REAL-TIME MODELLING OF WOOD DRYING SYSTEMS
Learning from Experiment and Theory

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Abstract: Predictive control in a wood drying systems is still at an early stage, because of the difficulties with the estimating a temporal moisture distribution for the whole dried lumber. Therefore, based on the dry and wet-bulb temperatures as the state variables the temporal moisture distribution in kiln-dried lumber is determined from numerical solutions of mathematical model for the wood drying systems. This computer model is represented by a set of several partial nonlinear differential equations coupled with the operating functions and a set of several calculating algorithms. The accuracy of the model solutions in a real-time calculation is evaluated by the on-line identification of the operating functions that represent both the system parameters (heat transfer coefficients, thermal conductivity, heat capacity etc) and selected state variables (air temperature, humidity, velocity etc).

1 INTRODUCTION

Though drying of lumber in the wood kiln is a simultaneous heat and mass transfer process, the temporal mass changes are less pronounced than the heat (energy) changes because of high latent heat of water and thus prevailing thermal effects during evaporation and condensation. Therefore, the classical approach to drying as water removal can conveniently be regarded as a heat exchange process between the drying gas (air) and the solid material (lumber). Because the lumber boards for drying are stacked into piles and several piles are placed in the kiln, the kiln and its load is considered as a wood drying system (WDS). Typically, the WDS is treated as a lumped-parameter system, and thus its dynamic behaviour can be described by the input-output transfer functions. However, establishing a dynamic mathematical model to be practical enough for control applications requires so many simplifying assumptions that the model hardly reflects the real situation. A compromise between the complex but adequate model and its simplification can be obtained when taking advantage of the measured temperature profiles in a given system, and solving numerically the partial differential equations by decomposing the solutions into the so-called regulated variables at the defined boundary conditions. The accuracy of these solutions has to be evaluated by the on-line identification (OLI) system. In return, the on-line identification, as a supporting tool for computer modelling, allows determination of the temperature profiles across the kiln as to avoid conditions that may lead to lumber degradation.

2 MATHEMATICAL FORMULATIONS

The model is based on the well established drying mechanism for lumber. During the pre-heating period, the temperature of stacked lumber is equilibrated to the air temperature by heating at the controlled rate to prevent condensation of water vapour. At the end of this period, the moisture content (MC) of lumber is assumed uniform. During the constant rate period, the vapour pressure at the lumber surface is equal to the saturated vapour pressure, and the surface temperature approaches the wet-bulb temperature.

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If the external conditions are constant, then the drying rate is also constant, down to the fibre saturation point (FSP) of about 30 % wb. Below the FSP, the drying rate decays exponentially whereas the surface temperature increases progressively towards the air temperature. The mathematical model for drying lumber that leads to temperature distribution along the kiln can be obtained by using the control volume method (Kada, B. and Tarasiewicz, S., 2004, and Tarasiewicz, S., 1984, Tarasiewicz, S. et al., 2000 and Tarasiewicz, S. et al., 1982). The moving control volume shown in Fig. 1 is selected as to comprise the lumber and the air gap. Normally, the control volume covers the length of the lumber board (L_z). However, it can be reduced to the incremental length (dz) to avoid local defects such as cracks or knots. The overall mathematical model for the WDS comprises the following equations (another form of the model is given in Appendix):

$$\begin{cases} \mathbf{A}_{w0}\cdot\dfrac{\partial \mathbf{z}}{\partial t} = \mathbf{A}_{w1}.\mathbf{z} + \mathbf{A}_{w2}\dfrac{\partial \mathbf{z}}{\partial x} + \mathbf{A}_{w3}\cdot\dfrac{\partial^2 \mathbf{z}}{\partial x^2} + \mathbf{B}_w.\mathbf{u} \\ \mathbf{A}_{a0}\cdot\dfrac{\partial \mathbf{u}}{\partial t} = \mathbf{A}_{a1}.\mathbf{u} + \mathbf{A}_{a2}\dfrac{\partial \mathbf{u}}{\partial x} + \mathbf{A}_{a3}\cdot\dfrac{\partial^2 \mathbf{u}}{\partial x^2} + \mathbf{B}_a.\mathbf{z} \end{cases} \tag{1}$$

where: $\mathbf{z}(x, t) = [\, M(x, t)\; T(x, t)\,]^T$ is the vector of distributed state variables (MC and wood temperature); $\mathbf{u}(x, t) = [\, T_a(x, t)\; v_a(x, t)\,]^T$ is the vector of distributed control variables, namely air temperature and air velocity (air mass displacement), and $\mathbf{A}_{wi}$, $\mathbf{B}_w$, $\mathbf{A}_{ai}$, $\mathbf{B}_a$ are modified operating functions for i = 0, 1, 2, 3, and $\mathbf{A}_{w3}$ is proportional to $\mathbf{F}_{10}$ (see Appendix).
The initial and boundary conditions are

$$\begin{cases} \mathbf{z}(x,0) = \mathbf{z}_0(x) \\ \mathbf{u}(x,0) = \mathbf{u}_0(x) \end{cases} \tag{2}$$

$$\begin{cases} \mathbf{D}_{w0}(\bar{x},t)\mathbf{z}(\bar{x},t) + \mathbf{D}_{w1}(\bar{x},t).\dfrac{\partial \mathbf{z}(\bar{x},t)}{\partial x} = \mathbf{R}_w(\bar{x},t)\mathbf{u}(\bar{x},t) \\ \mathbf{D}_{a0}(\bar{x},t)\mathbf{u}(\bar{x},t) + \mathbf{D}_{a1}(\bar{x},t).\dfrac{\partial \mathbf{u}(\bar{x},t)}{\partial x} = \mathbf{R}_a(\bar{x},t)\mathbf{z}(\bar{x},t) \end{cases} \tag{3}$$

where: $\mathbf{D}_{wi}$, $\mathbf{D}_{ai}$, for i = 0 - 3 (number of the heating/drying zones), $\mathbf{R}_w$, $\mathbf{R}_a$ are the complementary OFs, and $\bar{x} = x$, for $0< x < L$ ($L = L_{x1} + L_{x2} + \ldots + L_{xn}$ is the total length of the n lumber piles).

This mathematical model follows the drying mechanism as it reflects the dynamics of moisture change during drying. The operating functions can be further improved through calculation procedures of all distributed variables (state variables and control variables), and compared with either the target values of the distributed state profiles or with the measured values, if possible.

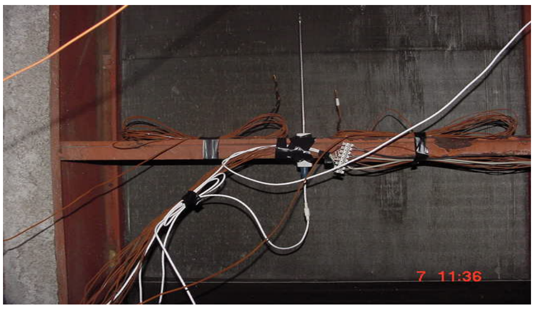
3 INSTRUMENTATION AND EXPERIMENTAL IDENTIFICATIONS

The experiments on on-line identification were performed in a typical wood kiln equipped with the data acquisition system (see Fig. 1a, 1b, 1c, 1d).
The experimental reconstructed profiles of the state distributed variables, for this system, are plotted in Figure 1e.
To validate the distributed state values calculated from the proposed mathematical model(see Fig. 2a), the operating functions in Eq. 1 (and Eqs. 5 through 7 in Appendix) should be decomposed into two independent functions either by using the hierarchical structure (see Fig. 2b) or by using the techniques of separated variables (Kada, B. and Tarasiewicz, S., 2004, and Tarasiewicz, S., 1994):

$$OF_i(x, t.) = f_i(x) \times g_i(t) \text{ for } i = 1,\ldots, N \tag{4}$$

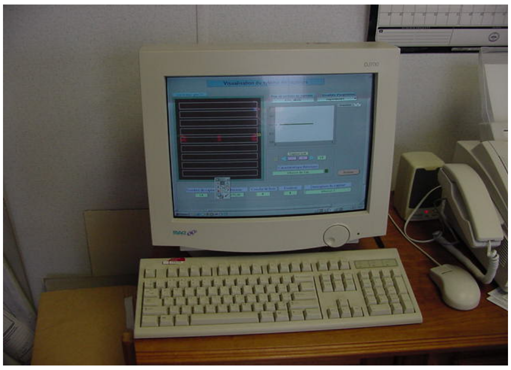
where: $f_i(x)$ are the distributed functions proportional to the mean parameters under consideration, $g_i(t)$ are the dynamic functions of physical parameters, and N is the number of the defined OFs.

a)

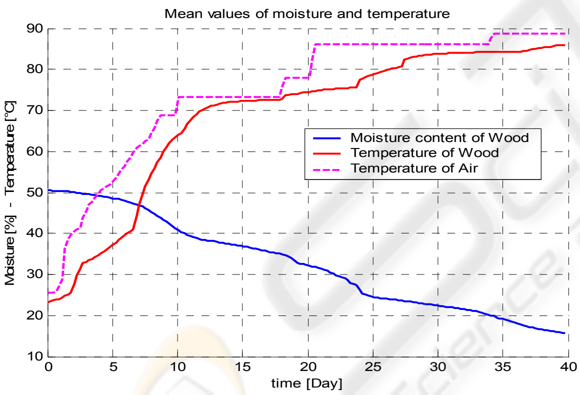


b)

c)



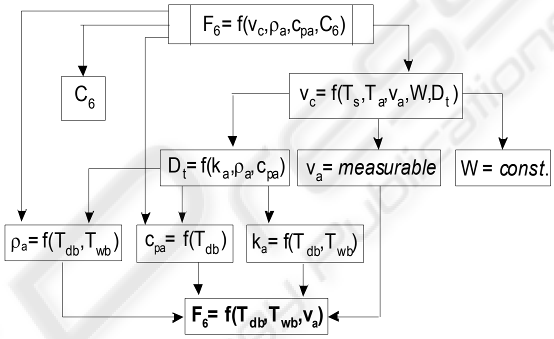
d)



e)

Figure 1: Data acquisition system; a) sensor locations in lumber; b) sensor locations in air; c) transducers; d) microcomputer-based network (implemented in the industry) as a Reconstruction System (RS) of the distributed state variables; e) reconstructed profiles of the state distributed variables for the WDS (see Fig. 1d)

a)



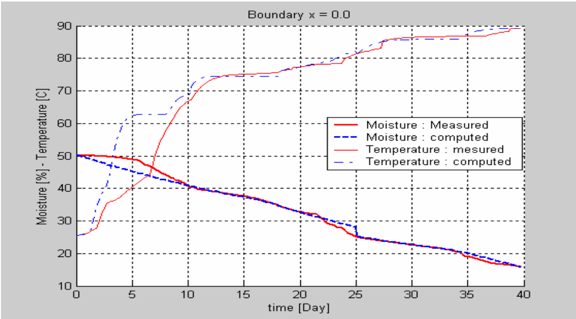
b)

Figure 2: Microcomputer-based network

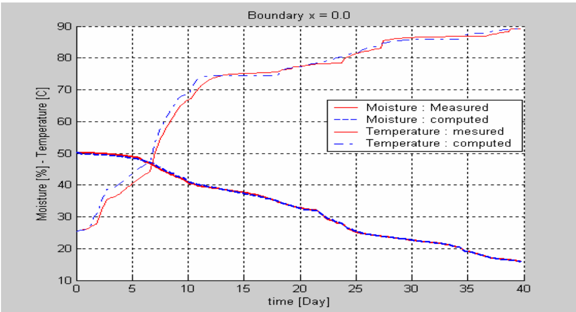
Where: a) Numerical Calculator (NC) to estimating the distributed state variables (implemented in the Complex Automation and Mechatronic Laboratory (LACM)); b) hierarchical structure of the sample operating function and its physical parameters (for details, see Tarasiewicz, S. et al., 2000); the C_6 is a tuning parameter.

The communication between NC and RS (see Fig.1d) were performed via Internet Network in real-time.

From the above subdivision of this operating function one can conclude that its calibrated parameters are the dry and wet-bulb temperatures ($\mathbf{T}_{db}$, and $\mathbf{T}_{wb}$) and air velocity ($\mathbf{v}_a$). Characteristically, for all operating functions it is possible to apply the same calibration procedure as shown in Fig. 2b, and the same calibrated parameters, namely $\mathbf{T}_{db}$, $\mathbf{T}_{wb}$ and $\mathbf{v}_a$.
To complete the validation (calculation) procedures, the Runge-Kutta method has been used. The software has been written in the C++ language, and the results of computations have been shown in Lab view windows (c.f., Figs. 3a, 3b, and 4).



a)



b)

Figure 3: Calculated profiles of the state distributed variables for the WDS; a) initial tuning parameters; b) tuning parameters are the air temperature function (for comparing, see Fig. 1e)

From the preliminary simulation tests shown in Figure 3a it was clear the operating functions in boundary conditions (Eq. 3) have to be modified. Thus, in the subsequent simulation tests, some physical properties of the drying lumber have been determined, and numerical results obtained for these boundary conditions are plotted in Figure 3b.

The proposed mathematical model (given either by Eq. 1 or Eqs. 5-7 with the admissible numerical values of all OFs determined by using the proposed algorithm (Tarasiewicz, S., et al., 2000, and Tarasiewicz, S., et al., 1994)), was validated and the results are plotted in Figures 3 and 5

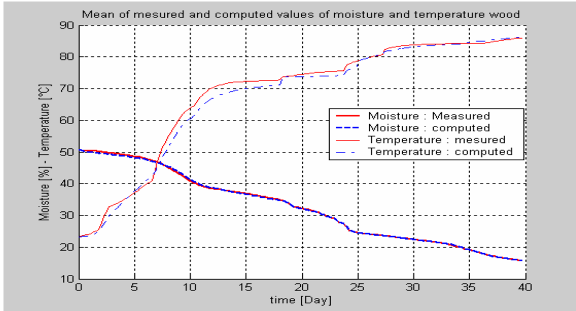


Figure 4: Evaluation and comparison of the state distributed variables inside the WDS (see Fig. 1e).

From these Figures it is evident that the numerical solution of the mathematical models for the WDS can adequately estimate (predict) the dynamic evolution of the distributed state variables.

4 SUMMARY

Using the calculated profile with the calibrated OFs (see Fig. 3b and Fig. 4) for the distributed air gap temperature ($\mathbf{T}_a$), and kiln temperatures ($\mathbf{T}_{db}$ and $\mathbf{T}_{wb}$) it is possible to estimate the distributed moisture content of lumber during drying (see Fig. 5). Also, by using the estimated profile of the MC with the calibrated OFs (Fig. 4) for the WDS it is possible to predict the distributed control variables for the air temperature in the WDS.

The fact that computation time taking by the NC is very short or much shorter as compared to the reconstruction time taking by the RS confirms that the numerical calculation can be utilized in a predictive control structure.

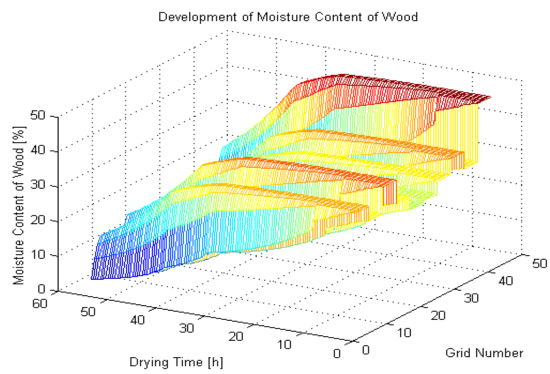


Figure 5: Evolution of the moisture content in the whole dried lumber for different values of the initial MC, and for each piece of wood

Because of system complexity, the control structure has to be subdivided into a multilevel hierarchical structure (Tarasiewicz, S., et al., 2000, and Tarasiewicz, S., et al., 1994). Further, the predicted profiles of the MC and air temperature would allow building design of industrial controllers providing real time control of the wood drying systems.

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APPENDIX

The alternative form of the mathematical model is give by the following equations:

$$F_{12}(x,t)\frac{\partial M(x,t)}{\partial t} = -\left[\begin{array}{c} F_{10}(x,t)\dfrac{\partial^2 M(x,t)}{\partial x^2} + \dfrac{\partial F_{10}(x,t)}{\partial x}\dfrac{\partial M(x,t)}{\partial x} + F_{11}(x,t)\dfrac{\partial^2 T(x,t)}{\partial x^2} \\ + \dfrac{\partial F_{11}(x,t)}{\partial x}\dfrac{\partial T(x,t)}{\partial x} + \dfrac{\partial F_{12}(x,t)}{\partial t}M(x,t) \end{array}\right]$$

$$F_8(x,t)\frac{\partial T(x,t)}{\partial t} - F_9(x,t)\frac{\partial M(x,t)}{\partial t} = \left[\begin{array}{c} F_5(x,t)\dfrac{\partial^2 T(x,t)}{\partial x^2} + \dfrac{\partial F_5(x,t)}{\partial x}\dfrac{\partial T(x,t)}{\partial x} - \\ \dfrac{\partial F_8(x,t)}{\partial t}T(x,t) + \dfrac{\partial F_9(x,t)}{\partial t}M(x,t) + \\ F_7(x,t)\left[T_a(x,t) - T(x,t)\right] \end{array}\right]$$

$$F_1(x,t)\frac{\partial v_a(x,t)}{\partial t} = \left[\begin{array}{c} -\dfrac{\partial F_1(x,t)}{\partial x}v_a^2(x,t) - \left[\dfrac{\partial F_1(x,t)}{\partial t} + F_1(x,t)\dfrac{\partial v_a(x,t)}{\partial x}\right]v_a(x,t) \\ + F_2(x,t)\dfrac{\partial P(x,t)}{\partial x} + \dfrac{\partial F_2(x,t)}{\partial x}P(x,t) - F_3(x,t)g + \tau\Pi \end{array}\right]$$

Where: F_j for j = 1,…,12 are the operating functions, P is the total pressure in the air gap, Π is the gap perimeter available to air flow, τ is the shear stress induced in wood by moisture and temperature gradients.