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# ENERGY SAVING DURING MATCH SPLINT DRYING

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Abstract. One of the most energy-intensive stages in match production is the drying of match splints. Therefore, the optimization of the drying process and the selection of optimal parameters is a relevant task. Filtration drying is proposed for the removal of moisture from match splints, as one of the highly effective and economical drying methods. The study of heat and mass exchange is a necessary step for the design of a filtration drying unit and the selection of optimal parameters. The article presents the results of experimental studies of heat and mass transfer during the filtration drying of match splints. The effect of the heat agent velocity on heat and mass transfer has been investigated. The heat and mass transfer coefficients during the drying of the wet material have been determined. To generalize the obtained data, criterion dependencies have been derived for determining the heat and mass transfer coefficients in the Reynolds number range of $200 \le Re \le 500$. The similarity of the dependencies for the heat and mass transfer coefficients has been established, demonstrating the identical influence of hydrodynamics on these processes. The error between the experimental and calculated values does not exceed 7.14 %.

**Keywords:** filtration drying, match splints, external heat transfer, external mass transfer, stationary layer.

## 1. Introduction

Drying is one of the most important and energy-intensive technological processes in industry. According to forecasts, drying costs are expected to reach 166.92 billion USD by 2027, which is more than 1.5 times higher compared to the figures for 2020 (Khan et al., 2022). Drying of match splints occurs in convective dryers using furnace gases from burning fossil fuels, which negatively affects the environment. Due to this, a large amount of carbon dioxide is released into the air. Carbon monoxide, sulfur oxides, and nitrogen oxides may also be released. In addition to harming the environment, convective dryers have low heat transfer coefficients, resulting in a high temperature at the dryer outlet. This means a large amount of heat is released into the environment.

One of the important components of an enterprise's environmental audit is the assessment of resource consumption indicators (Odnorih et al., 2024). Therefore, the study of match splint drying is a pressing issue.

To remove moisture, filtration drying is proposed, which makes it possible to reduce the environmental impact and decrease the use of energy resources. Since filtration drying allows for a reduction in process duration and a decrease in thermal energy consumption, it is more environmentally justified compared to traditional methods, thus promoting energy saving (Ivashchuk et al., 2024).

Wood drying is a complex heat and mass transfer process characterized by high energy consumption and the need to select optimal process conditions to ensure product quality. The study of drying processes makes it possible to develop more efficient operations with lower energy consumption (Chávez et al., 2021).

The drying of wood products is characterized by complex physical phenomena of heat and mass transfer that occur both inside the material and on its surface, significantly affecting the duration of the drying process (Sokolovskyy et al., 2024).

The movement of moisture depends on many factors, such as gravity, external pressure, capillarity, temperature gradient, flow rate, and the relative humidity of the drying agent. The influence of each of these factors varies depending on the type of wood, as well as on the drying method and conditions (Simo-Tagne et al., 2016, Zhao et al., 2022)

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Mass transfer occurs due to the input of heat energy from the drying agent into the material through conduction, convection, and phase transitions. The heat and mass transfer coefficients have a decisive influence on the drying kinetics (Khan et al., 2020). The results of studies on heat transfer during the filtration drying of match splints are presented in (Kuzminchuk & Atamanyuk, 2025).

The technical literature presents the results of theoretical and experimental studies on mass transfer during the drying of plant materials such as apple slices (Yuan et al., 2019), peach slices (Zhu & Shen, 2014), lavender (Chasiotis et al., 2021), olive pomace (Koukouch et al., 2020), and sweet potato (Zhu et al., 2020) However, the obtained mathematical models describe only specific types of raw materials and are not suitable for modeling mass transfer during the filtration drying of match splints, since this plant raw material significantly differs in porosity and chemical structure both among the samples and compared to the wood from which match splints are made. These differences make it impossible to obtain universal dependencies for mathematical models that would allow predicting the drying rate of any plant raw material (Gómez-de La Cruz et al., 2023, Gandía Ventura et al., 2024).

A mathematical model should make it possible to predict changes in temperature and moisture content at any point in the dryer based on boundary conditions (Zhu & Shen, 2014)

However, the analytical dependencies proposed in the technical literature, which describe the mass transfer process, do not account for all factors affecting drying. Therefore, they are used only for a qualitative assessment of the dependence of the mass transfer coefficient on various parameters, such as temperature and velocity. These analytical dependencies are obtained through experimental studies (Boshkova et al., 2024).

In numerous studies, the authors describe heat and mass transfer processes based on Fick's second law of diffusion, using a number of semi-empirical dependencies that account for material characteristics such as shape, structure, and thermal conductivity. The advantages of such models are their ease of use, consideration of the specific drying characteristics of the material, and high accuracy (Sahoo et al., 2024, Xing et al., 2023).

Alternative methods for studying heat and mass transfer include numerical techniques such as the finite element and finite difference methods (Turkan & Etemoglu, 2019, Zhao et al., 2022) or cellular automata (Ovsiak & Dendjuk, 2023). Although these methods are the most versatile, they require significant computational resources (Butcher, 2016).

Many models for describing mass transfer are based on the Sherwood number (Koukouch et al., 2020), which, in turn, depends on the Reynolds and Schmidt numbers, similar to heat transfer models based on the Nusselt and Prandtl numbers. However, these numbers primarily depend on the properties of the drying agent, which vary depending on its moisture content (Rémond & Almeida, 2011, Tarmian et al., 2012).

The analysis of studies (Lerman & Scheepers, 2023, Simo-Tagne et al., 2016, Zhao et al., 2022) shows that the proposed mathematical models involve a large number of assumptions and are not universal for different materials; therefore, they cannot be applied to the filtration drying of match splints. Consequently, the development of an adequate mathematical model requires both theoretical and experimental investigations.

Filtration drying has been proposed for match splints as one of the promising and highly efficient methods for moisture removal from wet materials. This method allows for increased drying efficiency and optimization of the drying equipment (Kuzminchuk & Atamanyuk, 2025).

## 2. Experimental part

The experimental The study of external heat and mass transfer was carried out using a filtration drying setup. A sample of match splints with an initial moisture content of 1.6 kg $H_2O$/kg d.m. was loaded into a container and weighed on an AXIS-AD3000 electronic balance. Drying was conducted in a "thin layer" to ensure uniform distribution of the drying agent throughout the wet material and to maintain a consistent temperature in both the upper and lower layers of the match splints. Experimental studies were performed at a constant temperature of 60 °C with an accuracy of ±0.5 °C, maintained using an SESTOS D1S electronic thermostat. The outlet temperature was measured using K-type thermocouples connected to an eight-channel measuring converter RT8-1000 at 1.8-second intervals, with data output to a personal computer. The material was dried for 15 seconds and then weighed. Weighing was carried out within 10–20 seconds after the completion of drying.

The heat transfer coefficients from the heat agent to the wet match splints were determined using the kinetic equation.:

$$\frac{\Delta W}{\Delta \tau} \cdot r = \alpha \cdot F \cdot \left(\frac{t_{en.} + t_{ex.}}{2} - t_{w.t.}\right), \tag{1}$$

where ΔW is the change in moisture mass, kg; Δτ is the duration of the experiment, s; r is the specific heat of vaporization, J/kg; F is the surface area of the match splints exposed to the heat agent, $m^2$; $t_{en.}$, $t_{ex.}$, $t_{w.t.}$ are the temperatures of the heat agent at the container inlet, at the container outlet, and the wet-bulb temperature, respectively, °C.

The mass transfer coefficient from the wet match splints to the heat agent was determined using the following dependency:

$$\frac{\Delta W}{\Delta \tau} = \beta \cdot F \cdot \left(x_{sat.} - \frac{x_{sat.} + x_0}{2}\right) \cdot \rho, \qquad (2)$$

where β is the mass transfer coefficient, m/s; $x_{sat}$ is the moisture content of the heat agent at full saturation, kg $H_2O$/kg d.m.; $x_0$ is the initial moisture content of the heat agent at the container inlet, kg $H_2O$/kg d.m.; ρ is the density of the heat agent, kg/m³.

To generalize the obtained results for the determination of heat transfer coefficients, the following calculation dependency was used:

$$Nu = A \cdot {Re_{\mathrm{e}}}^{n} \cdot Pr^{0.33}. \qquad (3)$$

The Reynolds number was determined using the following dependency:

$$Re_{\mathrm{e}} = \frac{v \cdot d_e}{\nu}, \qquad (4)$$

where $v$ is the actual velocity of the heat agent, m/s; $\nu$ – is the kinematic viscosity, m²/s; $d_e$ is the equivalent diameter of the channels through which the heat agent flows.

$$Pr = \frac{\nu}{a}, \qquad (5)$$

where *a* is the thermal diffusivity coefficient.

To determine the unknown values, a graphical dependency was constructed:

$$\frac{Nu}{Pr^{0.33}} = f(Re_e). \qquad (6)$$

The generalization of external mass transfer during the filtration drying of match splints was carried out using the following dimensionless dependency:

$$Sh = A \cdot {Re_{\mathrm{e}}}^{n} \cdot Sc^{m}. \qquad (7)$$

To determine the unknown criterion A and the exponent n, a graphical dependency was constructed:

$$\frac{Sh}{Sc^{0.33}} = f(Re_e), \qquad (8)$$

where A is a coefficient determined experimentally; Re is the Reynolds number; Sc is the Schmidt number; Sh is the Sherwood number; n and m are exponents determined experimentally.

The Schmidt number was determined using the following dependency:

$$Sc = \frac{\mathrm{v}}{D}, \qquad (9)$$

where D is the diffusion coefficient of water vapor in air, m²/s.

The Sherwood number:

$$Sh = \frac{\beta \cdot d_e}{D}. \qquad (10)$$

Therefore, the mass transfer coefficient can be determined using the following dependence:

$$\beta = \frac{A \cdot Re_e^{n} \cdot Sc^{0.33} \cdot D}{d_e}. \qquad (11)$$

## 3. Results and Discussion

Based on the data obtained during experimental studies, the heat transfer coefficients from the heating agent to the moist layer of match splints were determined using equation (1). The data are averaged over the layer of moist material, as the drying agent filters through curved channels, which causes a change in the local coefficients. The graphical dependence of the heat transfer coefficients on the velocity of the drying agent is shown in Fig. 1. The experimental values of the heat transfer coefficients were approximated by a linear dependence. As the velocity of the drying agent increases, heat exchange increases, since the amount of heat transferred from the drying agent to the moist material increases.

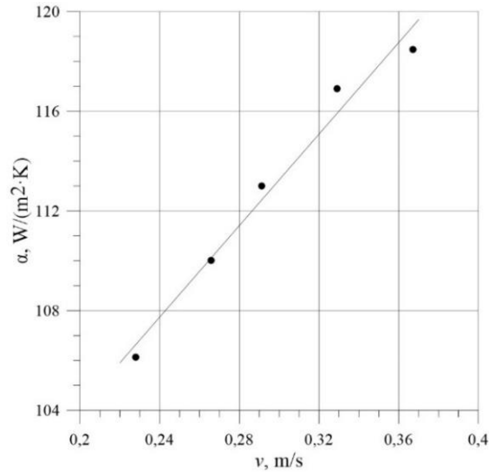


**Fig. 1.** Dependence of the heat transfer coefficient α on the actual velocity of the drying agent for the moist layer of match splints

To generalize the results of experimental studies on external heat exchange during the drying of match splints, the criterion dependence (3) was used. To determine the unknown exponent n and coefficient A, dependence (5) is presented in a logarithmic coordinate system in Fig. 2.

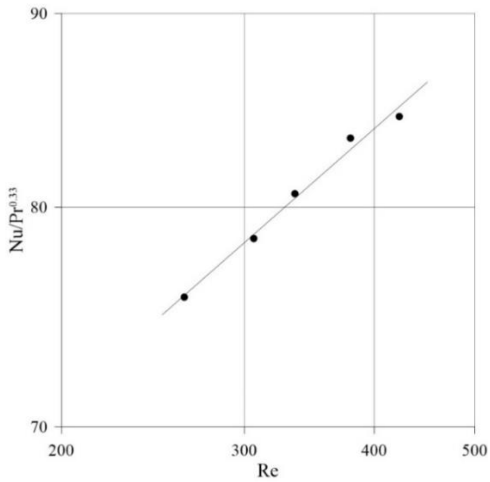


**Fig. 2.** Dependence of $Nu/Pr^{0.33}$ on the Reynolds criterion Re

Since the physical parameters of the drying agent varied within a narrow range, it is acceptable, according to the recommendations of (Mykychak et al., 2013), that Nu ~ $Pr^{0.33}$. Thus, the exponent n is 0.33.

From the graphical dependence (Fig. 2), it was determined that for external heat exchange during filtration drying of moist match splints, the coefficient A = 22,12 and the exponent m is 0.24.

Therefore, dependence (3) can be presented in the form:

$$Nu = 22.12 \cdot Re_e^{0.24} \cdot Pr^{0.33}.$$

The mass transfer coefficients $\beta$ for moist match splints at different drying agent velocities were determined using dependence (2) and are presented in Fig. 3. The mass transfer coefficients increase linearly with an increase in the drying agent velocity.

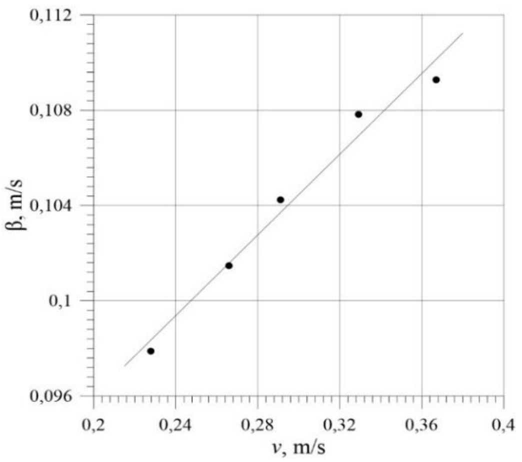


**Fig. 3.** Dependence of the mass transfer coefficient β on the actual velocity of the drying agent

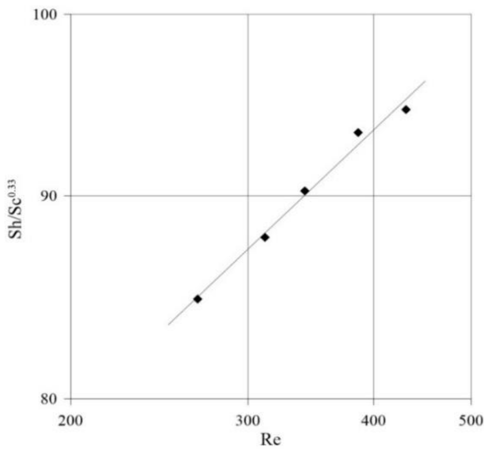


**Fig. 4.** Dependence of $Sh/Sc^{0.33}$ on the Reynolds criterion Re

To generalize external mass exchange during filtration drying of match splints, the criterion dependence (6) was used. The unknown coefficient A and exponent m were determined from the graphical dependence (Fig. 4) in the logarithmic coordinate system: A = 22.57, m = 0.24. Since the physical parameters of the drying agent varied within a narrow range, it is accepted, according to the recommendations of (Mykychak et al., 2013) that Sh ~ $Sc^{0.33}$. Thus, the exponent n is 0.33.

Therefore, the criterion dependence (6) can be presented in the form:

$$Sh = 22{,}57 \cdot Re_e^{0.24} \cdot Sc^{0.33}.$$

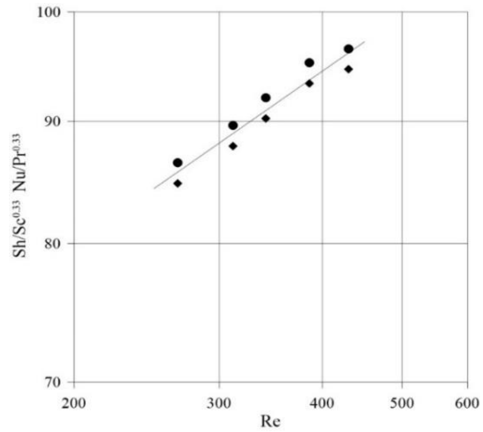


**Fig. 5.** Dependence of $Nu/Pr^{0.33}$ and $Sh/Sc^{0.33}$ on the Reynolds criterion Re

Fig. 5 shows the dependences of $Nu/Pr^{0.33}$ and $Sh/Sc^{0.33}$ on the Reynolds criterion. As the analysis of the obtained results shows, the criterion complexes $Nu/Pr^{0.33}$ and $Sh/Sc^{0.33}$ coincide for the same values of the Reynolds criterion with an error of 1.03 %. This indicates the similarity of these processes and the same influence of hydrodynamics, despite the different nature of heat and mass exchange.

To establish the similarity, we equate the obtained complexes:

$$\frac{Nu}{Pr^{0.33}} = \frac{Sh}{Sc^{0.33}}.$$

Substituting the dependences for determining the Nusselt, Prandtl, Sherwood, and Schmidt criteria and performing mathematical transformations, we obtain the equation:

$$\frac{\alpha}{c \cdot \rho} = \beta \cdot \left(\frac{a}{D}\right)^{0.67}.$$

From this dependence, the mass transfer coefficient can be determined based on the known heat transfer coefficient:

$$\beta = \frac{\alpha}{c \cdot \rho} \cdot Le^{\frac{2}{3}}.$$

The obtained kinetic dependences make it possible to determine the heat and mass transfer coefficients during filtration drying of match splints in a stationary layer of material in the Reynolds criterion range of 200 ≤ Re ≤ 500.

The maximum relative error between the theoretically calculated values of the heat and mass transfer coefficients and those determined on the basis of experimental data does not exceed 7.14 %. This makes it possible to determine these coefficients with sufficient accuracy for practical calculations of the technological process of filtration drying of moist match splints.

Fig. 6 shows the correlation dependence between the theoretically and experimentally determined values of the mass transfer coefficients. Fig. 7 shows the correlation dependence between the theoretically and experimentally determined values of the heat transfer coefficients.

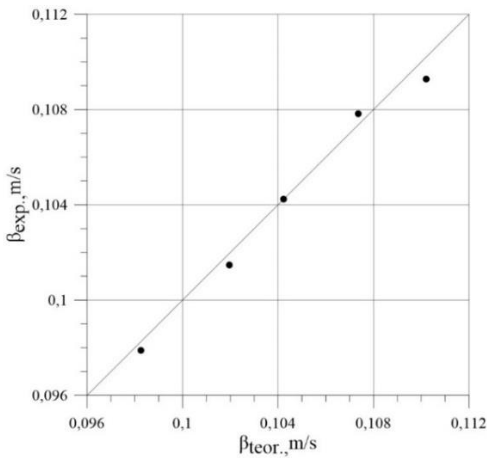


**Fig. 6.** Correlation dependence between the theoretically and experimentally determined values of the mass transfer coefficients for moist match splints

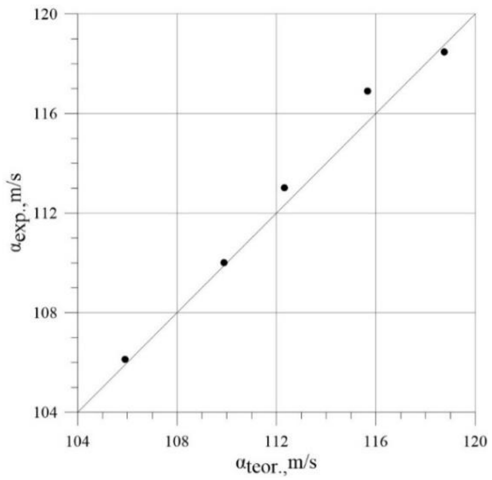


**Fig. 7.** Correlation dependence between the theoretically and experimentally determined values of the heat transfer coefficients for moist match splints

## 4. Conclusions

Based on experimental studies, the heat and mass transfer coefficients during filtration drying of match splints were obtained in the given Reynolds criterion range of $200 \leq Re \leq 500$ of the drying agent filtration. The results are generalized by the criterion dependences $Nu=22,12 \cdot Re_e^{0.24} \cdot Pr^{0.33}$ та $Sh=22,12 \cdot Re_e^{0.24} \cdot Sc^{0.33}$. The similarity of the criterion complexes for the heat and mass transfer coefficients was determined, despite the different nature of these processes. The relative error between the experimental and theoretically obtained values does not exceed 7.14 %. The obtained results make it possible to predict the heat consumption for the drying process and the operating costs of the filtration drying unit for match splints, as well as to rationally select the drying parameters.

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