IDENTIFICATION OF EFFECTIVE DIFFUSIVITIES IN ANISOTROPIC MATERIAL OF PINE WOOD DURING DRYING WITH SUPERHEATED STEAM

Robert Adamski, Zdzisław Pakowski

Department of Heat and Mass Transfer Processes, Faculty of Process and Environmental Engineering, Lodz Technical University, Wólczańska 213/215, 90-924 Lodz, Poland
adamski@wipos.p.lodz.pl, pakowski@wipos.p.lodz.pl

Abstract: Simulation of a 3D drying of anisotropic solids requires diffusivities of moisture in all three directions to be known. These are seldom available in the range of temperatures and moisture contents of interest. This paper presents methodology of identification of these diffusivities in wood in superheated steam drying and the results for wood of Pinus silvestris at steam temperature 160°C and atmospheric pressure. Radial diffusivity (across fibers) is 30% less than the axial one (along fibers) while tangential diffusivity is two orders of magnitude smaller.

Keywords: moisture diffusion, FEM model, inverse problem, pinus silvestris

INTRODUCTION

Numerous capillary-porous materials are anisotropic especially when they are of botanical origin like wood. Anisotropy causes sometimes significant differences between transport coefficients in three spatial directions. It is commonly known that transport of water in wood is higher along than across fibers.

In simulation of momentum heat and mass transfer in wood a 3D model is therefore required although 2D (Boukadida N., et al., 1995) and 1D models are also used. Assuming that water transport in wood is described by the Fick equation (this assumption is approximate but often employed eg. Datta A.K., 2007)

\[
j_{eff}^j = \left( -D_x \frac{\partial X}{\partial x} + D_y \frac{\partial X}{\partial y} + D_z \frac{\partial X}{\partial z} \right)
\]

and splitting each term into liquid phase and vapor phase contributions (Kolhapure N.H., et al., 1997) we obtain

\[
j_{eff}^j = j_{eff}^{jL} + j_{eff}^{jV} = \\
-\left( D_{Vx} \frac{\partial X}{\partial x} + D_{Vy} \frac{\partial X}{\partial y} + D_{Vz} \frac{\partial X}{\partial z} \right) + \\
-\left( D_{Lx} \frac{\partial X}{\partial x} + D_{Ly} \frac{\partial X}{\partial y} + D_{Lz} \frac{\partial X}{\partial z} \right) = \\
= -\left( D_{Vx} + D_{Lx} \right) \frac{\partial X}{\partial x} - \left( D_{Vy} + D_{Ly} \right) \frac{\partial X}{\partial y} + \\
- \left( D_{Vz} + D_{Lz} \right) \frac{\partial X}{\partial z} = -D_{eff} \frac{\partial X}{\partial x} + \\
- D_{eff} \frac{\partial X}{\partial y} - D_{eff} \frac{\partial X}{\partial z}
\]

A similar expression can be written for cylindrical and spherical geometry. The effective diffusivities can be identified experimentally (Erriguible A., et al., 2006). In this work the effective diffusivities in radial, axial and tangential direction in wood of common pine (Pinus silvestris) were determined experimentally.

MATERIAL AND EXPERIMENTS

Material

Wood of a freshly fallen (winter season) 6 year old common pine (Pinus silvestris) was used, a single branch of cylindrical geometry (bark removed) 22 mm in diameter.

Experiments

A set-up for superheated steam drying at atmospheric pressure described elsewhere (Adamski, Pakowski, 2008) was used in the experiments. Drying kinetics obtained by in situ weighing of the sample without
thermocouples was obtained at steam temperature 160°C and velocity 4.5 cm/s. Steam flow was vertical and sample main axis was horizontal. In the same experiment another identical sample with installed five thermocouples was used for measuring temperature distributions. Experiments with water transport in axial, radial and all three directions were performed. Unidirectional transport was forced by insulating the other surfaces with an epoxy layer. Measuring only tangential flow was impossible.

RESULTS AND DISCUSSION

Experimental results

The results of measured kinetics at 160°C are shown in Fig. 2 and temperatures measured 4 mm from the sample center are shown in Fig. 3.

Identification of effective diffusivities

To formulate an inverse problem a 3D FEM model of simultaneous heat and mass transfer was constructed in cylindrical geometry using COMSOL. The following BCs were used

\[-\rho D \frac{\partial X}{\partial t} \big|_{x,y,z,x,y,z} = w_D \]

\[-\lambda \frac{\partial T}{\partial t} \big|_{x,y,z,x,y,z} = \alpha(T) \cdot (t_s - t_w) - w_D \cdot \Delta h_{v} \]

where the drying rate was calculated as

\[w_D = \frac{\alpha(T) \cdot (t_s - t_w)}{\Delta h_{v}} \] (5)

Radial and axial diffusivities were obtained by minimization of the goal function which was the sum of squares of differences of experimental points of both normalized drying kinetics and normalized temperature change and the model results. These two diffusivities were in turn used to identify the tangential diffusivity in a similar procedure using experiments were 3D transport was allowed. Optimization was performed by Levenberg-Marquardt routine in Matlab using COMSOL program as a procedure. Exemplary results are shown in Fig. 4 through 7.

Fig. 2. Drying kinetics of a sample with axial, radial and 3D mass transfer.

Fig. 3. Read-outs of the thermocouple placed 4 mm from the sample centre.

Identification of effective diffusivities

To formulate an inverse problem a 3D FEM model of simultaneous heat and mass transfer was constructed in cylindrical geometry using COMSOL. The following BCs were used

\[-\rho D \frac{\partial X}{\partial t} \big|_{x,y,z,x,y,z} = w_D \]

\[-\lambda \frac{\partial T}{\partial t} \big|_{x,y,z,x,y,z} = \alpha(T) \cdot (t_s - t_w) - w_D \cdot \Delta h_{v} \]

where the drying rate was calculated as

\[w_D = \frac{\alpha(T) \cdot (t_s - t_w)}{\Delta h_{v}} \] (5)

Radial and axial diffusivities were obtained by minimization of the goal function which was the sum of squares of differences of experimental points of both normalized drying kinetics and normalized temperature change and the model results. These two diffusivities were in turn used to identify the tangential diffusivity in a similar procedure using experiments were 3D transport was allowed. Optimization was performed by Levenberg-Marquardt routine in Matlab using COMSOL program as a procedure. Exemplary results are shown in Fig. 4 through 7.

Fig. 4. Fitted and experimental drying kinetics – axial transport.

Fig. 5. Fitted and experimental temperature 4 mm from the center – axial transport.

Fig. 6. Fitted and experimental drying kinetics – radial transport.
The obtained effective diffusivities are shown below.

Table 1. Values of identified diffusivities

<table>
<thead>
<tr>
<th>Direction of transport</th>
<th>$D_{\text{eff}}$ [m$^2$/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axial</td>
<td>1.0123e-8</td>
</tr>
<tr>
<td>Radial</td>
<td>7.1422e-9</td>
</tr>
<tr>
<td>Tangential</td>
<td>3.6480e-10</td>
</tr>
</tbody>
</table>

CONCLUSIONS

3D models of drying require moisture diffusivities in all three dimensions. These are seldom available in elevated temperatures of superheated steam drying. The presented procedure allows for their identification on a basis of simple experiments and simulation model. The reported values of diffusivities in axial, radial and tangential directions were obtained for wood of common pine ($\text{Pinus silvestris}$). The diffusivity in axial direction is the largest, the radial one being ca. 30% smaller. The tangential diffusivity is two orders of magnitude smaller. The obtained values are close to the values available in literature (Siau J.F., 1984) obtained in high temperature air drying.

NOMENCLATURE

- $D$: diffusivity, m$^2$/s
- $\Delta h_v$: heat of vaporization, J/kg
- $j$: mass flux, kg m$^{-2}$/s
- $t$: time, s
- $T$: temperature, K
- $w_D$: drying rate, kg m$^{-2}$/s
- $X$: moisture content, kg/kg
- $\rho$: wood density, kg/m$^3$
- $\alpha$: heat transfer coefficient, W m$^{-2}$/K
- $\lambda$: wood thermal conductivity, W m$^{-1}$K$^{-1}$

Greek letters

- $\rho$: wood density, kg/m$^3$

REFERENCES

Adamski R., Pakowski Z., Superheated steam drying model for willow $\text{Salix viminalis}$, 2008, IDS2008-Hyderabad, India 9-12 November

Boukadida N., Nasrallah S.B., 1995, Two dimensional heat and mass transfer during convective drying of porous media, Drying Technology, 13, 3, 661-694

Datta A.K, 2007, Porous media approaches to studying simultaneous heat and mass transfer in food processes. I: Problem formulations., Journal of Food Engineering, 80, 80-95

Erriguible A., Bernada P., Couture F., Roques M., Simulation of superheated steam drying from coupling models, Drying Technology, 24, 941-951
