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WATER EVAPORATION RATES FROM THE END FACES OF BEECH WOOD AT DIFFERENT TEMPERATURES AND EQUILIBRIUM MOISTURE CONTENTS

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There are presented results of the research on the influence of equilibrium moisture content and temperature on the drying rate of beech wood in the longitudinal direction. The investigations were performed for laminar air flow. The drying rate was expressed by the flux density of evaporated moisture.

Key words: beech, wood drying, drying rate, temperature, equilibrium moisture content

INTRODUCTION

It was reported that in the extreme cases even 90% of sawn timber deliveries to furniture factories contain face checks growing during drying (Król 1988). The phenomenon of face checks occurring before starting the drying process or in the initial period of drying can be related to the much faster water transport in the longitudinal direction in comparison to the transverse direction. It is assumed that values of the permeability coefficient determining the rate of free water transport are 10 000 to 40 000 times greater in the longitudinal direction than in the transverse direction (Siau 1995).

The problem of face checks is particularly important during drying elements of the length varying from 0.3 to 0.4 m for parquet or furniture frames production. It may result in a large number of the elements defects in comparison to sawn timber. Therefore, even the whole packages of the elements may be rejected. Unfortunately, many of drying schedules, also that included in the still valid in Poland Instruction No

24 Tp-67 (Instrukcja... 1967), in the newer technological instruction of seasoning and technical drying of sawn timber (Czech and Miński 1993) or even schedules included in computer controlled dryers do not take into account the separate nature of the material. Therefore, the elements are dried in the same way as 30 to 35 mm thick sawn timber of a given species.

The unwanted effects of moisture evaporation from ends of logs, sawn timber or the elements can be reduced, as it is supposed, by more advanced methods of stresses development prediction. However, it requires data on changes of moisture content distribution in time. The data can be obtained from experiments or from mathematical modelling of drying, while values of water evaporation rates may be significant complementary data assisting stresses development prediction. Learning the influence of temperature and relative humidity of air on the rate of water evaporation from the end faces should help to predict moisture content distributions in the end face spaces of timber and therefore help in better modelling stresses development.

EXPERIMENTS

It is usually assumed that investigations of the influence of different factors on the drying rate should be performed in the way that allows to proceed moisture content changes in the whole mass of samples. Besides, samples should contain early and late wood. Satisfying that demands as a whole is of course impossible. However, it shows that dimensions of samples should not be too large, but containing basic elements of wood anatomical structure. It can be satisfied for hardwood samples when samples size in the longitudinal direction is equal to or smaller than two mean lengths of wooden fibers (Kass 1965). The mean length of wooden fibers is usually not longer than 1.2 mm (Siau 1984). For softwoods the limiting factor of the samples size in the same anatomical direction is the length of tracheids. The mean length of softwoods tracheids varies from 3.0 to 3.5 mm (Kollmann and Côté 1968). It means that during double-sided drying of samples the assumed size in the longitudinal direction should not exceed the double length of tracheids i.e. 6 to 7 mm. In order to satisfy the demand for softwoods and hardwoods, we assumed thickness of samples equal 5 mm. The described above criterion is also important because it allows for clear interpretation of results in order to distinguish the periods of the constant and the falling drying rates in the near-surface zone of wood.

The measurements were performed on the computerised stand containing the chamber with controlled temperature and relative humidity of air. The measured values of controlled parameters were recorded by the computer controlling the system. Changes of samples mass were also automatically recorded during experiments. The scheme of the experimental stand is presented in Fig. 1.

Samples of beech wood (*Fagus sylvatica* L.) were used in experiments. The choose of the species was motivated by the particular susceptibility of beech wood on face

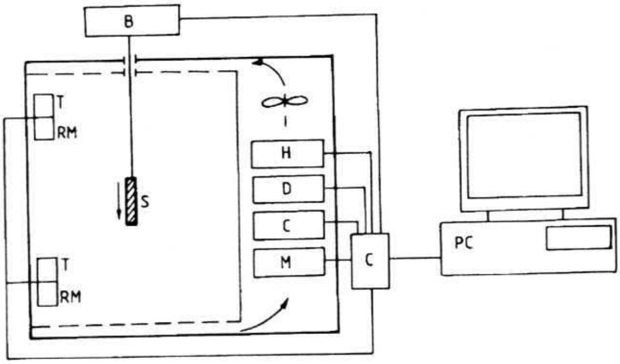

Fig. 1. Scheme of experimental stand: S - sample, B - balance, T - temperature sensor, RH - relative humidity sensor, H - heater, D - drying unit, C - cooler, M - moistening unit, C - a/d converter, PC - personal computer

Rys. 1. Schemat stanowiska badawczego: S - próbka, B - waga, T - miernik temperatury, RH - miernik wilgotności względnej, H - nagrzewnica, D - element osuszający, C - chłodnica, M - element nawilżający, C - przetwornik analogowo-cyfrowy, PC - komputer osobisty

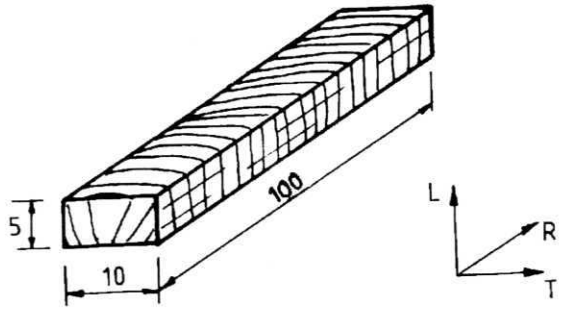

Fig. 2. Samples shape and dimensions

Rys. 2. Kształt i wymiary próbek

checks development during drying. Samples shape and dimensions are shown in Fig. 2. The samples were firstly soaked in distilled water in order to obtain the initial and uniform moisture content of ca. 120%.

After obtaining the initial moisture content the samples were placed in the chamber in air of constant velocity $w = 0.25$ m/s. The samples were linked to the balance by the connector. The measurements were done for given air parameters for the statistically significant number of samples (the number of samples was not lower than 8). Measurements of samples mass were automatic at time intervals depending on duration of a particular drying process. Fig. 3 presents an example of recorded values of temperature and relative humidity as well as changes of samples mass during a drying process.

The values of drying parameters were determined by taking into account industrial drying schedules as well as technical limitations of the experimental apparatus. The in-

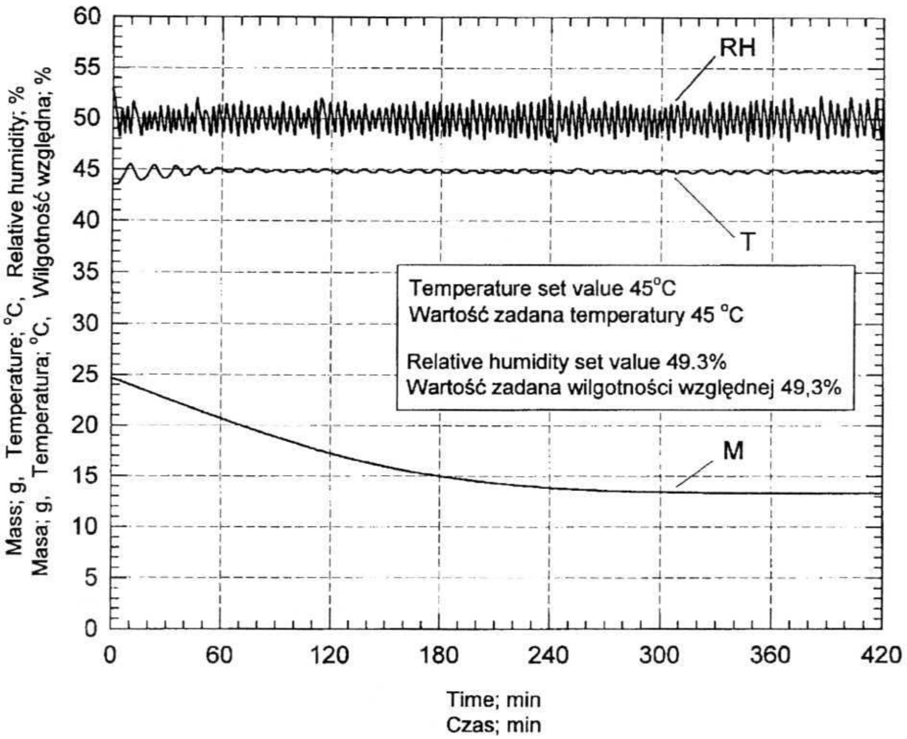

Fig. 3. Changes of samples mass and air parameters during a drying process (t = 45C, EMC = 8%)
Rys. 3. Zmiany masy próbek parametrów powietrza w czasie procesu suszenia (t = 45C, EMC = 8%)

ability to control relative humidity for temperatures lower than ambient air temperature and large water condensation on inner walls of the chamber for high temperatures were the most important limiting factors of obtaining drying parameters. Therefore, it was decided to make measurements for four values of temperature: 30, 45, 60, 75°C and four values of equilibrium moisture content: 4, 8, 12, 16%. Table 1 presents the values of air relative humidity for all drying experiments.

There were calculated flux densities of evaporated moisture $\dot{g}$; kg/(m^2·h) for all experiments i.e. for 57 drying processes. The calculated values were referred to the area of the end surface of samples. The influence of evaporation from the remaining surfaces was intentionally neglected. The flux density of evaporated moisture $\dot{g}$ was defined as follows:

$$\dot{g}_i = \frac{m_{i+1} - m_i}{A \cdot (\tau_{i+1} - \tau_i)} \qquad (1)$$

where: m; kg - mass, A; m^2 - surface area, τ ; h - time, i - step of mass and time measurement.

Table 1

Tabela 1

Air relative humidity in drying experiments

Wilgotność względna powietrza w czasie suszenia

Equilibrium moisture content; % Wilgotność równowagowa; %	Temperature; °C Temperatura; °C			
	30	45	60	75
	Relative humidity; % Wilgotność względna; %			
4	13.1	19.8	23.6	28.0
8	44.0	49.3	54.4	60.6
12	66.5	70.3	74.5	79.3
16	80.7	83.0	86.6	90.2*

* intensity of condensation resulted in rejection of the obtained results
intensywność kondensacji spowodowała odrzucenie otrzymanych wyników

The two characteristic runs of flux density of evaporated moisture are presented in Fig. 4. The first one is characterised by the distinct constant drying rate period (t = 30°C, EMC = 12%), the other one contains only the falling drying rate period (t = 30°C, EMC = 4%).

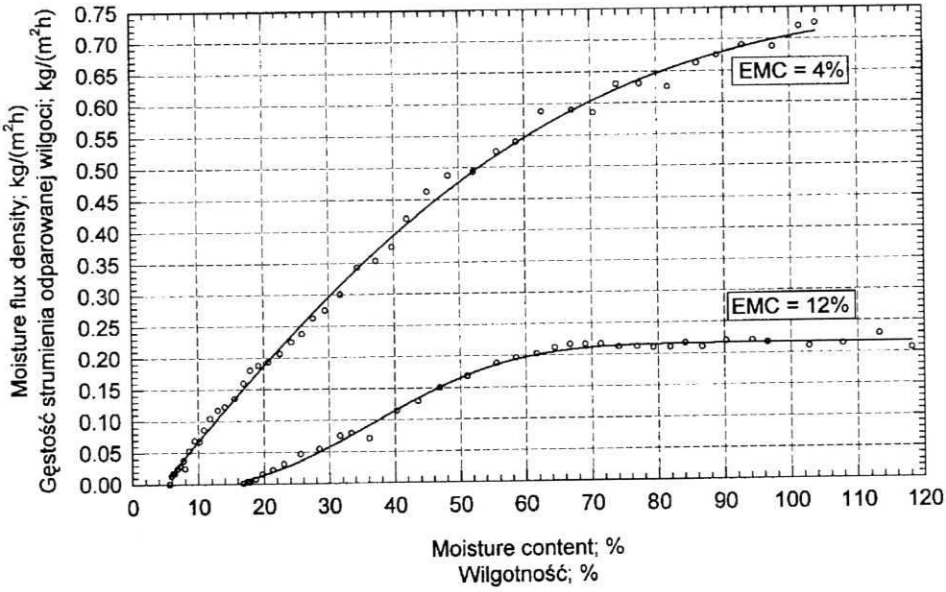

Fig. 4. The flux density of evaporated moisture vs. moisture content (t = 30°C, EMC = 12% and EMC = 4%)
Rys. 4. Gęstość odparowania wilgoci jako funkcja wilgotności (t = 30°C, EMC = 12% i EMC = 4%)

The values of flux density of evaporated moisture were approximated with the empirical model of the form:

$$\dot{g} = a + \frac{1}{2} b \left(1 + \text{erf} \frac{MC - c}{\sqrt{2} d} \right) \quad (2)$$

where: a, b, c, d - model coefficients, MC - moisture content, erf - error function. Table 2 presents the results of approximation for all processes at different temperatures and equilibrium moisture contents.

Table 2

Tabela 2

Coefficients of the approximated model (Eq. 2)

Współczynniki aproksymowanego modelu (równ. 2)

Equilibrium moisture content; % Wilgotność równowagowa; %	Temperature; °C Temperatura; °C	Parameters of the empirical model Parametry modelu empirycznego				
		a	b	c	d	R^2
4	30	-0.7359	1.5124	5.7508	50.3413	0.994
	45	-2.8956	3.9204	-32.7025	58.9691	0.993
	60	-21.0915	22.4062	-113.5552	75.3440	0.994
	75	-97.4085	99.0341	-170.5124	82.0818	0.991
8	30	-0.2159	0.6279	20.8589	27.7157	0.991
	45	-0.6790	1.2244	5.2598	34.6152	0.977
	60	-12.8930	13.5509	-92.7040	61.7981	0.996
	75	-10.6212	11.3236	-69.0631	51.5847	0.994
12	30	-0.0259	0.2399	35.9797	17.1614	0.966
	45	-0.0565	0.3435	30.9239	18.4368	0.981
	60	-0.3931	0.7015	9.9097	30.7938	0.988
	75	-0.8136	1.1924	-4.5785	37.1614	0.978
16	30	-0.0181	0.1102	40.7909	9.9425	0.927
	45	-0.0196	0.1492	41.4478	14.7677	0.978
	60	-0.0702	0.2517	31.8695	21.2936	0.990
	75	-	-	-	-	-

* intensity of condensation resulted in rejection of the obtained results
intensywność kondensacji spowodowała odrzucenie otrzymanych wyników

DISCUSSION

The results are obtained for laminar air flow (Re)≈100. Therefore, they determine the limiting values of flux density of evaporated moisture from the end faces. They let for the balance determination of moisture evaporation from the ends of sawn timber (precisely from thin layer of timber).

The values of flux density of evaporated moisture at temperature $t = 60^{\circ}C$ and selected equilibrium moisture contents as a function of wood moisture content together with the approximated empirical models are presented in Fig. 5. There is observed the period of the constant drying rate for equilibrium moisture contents of 12 and 16% and wood moisture contents much higher than the fiber saturation point (FSP). It means that, moisture evaporation from the surface was balanced by the rate of moisture transfer from the inner zone of wood and moisture content of surface was much higher than the FSP.

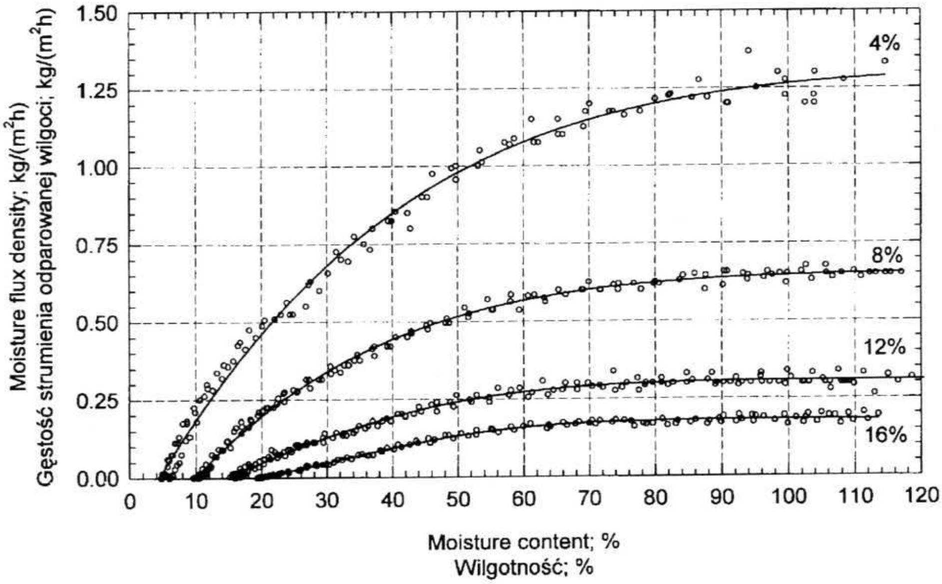

Fig. 5. The influence of equilibrium moisture content on moisture evaporation rate, temperature $t = 60^{\circ}C$
Rys. 5. Wpływ wilgotności równowagowej na szybkość odparowania wilgoci, temperatura $t = 60^{\circ}C$

Fig. 6 presents an example of the relationship between the flux density of evaporated moisture and temperature of drying for equilibrium moisture content of 4%. There were reported processes of the falling drying rate only.

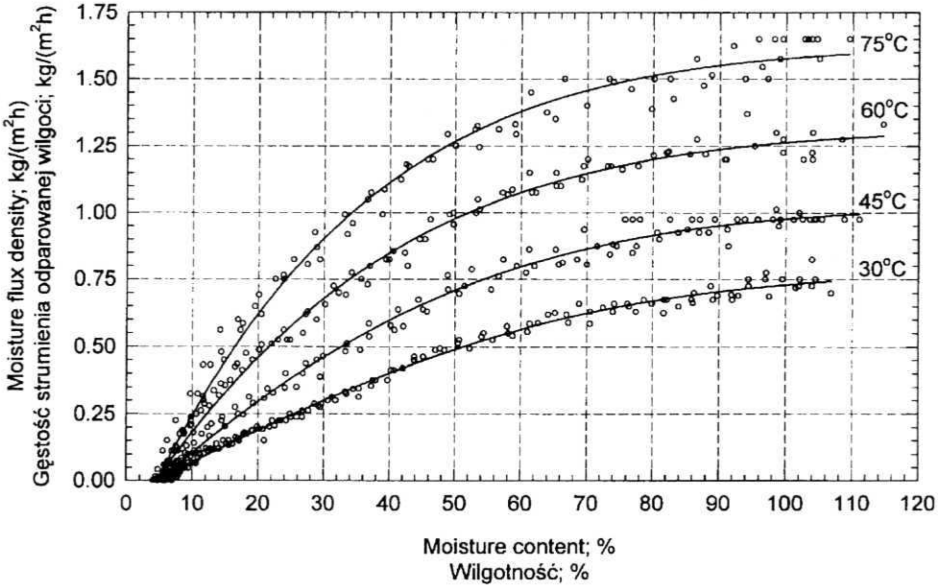

Fig. 6. The influence of temperature on moisture evaporation rate, equilibrium moisture content $EMC = 4\%$
Rys. 6. Wpływ temperatury na szybkość odparowania wilgoci, wilgotność równowagowa $EMC = 4\%$

CONCLUSIONS

1. The intensity of moisture evaporation from the end faces was quantitatively determined by the flux density of evaporated moisture $\dot{g}$ for the wide range of temperature and equilibrium moisture content.
2. The results of the empirical model approximation are sufficient to determine the boundary conditions for modelling of moisture content changes at the end faces of beech sawn timber.
3. The period of the constant drying rate was not reported for the majority of air parameters corresponding to industrial drying processes. In such cases, the evaporation front moves inward dried wood at all moisture contents. Therefore, the conditions for stresses development occur even for moisture contents very close to the initial.

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GĘSTOŚĆ ODPAROWANIA WILGOCI Z POWIERZCHNI CZOŁOWYCH DREWNA BUKA DLA RÓŻNYCH TEMPERATUR ORAZ WILGOTNOŚCI RÓWNOWAGOWYCH

Streszczenie

Badano szybkość odparownia wilgoci z powierzchni czołowej drewna. Pomiary prowadzono dla próbek z drewna bukowego o wymiarze charakterystycznym równym 2,5 mm (cienka warstwa). Wilgotność początkowa próbek była zawsze powyżej 100%. Parametry powietrza suszącego wynosiły odpowiednio: temperatura 30, 45, 60 oraz 75°C, wilgotność równowagowa 4, 8, 12 oraz 16%. Otrzymane wyniki wyrażono poprzez gęstość strumienia odparowanej wilgoci $\dot{g}$; kg/(m^2·h). Uzyskano dobrą korelację między modelem empirycznym a danymi doświadczalnymi dla wszystkich zrealizowanych procesów. Dla większości procesów nie stwierdzono występowania okresu stałej prędkości suszenia dla całego zakresu wilgotności drewna.

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