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MODELLING MOISTURE CONTENT CHANGES IN TIMBER DUE TO NATURAL VARIATION OF AMBIENT AIR PARAMETERS

Ryszard Guzenda, Wiesław Olek, Marta Gołębiewska

Department of Engineering Mechanics and Thermal Techniques,
The August Cieszkowski Agricultural University of Poznań

SYNOPSIS. The dry timber storage usually results in moisture content variation of wood before its further processing. The study presents results of numerical prediction of moisture content changes in already dried timber as induced by natural variation of ambient air parameters. The solution of the mass transfer problem was obtained for the variable boundary condition and the moisture content dependent diffusion coefficient. The validation of the modelling was made by the comparison of the results of the prediction to experimentally determined moisture content distributions of timber.

KEY WORDS: dry timber storage, Scots pine, European oak, modelling validation

INTRODUCTION

The investigations on moisture content changes in wood are mainly focused on timber drying. There can be found numerous publications on modelling heat and mass transfer during drying, stresses development causing surface and internal checking, energy consumption, drying quality, kiln drying operation (e.g. Vermaas 1992, Milota 1999, Keey et al. 2000). Much less attention is paid on investigations of moisture content changes in timber after drying, e.g. during long-lasting storage of dry timber before its further processing. The dry timber is usually stored in packages which are mainly placed in open sheds and less frequently in closed warehouses. The timber stored in open sheds is exposed to secondary moistening or drying. The direction of the moisture transfer depends on ambient air parameters. The air parameters are variable during a year and storage time of timber is very diversified. It causes distinct differences in the final moisture content of timber before further processing. It has also negative influence on quality of semi-finished and final products.

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The variation of the ambient air parameters is characterized by daily and yearly periodicities which are randomly disturbed by weather changes. Except the air parameters the mean moisture content is also influenced by timber dimensions, primary by thickness. When timber is stored in an open shed its moisture content changes due to the natural variation of the air parameters. HODGE (1960) found that in June timber obtains moisture content equal to 11.3%, while in January it increases to 20.8%. In the reported study the moisture content variation of timber was accompanied with the equilibrium moisture content changes from 10% to 25%. TSUOMIS (1960) investigated variation of the mean moisture content of timber stored in closed warehouses. The registered changes were from 9% to 14.5% for samples of thickness varying from 1 to 5 cm. According to HANN et AL. (1970) moisture content changes of timber structural members exposed to the ambient air parameters variation in USA were from 6.7% to 11.8% for loft exposure and from 9.2% to 25.8% for outside. For the conditions of European climate MEIERHOFER and SELL (1979) as well as MEIERHOFER (1980) found that timber structural members placed under a roof obtained moisture contents varying from 11% to 19%. GANOWICZ and GUZENDA (1996) had performed investigation for structural elements placed under a roof with yearly variation of the equilibrium moisture content from 5% to 25%. The obtained moisture content of timber surface was form 9% to 19%. The results showed the wide range of the potential changes of timber moisture content depending on the climate conditions as well as on the exposure. The similar relations can be expected for long-lasting storage of dry timber in open sheds. However, there is a lack of the relations for dry timber which could predict moisture content changes for variable parameters of the ambient air.

The objective of the present study was to predict moisture content changes of dry timber as induced by natural variation of ambient air parameters as well as to validate the modelling by the comparison of the results of the prediction to experimentally determined moisture content distributions of timber.

MOISTURE TRANSPORT MODEL

Moisture content of dry timber stored in open sheds, and therefore protected from rainfall, never exceeds the fiber saturation point. It means that the timber contains only one subsystem of water, i.e. bound water. Moreover, moisture is primarily transferred by wide side surfaces of timber. In such conditions the moisture transport can be described by diffusion in the R^1 space. Thus, the mathematical model of the process is given by the following transient form of the second Fick's law:

$$\frac{\partial M}{\partial t} = \frac{\partial}{\partial x}\left(D\frac{\partial M}{\partial x}\right) \tag{1}$$

with the initial condition:

$$M(x,\ 0) = M_0, \qquad x \in \overline{\Omega} \tag{2}$$

and the third kind boundary condition:

$$\left(-D\frac{\partial M}{\partial x}\right) = \sigma \cdot [M(x,\ t) - M_{\infty}], \quad (x,\ t) \in \Gamma \times [l,\ t_F] \tag{3}$$

$$\left(-D\frac{\partial M}{\partial x}\right) = \sigma \cdot [M(x,\ t) - M_{\infty}], \quad (x,\ t) \in \Gamma \times [-l,\ t_F] \tag{4}$$

The analysis of the experimentally determined values of the bound water diffusion coefficient in wood shows their high diversification (e.g. COMSTOCK 1963, CHOONG 1965, KIESSL and MÖLLER 1988, 1989 a, b, SKAAR 1988, VANEK and TEISCHINGER 1989, EL KOUALI et AL. 1992, MOUNJI and BOUZON 1992, SIAU 1995, LU and LEICESTER 1997, MEIJER and MILITZ 2000, 2001). The lowest values of the coefficient of $9.6 \cdot 10^{-11}$ m^2/s were reported by CHOONG (1965) for temperature of 40°C and the mean moisture content of 5%, while the highest, i.e. $1.7 \cdot 10^{-7}$ m^2/s, were given by SIAU (1995) for moisture content of 20%. Moreover, the assumption, that the coefficient does not depend on moisture content, is not valid in the case of wood. Thus, it was decided to apply in the modelling the semi-structural model relating the diffusion coefficient (D) to moisture content SIAU (1995):

$$D = \frac{1}{1 - v_a} \cdot \frac{D_{BT} D_v}{D_{BT} + D_v(1 - \sqrt{v_a})} \tag{5}$$

where: D_{BT} – diffusion coefficient in cell wall exponentially depending on moisture content,
D_v – vapour diffusion coefficient in moist air of lumens relating air parameters and moisture content through wood hygroscopic properties,
v_a – porosity.

EQUILIBRIUM MOISTURE CONTENT

The credible data on the equilibrium moisture content are another factor deciding on the accuracy of the prediction of moisture content changes of dry timber. The data have special importance as the equilibrium moisture content changes with seasons. However, the variation is highly influenced by random changes of ambient air parameters. Figure 1 presents examples of daily changes of the equilibrium moisture content in three different months. The presented data were registered in Poznań. The changes in winter are characterized by long periods of high and almost constant equilibrium moisture content. In late spring and summer the high daily variation is observed. Moreover, it is accompanied by very low values of the equilibrium moisture content lasting several hours at day-time as well as with short periods of high values of the equilibrium moisture content at night-time. Autumn is characterized by the similar periodic changes but the periods of the high equilibrium moisture content are much longer.

The boundary value problem of diffusion given by equations (1)-(5) was numerically solved for varying mean daily values of the equilibrium moisture content, which were calculated for measured values of air temperature and relative humidity using the Hailwood-Horrobin model adapted for wood by Simpson (1973).

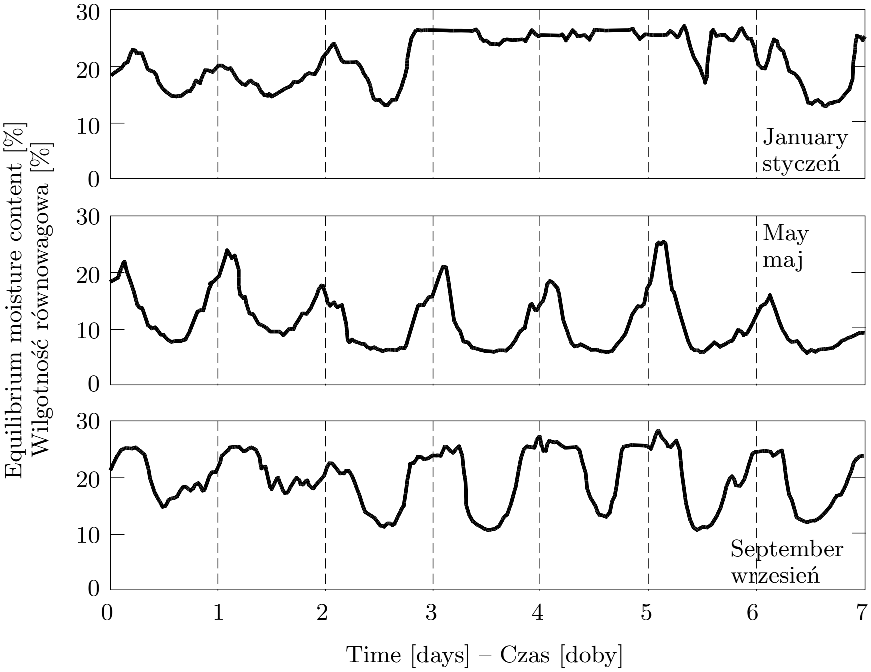

Fig. 1. Daily changes of the equilibrium moisture content
Rys. 1. Dobowe zmiany wilgotności równowagowej

NUMERICAL SOLUTION OF THE DIFFUSION PROBLEM

The boundary value problem of diffusion was solved using the finite element method. The operational form of the model described by equations (1)-(5) was obtained after approximation of the geometric domain with isoparametric elements. It was completed with the recurrence approximation of the time domain. The final operational model was given as the set of algebraic equations, in which the mean moisture content values at selected time instances were the values sought. The algorithm for solving the boundary value problem was described in details by Weres (1997) and Weres et al. (1997). On the basis of the algorithm a computer program was designed to solve the diffusion problem. It was implemented in Fortran 95 and coded in Lahey/Fujitsu Fortran 95 environment.

RESULTS

The prediction of the moisture content changes was performed for Scots pine and European oak wood of two different thickness of 25 and 50 mm. Figure 2 presents the mean moisture content changes in time as obtained for two extreme cases, i.e. 50 mm thick European oak and 25 mm thick Scots pine. Oak timber was used in the analyses as a typical hard drying European hardwood species, while pine timber was the most popular softwood species. The obtained results were presented together with the experimentally determined changes of the equilibrium moisture content which were registered in Poznań in 2001.

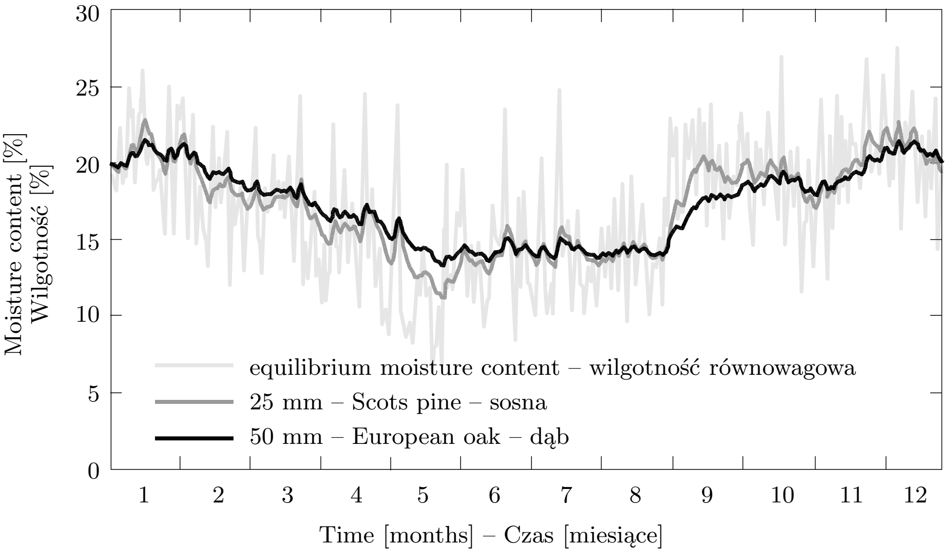

Fig. 2. Predicted changes of timber mean moisture content together with variation of the experimental values of the equilibrium moisture content
Rys. 2. Prognozowane zmiany średnich wilgotności drewna wraz ze zmianami eksperymentalnie wyznaczonych wartości wilgotności równowagowych

The results of the numerical modelling were compared to the experimental results of the moisture content changes of timber stored in an open shed. The experiments were made for both timber species and thicknesses. During the first year of timber storing in an open shed the mean moisture content dropped below the fiber saturation point and the moisture content gradients in boards were minimized. Thus, the mass of selected boards in packages was collected every week during the second year of timber storing. The oven-dry mass of timber was determined at the end of the experiment and the mean moisture contents were calculated. Figure 3 shows an example of the comparison between predicted and experimentally determined values of the mean moisture content for storing 50 mm thick oak timber. The comparison was quantified by calculating the local relative error defined as:

$$e(t_i) = 100\frac{|M_{\mathrm{exp}}(t_i) - M_{\mathrm{pred}}(t_i)|}{M_{\mathrm{exp}}(t_i)}, \quad i = 1, \ldots, NT \tag{6}$$

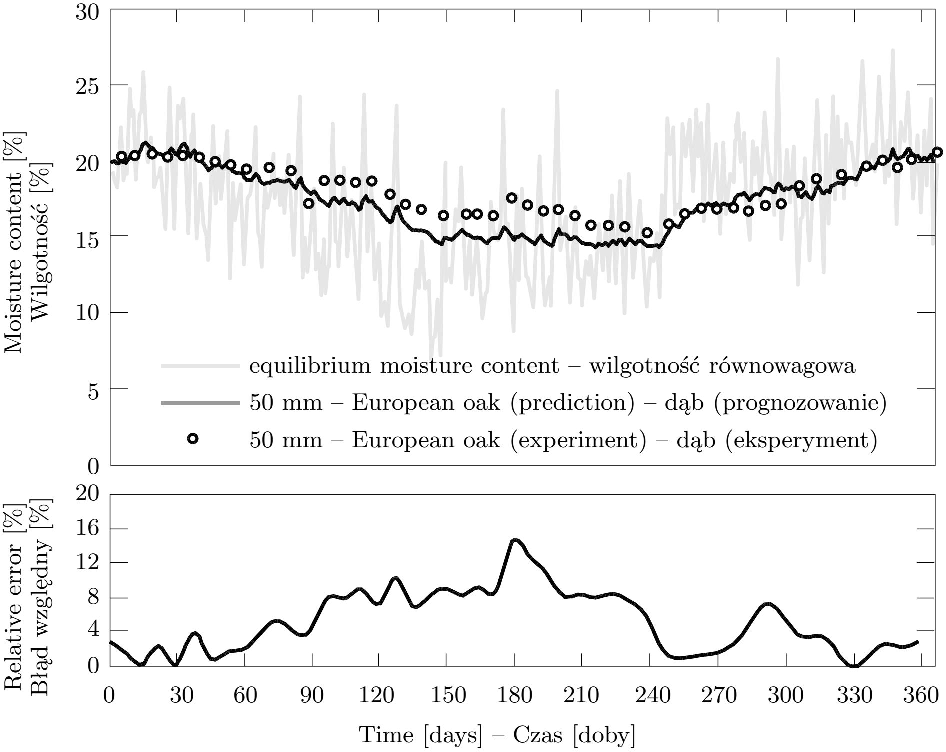

Fig. 3. Predicted and experimental changes of mean moisture content of 50 mm thick European oak (upper plot) together with quantification of the prediction similarity (lower plot)
Rys. 3. Prognozowane oraz określone eksperymentalnie zmiany średnich wilgotności drewna dębu o grubości 50 mm (górny wykres) wraz z ilościowym określeniem podobieństwa prognozowania (dolny wykres)

CONCLUSIONS

The good similarity was obtained between predicted and experimentally determined values of the mean moisture content of stored timber. It was primary due to the application of the experimentally determined values of the equilibrium moisture content in modelling the diffusion process. The present form of the model can be used for practical prediction of the moisture content changes of timber long-time stored in open sheds. However, the further improvement of the prediction similarity can be obtained after introducing the influence of randomly changing temperature.

SYMBOLS

D – diffusion coefficient, m^2/s
D_{BT} – diffusion coefficient in cell wall, m^2/s
D_v – vapour diffusion coefficient in moist air of lumens, m^2/s
l – half-thickness, m
M – moisture content, kg/kg
M_{exp} – experimental moisture content, kg/kg
M_{pred} – predicted moisture content, kg/kg
M_∞ – equilibrium moisture content, kg/kg
M_0 – initial water content, kg/kg
NT – number of time intervals,
t – time, s
t_F – final time, s
v_a – porosity, –
x – space dimension, m

Greek symbols
Γ – the boundary,
σ – surface emission coefficient, m/s
$\overline{\Omega}$ – geometric domain of the R^1 space with the boundary,

REFERENCES

Choong E.T. (1965): Diffusion coefficients of softwoods by steady-state and theoretical methods. For. Prod. J. 15: 21-27.

Comstock G.L. (1963): Moisture diffusion coefficients in wood as calculated from adsorption desorption, and steady-state data. For. Prod. J. 13: 97-103.

El Kouali M., Bouzon J., Vergnaud J.M. (1992): Modelling the process of absorption and desorption of water in a sheet beyond the fiber saturation point by considering a two-dimensional transfer. Holzforschung 46: 187-192.

Ganowicz R., Guzenda R. (1996): Destrukcyjny wpływ zmian wilgotności otoczenia na drewniane warstwowo klejone konstrukcje. Mat. symp. nauk. „Drewno i materiały drewnopochodne w konstrukcjach budowlanych”. 5-6.09.1996, Szczecin-Międzyzdroje: 71-80.

Hann R.A., Oviatt A.E., Markstrom D.M., Duff I.E. (1970): Moisture content of laminated timbers. US Forest Service, Res. Paper FPL 149.

Hodge R.E. (1960): The moisture content of roof timber variations in heated and unheated buildings. Timb. Technol. 68: 416-419, 435.

Keey R.B., Langrish T.A.G., Walker J.C.F. (2000): Kiln-drying of lumber. Springer, Berlin.

Kiessl K., Möller U. (1988): Stoffwertsammlung, Auswertung und rechnerische Vorbereitung zur Untersuchung des Feuchteverhaltens von Bauteilen aus Holz und Holzwerkstoffen. Fraunhofer – Institut für Bauphysik, IBP-Bericht FtB-3.

Kiessl K., Möller U. (1989 a): Zur Berechnung des Feuchteverhaltens von Bauteilen aus Holz und Holzwerkstoffen. Selektion feuchtetechnischer Stoffeigenschaften. Holz a. Roh- u. Werkst. 47: 317-322.

Kiessl K., Möller U. (1989 b): Zur Berechnung des Feuchteverhaltens von Bauteilen aus Holz und Holzwerkstoffen. Stoffeigenschaftsfunktionen und deren rechnerische Anwendung. Holz a. Roh- u. Werkst. 47: 359-363.

Lu J.P., Leicester R.H. (1997): Effect of cyclic humidity exposure on moisture diffusion in wood. Wood Fiber Sci. 29: 68-74.

Meierhofer U.A. (1980): Wetterbeanspruchte Holzbauteile. Schweiz. Ing. Arch. 8: 151-157.

Meierhofer U., Sell J. (1979): Physikalische Vorgänge in wetterbeanspruchten Holzbauteilen. 2 Mitteilung: Tragende Holzbauteile im Freien unter Dach. Holz a. Roh- u. Werkst. 37: 227-234.

Meijer de M., Militz H. (2000): Moisture transport in coated wood. Part 1. Analysis of sorption rates and moisture content profiles in spruce during liquid water uptake. Holz a. Roh- u. Werkst. 58: 354-362.

Meijer de M., Militz H. (2001): Moisture transport in coated wood. Part 2. Influence of coating type, film thickness, wood species, temperature and moisture gradient on kinetics of sorption and dimensional change. Holz a. Roh- u. Werkst. 58: 467-475.

Milota M.R. (1999): Drying wood: the past, present, and future. Proc. 6th Int. IUFRO Wood Drying Conf., 25-28.01.1999, Stellenbosch, South Africa: 1-10.

Mounji H., Bouzon J. (1992): Absorption and desorption of water in a wood beam, below and beyond the fiber saturation point, with three-dimensional diffusion. Holzforschung 46: 439-447.

Siau J.F. (1995): Wood: influence of moisture on physical properties. Virginia Tech., Blacksburg.

Simpson W.T. (1973): Predicting equilibrium moisture content of wood by mathematical models. Wood Fiber 5: 41-49.

Skaar C. (1988): Wood-water relations. Springer, Berlin.

Tsuomis G. (1960): Untersuchungen über die Schwankungen des Feuchtigkeitsgehaltes von lufttrockenem Holz. Holz a. Roh- u. Werkst. 18: 415-422.

Vanek M., Teischinger A. (1989): Diffusionskoeffizienten und Diffusionswiderstandszahlen von verschiedenen Holzarten. Holzforsch. Holzverwert. 41: 3-6.

Vermaas H.F. (1992): Developments in wood drying theory and practice since Seattle 1989. Proc. 3rd Int. IUFRO Wood Drying Conf., 18-21.08.1992, Vienna, Austria: 1-10.

Weres J. (1997): Finite element analysis of heat and mass transport in biological materials. Proc. 13th Polish Conf. “Computer Methods in Mechanics”. Ed. A. Garstecki, Poznań University of Technology 4: 1387-1392.

Weres J., Dworecki Z., Łoboda M. (1997): An algorithm for solving inverse problems of heat and mass transport in agricultural products. Computat. Meth. Sci. Technol. 3: 73-80.

MODELOWANIE ZMIAN WILGOTNOŚCI DREWNA SPOWODOWANYCH NATURALNYM WAHANIEM PARAMETRÓW POWIETRZA OTOCZENIA

Streszczenie

Zmiany wilgotności drewna po suszeniu są bardzo rzadko badane. Składowanie drewna wysuszonego powoduje zwykle zmiany jego wilgotności przed dalszą obróbką. Zmiany te zależą od pory roku, sposobu oraz czasu składowania. Niekontrolowane zmiany wilgotności drewna powodują obniżenie jakości produktów, straty materiałowe oraz wzrost kosztów produkcji ze względu na wymagane dodatkowe suszenie. W pracy przedstawiono wyniki numerycznego modelowania zmian wilgotności wysuszonego drewna spowodowane naturalnymi wahaniami parametrów powietrza otoczenia. Rozwiązanie zagadnienia wymiany masy uzyskano dla zmiennych wartości warunku brzegowego oraz współczynnika dyfuzji zmieniającego swe wartości wraz z wilgotnością. Walidację modelowania wykonano przez porównanie wyników modelowania z doświadczalnie określonymi zmianami wilgotności drewna.

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Authors' address:
Dr. Ryszard Guzenda,
Dr. Wiesław Olek,
Marta Gołębiewska
Department of Engineering Mechanics and Thermal Techniques
The August Cieszkowski Agricultural University of Poznań
ul. Wojska Polskiego 38/42
60-627 Poznań
Poland
e-mail: olek@au.poznan.pl