MATHEMATICAL MODELING AND COMPUTING, Vol. 12, No. 1, pp. 275–282 (2025)

Refinement of Nusselt numbers in drying processes

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(Received 12 October 2024; Revised 20 February 2025; Accepted 28 February 2025)

It is proposed to refine the calculation of Nusselt numbers by considering the mass transfer coefficient in the evaporation zone, which is significantly larger than the molecular mass transfer coefficient of vapour. This refinement aims to address the discrepancy between the elevated Nusselt criteria observed during drying and the criteria determined by the thickness of the boundary layer, which provides more accurate results.

Keywords: *Nusselt number; drying regimes; heat and mass transfer; capillary-porous materials; molecular vapor transport; diffusion; thermodiffusion; convective drying; optimization; electromagnetic heating; moisture migration; numerical modeling.*

2010 MSC: 76R99, 76T99, 80A20, 35Q79, 80A50 **DOI:** 10.23939/mmc2025.01.275

1. Introduction

Drying processes play a critical role in various industrial applications. The efficiency of drying largely depends on heat and mass transfer mechanisms, which are influenced by temperature and moisture gradients within the material. The practical implementation of optimization methods for drying processes, particularly in the design of drying equipment, is based on the analysis of drying regimes in accordance with the dry- and wet-bulb temperature relationship [1]. The drying process in steam chamber drying installations follows the regularities of changes in dry-bulb temperature T_c and wet-bulb temperature T_m. In Figure 1, the abscissa represents the relative change in the drying duration, equal to the ratio of the actual drying time τ to the nominal drying cycle time τ_{nom}, which lasts 48 hours. The ordinate axis shows the relative value of the dry-bulb temperature. The reference temperature is taken as 120°C.

During the drying process, three main stages are distinguished: the material heating stage, the isothermal heating stage across the entire cross-section, and the falling-rate drying stage. The dry-bulb temperature T_c takes different values at different stages of the drying process. In the heating stage, the temperature changes at the maximum rate (segment OA).

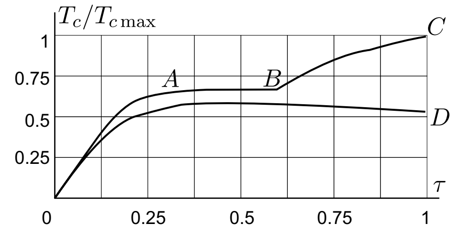

Fig. 1. Change T_c and T_m in the drying process.

In the isothermal heating stage across the entire cross-section (segment AB), the temperature increases slightly, and temperature equalization occurs across the thickness of the material. In the final stage (segment BC), significant moisture removal occurs, along with a change in the drying potential. During the first two stages (heating and isothermal heating across the entire cross-section), the reduction in moisture content per unit time (drying rate) remains constant. As long as the amount of moisture supplied to the surface is greater than the amount the environment can absorb, the surface moisture content remains at the achieved level, meaning the material remains moisture-saturated. The rate of moisture removal remains unchanged during this period. The surface temperature of the material does not change and equals the adiabatic saturation temperature of the air (the wet-bulb temperature T_m). The central part of the material thickness heats up more slowly compared to the surface at the beginning of the drying process and reaches the wet-bulb temperature slightly later.

2. Drying mode specificity

The characteristics of drying processes under **intense (rigid) regimes** and the issues of their optimization were examined in [2]. Under **mild drying modes**, there is no temperature difference in the first period, and the relative moisture content difference is directly proportional to the Kirpichov criterion. The criterion Ki' can be determined in various ways: by the evaporation intensity q', by the moisture content difference $u_c - u_n$, by the surface moisture content gradient, or by the moisture content decrease over time:

$$\mathrm{Ki}' = \frac{q'R}{a'\gamma_0\bar{u}_0} = \frac{2\,(u_c - u_p)}{\bar{u}_0} = -\frac{R\,(\nabla u)_p}{\bar{u}_0} = \frac{(\bar{u}_0 - \bar{u})}{\bar{u}_0\,\mathrm{Fo}'}, \tag{1}$$

where $\bar{u}$ is the average moisture content corresponding to the Fourier criterion:

$$\mathrm{Fo}' = \frac{a'\tau}{R^2} \tag{2}$$

in the constant drying rate period. The maximum allowable Kirpichov criterion depends on the moisture content of the body; as the moisture content decreases, the criterion increases. This criterion is directly proportional to the drying intensity q' and inversely proportional to the potential conductivity coefficient a'. Other parameters included in the criterion are the dry body density γ_0, the initial moisture content u_0, and the characteristic size R. At low drying intensities q', it can be assumed equal to the evaporation intensity of liquid from a free surface. The evaporation intensity of the liquid is uniquely determined by the formula:

$$q' = \mathrm{Nu}'\,\frac{\lambda'}{l}\Delta p_i, \tag{3}$$

where λ' is the moisture conductivity coefficient. Heat and mass transfer coefficients under natural convection conditions are determined using Nesterov's formulas, which are provided later. These formulas are used to calculate the drying intensity at various air temperatures and humidities. During the constant drying rate period, the body temperature can be assumed to be equal to the wet-bulb temperature. Given the parameters T_s and φ, the material body temperature and coefficient a' are uniquely determined. A graph of coefficient a' variation with temperature is used to construct a family of curves $\mathrm{Ki}' = f(T_s)$ for different values of φ at a constant airspeed and characteristic body size.

If the maximum allowable Kirpichov criterion is known and dependency graphs of Ki' at different moisture contents are constructed, an entire range of regimes is obtained, from which the mode with the highest drying intensity is selected. At the same time, the drying apparatus should have minimal heat and electricity consumption. As the moisture content decreases, the criterion $Ki'_{\max}$ increases, and the range of allowable drying regimes expands. Therefore, optimal regimes should be stepped, with drying intensity increasing as drying progresses. Increasing the air velocity reduces the range of allowable regime parameters T_s and φ (the family of curves $\mathrm{Ki}' = f(T_s)$ shifts upward), so at the beginning of the drying process, air velocities should be low. The air velocity is selected by analyzing the allowable regime range together with calculated data on energy consumption and air temperature and humidity differences for the chosen modes within the drying installation. At high air humidity levels (low drying intensity), heat transfer coefficients are close to those of heat transfer without mass exchange. The longer the sample in the flow direction, the lower the drying intensity.

Under the mild drying mode, during the constant rate period, the partial vapor pressure near the body surface $p_{p.m}$ equals the saturated vapor pressure at the wet-bulb temperature $p_{n.m}$. This value remains constant, although the moisture content at the surface decreases to the maximum hygroscopic moisture content $u_{m\Gamma}$. The moisture content decrease follows a complex curve asymptotically approaching equilibrium moisture content. During this period, the body temperature equals the wet-bulb temperature.

Cooling the product after reaching the maximum temperature is as crucial a phase of drying as heating. In the initial cooling period, as the temperature decreases, materials undergo shrinkage and plastic deformation under minor loads. Cracking of the material may occur during this period. The cooling intensity should vary at different temperature intervals.

3. Chamber drying of lumber

As an example, consider the **intensification process of chamber drying of lumber**. Drying is performed at atmospheric pressure.

Evaporation occurs at any temperature, but the higher the temperature, the more intense the evaporation process. During evaporation, liquid molecules near the surface have a higher velocity than others and overcome molecular cohesion forces, escaping into the surrounding space. Evaporation is explained by the fact that the surface layer is heated slightly above the wet-bulb temperature indicated by a psychrometer placed in the surrounding medium. As a result, the vapor pressure of the liquid on the surface is higher than in the drying agent.

Boiling occurs only at the saturation temperature. The steam produced from boiling water is called wet saturation. During boiling, the amount of water decreases until the last drop turns into steam. When all droplets evaporate, the steam becomes dry and saturated. Under constant pressure, the water temperature remains unchanged. Saturated steam is the steam with the temperature of the water from which it forms. If the temperature of dry saturated steam rises without changing the pressure, the steam becomes superheated. Removing heat from superheated steam reduces its temperature and specific volume. Condensation occurs only after the steam temperature drops below the saturation temperature. These steam properties are utilized in drying technology.

Superheated steam, by expending part of its heat, can heat the material and evaporate moisture from it. As moisture evaporates from the material, the amount of steam increases. To maintain pressure in the lower part of the chamber, a steam outlet to the atmosphere or a heat exchanger is necessary. The saturation temperature of steam depends only on pressure. Any given saturated steam pressure corresponds to a specific saturation temperature. Knowing the steam pressure allows determining its temperature and vice versa. When cooled, saturated steam condenses into water, releasing the total heat of vaporization. This heat is utilized in dryers for heating calorifiers. The drying agent receives heat from calorifiers and transfers it to the material via convection, promoting evaporation.

Drying lumber with superheated steam. Lumber drying with superheated steam can be performed using the following methods:

1. Superheated steam from a boiler is introduced into a sealed drying chamber, where forced circulation occurs through a stack of material. The spent superheated steam, after mixing with the vapor evaporated from the wood moisture, is removed from the chamber.
2. A sealed chamber with a steam outlet pipe is created. A calorifier with high thermal power and devices for circulating the drying agent are installed in the chamber. During the initial drying period, saturated steam is introduced into the chamber, heating the wood and expelling air. Simultaneously, the steam is forced through calorifiers by fans, where it is superheated. Once the introduced steam becomes superheated, it evaporates moisture from the wood and mixes with the vapor of this moisture. At this point, the steam supply into the chamber stops, as sufficient steam is generated from the evaporated moisture of the dried wood. The mixture is circulated by a fan through the calorifiers, increasing its degree of superheating, then passes through the stack, and so on. Excess steam is removed through the steam outlet pipe or into heat exchange systems.

The second method is more advantageous than the first since in sealed chambers with steam outlet pipes, heat losses associated with introducing superheated steam from the boiler into the chamber and releasing it into the atmosphere are eliminated.

At the beginning of drying, when the material has not yet warmed up, its surface layers in contact with the hot chamber environment have a higher temperature than the material's core. A temperature gradient appears, causing moisture flow towards lower temperatures, that is, from the surface to the center. This movement is called thermomoisture conductivity. If wood is dried in an environment where the temperature exceeds 100°C, an excess pressure of steam-air mixture (compared to atmospheric pressure) can form and be maintained for a long time inside the wood. This pressure causes a stable movement of water vapor (along with liquid) directed from the center to the material's surface. This phenomenon is known as molar moisture transfer. During drying, when all driving forces are active, their effects accumulate.

4. Transition from mild to intense drying modes

In the transition region from mild to intense drying modes, the rate of deepening of the evaporation surface in the first period remains constant, and evaporation occurs at a certain fixed depth. The temperature distribution curves at different moments of the first period coincide. The same is observed with the moisture distribution curves. Under mild drying modes in the first period, the evaporation surface is close to the surface of the body. The Nusselt numbers, which characterize external heat and mass exchange, are inversely proportional to the thickness of the effective boundary layer; therefore, they remain constant during the constant rate period and decrease over time in the falling rate period.

The peculiarity of molecular flow is the movement of gas from less heated parts of a capillary to more heated ones at constant pressure p. During drying, the body surface has a higher temperature compared to the evaporation zone surface. This temperature gradient accelerates molecular flow since the potential of effusion flow is given by $\frac{p}{\sqrt{T}}$. In the case of diffusive transport, the presence of a temperature gradient in the evaporation zone reduces the transfer rate. If capillaries in the body have a radius greater than 10^{-5} cm, a diffusion-effusion transfer mechanism takes place.

In the presence of macroscopic capillaries, diffusion transfer of vapor is complicated by thermal slip, which manifests as follows. If a temperature gradient exists along the macroscopic capillary walls, circulation currents of moist gas appear. Gas near the capillary wall moves against the heat flow, while along the capillary axis, it moves in the direction of heat flow. Since the capillaries near the evaporation surface have a lower temperature compared to those in the surface layer of the body, thermal slip facilitates vapor transport through the evaporation zone [3].

From the body surface to the surrounding environment, vapor transfer mainly occurs via a molar pathway. The coefficient of mass conductivity λ' in the evaporation zone, which defines the boundary layer near the body surface, is significantly higher than the molecular mass conductivity coefficient of vapor. Consequently, the Nusselt numbers are overestimated compared to those determined based on boundary layer thickness, which yield more accurate results. This new vapor mass transfer mechanism affects both heat transfer and the hydrodynamics of thermal exchange.

Drying with heated gas. In many cases, drying of wet materials is carried out using heated gas. The drying process also takes place in drying chambers, where the drying mode changes over time. The drying mode is characterized by three parameters: gas temperature t_c, humidity φ, and gas velocity υ. These parameters influence both drying time and material quality. Therefore, it is necessary to find an optimal mode that minimizes drying duration and heat consumption while ensuring the best technological properties of the material.

To understand the effect of the drying mode on duration, it is necessary to obtain drying kinetics curves depending on the parameters characterizing the mode. Practical experience shows that increasing the drying agent temperature enhances drying intensity and critical moisture content [4, 5]. Increasing temperature from 15°C to 45°C increases drying intensity in the first period by a factor of 2.5. Increasing air humidity significantly reduces drying intensity and critical moisture content. For example, increasing air humidity from 0.177 to 0.758 reduces drying intensity by approximately 4.5 times. Increasing air velocity enhances intensity in the first period but has a much smaller effect at the end of the process. The ratio between capillary moisture and adsorbed moisture significantly influences drying intensity in the second period and critical moisture content but has little effect in the first period [6].

At high gas temperatures, during the first period, drying speed is constant, while the material surface temperature continuously increases, significantly exceeding the wet-bulb temperature. Drying intensity equals mass transfer intensity, and heat and mass transfer intensities are given by:

$$q = \alpha(t_c - t_{p.m}) = \mathrm{Nu}\,\frac{\lambda_g}{l}\Delta t, \tag{4}$$

$$q' = \alpha'(p_{p.m} - p_c) = \mathrm{Nu}'\,\frac{\lambda_g'}{l}\Delta p, \tag{5}$$

where q and q' are the heat and mass flux densities, respectively; $\Delta t = (t_c - t_{p.m})$ is the temperature difference between gas and body surface (cal/m^2·h, kg/m^2·h); $\Delta p = (p_{p.m} - p_c)$ is the difference in partial vapor pressure at the body surface and surrounding environment (mmHg); l is the characteristic length along the flow direction; and λ, λ' are the thermal and mass conductivities.

For humidity ranges between $50 - 70\%$, it is proposed the following formulas for water evaporation from a free surface:

$$\mathrm{Nu} = 0.46\,\mathrm{Re}^{0.53}, \quad \mathrm{Nu}' = 0.63\,\mathrm{Re}^{0.52}, \quad \text{for} \quad 3\times10^3 < \mathrm{Re} < 3\times10^4, \quad \mathrm{Re} = \frac{vl}{\nu}. \tag{6}$$

Based on numerous experiments on heat and mass transfer under forced moist gas flow, A. V. Nesterenko established the following relationships [7]:

$$\mathrm{Nu} = 2 + A\cdot\mathrm{Pr}^{0.33}\cdot\mathrm{Re}^{n}\cdot\mathrm{Gu}^{m}, \tag{7}$$

where the constants are given in Table 1.

Table 1. Coefficients for heat and mass transfer correlations.

Re	A	n	m	A'	n'	m'
$1 - 2\times10^2$	1.07	0.48	0.175	0.83	0.53	0.135
$3.15\times10^3 - 2.2\times10^4$	0.51	0.61	0.175	0.49	0.61	0.135
$2.2\times10^4 - 3.15\times10^5$	0.027	0.90	0.175	0.0248	0.90	0.135

For $\mathrm{Re} > 200$, the constant 2 is omitted, and the formula takes the form:

$$\mathrm{Nu} = A\cdot\mathrm{Pr}^{0.33}\cdot\mathrm{Re}^{n}\cdot\mathrm{Gu}^{m}, \quad (\mathrm{Pr} = \nu/a = \mu/(a\gamma)). \tag{8}$$

A similar relationship for mass transfer is given by:

$$\mathrm{Nu}' = 2 + A'\cdot(\mathrm{Pr}')^{0.33}\cdot\mathrm{Re}^{n'}\cdot\mathrm{Gu}^{m'}, \quad \big(\mathrm{Pr}' = \nu/D\big). \tag{9}$$

Here, ν is the viscosity coefficient, and D is the diffusion coefficient. For an ideal gas, $\mathrm{Pr} = \mathrm{Pr}' = 1$; for dry air, $\mathrm{Pr} = 0.73$; and for vapor transfer in an inert gas, $\mathrm{Pr}' = 0.75$.

Under natural convection conditions:

$$\mathrm{Nu} = 4(\mathrm{Pr}\cdot\mathrm{Ar})^{0.108}, \quad \text{for} \quad (\mathrm{Pr}\cdot\mathrm{Ar}) = 3\times10^6 - 2\times10^8, \tag{10}$$

$$\mathrm{Nu}' = 4(\mathrm{Pr}'\cdot\mathrm{Ar})^{0.248}, \quad \text{for} \quad (\mathrm{Pr}'\cdot\mathrm{Ar}) = 1\times10^4 - 3\times10^8. \tag{11}$$

For these calculations, the characteristic dimension is taken as the side of a square equivalent in area to the liquid surface:

$$\mathrm{Ar} = \frac{l^3 g}{v^2}\frac{\Delta\gamma}{\gamma_p}, \tag{12}$$

where l is the surface length in the flow direction, g is the gravitational acceleration (m/s^2), and $\Delta\gamma = \gamma_p - \gamma_c$ represents the density difference between moist gas near the liquid surface and in the bulk gas flow. In heat transfer, the density difference is replaced by the temperature difference and is referred to as the Grashof criterion.

In all these equations, the thermal conductivity of moist gas is calculated using the formula:

$$\lambda = \lambda_0 + 0.0041\varphi, \tag{13}$$

where λ_0 is the thermal conductivity of dry gas. The mass conductivity coefficient (diffusion coefficient relative to partial pressure differences) is computed as:

$$\lambda' = a_0'\frac{M_v T}{R T_0^2}\left(\frac{P_0}{p_b}\right), \tag{14}$$

where a_0' is the diffusion coefficient under normal conditions, with a value of $a_0' = 0.079$ m^2/h for water vapor. The molecular weight of vapor is $M_v = 0.018$ kg/mol, the total barometric pressure is $P_0 = 760$ mmHg, and the absolute temperature under normal conditions is $T_0 = 273.2$. The gas constant is $R = 0.06237$m^{3}mmHg/(K·mol), and the average absolute temperature of the boundary layer is given by:

$$T = 273 + \frac{1}{2}(t_c + t_p). \tag{15}$$

Here, p_b represents the partial pressure of dry vapor (mmHg).

5. Wood drying process

Initially, drying occurs rapidly and slows down towards the end. The first stage involves heating the wood in the chamber. During this stage, the moisture content in the wood does not decrease but slightly increases due to the condensation of vapor from the surrounding air on the cold wood surface.

In the second stage, drying proceeds from the high initial moisture content w_0 to the critical moisture content w_{kr}, which is slightly above the hygroscopic boundary. (The hygroscopic boundary is the threshold between free and bound moisture and is approximately 30%.) At this stage, free moisture is removed from the wood, and the process occurs with the highest intensity.

In the third stage, drying continues from the critical moisture content to the specified final level. Bound moisture is removed, and the process proceeds more slowly than in the second stage [8, 9].

Stresses developing in wood. During drying, moisture is initially removed from the surface, leading to an uneven distribution throughout the volume. When the moisture content falls below the hygroscopic boundary, shrinkage begins. The property of wood to reduce its linear dimensions and volume when bound water is removed (below 30% moisture content) is called shrinkage. This results in tensile moisture stresses in the surface layers, which can cause external cracks. To prevent this, the drying process should be slowed down by creating a high vapor-saturation environment in the chamber (steam-heat treatment).

As the moisture gradient across the thickness decreases, stresses also reduce. When the moisture content of the inner layers drops below the hygroscopic boundary, the inner part begins to shrink, while the dry and stretched outer layer resists the shrinkage of the inner layer. This results in tensile stresses in the inner layer. If these stresses continue to develop, internal cracks may form. Internal stresses can be reduced by heat and moisture treatment of the wood.

Based on temperature levels, the drying process can be categorized into low-temperature and high-temperature drying. Low-temperature drying occurs when the wood temperature remains below the boiling point of water at the prevailing pressure ($< 100^\circ$C). High-temperature drying occurs when the temperature in the inner zones exceeds 100°C. This process exhibits specific characteristics of vaporization at different temperature levels. For high-temperature drying, the temperature of both the drying environment and the material itself must exceed 100°C, and the wood must contain free water capable of boiling. An example of this process is drying wood with an initial moisture content exceeding the hygroscopic boundary in a superheated steam environment at atmospheric pressure. A notable feature of high-temperature drying is the intensive migration of moisture as vapor from central zones to peripheral areas. There exists a transition process between high and low-temperature drying.

The circulation of the drying agent can be natural or forced, unidirectional or reversible. It is implemented using fans in the chamber or through ejector nozzles. Such chambers are known as ejector-type. Based on the drying agent, chambers can be classified as air-based, superheated gas-based, or gas-based chambers using combustion gases and humid air. Depending on the operating principle, chambers are either batch-type or continuous-type. In batch-type chambers, materials are loaded to full capacity simultaneously. If the chambers operate cyclically, the process consists of loading, drying, and unloading. Continuous chambers operate without interruption. The drying process continues while materials are being loaded and unloaded. Materials move through the chamber from the loading end to the unloading end, with stacks shifting forward with each unloading cycle [10].

The method of heat supply to the material affects the mechanisms of substance and heat transfer during thermal treatment. In the steam-thermal method, saturated steam is used as the heat carrier. Heat transfer from the steam-air environment to the material occurs via convection, creating a significant temperature gradient that leads to internal stresses. Since the material temperature is lower than that of the steam-air environment, a condensation film forms on the surface. According to the law of moisture-thermal conductivity, moisture migration occurs from surface layers to central layers. Moisture absorption by the material is observed. Over time, developed reactive hydration enables the material temperature to exceed that of the surrounding environment. Consequently, intensive moisture evaporation occurs with a significant moisture gradient, leading to the formation of directed porosity in the material.

An important method of heat supply to the material is based on the interaction of an alternating magnetic field with ferromagnetic elements. The wet material, along with heat-generating ferromagnetic elements, is placed in the field of an electromagnetic coil powered by an industrial frequency current. Ferromagnetic materials heat up and transfer heat to the wet material. Depending on the properties of the material, the heat supply method is selected. This method can be adjusted based on the technological scheme for placing the ferromagnetic elements (within the volume, in a layer, in a stack, or in a mass). In this process, materials do not experience significant stresses or deformations and dry without warping or internal cracks.

During thermal treatment in an electromagnetic field, heat is transferred conductively from the formwork and reinforcement to the material. A minor temperature gradient is created within the material. In this case, the surface temperature is higher than the environmental temperature, and evaporation occurs with a minimal moisture gradient. This thermal treatment method increases the number of closed pores compared to steaming, thereby improving material quality. By utilizing the principles of diffusion and thermodiffusion, the substance transfer mechanism can be controlled. Since diffusion is determined by the diffusion coefficient and thermodiffusion by the thermodiffusion coefficient, controlling the transfer coefficient requires establishing the dependence of these coefficients on moisture content and temperature.

6. Conclusions

The Nusselt criteria are essential for understanding heat and mass transfer dynamics, especially in scenarios involving capillary-porous materials. Expressions for Nusselt numbers Nu and Nu' are derived from characteristic dimensions and thermal conductivities, highlighting their dependence on experimental curves and boundary layer thicknesses. The evolution of drying intensity over periods is explained by changes in mass transfer coefficients, particularly in the initial phase where surface evaporation deepens. Empirical relations link Nusselt criteria to moisture content, showing their consistency in the first phase and decline as drying progresses. Calculations demonstrate significant differences between theoretically computed Nu' using thermal conductivity and experimentally derived values, diminishing with decreasing moisture. Enhanced drying intensities amplify these variations, underlining the role of molecular vapor transfer mechanisms in deepening evaporation zones. To improve the accuracy of evaluating heat and mass transfer efficiency in the drying process, it is proposed that the methodology for determining Nusselt numbers be refined. This will allow adjustments in the calculation of convective drying and heat-mass exchange, considering the process's specific conditions and operational regimes.

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Уточнення чисел Нуссельта в процесах сушіння

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Пропонується уточнити розрахунок чисел Нуссельта, враховуючи коефіцієнт масопередачі в зоні випаровування, який значно перевищує коефіцієнт молекулярної масопередачі пари. Це уточнення спрямоване на усунення розбіжностей між підвищеними критеріями Нуссельта, які спостерігаються під час сушіння, та критеріями, визначеними товщиною граничного шару, що забезпечує більш точні результати.

Ключові слова: *число Нуссельта; режими сушіння; тепломасообмін; капілярно-пористі матеріали; молекулярне перенесення пари; дифузія; термодифузія; конвективне сушіння; оптимізація; електромагнітний нагрів; міграція вологи; чисельне моделювання.*