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HEAT TRANSFER PROCESS DURING FILTRATION DRYING OF MATCH SPLINTS

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Abstract. The study proposes filtration drying for drying match splints. Experimental methods for investigating heat exchange between the heat agent and the material are presented. Theoretical aspects of heat transfer during filtration drying are analyzed. The effect of the heat agent's velocity on heat exchange efficiency is determined within the Reynolds number range of $200 \leq Re \leq 500$. The experimentally obtained data are generalized using a dimensionless complex. A dependency for determining the heat transfer coefficient is proposed. A correlation between theoretical and experimental values of the heat transfer coefficient is provided.

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

1. Introduction

Matches are widely used in all countries around the world, both in daily life and in various economic activities. Their popularity is attributed to their ease of use, cost-effectiveness, compactness, versatility, and environmental friendliness.

In Ukraine, matches are manufactured at LLC “UKRAINIAN MATCH FACTORY”. One of the key stages of production is drying match splints before impregnation with paraffin. Match splints are produced by cutting steamed wood into veneer and then shredding it into blanks measuring 2×2×40 mm. The moisture content of match splints before drying is approximately 70 % by mass. Wet match splints are dried in tunnel dryers in a stationary layer with a height of 15 centimeters. This drying method requires significant energy consumption since the heat agent moves only above the material, while moisture diffuses from the lower layers toward the heat agent. As a result, the heat agent is only partially saturated with moisture, and its temperature at the dryer outlet ranges from 50 to 70 °C. Therefore, the equipment is not energy-efficient, making energy-saving solutions a relevant issue.

After all, one of the key goals of sustainable development is rational energy use. Over the years, energy demand has been increasing, significantly impacting the climate. Moreover, energy costs continue to rise. Therefore, improving the energy efficiency of equipment is one of the key concerns for manufacturing industries (Lawrence et al., 2019). As stated by the authors (Cavallaro et al., 2013), energy efficiency can be improved by 10–30 % using existing technologies in production. An important step in implementing lean manufacturing is finding ways to enhance equipment or seeking alternative methods to minimize energy consumption (Salah et al., 2021).

For drying crushed wood, the following types of dryers are used: fluidized bed dryers (Holubets et al., 2003), infrared radiation dryers (Bandura et al., 2019), vacuum dryers, and microwave (MW) dryers (Obleshchenko et al., 2021), whose efficiency is also relatively low. One of the promising methods for wood drying is filtration drying, which is a low-temperature process characterized by high heat and mass transfer coefficients (Mosiuk et al., 2015). Therefore, filtration drying has been proposed as one of the highly efficient and low-temperature methods for drying match splints.

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Considering the above, it can be stated that improving the energy efficiency of match splint drying is a relevant task. This will help reduce the production cost of matches and enhance the competitiveness of their manufacturing.

The filtration drying method is based on the filtration of the heat agent through a porous stationary layer of wet material. As a result, the heat and mass transfer surface includes the surface of all particles in the stationary layer. During drying in a tunnel dryer, the heat agent interacts only with the upper layer of wet match splints, while heat is transferred to the lower layers of splints through thermal conductivity, and moisture evaporation occurs through molecular diffusion.

Therefore, the advantage of the filtration drying method is the large phase contact area and the maximum utilization of the drying potential of the heat agent. Throughout the drying process, the temperature of the heat agent at the material outlet remains close to the wet-bulb temperature and increases only at the final stage, approaching the inlet temperature. This indicates that the heat agent becomes saturated with moisture throughout the entire drying process. Moreover, filtration drying allows the use of a low-temperature heat agent, promoting the rational utilization of secondary heat, which is often used inefficiently in industrial settings (Gnativ et al., 2020; Ivashchuk et al., 2024).

To determine the optimal parameters of the filtration drying process for match splints, it is important to establish the heat transfer coefficients and their dependence on the velocity of the heat agent through the stationary layer of material. Since the intensity of heat transfer directly affects the drying duration and energy costs.

The moisture in match splints is primarily internal and is contained within the pores of the wood. Therefore, during drying, heat is spent on detaching moisture molecules from the cellulose fibers and on moving the moisture to the phase interface through molecular diffusion (Sokolovskyi, 2019).

A significant number of scientific studies are dedicated to heat transfer during drying. In particular, the authors (Pazyuk et al., 2018) analyzed the heat and mass transfer processes during the drying of capillary-porous bodies of spherical shape and proposed equations for determining heat transfer coefficients under various drying conditions. However, since match splints have a parallelepiped shape, the obtained dependencies cannot accurately describe the drying of match splints.

The authors (Kumar et al., 2022; Koukouch et al., 2020) have proposed using thin-layer drying models to describe heat and mass transfer during the convective drying of plant raw materials. According to the authors, these models provide a high level of drying prediction accuracy and demonstrate agreement with experimental data. However, applying the thin-layer model requires obtaining semi-empirical dependencies based on experimental data that consider the influence of the material's structure, shape, and physical properties. Additionally, in industrial drying processes, thin-layer drying is not considered efficient.

In the study by (Messai et al., 2014), heat transfer during the convective drying of spherical aluminum particles in a packed bed was investigated. The authors proposed calculating the heat transfer coefficient from gas to material using the logarithmic mean temperature difference method. The experiments were conducted at temperatures ranging from 120 to 158 °C and air velocities of 1.7 to 3 m/s. However, such drying conditions are unacceptable for match splints, as they would lead to the cracking of wood particles and, consequently, a deterioration in their quality.

In the study by (Mykychak et al. 2013), external heat and mass transfer during the filtration drying of peeled birch veneer was investigated. The obtained dependencies allow for the determination of heat transfer coefficients. However, the study examined a specially formed package of birch veneer with dimensions of 100×100×30 mm, whereas match splints are dried in a randomly formed layer.

The study (Kindzera et al., 2021) presents the results of heat transfer research during the filtration drying process, with the findings generalized in the form of dimensionless dependencies. However, the obtained equations are of a specific nature and describe crushed sunflower biomass. Therefore, they cannot be applied to determine the heat transfer coefficients during the filtration drying of match splints. Since the shape, physical properties, sizes, and surface roughness differ significantly from the materials studied, this leads to substantial errors between experimental and theoretically calculated results.

Filtration drying of wet materials in a stationary layer has a zonal nature. The mass transfer zone during filtration drying moves in the direction of the heat agent, and in the stationary layer, both dry and wet material layers exist simultaneously. The height of the dry material layer increases during drying, while the wet material layer decreases. As the heat agent filters through the dry material layer, it transfers part of its heat to the match splints. Therefore, it is important to determine how much heat remains in the dry material layer and how much is used for drying the wet material.

Thus, the purpose of this work is to determine the heat transfer coefficients from the heat agent to the dried match splints during the filtration drying process, to assess the impact of the heat agent's velocity on the efficiency of heat exchange, and to obtain semi-empirical dependencies to describe the process.

2. Experimental part

The experimental studies were conducted using a filtration drying setup, the operating principle of which is described in (Kuzminchuk et al., 2023). To determine the heat transfer coefficients of match splints, a cylindrical container (1) (Fig. 1) made of insulating material with a diameter of 190 mm was used. The studies were carried out in a "thin" layer of match splints (2), previously dried to a constant weight. The material sample was placed on a perforated bottom (3). The heating agent was heated to the required temperature using a calorifier and filtered through a layer of match splints. The study was conducted at different flow velocities of the heating agent: 0.18, 0.21, 0.23, 0.26, and 0.29 m/s. The inlet air temperature was maintained at a co nstant level (t_in = 60 °C) with an accuracy of ±0.5 °C using an electronic temperature controller SESTOS DIS 10 (4). To measure and monitor the temperature of the heating agent, thermocouples were installed 20 m m above the match splint layer and 20 mm below the perforated partition. The temperature values were recorded on a personal computer using an eight-channel intelligent measuring transducer PT8-1000 (5) connected to the thermocouples. At the outlet, the temperature was measured at three points every 1.8 seconds: at the center of the flow and at distances of 35 mm and 60 mm from the wall. The average of the three values was used for calculations. The experimental study was conducted until the drying agent's temperature approached the inlet temperature of the cylinder.

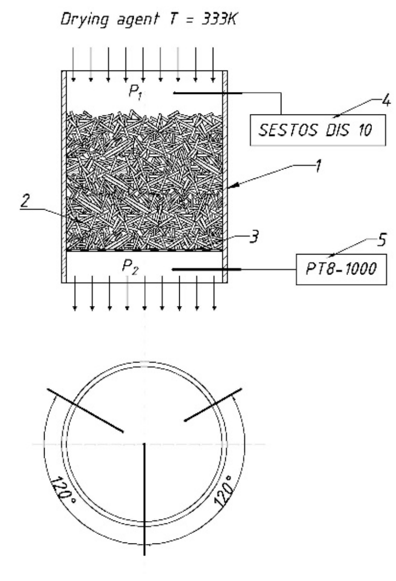

Fig. 1. Schematic representation of the container for investigating heat and mass transfer processes: 1 – cylindrical container; 2 – layer of match splints; 3 – perforated bottom; 4 – electronic temperature controller; 5 – measuring transducer

The experimentally obtained average temperature values allow for the determination of heat transfer coefficients (α) according to the following equation:

$$\alpha = \frac{\Delta Q}{F \cdot (\bar{t} - \overline{T_n}) \cdot \Delta\tau}, \quad (1)$$

where ΔQ is the amount of heat transferred from the heating agent to the match splints, $\bar{t}$ is the average temperature at the inlet and outlet of the container, $\overline{T_n}$ is the average temperature on the surface of the match splints, F is the surface area of the material particles, and $\Delta\tau$ is the time interval between measurements.

The amount of heat was determined using the material balance equation for the heating agent:

$$\Delta Q = G \cdot c_a \cdot (t - \overline{T_n}) \cdot \Delta\tau, \quad (2)$$

where G is the mass flow rate of the heating agent in the range of 0.005 to 0.01 kg/s, c_a is the heat capacity of the heating agent at a temperature of 60 °C, which is 1005 J/(kg·K), and t is the temperature of the heating agent at the inlet of the container.

The surface temperature of the particle is practically impossible to determine experimentally, so the temperature was taken based on analytical dependencies (Atamanyuk, Humnytskyi, 2013).

Based on the determined heat transfer coefficients (α) for different flow velocities of the heating agent through the material layer, a dependence $\alpha = f(v)$ was constructed. The obtained data were approximated by a linear function.

To generalize the results of the heat transfer study, a criterion equation was used (Atamanyuk, Humnytskyi, 2013):

$$Nu = A \cdot Re_e^n \cdot Pr^m, \quad (3)$$

where the Nusselt number was determined from the equation:

$$Nu = \frac{\alpha \cdot d_e}{\lambda}, \quad (4)$$

where d_e is the equivalent diameter of the channels between match splints through which the heat agent flows, which is 0.021 m, λ is the thermal conductivity coefficient of the heat agent, which is 0.03 W/(m·K).

The Reynolds number was determined using the dependency:

$$Re_e = \frac{v \cdot d_e}{\nu}, \quad (5)$$

where v is the actual velocity of the heat agent, and ν is the kinematic viscosity coefficient, which is 1.89×10^{-5} m²/s for temperature 60 °C.

The Prandtl number was determined using the dependency:

$$Pr = \frac{\nu}{a}, \quad (6)$$

where a is the thermal diffusivity coefficient, which is 2.81×10^{-5} m²/s for temperature 60 °C.

To determine the unknown coefficient A and the exponent n, dependency (3) is expressed in a logarithmic coordinate system:

$$\frac{Nu}{Pr^{0.33}} = f(Re_e). \quad (7)$$

Based on dependencies (3) the heat transfer coefficient α was determined:

$$\alpha_t = A \cdot \left(\frac{v \cdot d_e}{\nu}\right)^n \cdot \left(\frac{\nu}{a}\right)^m \cdot \frac{\lambda}{d_e}. \quad (8)$$

3. Results and Discussion

The values of the heat agent temperature at the outlet of the match splint layer at different velocities are shown in Fig. 2.

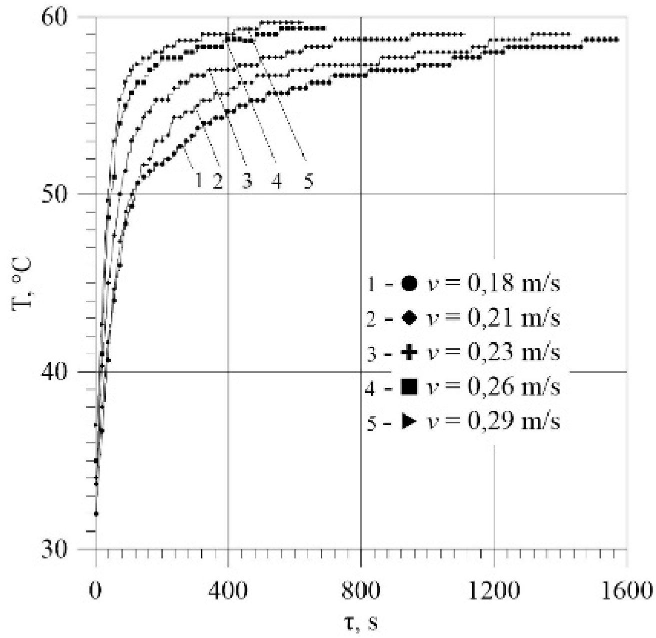

Fig. 2. Heat agent temperature at the outlet of the material at different superficial velocity

The analysis of the figure shows that as the velocity of the heat agent through the match splint layer increases, the temperature at the outlet of the cylinder rises more rapidly. At a heat agent velocity of 0.18 m/s, a temperature of 58.7 °C is reached in 1463 s, whereas at 0.29 m/s, it is achieved in just 243 s. Thus, with a 1.6-fold increase in the heat agent velocity, the temperature of 58.7 °C is established six times faster. A temperature of 59.7 °C is reached in 495 s at a velocity of 0.29 m/s, whereas at 0.18 m/s, this temperature was not attained during the experimental studies.

The reduction in the time required to reach the outlet temperature of the container is due to the increased velocity, as a greater amount of heat is transferred to the material per unit of time, leading to an increase in heat transfer coefficients.

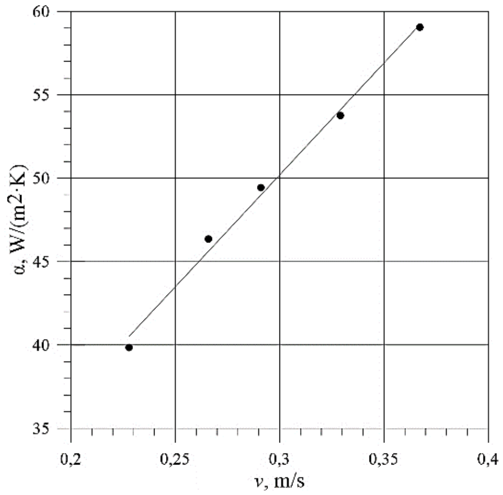

Fig. 3. Dependence of the heat transfer coefficient α on the actual velocity of the heat agent through the layer of match splints

Based on the determined heat transfer coefficients α for different velocities of the heat agent through the material layer, the dependency $\alpha = f(v)$. was constructed.

The obtained heat transfer coefficients represent average values for the entire layer, as the heat agent flows through the curved channels formed by the particles. Due to the uneven arrangement of the match splints, the cross-sectional area of the material layer changes with height. This causes multiple variations in the velocity of the heat agent near the surface of the particles. As a result, the local heat transfer coefficient also changes continuously.

Based on the obtained values, the Reynolds, Nusselt, and Prandtl numbers were determined, and the dependency $Nu/Pr^{0.33} = f(Re_e)$ was constructed in a logarithmic coordinate system (Fig. 4).

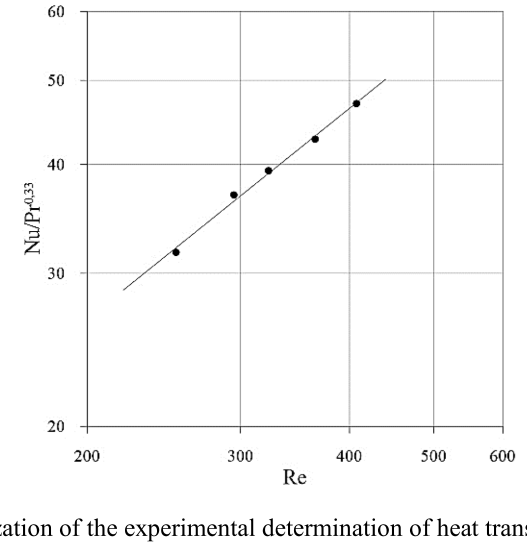

Fig. 4. Generalization of the experimental determination of heat transfer coefficients α

By approximating the obtained dependency with a power function, it was determined that the coefficient A is 0.385, and the exponent n = 0.8. Therefore, equation (3) takes the following form:

$$Nu = 0.385 \cdot Re_e^{0.8} \cdot Pr^{0.33}. \quad (9)$$

The equation for the theoretical determination of the heat transfer coefficient can be written as:

$$\alpha_t = 0.385 \cdot \left(\frac{v \cdot d_e}{\mathrm{v}}\right)^{0.8} \cdot \left(\frac{\mathrm{v}}{a}\right)^{0.33} \cdot \frac{\lambda}{d_e}. \quad (10)$$

The obtained equation allows for the theoretical determination of the heat transfer coefficient during the filtration drying of match splints with sufficient accuracy within the Reynolds number range of 200 ≤ Re ≤ 500. This is essential for further calculation of heat energy consumption.

Fig. 5 presents the correlation between theoretical and experimental values of the heat transfer coefficient.

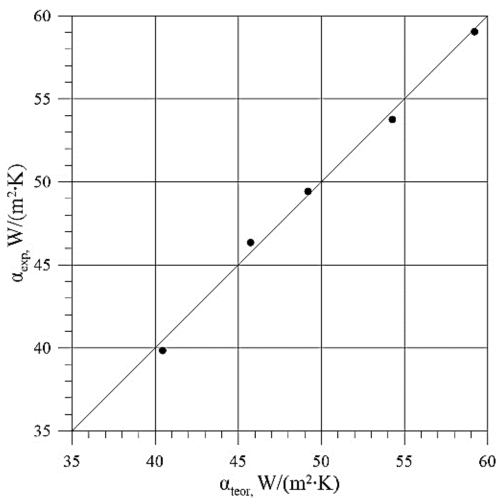

Fig. 5. Correlation dependence between theoretical and experimental values of the heat transfer coefficient

The maximum value of the relative error does not exceed 7 %, which is acceptable for design calculations.

4. Conclusions

For drying match splints, the filtration method has been proposed as a highly efficient and low-temperature. This method enables maximum utilization of the drying potential of the heat agent. The study investigates heat transfer during filtration drying. Based on experimental data, heat transfer coefficients were determined within the Reynolds number range of 200 ≤ Re ≤ 500, ranging from 39 to 60 W/(m²·K). The determined coefficients are expressed through a dimensionless equation: $Nu = 0.385 \times Re_e^{0.8} \times Pr^{0.33}$

For the theoretical determination of the heat transfer coefficient, the following dependence is proposed: $\alpha_t = 0.385 \times (v \times d_e/\mathrm{v})^{0.8} \times (\mathrm{v}/a)^{0.33} \times \lambda/d_e$. The maximum value of the relative error between the experimentally and theoretically determined heat transfer coefficients does not exceed 7 %, which is acceptable for design calculations. The obtained dependencies allow for the determination of heat transfer coefficients with sufficient accuracy, enabling the prediction of energy consumption during drying and the identification of optimal process parameters.

References

Atamanyuk, V. M., & Humnytskyi, Ya. M. (2013). *Naukovi osnovy filtratsiinoho sushinnia dyspersnykh materialiv*. Vydavnytstvo Natsionalnoho universytetu "Lvivska politekhnika", Lviv.

Bandura, V., & Yaroshenko, L. (2019). Rationale of parameters of the process of drying sunflower green in the vibro-suspended layer on the basis of infrared risk. *Scientific Works*, *83*(1), 110–116. DOI: https://doi.org/10.15673/swonaft.v83i1.1427

Cavallaro, F., Ciraolo, L., Mavrotas, G., & Pechak, O. (2013). Assessment and simulation tools for sustainable energy systems. *Green Energy and Technology*, *129*, 333–356.

Gnativ, Z. Ya., Ivashchuk, O. S., Hrynchuk, Yu. M., Reutskyi, V. V., Koval, I. Z., & Vashkurak, Yu. Z. (2020). Modeling of internal diffusion mass transfer during filtration drying of capillary-porous material. *Mathematical Modeling and Computing*, *7*(1), 22–28. DOI: https://doi.org/10.23939/mmc2020.01.022

Holubets, V. M., Ozarkiv, I. M., & Atsberher, Y. L. (2003). Heat exchange during the drying of wood-based bulk materials in a fluidized bed. *Scientific Bulletin of UNFU*, *13*(1), 93–100.

Ivashchuk, O. S., Atamanyuk, V. M., Chyzhovych, R. A., Manastyrska, V. A., Barabakh, S. A., & Hnativ, Z. Ya. (2024). Kinetic regularities of the filtration drying of barley brewer's spent grain. *Chemistry & Chemical Technology*, *18*(1), 66–75. DOI: https://doi.org/10.23939/chcht18.01.066

Kindzera, D. P., Atamanyuk, V. M., Hosovskyi, R. R., & Symak, D. (2021). Heat transfer process during filtration drying of grinded sunflower biomass. *Chemistry & Chemical Technology*, *15*(1), 118–124. DOI: https://doi.org/10.23939/chcht15.01.118

Kumar, A., Kandasamy, P., Chakraborty, I., & Hangshing, L. (2022). Analysis of energy consumption, heat and mass transfer, drying kinetics, and effective moisture diffusivity during foam-mat drying of mango in a convective hot-air dryer. *Biosystems Engineering*, *219*, 85–102. DOI: https://doi.org/10.1016/j.biosystemseng.2022.04.026

Koukouch, A., Bakhattar, I., Asbik, M., & et al. (2020). Analytical solution of coupled heat and mass transfer equations during convective drying of biomass: Experimental validation. *Heat and Mass Transfer*, *56*, 1971–1983. DOI: https://doi.org/10.1007/s00231-020-02817-w

Kuzminchuk, T. A., Atamanyuk, V. M., Duleba, V. P., & Janabayev, D. (2023). Kinetics of drying of match splints. *Chemistry, Technology and Application of Substances*, *2*, 119–125.

Lawrence, A., Thollander, P., Andrei, M., & Karlsson, M. (2019). Specific Energy Consumption/Use (SEC) in Energy Management for Improving Energy Efficiency in Industry: Meaning, *Usage and Differences. Energies*, *12*(2), 247. DOI: https://doi.org/10.3390/en12020247

Messai, S., El Ganaoui, M., Sghaier, J., & Belghith, A. (2014). Experimental study of the convective heat transfer coefficient in a packed bed at low Reynolds numbers. *Thermal Science*, *18*(2), 443–450.

Mosyuk, M. I., Psiuk, Yu. Ya., & Rudei, I. A. (2015). Kinetics of filtration drying of crushed wood. *Scientific Works Odessa National Academy of Food Technologies*, *47*(1), 194–198.

Mykychak, B., Biley, P., & Kindzera, D. (2013). External heat-and-mass transfer during drying of packed birch peeled veneer. *Chemistry & Chemical Technology*, *7*(2), 191–195.

Obleshchenko, A. D., & Hulevskyi, V. B. (2021). Comparison of wood drying technologies: Vacuum and microwave. In Technical support of innovative technologies in the agro-industrial complex: *Proceedings of the III International Scientific and Practical Internet Conference* (Melitopol, November 1–26, 2021) (pp. 223–227).

Pazyuk, V. (2018). Investigation of low-temperature drying modes of plant capillary-porous materials with spherical shape. *Ceramics: Science and Life*, *4*(41), 7–14. DOI: https://doi.org/10.26909/csl.4.2018.1

Salah, S. A., & Mustafa, A. (2021). Integration of energy saving with lean production in a food processing company. *Journal of Machine Engineering*, *21*(4), 118–133. DOI: https://doi.org/10.36897/jme/142394

Sokolovskyi, I. A. (2019). Energy characteristics of drying modes of beech lumber. *Scientific Bulletin of UNFU*, *29*(1), 106–109. DOI: https://doi.org/10.15421/40290123