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W. OLEK*, J. WERES**

COMPUTER—AIDED IDENTIFICATION OF TRANSPORT PROPERTIES OF WOOD AND WOOD-BASED PANELS

KOMPUTEROWO WSPOMAGANA IDENTYFIKACJA WŁAŚCIWOŚCI FIZYCZNYCH DREWNA I MATERIAŁÓW DREWNOPOCHODNYCH

The concept of solving inverse heat and mass transfer problems with the use of optimization techniques and adequate mathematical models corresponding to direct problems of transport was applied to identify transport properties of solid wood and wood-based panels. The paper presents examples of the application of the inverse method in the following areas: thermal conductivity of solid wood in the three principal anatomic directions as a function of temperature, the diffusion coefficient dependency on the bound water content together with the boundary condition estimation, and gas permeability of mats during pressing of wood-based panels.

Keywords: x ray diffraction, dislocation densities, rolled fcc and bcc metals, texture components.

W celu identyfikacji właściwości fizycznych drewna i materiałów drewopochodnych zastosowano metodę rozwiązywania zagadnień odwrotnych wymiany ciepła i masy wraz z technikami optymalizacyjnymi jak i modelami matematycznymi odpowiadającymi zagadnieniom prostym. Artykuł przedstawia przykłady zastosowań metody zagadnienia odwrotnego w następujących obszarach: określenie wartości współczynnika przewodzenia ciepła litego drewna jako funkcji temperatury dla trzech głównych kierunków anatomicznych, wyznaczenie zależności współczynnika dyfuzji od zawartości wody związanej w drewnie wraz z identyfikacją współczynnika warunku brzegowego oraz określenie w trakcie procesu prasowania przepuszczalności wobec gazów kobierców służących do wytwarzania materiałów drewopochodnych.

Symbols

C — capacitance properties,
h — convective coefficient,

* DEPARTMENT OF MECHANICAL ENGINEERING AND THERMAL TECHNIQUES
** DEPARTMENT OF AGRICULTURAL ENGINEERING, AGRICULTURAL UNIVERSITY OF POZNAŃ, UL. WOJSKA POLSKIEGO 28, 60-637 POZNAŃ, POLAND

k_L — thermal conductivity for the longitudinal direction,
k_R — thermal conductivity for the radial direction,
k_T — thermal conductivity for the tangential direction,
K_H — horizontal gas permeability,
K_V — vertical gas permeability
$\mathbf{K}$ — conductivity vector,
$\mathbf{n}$ — unit vector normal to the surface $delta\Omega$, directed outward,
NT — number of time intervals,
S — objective function,
t — temperature,
w — weight function,
$\mathbf{x}$ — coordinates of a point in the orthocartesian system of coordinates,
τ — time,
τ_F — final time,
ϕ — driving force (i.e. potential) of the processes represented by temperature (t), moisture content (M) or air pressure (p) at point $\mathbf{x} \in \Omega$ and time $\tau \in (0, \tau_F]$,
ϕ_{exp} — experimental values of driving force,
ϕ_{pred} — predicted values of driving force,
ϕ_s — driving force at point $\mathbf{x} \in \partial\Omega$ and time $\tau \in (0, \tau_F]$,
ϕ_0 — driving force at point $\mathbf{x} \in \Omega$ and time $\tau = 0$,
ϕ_∞ — driving force at points outside the boundary layer of Ω at time $\tau \in (0, \tau_F]$,
Ω — domain of the body examined in the three-dimensional euclidean space,
$\partial\Omega^{I}$ — boundary of the domain Ω for the boundary condition of the first kind,
$\partial\Omega^{III}$ — boundary of the domain Ω for the boundary condition of the third kind.

1. Introduction

Wood is a complex natural copolymer consisting of cellulose, lignin, hemicelluloses, and minor amounts of extraneous materials. It is also one of a few renewable materials having wide application in engineering. The complex structure of the copolymer reveals in submicroscopic, anatomical as well as macroscopic level. It results in high anisotropy, periodical variation of properties etc. However, the wood density variation is the most important practical feature influencing majority of its properties. The variation is observed among species, between trees of the same species and between pieces from the same tree. The periodic density variation of the gradient character is observed within annual rings of species with distinguished earlywood and latewood. These features are responsible for inhomogeneous wood properties and serious problems in the practical application of the material. Therefore, solid wood is very often reengineered into wood-based panels (composites) in order to obtain predictable properties of the material. Various panels are made of wood fibers, particles, strands or veneer bonded with adhesives in a hot pressing process (Wood handbook... 1999).

The schedules of hot pressing are used to create the proper density profiles of panels in their thickness.

The standard experimental methods for determination of the transport properties of wood and wood-based panels are usually laborious, difficult to apply, and often generate significant inaccuracy in results due to the assumptions required for the application of the methods (e.g. Weres et al. 2000, Olek 2003). An alternative method was recently applied by the authors. The method is based on the concept of solving the inverse heat and mass transfer problems. It has already beeb shown that the application of the method resulted in significant improvement of the accuracy of the properties determination (e.g. Olek et al. 2003, Olek et al. in press).

The objective of the study was to present the application of the developed inverse method for evaluating the transport properties of wood and wood-based panels.

2. Material

The analyses were performed for solid wood of Scots pine (*Pinus sylvestris* L.) and European beech (*Fagus sylvatica* L.) as well as mats used for producing particleboards, fiberboards and Oriented Strand Boards (F r ü h w a l d et al. 2002, O l e k et al. 2003, O l e k et al. in press).

3. Methods

The method of the inverse analysis required developing the structural models of the analyzed processes, here transport of heat and mass. The models were represented by quasi-linear parabolic partial differential equations, the initial and the first and/or third kind boundary conditions and supplemental empirical formulas for already known properties. The mathematical form of the models was as follows

$$C\frac{\partial \phi}{\partial \tau} - \nabla (\mathbf{K} \cdot \nabla \phi) = 0, (\mathbf{x}, \tau) \in \Omega \times (0, \tau_F], \tag{1}$$

$$\phi(\mathbf{x}, 0) = \phi_0(\mathbf{x}), (\mathbf{x}) \in \Omega, \tag{2}$$

$$\phi(\mathbf{x}, \tau) = \phi_s(\mathbf{x}), (\mathbf{x}, \tau) \in \partial\Omega^I \times (0, \tau_F], \tag{3}$$

$$\mathbf{K}(\nabla\phi)\mathbf{n} + h(\phi - \phi_\infty) = 0, (\mathbf{x}, \tau) \in \partial\Omega^{III} \times (0, \tau_F]. \tag{4}$$

The operational form of the models (1) — (4) was obtained by the application of the finite element method using isoparametric, curvilinear, 3D-space elements (rectangular prisms), absolutely stable three-point recurrence scheme in time and iteration procedures to deal with the quasi-linearity of equations at each time step. The final form of the operational models was given as the sets of algebraic equations in which the nodal values of the driving force (i.e. temperature, moisture content or pressure) at selected time instants were the values sought (W e r e s et al. 2000).

The method also required collecting sets of experimental data of the driving force in selected locations and specified time instants during the investigated transport processes occurring in wood or wood-based panels. The experimental data as well as the results of the direct problem solution were used to calculate the objective function defined as

$$S = \sum_{i=1}^{NT} w_i \left[\phi_{exp}(\tau_i) - \phi_{pred}(\tau_i)\right]^2. \quad (5)$$

The optimization procedure was used to determine the minimum of the objective function with respect to the mathematical model coefficients subject to estimation.

The original software was developed according to the presented method. The computer program was implemented and coded in Lahey/Fujitsu Fortran 95.

4. Results

The inverse analysis of heat and mass transfer was performed for several case studies in order to present the ability of the method to identify transport properties of materials with complex structure and variable density. The obtained results were grouped into three areas presented below.

Thermal conductivity of solid wood

The property was simultaneously identified in the three principal anatomic directions. The thermal conductivity was expressed in W/(m · K) and given by sets of functions of wood temperature in °C. The results obtained for European beech W e r e s et al. 2000) were

$$k_T = 0.19933 + 0.18888 \cdot 10^{-3} \cdot t \quad (6)$$

$$k_R = 0.19958 + 0.33211 \cdot 10^{-3} \cdot t \quad (7)$$

$$k_L = 0.29937 + 0.70147 \cdot 10^{-3} \cdot t \quad (8)$$

while for Scots pine (O l e k et al. 2000)

$$k_T = 0.1989 + 0.8314 \cdot 10^{-4} \cdot t \quad (9)$$

$$k_R = 0.1990 + 0.8393 \cdot 10^{-4} \cdot t \quad (10)$$

$$k_L = 0.2991 + 0.6184 \cdot 10^{-4} \cdot t \tag{11}$$

The obtained models proved their high usefulness in heat transfer modeling (O l e k et al. 2003). The performed analysis of similarity between the results of experiments and modeling made for different sets of empirical models of wood thermal conductivity showed that the best accuracy of the temperature prediction was obtained for the thermal conductivity models developed in the inverse heat transfer problem approach (in most cases, the relative error of predictions was significantly under the level of 2%).

Bound water diffusion coefficient of solid wood

The standard cup or sorption methods of the bound water diffusion coefficient determination in wood do not provide credible results on that coefficient as well as on the boundary condition. It is primary due to the simplifications in the applied analytical solution required by the methods. It causes significant errors leading to false values of the diffusion coefficient as well as the boundary condition (Söderström and Salin 1993). The inverse identification of the diffusion coefficient, which was made for Scots pine and European beech (O l e k and W e r e s 2001, O l e k et al. 2005), allowed not only determining the coefficient as a function of bound water content in the three principal anatomic directions but also estimating the convective boundary coefficient (i.e. emission factor). The obtained improvement of the diffusion coefficient identification can be illustrated by the comparison of the experimental results to the results of diffusion modeling made for the coefficients determined with the use of the cup method (O l e k 2003) and the inverse approach (O l e k and W e r e s 2001) — Figure 1.

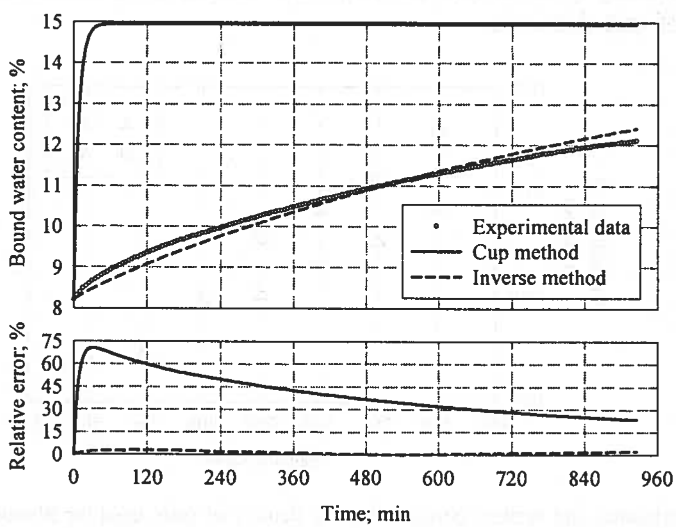

Fig. 1. Validation of the diffusion coefficient determination (experimental data vs. bound water content predictions for two variants of the identification, i.e. the cup and the inverse methods)

The other probable factor influencing the diffusion coefficient values and therefore its inverse identification is a history of adsorption and desorption of bound water in wood. It was recently proved (B o n a r s k i and O l e k 2004) that the cycling changes of the bound water in wood are accompanied by rearrangement of the submicroscopic structure. The reported analysis consisted of the cycling sorption experiments followed by the texture examination. The (101), (010) and (001) pole figures were registered in X-ray diffraction experiments and next used as input data in determining the texture function (here the Orientation Distribution Function) as well as in deriving the complete and inverse pole figures. The obtained results let to observe the additional ordering of cellulose crystalline areas, which was not accompanied with changes of the degree of crystallinity but with the rotation of the areas around the longitudinal axis of microfibrils. The additional ordering of the cellulose is not only responsible for reduction of sorption hysteresis but also for possible changes in the bound water diffusion coefficient.

Gas permeability of mats during wood-based panels pressing

The schedules of hot pressing are among others responsible for creating the desired density profiles of wood-based panels. However, their construction has to take into account changes in gas permeability of mats as the densification progresses during hot pressing. The traditional methods for the permeability determination require performing measurements for separate samples for a single direction of a mat (i.e. horizontal or vertical) and at each level of density of pressed mats. This makes it impossible to preserve continuum of the material for the whole range of density variation. The application of the inverse method enabled determining, for a single sample, coefficients of the permeability in the horizontal (K_H) and vertical (K_V) directions as well as for a wide range of mat densities.

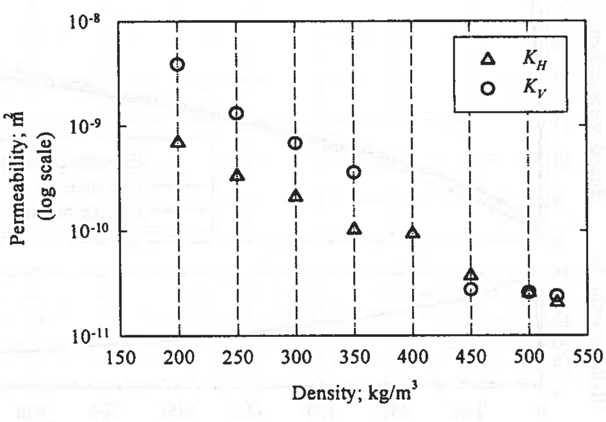

Fig. 2. Horizontal and vertical permeability vs. density of mats used for fiberboard production

Figure 2 presents an example of results obtained during the inverse identification of permeability of mats used for fiberboard production. The presented values were obtained during a single run of densification. The applied method let to separate permeability values for the two principle directions. The same analysis was made for several replications as well as mats used for producing particleboards, fiberboards and Oriented Strand Boards (F r ü h w a l d et al. 2002).

5. Final remarks

The application of the inverse method for identifying transport properties of solid wood and wood-based panels allowed improving accuracy of determining the properties. The method can handle transient character of the transport processes, boundary conditions of the first and third kind, heterogeneity, anisotropy and geometric irregularity of three-dimensional objects, and dependence of the transport coefficients on the driving force of the processes. The method can significantly improve accuracy of determination transport properties as compared to the traditionally used methods.

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