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HEAT AND MASS TRANSFER UNDER THE INFLUENCE OF IR AND CONVECTIVE ENERGY FLOWS ON FRUITS-VEGETABLES

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ABSTRACT: One of the most important tasks of agricultural production is to obtain food products of plant origin, which include legumes, vegetables, fruits, etc. Long-term storage of many plant species in their natural form under normal conditions is impossible and requires the use of processing, such as drying. A special niche is occupied by medicinal plants, on the basis of which medicinal preparations, biologically active additives, as well as spices are made for food. Along with natural drying methods, artificial methods are widely used with the help of special drying plants. However, it is not always possible to achieve the required product performance. The use of electric energy seems to be the most preferable, since it eliminates the cost of delivery, storage of solid or liquid fuels, reduces environmental damage to the environment, and obtains the necessary properties due to the "thin" control of the drying technology. The use of electrical methods for generating thermal energy for technological processes in a small-sized drying plant is the most rational. This work is dedicated to solving an important scientific and technical problem in the field of electrification of agriculture, namely, increasing the efficiency and quality of drying of plant products while reducing energy costs and drying time.
Key words: fruits, vegetables, drying, heat, infrared heating, convection.

1. Introduction

Consider the patterns due to the energy of heat and mass transfer during thermal exposure to plant material (stems, leaves, roots, inflorescences). The medicinal value of such a material depends on the quality of drying, which, in turn, is associated with the amount of heat supplied, the duration of exposure, and the drying speed. At the same time, the effectiveness of such a process is directly related to the method of heating, stimulation of the displacement of moisture and its removal outside the dryer [1-9].

In our study, the main heat treatment of the material occurs due to heating from an IR source of thermal energy. Cooling the material with cold air is an auxiliary operation that lowers the surface temperature of the body in order to intensify the displacement of moisture. The subsequent blowing, with heated air, removes moisture that has protruded to the surface and carries it out of the chamber [10-16]. Therefore, when considering the theoretical provisions of heat and mass transfer, we will be based on the above-mentioned features of this method of drying medicinal plants.

In general, during IR heating of a material, an electromagnetic wave from a source reaches a heated body, penetrates into it to a certain depth and is converted into thermal energy and heats the body throughout the depth of penetration. The quality of the dried material largely depends on the amount of heat supplied to the material and the duration of exposure to the drying object [17-23]. In this case, the efficiency of the drying process is determined by the method of supplying heat and the ratio of the quantities of heat to heat and to evaporate moisture from this material.

2. Mathematical model and method

The amount of heat transferred from the IR source to the material is determined according to the Stefan-Boltzmann law, the following expression

$$Q = \iint_F 5.67 C_{red} \left[\left(\frac{T_H}{100} \right)^4 - \left(\frac{T_M}{100} \right)^4 \right] dF \qquad (1)$$

where C_{red}-reduced degree of black emitter and material; 5.67 - Stefan-Boltzmann constant, W/m^2-K4; T_H, T_M are the absolute temperatures of the emitter and the material, K, dF is the elementary surface area of the heating material.

The integration of equation (1) is carried out over the surface F (m^2). The generated heat is partially spent on heating the material, evaporation of moisture, heat loss into the environment and can be expressed as follows:

$$Q = \iiint_V C_\gamma \left(\frac{dt}{d\tau} \right) dV + \gamma_T M \left(\frac{du}{d\tau} \right) + \iint_F \alpha (t_M - t_0) dF \qquad (2)$$

where C is the specific heat of the dried material, kJ/kg °C; $C\gamma$-specific density of the material, kg/m^3; γ_T-specific heat of evaporation of moisture from the material, kJ/kg; α-coefficient of convective heat transfer of the material with the surrounding air, kJ/m^2 °C; *M*-mass of dried material, kg; t_M, t_0 - material and ambient air temperatures, °C; dt is an infinitesimal increment of the material temperature per time element dτ.

The integration of equation (2) over the volume *dV* and the area *dF*, which is a solution to the three-dimensional problem, is very cumbersome and difficult to analyze. In order to simplify further conclusions, it is advisable to consider heat and mass transfer as a one-dimensional problem, assuming that the movement of moisture from the center goes in the direction normal to the surface of the material, which actually happens in practice [26-29].

As noted earlier, the heating efficiency of the material is achieved by choosing the spectrum of infrared radiation that is most consistent with the optical properties of the heated body. In other words, the maximum absorption of the radiant flux by the material is possible if the wavelength at which the maximum radiation source λ_{max} corresponds to the wavelength λ_M of the maximum absorption capacity of this material, i.e. $\lambda_{max}\approx\lambda_M$.

The heating efficiency of the material depends on the absorption coefficient of the radiation flux of the IR source $K_\lambda(x)$, which at $\lambda_{max}\approx\lambda_m$ is taken to be 1,0:

$$\left(\frac{\lambda_{max}}{\lambda_M};\ \frac{\lambda_M}{\lambda_{max}}\right) = K_\lambda \to 1{,}0 \quad (3)$$

whereK_λ is a quantitative indicator, i.e.; *x*-factors affecting the value of λ_M the main of which is the moisture content of the material.

We take this coefficient into account in the one-dimensional solution of equation (2). Next, we introduce the concept of average temperature (t_{cp}), i.e. the average value of this parameter over the volume of the body, "average specific density of the material" (γ_{cp}), "its average heat capacity" (C_{cp}), and also the temperature difference (t_M-t_0) with the index "*cp*". Then, after transformations, equation (1) for a one-dimensional problem takes the form:

$$Q = K_\lambda = \left[\left(c_0 + \frac{c_B w}{100}\right)\gamma_0 V \frac{dt_{cp}}{d\tau} + \gamma_T M\left(\frac{du}{d\tau}\right) + F\alpha(t_M - t_0)_{cp}\right] \quad (4)$$

wherec_0 is the heat capacity of absolutely dry material, kJ/kg °C; c_B-heat capacity of the moisture of the material, (4,19 kJ/kg-°C); γ_0 - specific density of absolutely dry material, kg/m^3; *V*-volume of the dried material, m^3.

Wherein

$$c_{cp}\cdot\gamma_{cp} = \left(c_0 + \frac{c_B u}{100}\right);\ \gamma_0 = \frac{m_0}{v_0} \quad (5)$$

where$u$ is the average moisture content of the material, kg/kg; m_0 is the absolutely dry mass of the material, kg; γ_0 volume of absolutely dry mass, m^3.

If we neglect the shrinkage of the material during its drying, i.e. take $V=V_0$, then the final solution of the equation of the heat balance of drying using the IR energy flow is written as follows:

$$5.67C_{np}\left[\left(\frac{T_u}{100}\right)^4 - \left(\frac{T_M}{100}\right)^4\right]F = K_\lambda\left[\left(c_0 + \frac{c_B w}{100}\right)m_0\frac{dt_{cp}}{d\tau} + M\left(\frac{du}{d\tau}\right) + F\alpha(t_M - t_0)_{cp}\right] (6)$$

The left side of the equation is the amount of infrared radiation penetrating the material. Quantitatively, this energy depends on the temperature difference T_u and T_M, given the degree of blackness,

$$C_{cp} = \frac{1}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} + 1} \quad (7)$$

whereε_1, ε_2 is the degree of blackness of the emitter and the heated material, and is also determined by the area of the infrared emitter Fu, which is taken to be equal to the area of the heated material: $F_u=F_m=F$ (m^2).

The first term on the right-hand side of equation (6) is the heat used to heat the substance, the second term determines the amount of heat used to evaporate moisture, and the last term on this equation takes into account the heat loss to the environment. We will carry out a further transformation of the heat balance equation for IR-drying of the medicinal material. To do this, we denote the average moisture content w,% by volume of the material, as follows:

$$w = \frac{m_B}{M}\cdot 100 \quad (8)$$

and substitute into equation (6). After the conversion, we obtain the equation $\frac{dw}{d\tau}$ connecting the drying rate of the material with the technological parameters of heating $\frac{dt_{cp}}{d\tau}$

$$5{,}67\frac{C_{np}}{m_c}\left[\left(\frac{T_u}{100}\right)^4 - \left(\frac{T_M}{100}\right)^4\right]F = K_\lambda\left[r_T\frac{dw}{d\tau}\cdot 100 + \left(c_0 + \frac{w}{100}\right)\frac{dt_{cp}}{d\tau} + \frac{Fd}{m_c}(t_m - t_B)_{cp}\right] (9)$$

wherem_B, m_C, respectively, is the mass of moisture and the mass of absolutely dry matter, kg. Solving this equation with respect to the drying speed of the material, $\frac{dw}{d\tau},\frac{\%}{hour}$, we obtain:

$$\frac{dw}{d\tau} = \frac{100K_\lambda}{r_T m_c}\cdot F\left\{5{,}67C_{np}\left[\left(\frac{T_u}{100}\right)^4 - \left(\frac{T_M}{100}\right)^4\right] + \alpha(t_m - t_B)_{cp}\right\} - \left(c_0 + \frac{w}{100}\right)\frac{dt_{cp}}{d\tau} (10)$$

In the steady state, when the heating of the material is completed, $\frac{dt_{cp}}{d\tau} = 0$. The term $\left(c_0 + \frac{w}{100}\right)\frac{dt_{cp}}{d\tau}$, equation (10) will also be equal to zero.

From equation (10) it follows that the drying rate is determined by the magnitude of the input infrared energy flux, as well as by the quantitative value of the absorption coefficient of the infrared radiation material K_λ.

The coefficient *Kλ* in the heat transfer equations is a controllable factor. For maximum penetration into the material of infrared radiation, it is necessary that K_λ=1,0. This is possible if it has the equality $\lambda_{max}=\lambda_M$, which is achieved by choosing, according to Wien's law the corresponding temperature of the IR source.

Now consider the mass transfer during drying of the material. It both quantitatively and qualitatively depends on the heating temperature of the material. Based on the heat transfer equations (1; 2) and the law of conservation of the substance in the drying process, we compose the equation of mass transfer balance in the volume of material *V*, limited by the surface area *F*. In general, it can be expressed as follows:

$$\iiint_V M\left(\frac{d_u}{d_\tau}\right)dV = \iint_F i_m dF \quad (11)$$

wherei_m is the density of the moisture flux moving per unit time through a unit surface of the material, kg/m^{2}s.

In solving this equation, we use the same approach as in the integration of equation (2), i.e. Let us imagine mass transfer as a one-dimensional problem in which moisture moves in the material from the central layers of the material to its surface along the normal.

The left side of equation (11) determines the amount of moisture evaporated from the material per unit time (kg/s). We set the task to intensify this process. Consider this in more detail.

The effectiveness of the movement of moisture in the material is due to two factors that arise when it is heated: the gradient of moisture content grad and the temperature gradient *grad t*. They can have both positive and negative signs.

We agree that if gradients *grad u, grad t* have negative signs, then this contributes to the drying process of the material. The opposite sign of the gradients is an obstacle to the movement of moisture to the surface of the material.

Let us explain this in more detail. If the sign of the gradient of moisture content is negative -*grad u*), then this means that it does not coincide with the vector of the moisture flow, which tends from the center of the material to its surface, which contributes to the drying process. A negative sign at the temperature gradient (-*grad*) indicates that the heat flux vector in the material is directed from its central layers to the surface, which coincides with the direction of the moisture flow, which also tends to the surface layers of the material. It also contributes to the drying process.

Consider the right side of equation (11). The mass transfer equation in a solid can be written similarly to the Fourier thermal conductivity process.

$$i_m = -\lambda_m grad\, u = -a_m \gamma_0 grad\, u \quad (12)$$

where i_m is the density of the flow of moisture transferred inside the body during the drying process, kg/m^2 s; *grad u* - moisture content gradient, defined as the ratio of mass to mass of absolutely dry material; λ_m is the mass conductivity coefficient of the dried material, kg/m s; a_m-potential conductivity coefficient, m^2/s; γ_0 is the specific gravity of dry material, kg/m^3.

From the expression (11) it follows that the moisture flux density i_m when drying the material depends on the potential conductivity coefficient at, which is determined by the moisture content of the body, its structural structure, moisture state (osmotically coupled, capillary moisture, etc.), as well as the gradient *grad u* on the amount of moisture flow inside the body.

Academician A. Lykov [1] the phenomenon of thermal diffusion of liquid moisture in a material was discovered during its drying, or the so-called thermal moisture conduction, and a new factor was established that causes the movement of moisture – the temperature gradient and the corresponding coefficient of thermal moisture conduction δ. When drying the material with a convective method of supplying heat at low temperatures, this will not have the proper effect on the drying process.

The intensification of drying, in particular, due to the use of IR heat sources, showed a significant effect of this factor on the efficiency of moisture removal from the material [1-2]. Then, taking into account IR heating, the mass transfer equations will take the following form:

$$i_{mt} = -a_m \gamma_0 grad\, u - a_m \gamma_0 \delta grad\, t = i_m + i_t \quad (13)$$

where imt is the density of the flow of moisture, sometimes a vapor-liquid emulsion carried out from the material due to moisture conduction and thermal moisture conduction, kg/m s; grad t-temperature gradient, °C/m; δ-coefficient of thermal conductivity of the material, 1/°C; im, it - components of the moisture flow due to moisture conduction and thermal moisture conduction, kg/m^2 s.

3. Results and discussions

In a general consideration of mass transfer equation (13) in the material, it follows that the higher the temperature and the moisture concentration in the central layers with respect to the periphery, the higher the moisture flux density i_{mt} to the surface of the material.

Now we consider the terms of this equation from the point of view of their controllability. The moisture content gradient *grad u* is an uncontrollable factor. Its scalar value and direction of the vector are determined by the temperature field in the material and, therefore, only secondarily affects the component i_{mt} through the temperature parameter. The temperature gradient *grad t*, according to the proposed drying method, is a controllable factor. Cyclical blowing of the surface of the material with cold air lowers its temperature, increasing the scalar value of *grad t* while the direction of the vector remains unchanged. As a result of this, the heat flux from the center of the material to its surface increases, thereby increasing the coefficient of thermal moisture conductivity δ, and this, in turn, enhances the process of moisture migration (component i_t).

In order to take this factor into account, we introduce into the second term the dimensionless coefficient μ in the second term:

$$\mu = \frac{\delta'}{\delta} > 1{,}0, o.e., \tag{14}$$

whereδ` is the coefficient of thermal moisture conductivity, contributing to an increase in the yield of moisture from the material with the claimed drying method.

The coefficient μ, we call it the thermogradient coefficient, takes into account the increase in the material of the temperature gradient *grad t*, and, as a consequence, the temperature head from the center of the material to its surface.

Then, taking into account the proposed drying method, the new coefficient of thermal moisture conductivity will be equal to:

$$\delta' = \mu\delta, \tag{15}$$

and the mass transfer equation is written as follows:

$$i_{mt} = -a_m\gamma_0 grad\, u - a_m\gamma_0\delta\mu\, grad\, t = i_m + \mu \cdot i_t, \tag{16}$$

whereμ,i_t, is the component of the moisture flux density taking into account the thermal gradient coefficient.

The magnitude of the thermal gradient μ depends on the ratio of the components of the time cycle of thermal action τ_{tc} to the material: τ_{IR} -infrared heating, τ_0-cold airflow.

$$\tau_{tc} = \tau_{IR} - \tau_o, \text{min} \tag{17}$$

and is determined by the so-called indicator of the structure of the cycle - ε:

$$\varepsilon = \frac{\tau_{IR}}{\tau_{IR}+\tau_o}, \tag{18}$$

The time of blowing the material with heated air, the so-called technological pause between cycles, is not taken into account in determining ε.

The task is to find experimentally the optimal value of ε for drying each specific medicinal material, as well as time *t* for the effective removal of moisture from the surface of this material and its removal.

We continue the analytical consideration of the moisture conductivity of the dried material. For the case of a one-dimensional problem, the gradients of moisture content and temperature can be represented by the corresponding partial derivatives in the form:

We continue the analytical consideration of the moisture conductivity of the dried material. For the case of a one-dimensional problem, the gradients of moisture content and temperature can be represented by the corresponding partial derivatives in the form:

$$grad \cdot u = \frac{\partial u}{\partial x}; grad \cdot t = \frac{\partial t}{\partial x} \tag{19}$$

And further:

$$\frac{\partial i_x}{\partial x} = -\gamma_0 \frac{\partial u}{\partial \tau}, \tag{20}$$

Then equation (17) can be written as follows:

$$i = -\alpha_m\gamma_0 \left(\frac{\partial u}{\partial x} + \delta' \frac{\partial t}{\partial x}\right), \tag{21}$$

Differentiating this equation with respect to *x*, we obtain:

$$\frac{\partial i}{\partial \tau} = -\alpha_m\gamma_0 \left(\frac{\partial^2 u}{\partial t^2} + \delta' \frac{\partial^2 t}{\partial x^2}\right), \tag{22}$$

If we jointly convert equations (20) and (22), then in the final form the differential equation for the movement of moisture for the above conditions can be written in the following form:

$$\frac{\partial u}{\partial \tau} = \alpha_m \left(\frac{\partial^2 u}{\partial x^2} + \delta' \frac{\partial^2 t}{\partial x^2}\right) \tag{23}$$

4. Conclusion

This differential equation describes the rate of molar and molecular movement of moisture in a medicinal plant material during infrared drying with stimulating blowing with cold air. It depends on the individual potential conductivity of the material ∂u, as well as on the thermal gradient ∂u in the coefficient of thermal moisture conductivity 57, the extremum of which is determined by the time cycle of the thermal action of the thermal current, which is the task for the experiment.

5. References

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