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## ХІМІЧНА ІНЖЕНЕРІЯ ТА ЕКОЛОГІЯ

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# KINETICS OF DRYING OF MATCH SPLINTS

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**The research results of the kinetics of match splints drying in a stationary layer are presented. The kinetic curves of match splints drying were obtained. The effect of the height of the stationary layer on the drying time is investigated. The influence of temperature and filtration velocity of the heating agent on the drying velocity was determined. The values of the critical moisture content and the time for the mass transfer front to reach the perforated partition were determined.**

**Key words: match splints; filtration drying; kinetics of drying; production of matches; stationary layer.**

### Introduction

Drying is the process of removing moisture from a material, during which structural, mechanical, technological and biological properties change due to changes in the moisture bond with the material. The analysis of drying kinetics is quite complex. The intensity of drying is determined by the temperature and moisture content of the heating agent. An increase in the velocity of the drying agent increases the coefficients of heat and mass transfer and, therefore, intensifies the process of removing free moisture [1].

Matches are common household items needed in almost every home. They are an essential commodity [2]. The main raw material for the production of matches is aspen. The technology of match production has many stages. First, the trunks of this wood are soaked in hot water to make it easier to process and to even out the moisture content throughout the wood. The wood is then cut into 65 cm long pieces, stripped of bark and peeled into veneer, 2 millimetres thick and 3 metres long. The prepared veneer is chopped into match splints (MS), sieved from the chips formed during the cutting of the veneer and sent to the storage bunker. From the bunker, the MS are fed to be impregnated with an ammonium phosphate solution. The moisture content of MS after chopping is approximately 50 % and after impregnation – 70 %. The MS are then dried to less than 6 % moisture content. After drying, the MS are ground and calibrated. Next, the MS are impregnated with paraffin to make the matches more flammable and then dipped in the ignition mixture. After dipping, the finished matches are blown with a heating agent to solidify the ignition mixture. The finished matches are then packed into boxes.

Drying is an important step in the production of matches. Matches are dried in a belt dryer in a stationary layer 15 cm high. Drying takes place in three zones. The first zone has a temperature of 80–90 °C, the second 90–100 °C and the third 80– 90 °C again. Depending on the initial moisture content of the MS, drying takes 20–45 minutes.

Large dryers are used to achieve the required productivity, as this drying method requires significant energy consumption.

More than 8 % of the energy used in the world is spent on moisture removal. It is important to note that the energy consumption for drying is 2.5–3 times higher than that required to convert water into steam. Therefore, the current issue is to optimise drying processes to reduce energy consumption per unit of material [3, 4].

Drying is a complex diffusion process involving the transfer of heat from a heating agent to the interior of the material, which results in the heating and diffusion of moisture from the interior to its surface, where it evaporates.

A rational drying regime should ensure the minimum duration of the process while maintaining the quality characteristics of the material, following its intended use.

In designing drying equipment, the following requirements should be taken into account: the equipment should ensure uniform heating and drying of the product with control of its temperature and moisture content, and it is also necessary to minimise the metal consumption of the equipment [5, 6].

The authors of [7] recommend drying chipped wood with a decrease in the temperature of the drying agent during the process. Since intensive moisture evaporation occurs at the beginning of the process, the temperature does not rise above the boiling point of water. Therefore, the temperature can be increased up to 200–300 °C. During the drying of chopped wood, the period of constant drying velosity (the period of intensive evaporation of moisture from the wood) is quite significant, and internal stresses do not play a significant role.

At the second stage of drying, which corresponds to the second drying period, the evaporation process slows down and the temperature of the drying agent can be lowered to 100–120 °C. In this case, the relative moisture content of the heating agent does not play an important role in the drying process of chipped wood.

The most promising methods of drying plant material are drying using electromagnetic energy sources [8], filtration method [9] and convective method with variable temperature conditions [10].

It has been proven that one of the most intensive methods of drying material is filtration drying, during which the heating agent is filtered through the wet material from top to bottom. This method of moisture removal provides a high phase contact area, as all particles are contacted with the gas stream. This increases the heat and mass transfer coefficients and thus increases the drying velocity while reducing energy consumption and process time. In addition, filtration drying uses a low-temperature heating agent, which reduces energy consumption for heating the material [9]. Reduction of heat and electricity consumption for the process due to high heat and mass transfer coefficients as a result of the drying agent supply through a porous layer of wet material, which provides the best conditions for interfacial heat transfer; increase in drying velocity; improvement of the quality of dried materials [11].

To design a filtration drying plant for MS, it is necessary to investigate the kinetic features of material drying. The drying velocity is influenced by the material properties (initial and final moisture content, moisture bonding with the material), the parameters of the heating agent (moisture content, drying potential, temperature, velocity), and the state of the material layer in the drying zone. The drying kinetics is studied experimentally and characterised by the construction of drying kinetic curves [6].

Several scientific researchers are devoted to the study of filtration drying kinetics. The authors of [13, 14] studied the kinetics of filtration drying of various materials. Based on the data obtained, they concluded that the height of the stationary material layer, temperature, and the rate of filtering of the heat transfer agent affect the drying velosity. However, the obtained dependencies characterise only the material under study, its shape, density and particle structure, and therefore cannot be used for other materials. The error between experimental and theoretical data will be significant.

It is known that filtration drying is of a zonal type when the mass transfer front moves in the direction of the perforated partition along the direction of filtration of the heating agent. For further analysis of the kinetics of filtration drying, it is necessary to determine the critical moisture content, which characterises the achievement of the mass transfer front of the perforated partition and the critical time at different material layer heights, different temperatures of the heating agent and different filtration velocities of the heating agent. To do this, we can use the method described in [15], which consists in constructing kinetic curves in the coordinates $\lg(w^c - w^c_p) = f(\tau)$.

For the filtration drying of MS, the model of ideal displacement can be used, since the Pekle criterion ($Pe \gg 1$), which is given in [15].

Therefore, to summarise the kinetics of filtration drying of MS in the period of complete saturation of the heating agent with moisture, we use the system of differential equations of the material balance of moisture in MS and the kinetics of their drying [15], which is valid within the limits of: $0 < \varphi < 1$:

$$\begin{cases} \dfrac{\partial \varphi}{\partial H} = a \cdot (1 - \varphi); \\ -\dfrac{\partial w^c}{\partial \tau} = n \cdot (1 - \varphi); \end{cases}$$

де $\varphi$ – relative air moisture content, in parts; $H$ – height of the material layer, m; $w^c$ – variable material moisture content, kg $H_2O$/kg d.m.; $a$ – kinetic coefficient, $\frac{1}{м}$, which is independent of process parameters and depends only on the material structure.

Therefore, this **research aims** to investigate the kinetics of filtration drying of MS.

## Materials and research methods

For the research, we used match splints from the match factory of the Ukrainian Match Factory LLC. The raw material was taken directly from the production line after chopping the veneer. The average size of one match blank is 2×2×40 mm. The moisture content of the MS is approximately 1.6 kg $H_2O$/kg d. m. For the experiments, aspen MS were used. The density is 480 kg/m$^3$ with a moisture content of 1.6 kg $H_2O$/kg d. m. Experimental studies were conducted at the same bulk density of MS of 200 kg/m$^3$.

Experimental studies were carried out at a filtration drying plant in a stationary layer (Fig. 1). The drying kinetics were studied according to the following procedure. A layer of MS was poured into container 1, which was installed on receiver 2. The receiver is connected by a pipeline system through shut-off 4 and control 5 valves to a water-ring vacuum pump 6. The air is heated to the required temperature by passing through a heater 7 using a fan 8. A thermocouple 9 is installed above the container, which is connected to an electronic thermostat SESTOS DIS 10, which controls compliance with the required temperature. The pressure loss was determined using a vacuum gauge 11.

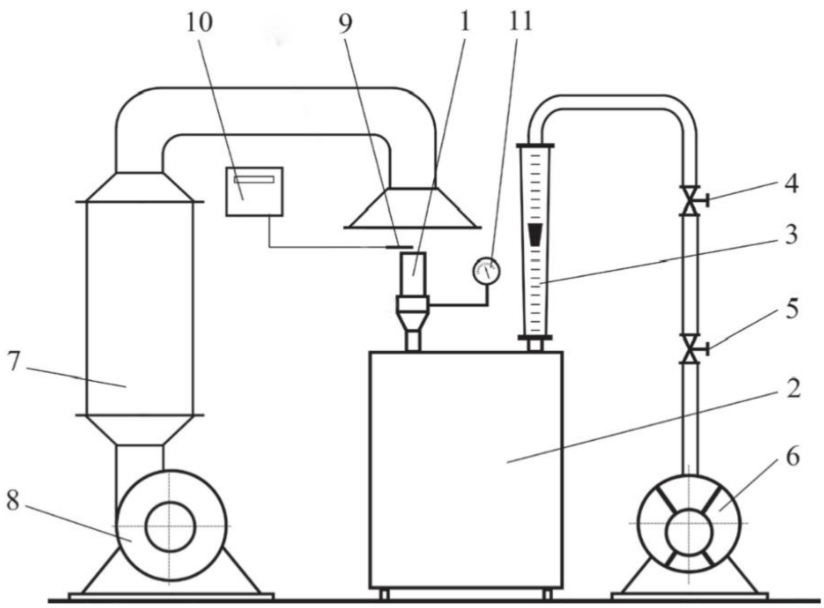


*Fig. 1. A filtration drying plant in a stationary layer: 1 – container, 2 – receiver, 3 – rotameter, 4, 5 – shut-off and control valves, 6 – vacuum pump, 7 – heater, 8 – fan, 9 – thermocouple, 10 – measuring device, 11 – vacuum gauge*

We studied the change in the moisture content of MS over time and the effect of the height of the material layer, temperature and filtration velocity of the heating agent on the kinetics of the drying process. For this purpose, three series of experiments were conducted. In the first series, the height of the stationary MS layer was changed. Experiments were conducted with heights: 150 mm, 200 mm, 250 mm, 300 mm, 350 mm. The temperature of the heating agent was 60 °C and the filtration velocity was 0.23 m/s.

In the second series of experiments, the layer height was 250 mm, the velocity was 0.23 m/s, and the temperature was changed. Experiments were carried out at temperatures of 40, 50, 60, 70, and 80 °C.

In the third series, the temperature and height were 60 °C and 250 mm, respectively. Experiments were carried out at the velocity of the heating agent of 0.18, 0.21, 0.23, 0.26, and 0.29 m/s.

During the experiment, the mass of the material was recorded at regular intervals. The experiment was carried out until a predetermined final moisture content was established. From the mass values obtained during the experiments, the moisture content of the MS during the experiment was calculated.

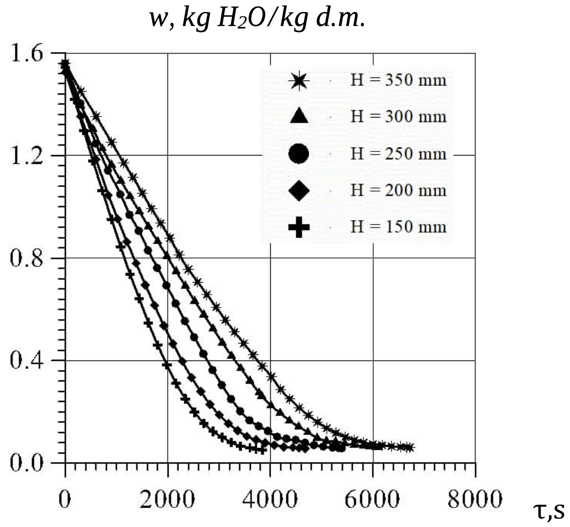


*Fig. 2. Kinetic curves of filtration drying of match splints at different layer heights*

## Results and discussion

The results of studies of the effect of the height of the stationary layer of MS from 150 to 350 mm on the drying time are shown in the form of kinetic curves in Fig. 2. The analysis of the dependencies shows that the drying time to a given moisture content increases with an increase in the height of the layer (at the same temperature and heating agent velocity). Changing the layer height from 150 mm to 350 mm leads to an increase in the drying time from 4080 s to 6840 s. This is due to an increase in the amount of material and therefore the moisture that needs to be evaporated from the layer. In addition, the temperature of the heating agent decreases with the height of the layer, as part of the heat is transferred to the already dried MS. This causes the upper layers to heat up to higher temperatures.

The kinetic curves of the dependence of the MS drying time on the temperature of the heating agent are shown in Fig. 3. An increase in temperature from 313 to 353 K (at the same layer height and heating agent velocity) leads to a decrease in drying time from 8520 to 4140 s. An increase in temperature increases the amount of heat applied per unit of time. This leads to an increase in the drying potential of the heating agent. In addition, an increase in temperature leads to an increase in the internal diffusion coefficient, which accelerates the process of moisture movement from the centre of the MS to the interface.

However, heat loss increases with temperature. The heat is carried away with the exhaust heating agent and the dried material.

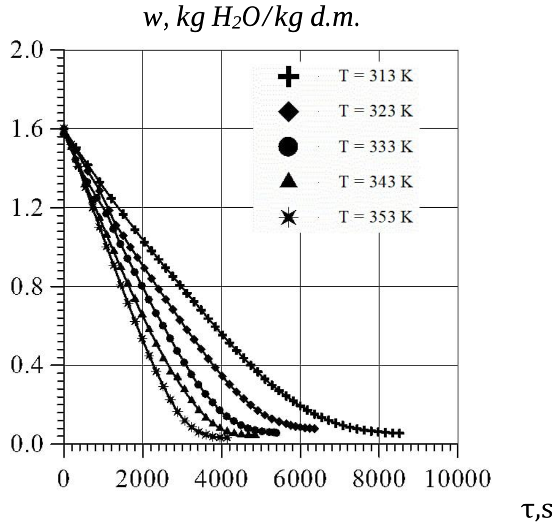


*Fig. 3. Kinetic curves of filtration drying of match splints at different temperatures of the heating agent*

The effect of the velocity of the heating agent through the stationary layer MS on the drying time is shown in the form of graphical dependencies in Fig. 4. An increase in the air filtration velocity (at the same temperature and layer height) causes a decrease in the drying time of MS. A change in velocity from 0.18 to 0.29 m/s leads to a reduction in time from 7200 to 4920 s. This is due to an increase in the amount of heat introduced per unit of time. In addition, the increase in velocity increases the heat and mass transfer coefficients. Due to the increase in air velocity, the flow is turbulent, which helps to reduce the thickness of the hydraulic, thermal and diffusion layers, and thus intensify drying.

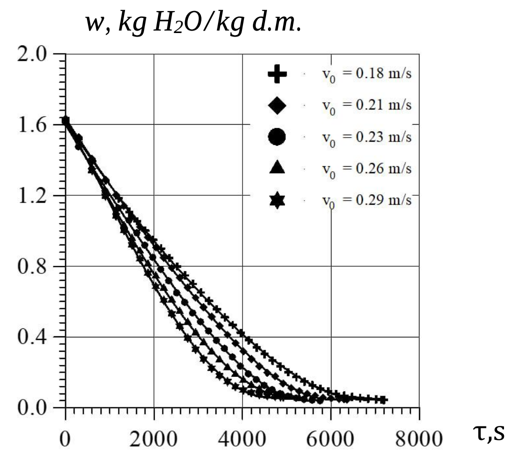


*Fig. 4. Kinetic curves of filtration drying of match splints at different velocities of the heating agent*

As shown in the graphical dependences in Figs. 2–4, the curves are characterised by two sections corresponding to the periods of complete and partial saturation of the heating agent with moisture. The change in the period occurs when the mass transfer front reaches the perforated partition.

To summarise the kinetics of filtration drying, it is necessary to find the point of transition from the period of complete air saturation to the period of partial saturation. The change in the period is characterised by the value of the critical moisture content $w_{cr}$ and the critical time $\tau_{cr}$.

To determine the critical time and moisture content at different heights of the stationary MS layer, different temperatures, and the velocity of the heating agent, the experimental data shown in Figs. 2–4 were presented as a functional dependence $\lg(w – w_p) = f(\tau)$ in Figs. 5–7.

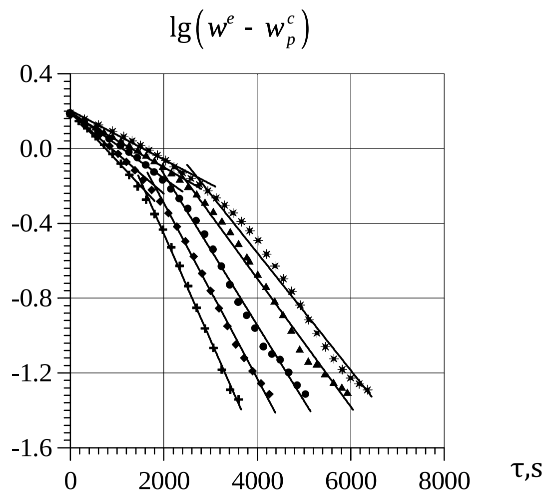


*Fig. 5. Determination of the critical moisture content at different layer heights (notations correspond to Fig. 2)*

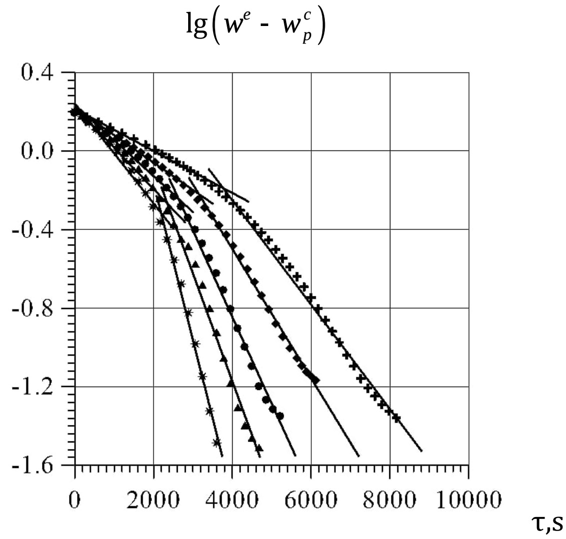


*Fig. 6. Determination of the critical moisture content at different temperatures of the heating agent (notations correspond to Fig. 3)*

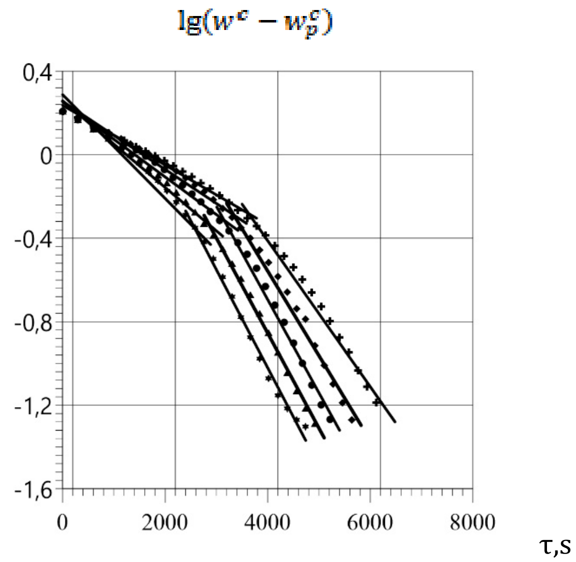


*Fig. 7. Determination of the critical moisture content at different velocities of the heating agent (notations correspond to Fig. 4)*

The critical moisture content was determined by the following equation:

$w_{cr} = 10^x + w_p^c$ in which $x$ is the ordinate of the point of intersection of two lines corresponding to the periods of full and partial saturation of air with moisture.

The values of the critical moisture content $w_{cr}$ and the critical time $\tau_{cr}$ determined by the graph-analytical method are given in Table.

**The value of the critical moisture content $w_{cr}$ and the time of its achievement $\tau_{cr}$**

| H, mm | $v_0$, m/s | t, °C | $lg(w-w_p)$ | $w_{cr}$ | $\tau_{cr}$ |
|---|---|---|---|---|---|
| 150 | 0.23 | 60 | –0.284 | 0.535 | 1800 |
| 200 | | | –0.252 | 0.575 | 2120 |
| 250 | | | –0.231 | 0.602 | 2520 |
| 300 | | | –0.219 | 0.619 | 2710 |
| 350 | | | –0.198 | 0.649 | 3150 |
| 250 | 0.18 | | –0.161 | 0.705 | 3390 |
| | 0.20 | | –0.202 | 0.643 | 3020 |
| | 0.23 | | –0.231 | 0.602 | 2520 |
| | 0.26 | | –0.28 | 0.540 | 2360 |
| | 0.29 | | –0.32 | 0.494 | 2010 |
| | 0.23 | 40 | –0.183 | 0.671 | 3720 |
| | | 50 | –0.205 | 0.638 | 3140 |
| | | 60 | –0.231 | 0.602 | 2520 |
| | | 70 | –0.265 | 0.558 | 2340 |
| | | 80 | –0.319 | 0.498 | 2200 |

As the analysis of Table shows, with a change in the height of the layer, the critical time increases, since the distance of movement of the mass transfer front from the entrance of the heating agent into the material layer to the perforated partition increases. The critical moisture content increases too, because the mass of dry material increase.

As the temperature of the heating agent increases, its drying potential increases, i.e. more moisture can be removed by the air per unit time. In this regard, the critical time $\tau_{cr}$ decreases. In addition, the critical moisture content at the moment when the mass transfer front reaches the perforated partition will be lower at a higher temperature.

Also, as the filtration velocity increases, the amount of heat input per unit time increases. In this regard, the critical time decreases with the increase in the velocity of the heating agent, and therefore the change from full saturation to partial saturation is faster. With an increase in the velocity of the heat transfer agent, the value of the critical moisture content decreases. This is because with an increase in the filtration velocity of the heat transfer agent, the amount of moisture it can absorb increases and the time for the mass transfer front to reach the perforated partition decreases.

To summarise the kinetics of MS drying during the period of full moisture saturation, the kinetic coefficients were found from experimental data. A graphical dependence $\ln((1 - w^c/w_0^c)/\tau) = f(H)$ was constructed. The coefficients *A*, *m* and *n* are determined, which show the influence of external conditions on the intensification of the process.

The period of full saturation with moisture can be represented as equation:

$$\frac{w^c}{w_0^c} = 1 - 3{,}23 \cdot 10^{-5} \cdot t^{1{,}05} \cdot v_0^{1{,}03} \cdot \tau \cdot e^{-3{,}137 \cdot H}$$

## Conclusions

The kinetics of filtration drying of match splints at different heights of the stationary material layer, different temperatures of the heating agent, and different velocities of the heating agent filtration through the material layer were investigated. The kinetic curves of moisture content change in time were constructed. The results of experimental studies show that the process proceeds in periods of complete and partial saturation of the heating agent with moisture. The change from full saturation to partial saturation occurs when the mass transfer front reaches the perforated partition and is determined by the critical moisture content and critical time. To determine these values, graphical dependencies in the coordinates $\lg(w - w_p) = f(\tau)$

The data obtained make it possible to determine the kinetic coefficients of the filtration drying process, the drying velocity coefficient K, calculate the drying velocity of the period of full saturation N, and the relative drying coefficient c.

And also to describe the drying kinetics during the period of full and partial saturation.

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## КІНЕТИКА СУШІННЯ СІРНИКОВОЇ СОЛОМКИ

**Наведено результати дослідження кінетики сушіння сірникової соломки в стаціонарному шарі. Отримано кінетичні криві сушіння сірникової соломки. Досліджено вплив висоти насипного шару на час сушіння. Визначено вплив температури та швидкості фільтрування теплового агенту на швидкість сушіння. Визначено значення критичного вологовмісту та часу досягнення фронтом масообміну перфорованої перегородки. Описано період повного насичення вологою у вигляді рівняння та знайдено кінетичні коефіцієнти.**

**Ключові слова: сірникова соломка; фільтраційне сушіння; кінетика сушіння; виробництво сірників; стаціонарний шар.**