Modeling the change of water content in wood at atmospheric drying

M Zaitseva*, J Nikonova¹ and G Kolesnikov¹

¹ Petrozavodsk State University, Petrozavodsk, Russian Federation

E-mail: *2003bk@bk.ru, juli4455@mail.ru, kgn@petrsu.ru

Abstract. Objective: to develop a methodology for predicting changes in the water content in wood during atmospheric drying, taking into account the fast and slow stages of this process. Research methods: mathematical modeling, applied analysis of results, comparison with experimental data known from the literature, synthesis in order to better understand the regularities of drying. Results: a two-parameter model is developed, in which a phenomenological approach is used, focused on obtaining averaged estimates of wood moisture during atmospheric drying. Causal relationships are not detailed, but are taken into account in an integral form. Calculation formulas are obtained, the use of which simplifies the procedure for predicting changes in the water content in wood during atmospheric drying. The adequacy of the model and the reliability of the calculation results are confirmed by their consistency with the experimental data known in the literature. Research prospects can be focused on adapting the model to other drying methods in order to reduce the energy and time spent on a given technological process.

1. Introduction

Drying of wood is a necessary link in the technology of its further use. There are many drying methods, of which atmospheric drying is the least energy intensive and, at the same time, the longest. The duration of atmospheric drying depends on a number of conditions and can be, for example, 24 weeks [1]. In this regard, there is a problem of predicting changes in wood moisture during atmospheric drying.

It should be noted that this problem is relevant not only for improving the technology of wood drying at the stage of its preparation for further use. Obviously, in the regime of atmospheric drying, roof trusses and other supporting and enclosing structures of wooden buildings function. Regularities of changes in wood moisture in such structures are necessary, first of all, for specialists in the field of protection of unique monuments of wooden architecture [2, 3].

Theoretical aspects directly related to the problem of drying, including atmospheric drying, taking into account the effect of equilibrium moisture of wood as a capillary-porous material, are most fully presented in the monograph [4]; applied issues are considered, for example, in articles [5, 6].

A one-parameter model of wood drying was proposed in [7], which, however, did not take into account the influence of the fast and slow drying stages (although the fast and slow stages of moisture transfer were taken into account when impregnated). The adequacy of the results obtained in this work indicates the practical feasibility of developing a drying model taking into account the fast and slow stages of moisture transfer. Such an improvement, from a physical point of view, is objectively due to differences in the regularities of transfer of free and bound moisture in wood [8].
Thus, in order to get a more complete understanding of the drying process of wood, it is advisable to develop a two-parameter model, which takes into account the two above stages of the process under consideration.

We will develop a two-parameter model based on the logic of inductive conclusions, based on the analysis of particular premises and their mutual influence within the framework of a generalized mathematical model. In other words, we are transforming a one-parameter model of wood drying [7] into a two-parameter model.

2. Method
It is known that the relative moisture of wood $C_{b1}$, depending on the initial moisture $C_{b0}$ and the drying time $t$, can be determined using the formulas [7]:

$$C_{b1} = \frac{C_{b0}(1+0.01)}{C_{b0}+0.01}, \quad (1)$$

$$C_{b} = e^{-\frac{\tau}{t}}, \quad (2)$$

$$\tau = \frac{t}{\tau}, \quad (3)$$

Here $\tau$ is the model parameter, measured in units of time. From a formal point of view, the parameter $\tau$ is necessary to write relation (2) in a dimensionless form. The physical (technological) meaning of this parameter is discussed below.

The relative moisture of the wood was determined by us, by analogy with [5], as the ratio

$$C_{b1} = \frac{\text{mass of water in wood}}{\text{mass of water in wood} + \text{mass of dry wood}}. \quad (4)$$

The conversion of relative moisture to absolute moisture, equal to the ratio of the mass of water in wood to the mass of dry wood, can be performed according to well-known formulas [4].

The value of the function $C_{b}(C_{b0})$ (1), which corresponds to specific values of $\tau$ and $\vartheta$, depends on the initial moisture $C_{b0}$, however, the initial moisture, in turn, depends on the species and age of the wood, storage conditions, and a number of other factors. For example, with decreasing atmospheric moisture and with increasing temperature, the drying rate increases, which is modeled by a decrease in parameter $\tau$. Given these circumstances, parameter $\tau$ can be called a technological parameter. If the initial relative moisture of the wood does not exceed 0.5 (which corresponds to an absolute moisture of 100%), then we can assume that the parameter $\tau$ is equal to the times $t$, during which the initial moisture of the wood decreases approximately by half (see Fig. 1).
To determine the value of $\tau$, we perform an experiment on drying the sample, reducing its relative moisture, for example, from $C_{b0} = 0.38$ to $C_{b1} = 0.19$. We experimentally determine the time $t$ for the implementation of this process. Substituting the measurement results of $C_{b1}$ and $t$ in (1), we obtain the equation from which we find $\tau$. Parameter $\tau$ is measured in units of time. In this experiment, $\tau = t$.

$$C_b = \frac{e^{-\frac{t}{C_{b0} + e^{-\frac{1}{1}}}}}{\tau(C_{b0} + 0.01)}.$$  

(5)

The graph of the function $C_b(C_{b0})$ is shown in Fig. 1.

The rate of the drying process decreases monotonically over time. The dependence of rate on time is determined by analogy with [7], differentiating relation (1) with respect to time $t$. After the transformations we get:

$$|V_d| = \left| \frac{dC_{b1}}{dt} \right| = \frac{C_{b0}C_b(1-C_b)}{\tau(C_{b0} + 0.01)}.$$  

(6)

In relation (6), the speed modulus was used to visually reflect the tendency for a decrease in the drying rate with an increase in the duration of this process. This question is considered in more detail below, using the two-parameter model as an example (see Fig. 3).

3. Results

Consider a model with weight coefficients, constructed taking into account the fast and slow stages of moisture transfer. Summarizing relation (2), we write the equation for determining the relative moisture in the following form:

$$C_{b2} = w_1 \frac{e^{-\vartheta_1}}{C_{b0} + e^{-\vartheta_1 - 1}} + w_2 \frac{e^{-\vartheta_2}}{C_{b0} + e^{-\vartheta_2 - 1}}.$$  

(7)

Here, where $\vartheta_1 = t/\tau_1$, $\vartheta_2 = t/\tau_2$. The adjusted value of relative moisture, by analogy with (1), we find by the formula

$$C_{b3} = \frac{C_{b0}(C_{b2} + 0.01)}{C_{b0} + 0.01}.$$  

(8)

The indices 1 and 2 at $\vartheta$ and $\tau$ relate, respectively, to the above two stages of drying (fast and slow). The model parameters $\tau_1$, $\tau_2$ and weights $w_1$, $w_2 = 1 - w_2$ are determined experimentally. To
minimize the volume and duration of the experiments, it is advisable to focus on the fast drying stage using the relations $t = \tau_1$, $\theta_2/\theta_1 = \tau_1/\tau_2 = t/\tau_2$. Substituting these relations into formula (6), we obtain an equation from which $\tau_2$ can be found, if $w_1$ is previously assigned, $w_2 = 1 - w_1$ is calculated, and $C_{B_2}$ and $t = \tau_1$ are determined from the experiment. To clarify the obtained value of $\tau_2$, formula (8) is used. The value of $C_{B_0}$ is assumed to be known. A more detailed consideration of the issue raised is beyond the scope of this paper.

To get a clearer understanding of the prospects for further research, we consider the application of the above formulas to the analysis of experiment of the atmospheric summer drying of wood with the initial relative moisture $C_{B_0} = 0.54$, i.e. 54%, known from the literature [1].

Using the weight coefficients $w_1=0.45$ and $w_2=0.55$ in formula (7), we obtain for the three options $\tau_1$ and $\tau_2$ the numerical results shown in Figure 2.

We determine the rate of the drying process by differentiating relation (6) with respect to time. In this case, sufficient accuracy provides numerical differentiation:

$$V_d \approx \frac{|\Delta C_{B_3}|}{\Delta t}.$$  

In relation (9), as in (6), the absolute value of rate was used to visually reflect the regularity of a decrease in the drying rate with an increase in the drying time; $\Delta C_{B_3} = C_{B_3,i+1} - C_{B_3,i}$; $\Delta t = t_{i+1} - t_i$; $i = 0 \ldots 23$. Figure 3 shows the results of calculations by formula (9) if $\Delta t$ is equal to one week (for the same initial data as in Fig. 2).

**Figure 2.** Calculated wood moisture during atmospheric drying (summer, 24 weeks).
4. Discussion and conclusion

The modeling results (Fig. 3) show that in the interval $0 < t < 10$ weeks, the drying rate decreases rapidly. This means that the initial stage of drying is most effective according to the criterion of energy consumption per unit mass of water removed from the wood. In the interval $10 \leq t \leq 15$ weeks, there is a point at which the drying rate is almost independent of the drying parameters. If $15 < t < 24$ weeks, then the rate decreases, but very slowly; this stage is the least efficient according to the criterion of energy consumption and drying time.

The modeling results (Figs. 2 and 3) do not contradict the experimental data known from [1, p. 5]. In addition, the drying rate trends predicted by formula (6) (Figure 3) do not generally contradict the experimental data from [9, p. 2001, Figure 2, c]. Using the proposed approach (in other words, taking into account relations (1)–(6)), modeling of drying features in other conditions can be performed. For example, a modeling of the known [9] experimental dependences of the rate of moisture removal on time at the temperature of the drying agent can be performed. The realism of this assumption is justified by the fact that the dimensionless variables $\vartheta_1 = t/\tau_1$ and $\vartheta_2 = t/\tau_2$ indicated above (formula (4)) relate, respectively, to the above two stages of drying (fast and slow). Indeed, with increasing temperature, the drying rate increases, which is modeled by a decrease in the parameter $\tau$ in formula (2) or a decrease in the parameters $\tau_1$ and $\tau_2$ in formula (4).

Summarizing, we note as a conclusion the following.

1. A method for predicting changes in the water content in wood during atmospheric drying is proposed. The method was built using mathematical modeling, applied analysis of results and comparison with experimental data known from the literature, in other words, the approach used for system analysis, including synthesis and analysis, was used to better understand the regularities of drying.

2. As a tool for applied analysis, a model is proposed in which a phenomenological approach is used when choosing an empirical formula, focused on obtaining averaged moisture estimates taking into account the fast and slow stages of drying.

3. The adequacy of the model and the reliability of the calculation results are confirmed by their consistency with the experimental data known in the literature.

4. The practical significance of the considered method lies in the possibility of its use for predicting changes in wood moisture during drying, depending on the values of technological parameters and weight coefficients.
5. Research prospects can be focused on adapting the model to other drying methods in order to reduce the energy and time spent on a given technological process.

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