Model of wood impregnation after incomplete drying as an additional energy management tool

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Abstract. The problem of rational energy use is directly related to sustainable socio-economic and technological development, so its solution is a complex priority. Energy efficiency in modern industry is achieved through the improvement of management methods and the use of energy-saving technologies. The aim of this work is to analyze the possibility of reducing energy consumption in the technology of wood fire-retardant impregnation after incomplete drying. The study uses experimental methods and methods of mathematical modeling. It is established that the efficiency of wood impregnation according to the criteria of time and energy consumption increases with a decrease in the time interval between the drying completion and the impregnation start, and also depends on the degree of pre-drying, which should be sufficient, but not excessive. The adequacy of the results is confirmed by their consistency with the known literature data.

1. Introduction
The problem of rational energy use is directly related to sustainable social, economic and technological development, so its solution is a complex priority. Energy efficiency in contemporary industry is achieved through the improvement of management methods and the use of energy-saving technologies [1].

Currently, the forest sector faces two global challenges: meeting the growing demand for quality wood and minimizing a possible negative impact on the environment. The main sources of environmental impact are found at all stages of wood harvesting and processing technologies [2]. Drying and, in many cases, impregnation for protection against fire [3] and biodegradation are a necessary link in the technology of preparation of wood for further use [4]. Drying requires much energy. The main instrument of energy management is the energy audit. To justify the possibility of energy saving, it is necessary to obtain a sufficiently large amount of data on the operation and energy consumption of each technological link. To obtain such data, it is advisable to use not only experimental methods, but also methods of mathematical modeling. Accordingly, the model of functioning of the system of technological links is an additional tool of energy management. Analysis of the literature [2–7] shows that the improvement of drying technologies of the wood requires further research. The aim of this work was to analyze the possibility of reducing energy consumption in the technology of wood fire-retardant impregnation after incomplete drying.

In accordance with the above objective, this work addresses the following tasks: to set the
permissible degree of incomplete drying of wood; to determine the moisture content of the wood at which it is advisable to start impregnation; to define the time interval between the end of incomplete drying and the beginning of impregnation; to estimate the duration of impregnation of wood after predrying.

2. Materials and methods

For the theoretical study of the above problems we use methods of mathematical modeling. Two mathematical submodels are used as a research tool in the framework of this work (convective drying and impregnation), the adequacy of which is verified by experimental data obtained using the capabilities of the drying chamber of the Shimadzu MOC-120H moisture analyzer. Samples of aspen wood in the form of a parallelepiped with average edge sizes of 10, 33 and 40 mm have been studied.

Concerning the modeling technique, let us note that wood, as is well known, is characterized by a large variability of physical and mechanical properties, the detailed account of which in mathematical models is difficult. Taking into account the purpose and objectives of our work, we use the approach, in which the properties of wood affecting the characteristics of drying and impregnation are taken into account in an integral form. When testing the model, of course, some quantitative initial data are needed, which are obtained in experiments on the aspen samples noted above.

3. Wood drying model

Simulating the process of changing the moisture content during drying of wood, let us consider a sample of mass $M$. Let $M_b$ — total mass of free and bound moisture in the sample (including the other substances extracted during drying). Over time, $t$, by reducing the humidity, the values of $M_b$ and $M$ are reduced by the same value $\Delta M_b$. Then at times $t$ and $(t+\Delta t)$ the mass of moisture is, respectively, $M_b$ and $(M_b-\Delta M_b)$; the mass of the sample at the same time is equal to $M$ and $(M-\Delta M_b)$. Accordingly, the relative humidity of wood at the same time is equal to $C_i=M_b/M$ and $C_{i*}=(M_b-\Delta M_b)/(M-\Delta M_b)$.

From the physical point of view, it is reasonable to assume that $\Delta M_b$ is proportional to $\Delta t$ and $M_b$. The value of $\Delta M_b$ depends on temperature, humidity, drying time, wood species and other factors [3, 5–7], the total effect of which is taken into account by the technological parameter of the model $\tau$. The parameter $\tau$ has the dimension of time; its value is determined using experimental data. Let us denote $\Theta=t/\tau$ and $\Delta \Theta=\Delta t/\tau$. Then $\Delta M_b=\Delta \Theta M_b$ and, respectively, $C_i=(C_{i*}-\Delta \Theta C_i)/(1-\Delta \Theta C_i)$. Using this ratio and neglecting the values of the second order of smallness, we determine the change in relative humidity over a period of time $\Delta t=\tau \Delta \Theta$: $\Delta C_b=-\Delta \Theta C_i(1-C_i)$. In the limit when $\Delta \Theta \to 0$ we obtain: $dC_b/(C_b(1-C_b))=-d\Theta$. Integrating, we find that $\ln(C_b/(1-C_b))=\Theta+A$. The integration constant $A$ is found from the condition that the initial relative humidity of the wood is known, i.e. $C_b=C_{i0}$ at the start of drying (if $\Theta=0$). Then we obtain $C_b=\exp(-\Theta)/(1/C_{i0}+\exp(-\Theta)-1)$. Let us note that, for example, $C_{i0}=0.5$ is for freshly harvested wood. When assessing the physical adequacy of the resulting formula, we should take into account the following circumstances.

If the drying time $t \to \infty$, and hence the above parameter $\Theta \to \infty$, then $C_b \to 0$. However, according to recently published data [7], the relative humidity of wood dried by standard technologies cannot be less than ~1% (or 0.01), i.e. 0.01 < $C_b$ < 1. To take into account this fact, we add to the right side of the resulting formula the summand, which depends on $\Theta$, and, consequently, depends on the investigated value of $C_b$, namely, the summand is zero at $\Theta=0$ and $\Theta=0.01$, if $\Theta \to \infty$. Thus, it is possible to write $C_b=\exp(-\Theta)/(1/C_{i0}+\exp(-\Theta)-1)+0.01(1-C_b/C_{i0})$. Then after simple transformations we find: $C_b=(\exp(-\Theta)/(1/C_{i0}+\exp(-\Theta)-1)+0.01)/(1+0.01/C_{i0})$.

The diagram of changes in the relative humidity of $C_b$: 100% of aspen samples depending on the drying time for some values of the parameter $\tau$ are shown in Fig. 1. The initial relative humidity of the samples is equal to 38%, drying is carried out at temperature of 100 °C.
Figure 1. Changes in the relative humidity of aspen samples during drying.

Above (Fig. 1) the dependences show that the drying intensity decreases with the increase in the duration of the process, which corresponds to the known pattern: at the initial stage of drying, the free (capillary) moisture is most intensively removed [6]. Removing the bound moisture from the wood requires more energy, so the speed of the process decreases over time. If the specified technological parameter \( \tau \) decreases, the drying speed increases, but in any case at the final stage the speed (drying intensity) tends to zero. Thus, it is reasonable to assume that the initial stage of drying is the most effective according to the criterion of energy consumption.

The change in the relative humidity of \( C_b \) can be considered as a quantitative assessment of changes in the weight of wood during drying. The results of experiments and calculations of \( C_b \) are shown in Fig. 2.

Figure 2. Reducing the mass of samples depending on the drying.

4. Wood impregnation model

The approach used above for the theoretical determination of the relative humidity in the drying of wood \( C_b \) (i.e., with a decrease in humidity), can be used in the simulation of the reverse process, namely, the process of increasing the moisture content of wood during impregnation. Let \( C_{bi} \) – relative humidity during impregnation. Using the above designations, it can be shown that the concentration of impregnating liquid in the wood is determined by the ratio of \( C_{bi} = \exp \Theta / (1/C_{bi} + \exp \Theta - 1) \).
However, assessing the physical adequacy of this formula, it is necessary to take into account the peculiarities of the impregnation process. Experiments have shown that the impregnation process includes fast and slow stages, which correspond to an increase in the amount of free and bound moisture [6]. Both stages are described by the same ratio, but at different values of the parameter $\tau$: with decreasing $\tau$ the rate of change of wood moisture in the model process increases.

Let us note also that if $\Theta \to \infty$, then $C_{bi} \to 1$. Formally, this means that with a sufficiently long time of impregnation, the sample will contain only the impregnating liquid, which is not true. Using known data about the moisture content in the rafting wood, by analogy we assume that the largest value of $C_{bi}$ is 0.8, i.e. it is necessary to correct the formula of the definition of $C_{bi}$ in the impregnation. Then $C_{bi}=0.8 \exp\Theta/(0.8/C_{bi}+\exp\Theta-1)$.

This ratio is used to model the above-mentioned fast stage by taking $\tau=0.8$; to model the slow phase, we take $\tau=20$. The end result ($C_{bi}$) is defined as the sum of the weights $w_1$ for the fast stage and $w_2$ for the slow stage. Thus, $C_{bi}=w_1C_{bi1}+w_2C_{bi2}$, where $w_1=0.7$ and $w_2=0.3$, $C_{bi1}=C_{bi}(\tau=0.8)$ and $C_{bi2}=C_{bi}(\tau=20)$. In this case, it is assumed that the values of the weight coefficients $w_1$ and $w_2$ correspond to the amount of free and bound moisture in the wood. As it is known, the content of bound moisture is about 30% and practically does not depend on the wood species [6]. The results of modeling and experimental data are shown in Fig. 3.

![Figure 3. Changes in the relative humidity of the samples during impregnation.](image)

5. Results and discussions
Experimental data (Fig. 3) refer to the impregnation of samples from aspen wood after preliminary incomplete drying. The flame retardant MEDERA 200 Cherry with antiseptic properties was used as a impregnating liquid. According to the results of the experiments, it was found that to improve the efficiency of impregnation of aspen wood with fire retardant MEDERA 200 Cherry, incomplete drying should be performed at a temperature of 100 °C with a loss of 10 to 20% of moisture and subsequent impregnation by immersion.

It is important to emphasize that the time interval between the completion of the incomplete drying process and the beginning of the impregnation process should be minimized taking into account technological limitations and equipment features. Minimizing this interval is necessary for a number of reasons. First, there is a rapid absorption of moisture from the surrounding area to establish the equilibrium moisture content of the wood with a decrease in its temperature after pre-drying (Fig. 3). This effect is advisable to use to reduce energy costs and time for impregnation. In this case, pre-drying may be incomplete, which reduces the time and energy costs for the implementation of this process.

Simulation results and experiments have shown that the initial stage of the drying process is realized
at a high speed, then the drying rate decreases over time. A similar pattern occurs during impregnation (Fig. 1–3). This means that the most efficient use of energy, time and process equipment at the first (fast) stages of the drying and impregnation processes. The developed submodels make it possible to predict changes in humidity in wood both during drying ($C_b$) and impregnation ($C_{bi}$). Thus, model of timber impregnation after incomplete drying can be used as an additional energy management tool.

Let us note that the above results apply only to the technology of impregnation of aspen wood. This method of samples impregnation from the pine core did not lead to an equally significant increase in the efficiency of impregnation. This is due to the fact that the impregnating properties of aspen wood differ little from the properties of pine sapwood, but the differences are significant for pine sapwood and pine core [5].

6. Conclusion
After studying the possibility of reducing energy consumption in the technology of fire-retardant impregnation of wood after incomplete drying, it can be concluded that the efficiency of impregnation of wood according to the criteria of time and energy consumption increases with a decrease in the time interval between the completion of drying and the beginning of impregnation, and also depends on the degree of pre-drying, which should be sufficient, but not excessive.

Reduction of drying time is rational from the ecological point of view, as it leads to a decrease in the amount of substances extracted from wood (such as furfural and phenol formaldehyde), polluting the environment.

The adequacy of the results is confirmed by their consistency with the known literature data.

The results of the study can be used to justify technological solutions to improve the methods of impregnation.

The prospects of the study are associated with the refinement of the method for determining the technological coefficient, which is used as a parameter in the simulation of drying and impregnation. First of all, it is necessary to investigate the dependence of this parameter on the thickness of the treated wood, as well as to clarify its values, taking into account new results in this field of applied research [5–10].

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