy supply device, and a vacuum and vapor removal system [1].

![Figure 1. Scheme of the experimental vacuum microwave installation](image)

A working vacuum was created by a rotary oil pump. The experimental setup includes: 1 - a vacuum chamber; 2 - frame; 3 - vapor removal system; 4 - vacuum pump; 5 - pump control panel; 6 - control unit; 7 - manometer; 8 - magnetron; 9 - fan; 10 - viewing window, 11 - metal mesh.

The installation allows the process of vacuum-microwave drying in various modes, to control and register the necessary parameters of the process. For the experiment, a portion of the test product was placed on a metal mesh 11, simulating a portion of the conveyor belt. The vacuum chamber 1 was hermetically closed. The temperature of the dried product during the experiment was recorded using an AKIP 9303 pyrometer. To determine the humidity, a FD-610 moisture meter from Kett (Japan) was used. To measure the residual pressure, a strain gauge was used. The value of the specified microwave power was maintained using an automatic power regulator for voltage, which was removed from an external sensor.
3. Results

3.1. Study of the influence of various factors on the kinetics of the vacuum microwave drying process

Using the experimental design method, we studied the kinetics of drying the fruits of black currant in an experimental vacuum drying unit with a microwave energy supply.

The influence of the supplied microwave power on the kinetics of drying the fruits of black currant is shown in Fig. 2. As can be seen from the graphs, the supplied microwave power affects the ratio of the periods of constant and decreasing drying speeds. The drying speed is directly proportional to the input microwave power.

The effect of the height of the layer of blackcurrant fruit on the kinetics of drying the heating during the drying process is shown in Fig. 3. From the graphs it is seen that with decreasing layer height, the drying speed in the first period increases. This is due to the fact that the gradient of moisture content, which prevents the movement of moisture to the surface, decreases.

![Figure 2](image-url)  
**Figure 2.** Dependence of the kinetics of vacuum microwave drying on microwave power

![Figure 3](image-url)  
**Figure 3.** Dependence of the kinetics of vacuum microwave drying on the height of the product layer

3.2. Modeling the duration of vacuum microwave drying

In the theory of drying, a period of constant and decreasing drying speed is distinguished. The period of constant speed, ending when the product reaches critical moisture content, does not depend on moisture content, is a function of temperature, design parameters of the apparatus and other parameters of a particular drying method.

In the educational and scientific literature, numerous analytical and experimental methods for determining the constant drying speed for food are given [9,10]. Comparing various approaches to describing the speed of the first period, it should be noted that the most reliable mathematical model for engineering calculation is a description of the process in the form of a regression equation obtained by processing experimental data:

\[ N_1 = f(x_1, x_2, ... x_n), \]

(1)

where \( N_1 \) is the speed of the first drying period, \( s^{-1} \);

\( x_1, x_2, ... x_n \) – process factor.

The drying time of this (first) period \( \tau_1 \) is calculated by the expression:
\[ \tau_1 = \frac{U_n-U_p}{N_1}, \] (2)

where \( U_n, U_p \) is the initial and critical moisture content of the product, kg/vl / kg. \( N_1 \) - constant drying speed, s\(^{-1}\).

For a mathematical description of the kinetics of drying in a period of decreasing speed, we consider drying as a heterogeneous reaction and apply the laws of formal kinetics of chemical reactions to its description [5, 8]:

\[ \frac{\partial \alpha}{\partial \tau} = f(\alpha) \cdot A \cdot \exp \left( -\frac{E}{RT} \right), \] (3)

where \( \alpha = \frac{U_n-U}{U_n-U_p} \) - substance conversion;

\( A \) - coefficient, s\(^{-1}\);

\( f(\alpha) \) - substance conversion function;

\( R \) - universal gas constant, J/(mole*K);

\( T \) - absolute body temperature, K;

\( E \) - activation energy, J/mole;

\( U_n, U_p, U_r \) - initial, equilibrium and current moisture content of the material, kg/vl / kg.

Obtaining analytical dependences on the temperature of the drying agent and other process parameters for a period of decreasing speed, as is known [9, 10], is significantly difficult. Therefore, an empirical approach based on probability theory, mathematical statistics, similarity, and modeling is often used for these purposes [10]. Moreover, for specific drying methods tend to use simpler mathematical expressions. In this regard, in engineering practice, a method of modeling the drying rate based on the approximation and generalization of kinetic curves in the form of a relationship is widespread: \( N_2(U) = N_1 \cdot f(U) \). For example, a model based on the laws of chemical kinetics [6] for the second period gives satisfactory results for engineering practice:

\[ N_2(U) = N_1 \left( \frac{U-U_p}{U_p-U} \right)^n \cdot \phi(U,T) \cdot \exp \left( \frac{r}{Rc} \cdot \frac{Z(U)}{Z(U)+Tc} \right), \] (4)

where

\[ Z(U) = (T_k - T_c) \cdot \frac{\frac{1}{m}[\exp\{m(U_p-U)\}-1-(U_p-U)] - \frac{1}{m}[\exp\{m(U_p-U)\}-1-(U_p-U_p)]}{\frac{1}{m}[\exp\{m(U_p-U_p)\}-1-(U_p-U_p)]} \] (5)

\( N_2(U) \) – decreasing drying rate, s\(^{-1}\);

\( T_k \) – material temperature when critical moisture content is reached;

\( T_c \) – material temperature when equilibrium moisture content is reached;

\( n \) – reaction order;

\( m \) – empirical coefficient determined experimentally;

\( m \) – characterizes the form of moisture contact with the product and does not depend on other factors.

Based on (4), we calculate the drying time of the second period:

\[ \tau_2 = \int_{U_k}^{U_p} \frac{dU}{N_2(U)} = \frac{1}{N_1} \int_{U_k}^{U_p} \frac{dU \cdot \exp \left( -\frac{r}{RTc} \frac{Z(U)}{Z(U)+Tc} \right)}{\left( \frac{U-U_p}{U_p-U} \right) \cdot \phi(U,T)} \] (6)

From expressions (2) and (4) we obtain

\[ N_1 \cdot \tau = N_1 \cdot \tau_1 + N_1 \cdot \tau_2 = W_1 + W_2 = W_{ob} \approx \text{const} \] (7)

where \( W_1 = U_n - U_p \).

In establishing the physical meaning of the quantities \( W_1, W_2, \) and \( W_{ob} \), we proceed from the following reasoning. The dimension of these values coincides with the dimension of the moisture content of the product. Therefore, \( \tau \cdot W_{ob} \) corresponds to a certain estimated amount of moisture content, which could be removed from the product at a constant speed for a time equal to the drying time of the product.
in an industrial apparatus. We propose to call the value \( W_{ob} \) - the total equivalent moisture content, and \( W_1 \) and \( W_2 \) - respectively, the equivalent moisture content of the first and second drying periods. Since \( W_{ob} \) is a constant value for a specific product in a particular design of a drying plant, it is relatively easy to determine experimentally from the drying curve (the dependence of the moisture content \( U \) on the drying time \( \tau \)).

3.3. **Experimental determination of total equivalent moisture content**

The experimental determination of the total equivalent moisture content and verification (7) are shown on the experimental curves of vacuum microwave drying of black currant. To determine \( W_{ob} \) on the graph of the drying curve, it is necessary to construct a scale of equivalent moisture content, having a scale equal to the scale of moisture content of the product. The point \( U_0 \) corresponds to zero on the scale \( W \), the axis of which is directed opposite to the axis \( U \). The drying time \( \tau \) is determined by the value of \( U_0 \). On the drying curve from the point \( U_0 \), a tangent to the graph \( U = f(\tau) \) is carried out, which characterizes the process of removing the equivalent moisture content with a constant speed \( N_1 \). According to a previously determined drying time, \( W_{ob} \) is determined.

![Graph](image_url)

1 – \( h=0.015m, p=75 \) kPa, \( P=750 \) W; 2 – \( h=0.015m, p=75 \) kPa, \( P=455 \) W; 3 – \( h=0.015m, p=75 \) kPa, \( P=160 \) W

**Figure 4.** Determination of the total equivalent moisture content during vacuum microwave drying of black currant

The experimental data presented by us in Fig. 4 and the scheme for determining the equivalent moisture content, which proves the validity of our reasoning and the possibility of applying the laws of chemical kinetics to the modeling of vacuum microwave drying processes.

**4. Conclusion**

Vacuum microwave drying can be considered from the standpoint of physical chemistry as a quasi-topochemical heterogeneous reaction. Her mathematical modeling can be based on the application of the laws of chemical kinetics. The proposed method for determining the duration of vacuum microwave drying, based on the experimentally determined value of the total equivalent moisture content, greatly simplifies this calculation in comparison with existing methods. The value of the total equivalent moisture content characterizes the product as an object of drying, is easily determined by the
experimental drying curves, and is a constant value for a particular product when it is dried in a specific apparatus.

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