HEAT TRANSFER IN THE PERIOD OF FALLING DRYING RATE FOR PLYWOOD

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Results are given from experimental measurements on the heat transferred during the falling period in the rate of convective drying of thin wooden sheets for $\alpha/\alpha_n = (u/u_{cr})^n$.

There are several papers [1-3] on heat transfer during the period of falling rate of convective drying for various moist materials; these give the variation in the heat-transfer coefficient incorporating the parameter $\alpha = 0$. However, the structure of this parameter is not very good, because it gives the trivial result $\alpha = 0$ when $u = 0$; moreover, most papers deal with experiments on heat transfer during convective drying characterized by ($Re < 4 \cdot 10^4$), whereas it is common industrial practice to intensify convective drying and improve the quality (high uniformity in the final water content) by using fast air currents. Sheet materials containing water are often dried as continuous films or strips, when the important parameters are the effective size of the material, the air speed, and the Reynolds number. We examined the heat-transfer coefficient during convective drying of thin sheets of wood (plywood) for $Re = (0.16\text{–}4.0) \cdot 10^5$ in a special drying oven.

We recorded drying and temperature curves for various kinds of wood, and from these we drew up the drying rate and heat-transfer coefficient as functions of water content. The heat-transfer coefficient is defined by

$$\alpha = \frac{\rho R \left(r \dfrac{du}{d\tau} + c \dfrac{dt}{d\tau} \right)}{t_m - t_s} . \quad (1)$$

The drying rate $du/d\tau$, the heating rate $dt/d\tau$ and the temperature of the surface of the material t_s were deduced from the experimental drying curves and the temperature curve for fixed values of the current water content of the wood. The specific heat of vaporization r was deduced from steam tables at a

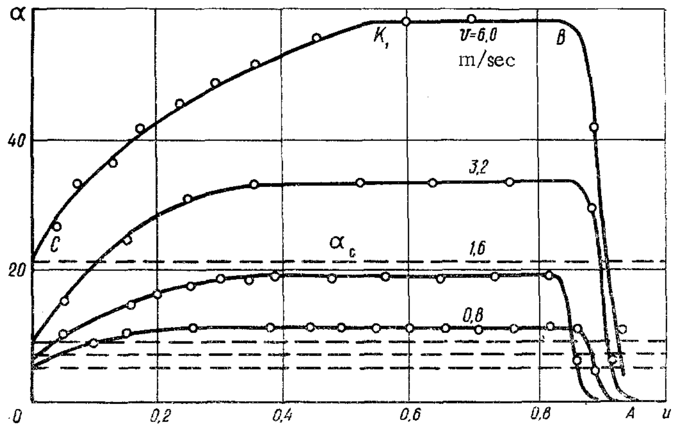

Fig. 1. Dependence of the heat-exchange coefficient on water content in the convective drying of plywood.

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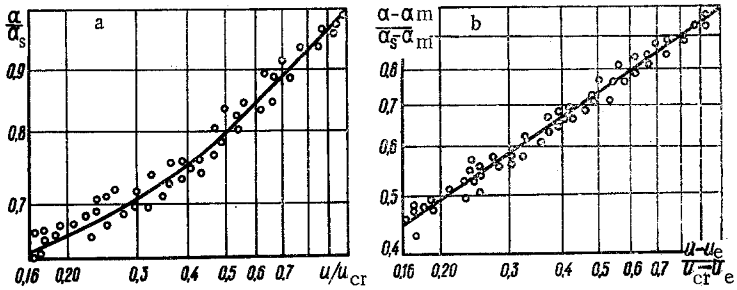

Fig. 2. The dependences: a) $\alpha/\alpha_s = f(u/u_{cr})$; b) $(\alpha - \alpha_m)/(\alpha_s - \alpha_m) = f[(u - u_e)/(u_{cr} u_e)]$.

saturation temperature corresponding to the surface temperature of the wood. The thermal capacity of the wood was taken from tables [4] for the mean current water content and the surface temperature of the material during the drying.

It is evident from Fig. 1 that during the heating period (part AB) the heat-exchange coefficient increases continuously; during the period of constant drying rate (part BK_1) it remains constant; and during the period of falling rate (part K_1C) it falls as the water content decreases and, at the equilibrium water content, it takes values corresponding to those uncomplicated by mass transfer (broken lines).

To determine the heat-transfer coefficient as uncomplicated by mass transfer we used the equations [6]:

$$\text{for} \quad Re < 10^5 \quad \alpha_m = \frac{Nu_m \lambda_m}{l} = \frac{0.66\, Re^{0.5}\, \lambda_m}{l}, \tag{2}$$

$$\text{for} \quad Re > 10^5 \quad \alpha_m = \frac{0.032\, Re^{0.8}\, \lambda_m}{l}. \tag{3}$$

It is also seen in Fig. 1 that the $\alpha = f(u)$ curves are convex with respect to the horizontal axis during the period of falling rate; this is due to details of the drying mechanism for a thin material with a considerable specific evaporation surface.

In Fig. 2a $\alpha = \alpha_s = f(u/u_{cr})$ is plotted in a logarithmic coordinates for the period of falling rate; it is seen that a straight-line relationship applies only for $u/u_{cr} > 0.4$. For $u/u_{cr} < 0.4$ there are sections with different powers of the parameter u/u_{cr}. Therefore the structure of the parametric factor u/u_{cr} is not universal over a wide range of water content; moreover, at $u = 0$, $u/u_{cr} = 0$ means that $\alpha = 0$, whereas in Fig. 1 it is clear that at $u = 0$, α takes the value of the heat-exchange coefficient uncomplicated by mass transfer, α_m. This means that u/u_{cr} cannot be used to determine α during the period of falling drying rate for wide ranges in the current water content; an awareness of this fact is particularly important in studying the convective drying of thick materials, when the first critical water content may be quite high.

An analysis of the experimental data and of the physics of the heat-exchange process shows that the following should be a better universal equation for α as a function of current water content during the period of falling rate:

$$\frac{\alpha - \alpha_m}{\alpha_s - \alpha_m} = \left(\frac{u - u_e}{u_{cr} - u_e}\right)^{\sigma}. \tag{4}$$

In Fig. 2b this dependence is plotted in logarithmic coordinates for several conditions of convective drying of plywood; many tests have shown that the observed points for the various conditions of convective drying and properties of the wood fit closely to a single straight line of slope $\sigma = 0.4$ over a wide range of values of current water content.

As a result of the experiments we obtain the following equation in dimensionless terms for the entire process of convective drying of plywood:

$$\frac{Nu - Nu_m}{Nu_s - Nu_m} = \left(\frac{u - u_e}{u_{cr} - t_e}\right)^{0.4}. \tag{5}$$

Equation (5) is free from the deficiencies of $\alpha/\alpha_s = (u/u_{cr})^n$, because $u = u_e$ for $u = u_s$, while for $u = u_{cr}$ it is equal to Nu_s, the Nusselt number for the period of constant drying rate.

Then the following Nusselt number for the period of falling rate of convective drying of plywood is defined by:

$$Nu = Nu_m + (Nu_s - Nu_m)\left(\frac{u - u_e}{u_{cr} - u_e}\right)^{0.4}. \tag{6}$$

To use (6) we need to know the first critical water content u_{cr}, which for plywood, as shown by experiment, is given by a known formula [7] in the theory of drying.

The equation for this first critical water content contains the diffusion coefficient, which is given by the following empirical equation:

$$a' = 4.625 \cdot 10^{-6}\left(\frac{T_{sm}}{100}\right)^{14}\left(1 + \frac{2R}{100}\right)\rho^{-3.9}. \tag{7}$$

Tests show that a' is dependent only on the surface temperature during the period of constant drying rate T_{sm} and on the nature ρ of the wood.

The critical water content at the surface of plywood is given by the empirical equation

$$u_{cr} = 0.324 - 0.125 \cdot 10^{-2}(T_{sm} - 273). \tag{8}$$

These equations and the data of [5] allow one to determine α during the period of falling rate of convective drying.

NOTATION

α_s, α_m	are the coefficients of convective heat transfer for the period of constant drying rate and uncomplicated by mass transfer, $W/m^2 \cdot deg$;
$du/d\tau$	is the drying rate, kg/kg · sec;
ρ	is the conditional density of wood, kg/m^3;
r	is the specific heat of evaporation, J/kg;
t_m, t_s	are the temperature of medium and of surface of material, °C;
u, u_e, u_{cr}	are the mean current, equilibrium, and first critical water content, kg/kg;
c	is the specific heat, J/kg · deg;
Nu_s, Nu_m	are the Nusselt numbers for period of constant drying and for pure heat transfer, uncomplicated by mass transfer;
Re	is the Reynolds number;
l	is the characteristic dimension, m;
T_{sm}	is the absolute temperature of surface of material in period of constant drying rate, °K;
R	is the volume of medullary rays per total mass of wood, %;
a'	is the moisture diffusion coefficients, m^2/sec.

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