Analysis of the process of mass transfer during drying

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Abstract. This article describes the important parameters of the drying process. the relationship between mass transfer and heat transfer is given. Medicinal plants were selected for the drying process. Stinging nettle, ginger root and chopped leaves of elecampane are placed evenly in stainless steel meshes with an area of 0.5 m² each and a depth of 5 cm, raw material from 50 to 90 kg (depending on the plant). Each raw material is dried separately without mixing with each other. The drying process is provided with a heat carrier.

1. Introduction
Drying is one of the most important and fundamental operations in the post-harvest processing of medicinal plants. The quality of the medicinal product and, therefore, the income is significantly influenced by the drying regime. The energy requirement for drying can also be a very important factor due to the high initial moisture content of flowers, leaves and roots. For the preparation of quality products, great attention should be paid to the dryer itself and the drying process. The theoretical foundations for calculating the thermophysical processes of heat and mass transfer during the drying of medicinal plants, given in the article, require knowledge of the specific values of the heat and moisture exchange coefficients. Obtaining these values is possible only in the process of conducting special laboratory, semi-industrial and field studies.

2. Dependence of mass transfer on the heat transfer coefficient
In solar drying systems, energy studies are carried out to determine the amount of energy received from the solar air collector and the ratio of the energy consumption of the drying chamber. Energy analysis of the drying process of many food and pharmaceutical products is based on the conservation of mass and energy in a steady state and can be expressed by equations (1, 2) and equation (3), respectively [1]:

Mass Conservation Equation for Air Drying:

\[ \sum m_i = \sum m_0 \]  

where \( m_i \) and \( m_0 \) are the mass flow rates of air at the inlet and outlet, respectively.

Moisture Conservation Equation for Air Drying

\[ \sum (m_{wi} + m_{mp}) = \sum m_{w0} \]
\[ \sum (m_i w_i + m_{mp}) = \sum m_i w_0 \]  

(2)
where \( m_{wi} \) and \( m_{wo} \) are the mass flow rate of moisture at the inlet and outlet, respectively; \( m_{mp} \) is the mass flow rate of moisture in the product; \( w_i \) and \( w_o \) - specific humidity at the inlet and outlet, respectively [2].

And the energy conservation equation

\[
Q - W = \sum m_0 \left( h_0 + \frac{v_i^2}{2} \right)
\]

(3)

where \( Q \) is the total heating rate; \( W \) is the energy use factor; \( h \) is the enthalpy; \( v \) - drying speed.

The second law of thermodynamics concerns both the quality and quantity of energy and states that the actual process takes place in the direction of decreasing the quality of energy [3,4].

In the second period of the drying rate when falling, the movement of moisture starting from the marketable core to the outside is usually carried out by molecular diffusion, that is, the moisture flow is directly proportional to the moisture content gradient. In other words, moisture moves from an area with a higher moisture content to an area with a lower moisture content, and this phenomenon is explained using the second law of thermodynamics. The convenient concept of exergy in the study of thermal systems is also explained by the second law of thermodynamics, and it says that the share of exergy that fills a thermal system with current flows of matter, fuel, electricity, etc., breaks down inside the system due to irreversibility [5-6].

The general view for the equation of the total exergy of the system is given by the formula (4):

\[
E_x = E^{PT} + E^{KN} + E^{PH} + E^{CH}
\]

(4)

where \( E_x \) is the exergy of the entire system, while \( E^{PT}, E^{KN}, E^{PH} \) and \( E^{CH} \) represent potential, kinetic, physical and chemical exergy, respectively [2-5].

During the transfer of heat between the drying medium and the product, knowledge of Fourier's laws of thermal conductivity and Newton's law of cooling is mandatory. Fourier's law is an empirical law that made an important contribution to the analytical treatment of the heat flux of conduction and states that the rate of heat flux per unit area through a homogeneous solid is proportional to the normal temperature gradient.

Mathematically, Fourier's law is represented by the formula (5) [4]:

\[
\frac{Q}{A} = -k \frac{dT}{dx}
\]

(5)

where \( Q \) is the current of the conducting heat flux in J/s; \( A \) is the surface area of the heat flux in m².

The fundamental law of convection is Newton's law of cooling (6), according to which heat transfer per unit area is proportional to the temperature difference between the liquid and the product surface [4]:

\[
Q = h * A * \Delta T
\]

(6)

where \( Q \) is the convective heat flow rate in J/s; \( A \) is the surface area of the heat flux in m²; \( \Delta T \) - temperature difference between liquid and surface.

When modeling solar dryers for drying products, it is necessary to know the coefficient of convective mass transfer and moisture diffusion. Fick's law of diffusion is used to determine the diffusion coefficient (7) and states that the mass flux of components per unit area (molar flux) is proportional to the concentration gradient [5]:

\[
\frac{m_A}{A} = -D \frac{\partial C_A}{\partial x}
\]

(7)

where \( m_A \) is the mass flow per unit area in kg/s; \( D \) is the constant of diffusion in m²/s; \( C_A \) is the mass concentration of component \( A \) per unit volume in kg/m³.

The convective mass transfer coefficient (8) can be determined in a similar way, which is used to determine the convective heat transfer coefficient [4]:

\[
m_{conv} = h_m * A * \Delta C
\]

(8)
where $m_{\text{conv}}$ - the rate of convection of the mass across the border; $h_m$ is the average mass transfer coefficient; $A$ is the surface area; $\Delta C$ is the difference in mass concentration [4].

3. Study and analysis of the drying process of medicinal plants

Part of the experimental studies of the drying process of plant raw materials were carried out by us in the laboratory of the Tashkent State Technical University. The main requirement for these experiments was the most accurate reproduction of heat and mass transfer processes during convective drying of medicinal plants [6].

To carry out laboratory studies, an experimental helium-water heating convective drying unit was manufactured, which allows to carry out the process of dehydration and fixing the optimal parameters of dried medicinal plants (figure 1) [5].

Our proposed solar water heating convection unit allows you to intensify the technological process of drying plant materials such as ginger roots, nettle leaves, elecampane roots, etc.

Three different types of medicinal plants were used for drying: ginger root, nettle leaves and elecampane root. For each of the three medicinal plants, experiments were carried out at temperatures of 45, 55 and 65 °C in two types of drying units, in a solar water heating drying unit and a convective drying unit.

Fresh ginger (figure 1-a) was sorted from weeds, washed from dust and cleaned from other contaminants. They were cut into annular slices with a size of 0.5-0.6 mm and pre-dried in the shade in the open air for 1 - 2 hours to reduce the initial moisture content. Also, fresh nettle leaves were sorted and washed from dust (figure 1-c).

![Figure 1](image)

**Figure 1.** Appearance of the investigated medicinal plant: a - ginger root (zingiber) before drying; c - Fresh nettle leaves (Urtica) before drying

In figure 2 shows the curves obtained in the process of drying the ginger root. The graph shows that the drying of the ginger root proceeded for 770 minutes in a convective drying unit at a temperature of 45 °C. The drying process lasted 815 minutes in a solar water heating dryer, also at a temperature of 45 °C. Initial moisture was 70%, final drying was adjusted to 14% moisture. The drying process, which was carried out in a convective drying unit at a temperature of 55 °C, lasted 370 minutes, in a solar water heating drying unit for 650 minutes, the final moisture content was 14%. The next drying was carried out at a temperature of 65 °C, the duration of the convection drying was 490 minutes, the solar water heating drying unit was dried for 545 minutes.
Figure 2. Curves graphs of drying ginger root at temperatures of 45, 55 and 65 °C.

The drying temperature used averaged 45-65 °C to remove about 70% moisture from products initially containing 70 to 86% moisture. The ambient temperature outside and inside the drying chamber was recorded using thermocouples located at strategic points and connected to a potentiometer. Hygrometers were used to measure the humidity of the air entering and leaving the drying chamber. Drying times were recorded and the samples were analyzed for residual water-soluble vitamins and oiliness. The dried medicinal plants in the water heating drying plant showed a longer shelf life and higher quality compared to dried convection drying plants and domestic producers.

4. Conclusion
Experimental studies were carried out on a laboratory solar water heating drying unit at 45, 55, 65 °C and the optimal temperature was determined and curves of the duration and temperature of the drying process of medicinal plants were obtained.

Based on the results of experimental studies of the dehydration process in a laboratory unit, an engineering method for calculating design and technological parameters has been developed.

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