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EXTERNAL HEAT-AND-MASS TRANSFER DURING DRYING OF PACKED BIRCH PEELED VENEER

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Abstract. External heat-and-mass transfer during filtration drying of packed birch peeled veneer has been investigated. The dependence of heat-and-mass transfer coefficients on actual speed of heat agent filtration has been determined for dry and wet veneer sheets. The effect of heat agent temperature on the values of diffusive, heat and hydrodynamic boundary layers, and as a result, on heat-and-mass transfer intensity has been established by the experiments during filtration drying of packed veneer.

Keywords: birch peeled veneer, heat-and-mass transfer, filtration drying.

1. Introduction

Veneer is widely used in furniture and veneer industries. The increasing demands of woodwork and furniture production which use veneer of valuable wood as well as severe competition need the decrease in cost and increase in products quality. Nowadays convective dryers and dryers with jet blowing of the surface are used for veneer drying. They are very power-consuming technological processes. The energy consumption of veneer drying till its moisture of $8 \pm 2\,\%$ is approximately $60\,\%$ of the total energy consumption. Therefore, the investigations concerning veneer drying with less energy consumption is very urgent.

It is well-known that drying intensity is determined by the process time and regimes ensuring the necessary strength index and characteristics of dry wood (absence of surface and internal cracks) and drying efficiency – by heat energy consumption for drying of $1\,\mathrm{m}^3$ of the materials. Batch dryers with stepped drying low-temperature regimes are widely used in industry for carving wood drying. However the design and operation simplicity of the mentioned dryers cannot offset a disadvantage of high energy consumption due to the low heat-transfer coefficients of the heat exchangers [1-3]. Using jet blowing the veneer convective drying is intensified by 2-3 times but fans capacity increases as much. The result is the higher cost of the drying process compared with that in convective dryers [1]. Therefore the search and usage of veneer alternative drying are the problem of prime importance [4].

To simulate the heat-transfer processes it is necessary to determine the coefficients of heat-transfer between the heat agent and veneer sheets. Actually the experimental methods are widely used for this purpose. The criteria equations for the calculations of heat-transfer coefficients depending on Reynolds criteria during wood stack drying are given in [2] but it is impossible to use them for packed veneer drying because of the great error between experimental and calculated values. The analysis of literature data shows [5-7] that the majority of authors use calculated dependencies with heat-transfer coefficients. However the criteria dependencies due to which the coefficients may be determined are absent in the literature.

Thus the existing calculated relations allowing to settle the well-founded optimal drying regime for veneer and ensure the maximal drying potential of the heat agent are insufficient. Therefore, the investigation of heat-and-mass transfer processes is the actual task.

We suggest the plant for packed veneer drying [8] that permits to use the drying potential of the heat agent to the maximum, and as a result, to decrease the energy consumption for drying (compared with the existing equipment) and to ensure the high quality of dried veneer.

2. Experimental

The sheets of birch peeled veneer with the thickness of 1.5 mm were the investigation object. The

initial moisture was 58 %. It was stipulated by the presence of free (capillary) moisture in the cells cavity, intercellular space and bound moisture in the cells wall. Heat conductivity of the dried birch wood varies from 0.1 to 0.4 W/m·K. This insignificant value is caused by the porosity of wood structure.

The experiments were carried out using the plant represented in [4]. In order the whole surface of veneer sheet participated in the heat-and-mass transfer, as well as the heat agent temperature along the sheet surface were constant, the sheet height according to the heat agent driving direction should be 30 mm and pack size should be 100x100x30 mm.

The packed veneer was formed from the wet sheets of birch peeled veneer by the size of 100x30x1.5 mm (layer pad thickness was 0.8 mm), dried in the drying chamber till the constant mass and installed on the plant in the container made of the heat-insulating material (fiber-glass plastic). To determine the heat agent temperature thermocouples were placed over and under the packed veneer at the distance of 20 mm. Six thermocouples under the packed veneer were placed in the different points relative to container walls and the heat agent temperature was determined as an arithmetical mean value. The temperature at the exit of packed veneer was automatically recorded using octa-channel temperature indicator RT8-1000 with data computer processing. The constant temperature over the pack was sustained at the level of 343 ± 0.5 K using thermoregulator RT-100 and chromel-copel thermocouple.

The drying process was carried out for 20 s at the heat agent temperature of 323, 343 and 373 K. The weighting time was approximately 10 s. To exclude the evaporation during pack weighting it was covered by the cover plate made of heat-insulating material. Every experiment was carried out minimum three times to obtain the reliable data.

Taking into account that the pack surface contacting with the heat agent during the drying is large (0.1–0.2 m^2 depending on pack thickness) and the thickness is small (($(1.5–4.0)\cdot10^{-3}$ m) we investigated the external heat transfer between the heat agent and the surface of dried and wet veneer.

3. Results and Discussion

3.1. External Heat Transfer between the Heat Agent and Dried Sheets of Birch Peeled Veneer

The averaged temperatures of the heat agent at the pack exit are represented in Fig. 1 at different speeds of the heat agent which varied from 1.35 to 4.32 m/s.
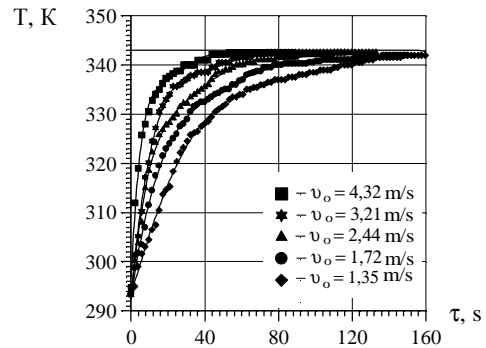

Fig. 1. Change of the heat agent temperature at the exit of dried packed veneer (thickness 1.5 mm)
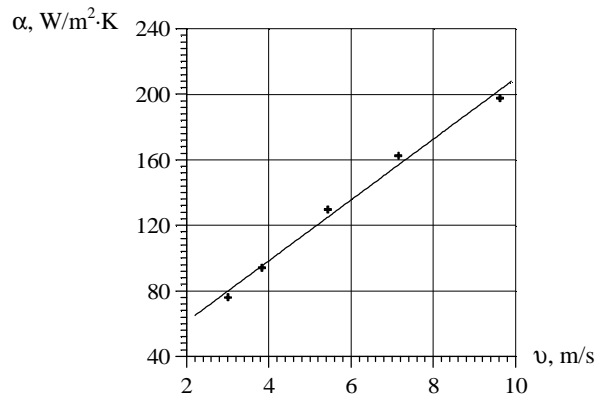

Fig. 2. Heat transfer coefficient *vs* actual speed of the heat agent

The heat agent temperature of 343 K over the packed veneer was chosen taking into account the short heating time. Data in Fig. 1 allow to determine the coefficient of heat transfer from the heat agent to the dry surface of veneer sheets.

The values of heat transfer coefficients α were calculated in accordance with the equation of heat transfer [9] on the basis of experimental data given in Fig. 1:

$$a = \frac{\Delta Q}{F \cdot \left(\bar{t} - \bar{T}_{av}\right) \cdot \Delta t} \qquad (1)$$

where ΔQ – amount of heat needed for the heating of packed veneer sheets and calculated in accordance with the equation of heat balance for the heat agent; $\bar{t}$ is assumed to be the arithmetic mean temperature of the heat agent at the entrance and exit in accordance with the measurements given in Fig. 1; Δt – experiment time.

The average temperature of sheets surface $\bar{T}_{av}$ is estimated as follows. The average temperature of veneer sheets $\bar{T}$ is determined using the heat balance:

$$\Delta Q = m \cdot c_s \cdot \left(\bar{T} - T_0\right) \qquad (2)$$

where T_0 – the initial temperature of the veneer sheet; m – mass of packed veneer sheets; c_s – heat capacity of the dried birch veneer.

Obviously, the surface temperature is higher than the average temperature inside the veneer sheet. However, it is difficult to measure the temperature on the veneer surface in the pack because of the small distance between sheets. In case when the temperature at both sides of veneer sheet is the same and equal to the heat agent temperature and when the sheet structure is homogeneous, it may be assumed that distribution of the temperature field along the sheet thickness will have parabolic nature.

Taking into account that the veneer sheet temperature varies in the narrow range of temperatures, we admit that l = const. Moreover, we assume that the temperature of the veneer sheet is changed only along its thickness, in other directions it is constant, *i.e.* we have unvaried symmetric task. Taking into consideration that the heat agent temperature on the veneer sheet surface is known and constant, and heat transfer between the heat agent and veneer sheet surface takes place in accordance with Newton's law, we may use boundary conditions of the third type with corresponding initial and border conditions in order to determine the temperature on the veneer sheer surface. Then the solution of differential equation may be expressed as follows [10]:

$$\frac{T(x,t)-T_0}{t_c-T_0}=1-\sum_{n=1}^{\infty}A_n\cdot\cos m_n\cdot\frac{x}{R}\cdot\exp\left(-m_n^2\cdot Fo\right) \quad (3)$$

where t_c – the heat agent temperature; $T(x,t)$ – temperature on the veneer sheet surface $(x=R)$; A_n – coefficient from Ref. [10]; R – ½ of the sheet thickness $(d=2\cdot R,\ 0<x<R)$; m_n – root of the characteristic equation, $\left(ctg\,m=\frac{m^2-Bi^2}{2\cdot m\cdot Bi}\right)$; *Fo*, *Bi* – Fourier and Bio criteria, respectively.

It is well-known from literature data that by Fourier numbers $Fo>0.3$ [10] it is sufficient to confine to the first root of the characteristic equation (to choose the regular regime). Therefore in our calculations we were confined to the first root of the characteristic equation. The validity of the mentioned assumption is determined by the checking *Fo* and *Bi* values. The root values are taken from the tables represented in [10].

The obtained values of the heat transfer coefficients are averaged relative to the surface of veneer sheets forming the pack.

The experimental results represented in Fig. 2 are summarized in accordance with Eq. (4) [9]:

$$Nu_e=A\cdot\mathrm{Re}_e^n\cdot\mathrm{Pr}^m \quad (4)$$

Reynolds number for the heat agent motion inside the flat channels is calculated in accordance with Eq. (5) [9]:

$$\mathrm{Re}_e=\frac{u\cdot d_e\cdot r}{m}=\frac{u\cdot 4\cdot F\cdot r}{m\cdot \Pi} \quad (5)$$

where u, r, m –actual speed, density and viscosity of the heat agent, respectively; d_e – equivalent diameter of free area between veneer sheets; F – cross-section area of the space between veneer sheets; Π – wet perimeter.

The parameters of flat channel in the pack are determined by its width a and thickness of layer pad b between sheets. Reynolds number is calculated in accordance with Eq. (6):

$$\mathrm{Re}_e=\frac{2\cdot a\cdot b\cdot u\cdot r}{m\cdot (a+b)} \quad (6)$$

Taking into account that air physical parameters are changed within the narrow interval we assume $Nu_e\sim\sqrt[3]{\mathrm{Pr}}$ [9].

To define the unknown coefficients A and n in Eq. (4) the experimental values are represented by the relation $Nu_e/\sqrt[3]{\mathrm{Pr}}=f\left(\mathrm{Re}_e\right)$ in the logarithmic co-ordinates (Fig. 3). Every point is obtained as the arithmetical mean value of minimum three experiments.

The approximation of experimental values by power function represented in Fig. 3 allows to determine the unknown coefficients A and n and Eq. (4) transforms into Eq. (7):

$$Nu_e=0.055\cdot\mathrm{Re}_e^{0.84}\cdot\mathrm{Pr}^{0.33} \quad (7)$$

The obtained dependence (7) gives the possibility to calculate Nusselt number with the accuracy of ± 7.2 % within the range of Reynolds number $600\le\mathrm{Re}\le 2000$.
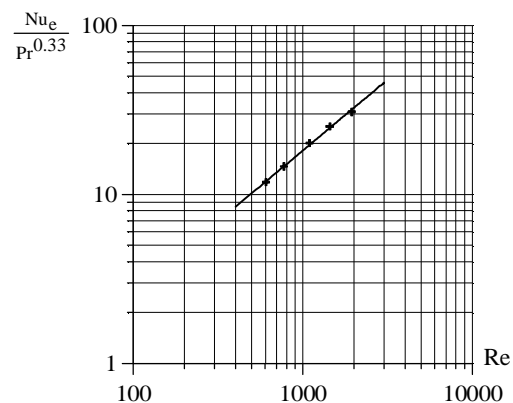

Fig. 3. Generalization of the heat transfer during the heating of dried sheets of birch peeled veneer

3.2. External Heat-and-Mass Transfer during the Heating of Packed Wet Birch Peeled Veneer

The intensity of veneer drying in the formed packs significantly depends on the amount of heat transferred from the heat agent to its surface and it is determined by

the heat agent filtration rate and temperature difference between the veneer sheet surface and the gas flow.

Veneer sheets contain free surface moisture and bounded moisture evaporated in the second period. The external diffusion kinetic area corresponds to the low values of Bio criterion (*Bi*). By great values of *Bi* (*Bi* > 50) the kinetics is determined only by intra-diffusion transfer. There is also an intermediate area where both transfer mechanisms exist simultaneously. During the drying the surface moisture is removed in the first period, and internal moisture – in the second one. In such case the free moisture is absent on the sheet surface.

The coefficients of mass and heat transfer are determined in accordance with the kinetic equations [9]:

$$\frac{\Delta W}{\Delta t} = b \cdot F \cdot \left(x_{sat.} - \frac{x_{sat.} + x_0}{2} \right) \cdot r , \qquad (8)$$

$$\frac{\Delta W}{\Delta t} \cdot r = a \cdot F \cdot \left(\frac{t_{en.} + t_{ex.}}{2} - t_{w.t.} \right) \qquad (9)$$

where *F* – heat-and-mass transfer surface; x_{sat} – moisture content of the heat agent in the saturation state; x_0 – the initial moisture content of the heat agent; *r* –specific

evaporation heat; t_{en}, t_{ex}, $t_{w.t.}$ – the heat agent temperature at the entrance, exit and wet thermometer temperature, respectively; *b* – mass transfer coefficient; *r* – density of the heat agent.

The experimental dependencies of heat-and-mass transfer coefficients upon the heat agent actual speed are represented in Fig. 4.

The data of Fig. 4a show that the increase of heat agent temperature decreases the heat transfer coefficient. The reason is that during convective heat transfer the increase in temperature is accompanied by the increase of agent viscosity and decrease of its density. The result is the increase of heat, hydrodynamic and diffusion boundary layers followed by the decrease of heat transfer coefficient at the same speeds of the heat agent. To confirm the above-mentioned the dependence of heat transfer coefficients during veneer drying on Reynolds number is represented in Fig. 5. One can see that experimental values may be approximated by the straight line. It means that the obtained values are not contrary to the process essence.
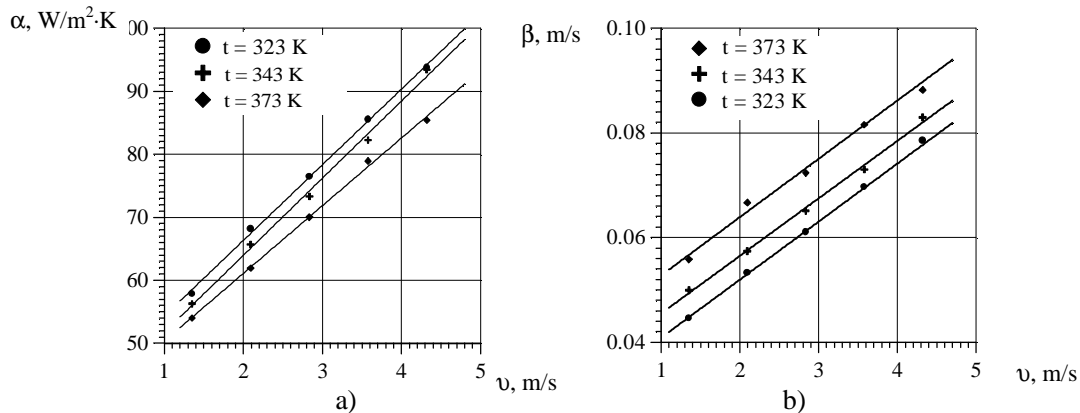

Fig. 4. Dependence of heat transfer (a) and mass transfer (b) coefficients upon the heat agent actual speed
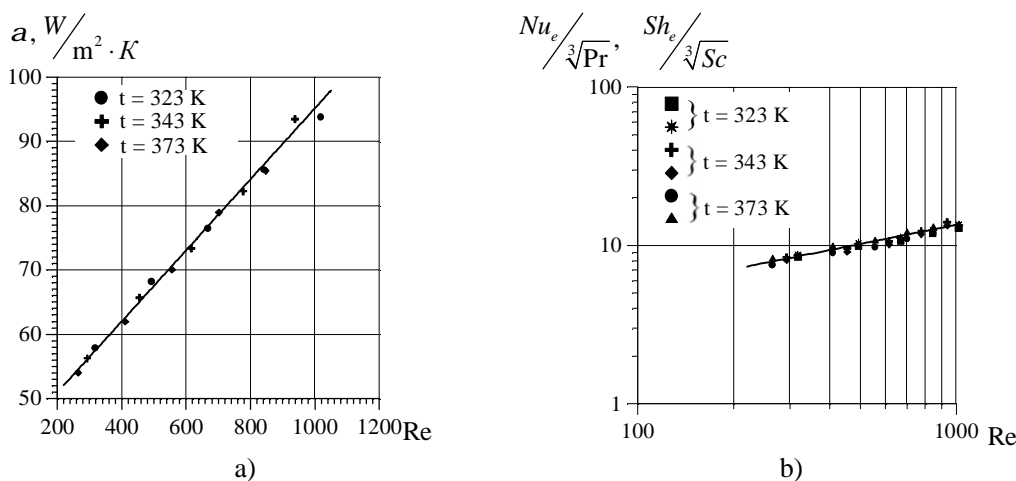

Fig. 5. Dependence of heat transfer coefficients on Reynolds number

The analysis of Fig. 4b shows that the increase in temperature increases the mass transfer coefficient *b* at the same speeds of the heat agent. It is explained by the fact that increase in temperature increases the drying effect of the heat agent and the amount of moisture evaporated from the veneer surface for the same period of time.

The experimental data represented in Fig. 4 are summarized in accordance with the Equations given in [9]:

$$Nu_e = A \cdot Re_e^n \cdot Pr^m \tag{10}$$

$$Sh_e = A \cdot Re_e^n \cdot Sc^m \tag{11}$$

The same as for the heat transfer, taking into account that physical parameters of the heat agent were insignificantly changed during the experiment, we assume $Sh \sim \sqrt[3]{Sc}$ according to recommendations [9].

Presentation of experimental values α and *b* in the form of dimensionless complexes in the logarithmic co-ordinates shows the numerical values of $Nu_e / \sqrt[3]{Pr}$ and $Sh_e / \sqrt[3]{Sc}$ are approximately the same at the same values of Reynolds number (Fig. 6). The unknown values of *A* and *n* in Eqs. (10) and (11) are determined using approximation of $Nu_e / \sqrt[3]{Pr} = f(Re_e)$ and $Sh_e / \sqrt[3]{Sc} = f(Re_e)$ experimental values by power dependence. Every point is obtained as the arithmetical mean value of minimum three experiments.

Generalization of the experimental data in Fig. 6 represents Eqs. (10) and (11) as follows:

$$Nu_e = 0.85 \cdot Re_e^{0.4} \cdot Pr^{0.33} \tag{12}$$

$$Sh_e = 0.85 \cdot Re_e^{0.4} \cdot Sc^{0.33} \tag{13}$$

The maximum error between experimental data and calculated in accordance with Eqs. (12) and (13) data does not exceed $\pm 9.2\%$ within the range of Reynolds number $200 \leq Re \leq 1000$.

4. Conclusions

The obtained calculated dependencies correlate with those obtained by other authors and allow to determine the coefficients of heat-and-mass transfer during drying of packed birch peeled veneer in the first period. On the basis of experimental results it is possible to calculate the optimum process parameters, predict necessary power consumption and service costs, determine the main structural dimensions of the drying plant, estimate necessary capital investments and establish the economic advisability of the process.

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ЗОВНІШНІЙ ТЕПЛОМАСООБМІН ПІД ЧАС ВИСУШУВАННЯ БЕРЕЗОВОГО ЛУЩЕНОГО ШПОНУ У ПАКЕТІ

Анотація. *Досліджено зовнішній тепло- і масообмін під час фільтраційного висушування пакету лущеного березового шпону. Для сухих і вологих листів шпону встановлена залежність коефіцієнтів тепло- і масовіддачі від дійсної швидкості фільтрування теплового агенту. Експериментально встановлено вплив температури теплового агенту на величину дифузійного, теплового і гідродинамічного пограничних шарів і відповідно на інтенсивність тепло- масообмінних процесів під час фільтраційного висушування шпону у пакеті.*

Ключові слова: *струганий березовий шпон, тепло-масообмін, фільтраційне висушування.*