Usage of the MATHCAD Framework for Energy Saving Simulation

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Abstract

This study explores the use of energy savings technologies in timber production for wood housing construction. Methods applied were based on the creation of system of optimized regimes of drying of sawn timber was carried out in two stages: computing experiment with the tools of MathCAD and production experiment. The findings discovered the following tendency: however the minimum cost of energy is achieved at the minimum time of drying that is explained by an essential difference in the cost of thermal and electric energy. The regimes of steeples structure received by computer modeling allow receiving sawn timber that fully meets the requirements of the consumer without application of moisture treatment and the conditioning processing. The developed technique of formation of the steeples regimes of drying of sawn timber allows determining structure and sizes of parameters of the regime depending on the required quality of drying and energy costs on its carrying out. Calculations of technical and economic efficiency have shown that the total annual economic effect in more than 17 dollars per 1 m3 and it can be extended by including on power component.

Introduction

Glued wall beam is one of main constructional materials in wooden housing construction. In this case the initial material in production of glued wall beam is sawn timber. The conducted researchers [1] showed that electric power consumption for chamber drying of sawn timber 1.5-2 times exceed those for their sawing. In addition, in the structure of complete cost of chamber drying of sawn timber the share of energy component is quite considerable about 60%, and in the total cost of drying of sawn timber up to 30%. Therefore, creation of energy-saving technology of drying of sawn timber is an economically efficient task.

This problem is highly actual for modern scientist. So the compression strengths are compared with steel and timber wall stud strengths and shown to be suitable for residential building applications. The combined plain channel and stiffened channel experimental data covers a broad range of section slenderness values, and design models are developed to predict their compression strength are investigated in the articles of Bambach, M. R. (2018) [2]. Also The European Committee for Standardization (CEN) thus developed horizontal standards to enable the sustainability assessment of construction works over their entire life cycle, which were analyzed in the works of Achenbach, H., Wenker, J. L., & Rüter, S. (2018) and in it for the categories GWP and AP, around 30% of the impacts originate from the prefabrication of the building elements, their transport and the processes at the construction site [3].

A tangible reduction of energy consumption is possible in the following directions [1]:

-costs on heating of outside air on the basis of air exchange between the chamber and surrounding atmosphere;

-electric power consumption for the drive of fan.

It should be noted that development of drying technology goes now mainly by improvement of the modes of drying on the basis of modern methods of computer modeling and optimization [2]. Surely that optimization of the modes of drying should not only increase their energy efficiency, but also provide quality of drying of sawn timber allowing making further both a glued wall beam and other types of products for housing construction.

The issues concerning effect of drying regimes on the quality of drying of sawn timber were in detail investigated in the 1950s-1980s [5,7, etc.].

P.S. Sergovsky, one of the founders of Russian science on wood drying [6,7,8]notes that not all quality indicators but only two of them depend on drying regime: integrity of the material caused by the size of internal tension in the wood and level of preservation of strength in the wood caused by the level and duration of temperature impacts on it.

Creation of drying regimes should be carried out in such a way that during the whole process the maximum values of internal tensions in wood do not exceed the maximum permissible value. The regime is characterized by a safety coefficient:

$$B = \frac{\sigma_{\text{пр.р.}}}{\sigma_{\text{макс}}} \tag{1}$$

where $\sigma_{\text{пр.р.}}$ – calculated strength of wood;
$\sigma_{\text{мах}}$ – the maximum size of internal tension.

If $B < 1$, then the regime does not provide integrity of material, if $B > 1$, the greatest possible intensity of process is not reached. However, the Guidance Technical Materials on physical and mechanical properties of wood for strength of wood give a variation factor of 10%. At the same time efficiency of drying can be completely guaranteed at $B = 1.3$ (with probability of $p = 99.73\%$). Respectively, at $B = 1.2$ it is guaranteed with probability $p = 95\%$, and at $B = 1.1$, $p = 90\%$. The set of parameters of regime uniquely determines the size of indicators of efficiency and quality of dried up wood [9].At the same time efficiency of drying can be unambiguously estimated by total power consumption per 1m^3 of sawn timber. Consequently, the task on increasing of data values of these indicators can be considered as optimization.

Methodology

Creation of system of optimized regimes of drying of sawn timber was carried out in two stages:

1. Computing experiment
2. Production experiment

Removal of moisture out of wood during the drying process is rather complex physical and chemical process accompanied by heat mass exchange (HME).

For mathematical description of the process of low-temperature convective drying of unlimited sawn timber, A.V. Lykov [10] proposes the following system of differential equations in private derivatives (DEPD HME).

$$\frac{\partial t}{\partial \tau} = a\nabla^2 t + \frac{\varepsilon \cdot \rho}{c}\frac{\partial u}{\partial \tau}, \tag{2}$$

$$\frac{\partial u}{\partial \tau} = a_{\text{м}}\nabla^2 u + a_{\text{м}}\delta\nabla^2 t, \tag{3}$$

For unlimited sawn timber the initial and boundary conditions of the III kind have the form:

$$t(x_0,0) = f(x), \tag{4}$$

$$u(x,0) = \varphi(x), \tag{5}$$

$$-\lambda\frac{\partial t(R,\tau)}{\partial x} + \alpha[t_c - t(R,\tau)] - (1-\varepsilon)\rho_{\text{б}}\alpha_m[u(R,\tau) - u_p] = 0 \tag{6}$$

$$a_m\frac{\partial u(R,\tau)}{\partial x} + a_m\delta\frac{\partial t(R,\tau)}{\partial x} + \alpha_m[u(R,\tau) - u_p] = 0 \tag{7}$$

Symmetry condition:

$$\frac{\partial t(0,\tau)}{\partial x} = \frac{\partial u(0,\tau)}{\partial x} = 0 \tag{8}$$

Where t – temperature, $^{\circ}$C;
u – humidity;
τ – time;
a – coefficient of thermal diffusivity, m^2/c;
a_m - coefficient of moisture conductivity, m^2/c;
ε – coefficient of phase transformation;
ρ – density of wood, kg/m^3;

c – thermal capacity of wood, kJ;
δ – thermogradient coefficient;
x – coordinate in the direction of thickness of a plate, m;
R – a half of thickness of a plate, m;
λ – coefficient of thermal conductivity, W/(м·град);
α – coefficient of heat exchange, W/(м^2·град);
α_m – coefficient of moisture exchange, м/с;
$\rho_б$ – basic density of wood, кг/м^3;
t_c – temperature of the medium, ^{0}C;
u_p – equilibrium humidity of wood.

For the solution of the system (2) – (10) software was developed in MathCAD computing environment [11] on the basis of the implicit method [12]. In addition, software was used to calculate internal stresses [13] on the basis of multi-rod model of the board [14]. Using the above – mentioned software, a computer experiment was implemented. During the experiment, constant factors were the following:

1. Type of sawn timber – conditional (pine, section 40x150mm);
2. Type of regime – step less

- temperature of processing medium

$$t_c = t_н + (t_к - t_н)\frac{(u_н - u)}{(u_н - 0{,}1)}; \tag{9}$$

- equilibrium humidity

$$u_p = u_{рк} + (u_{рн} - u_{рк})e^{-e^{-(b_0+b_1u)}}, \tag{10}$$

where $t_н$, $t_к$ – respectively, initial and final temperature of the agent of drying, ^{0}C;
$u_н$, u – respectively, initial and current humidity of wood;
$u_{рн}$, $u_{рк}$ – respectively, initial and final values of equilibrium humidity ;
b_0, b_1 – coefficients.

Expression (12) represents function of desirability [15] which is characterized by two transition values u, denoted respectively $u_{п1}$ and $u_{п2}$. Moreover, $u_{п2}$ = 0,35 and $u_н$ = 0,6 remained constant in all experiments. Variable factors during the experiment are:
$u_{рн}$ (x1), $u_{рк}$ (x2), $u_{п1}$ (x3), $t_н$ (x4), $t_к$ (x5).

The factors varied at three levels, their values in encoded and natural terms are presented in Table 1.

Table 1: Variable factors during a computing experiment

№	factors	Values of factors at levels					
		low		main		upper	
		coded	natural.	coded	natural	coded	natural
1	$u_{рн}$ (x1)	-	0,1	0	0,14	+	0,18
2	$u_{рк}$ (x2)	-	0,02	0	0,03	+	0,04
3	$u_{п1}$ (x3)	-	0,1	0	0,15	+	0,2
4	$t_н$ (x4)	-	60	0	70	+	80
5	$t_к$ (x5)	-	80	0	90	+	100

Output parameters:
τ1 (y1) – duration of drying of sawn timber to humidity of W = 12 %;
τ2 (y2) – duration of drying of sawn timber to humidity of W = 7 %;
$S_т$ (y3) – difference of humidity on board thickness;
S_w (y4) – an average square deviation of humidity ;
B_{min} (y5) – the minimum value of safety criterion of the regime during each drying;
$Q_т$ (y6) – costs of thermal energy for drying of 1m^3 of sawn timber;
$C_э$ (y7) – total costs of energy (electric and thermal) spent on drying of 1m^3 of sawn timber.

In the course of experiment Hartly plan [15] consisting of 27 issues (experiments) was implemented. As a result, the dependences of each output parameter on each input one were obtained in the form of polynoms of the second range.

Then optimization on each of output parameters was carried out (τ1, τ2, $S_т$, S_w, B_{min}).

Formulation of optimization problems was the following:

$$\left.\begin{array}{l} y1 \to \min \\ -1 \le X \le 1 \end{array}\right\} \tag{11}$$

$$\left.\begin{array}{l} y2 \to \min \\ -1 \le X \le 1 \end{array}\right\} \tag{12}$$

$$\left.\begin{array}{l} y3 \to \min \\ -1 \le X \le 1 \end{array}\right\} \tag{13}$$

$$\left.\begin{array}{l} y4 \to \min \\ -1 \le X \le 1 \end{array}\right\} \tag{14}$$

$$\left.\begin{array}{l} y5 \to \min \\ -1 \le X \le 1 \end{array}\right\} \tag{15}$$

where $X = \begin{vmatrix} x1 \\ x2 \\ x3 \\ x4 \\ x5 \end{vmatrix}$

Production tests were carried out for the purpose of check of practical suitability of received optimized regimes of drying.

As the main experiment plan of the kind B_3 was performed.

Calculation of consumption of thermal and electric energy was carried out by a standard technique [4]. The price of energy unit was taken as average for the Ural region of the Russian Federation.

Results and Analysis

Results of optimization performed in MathCAD computing system are given in Table 2.

However results of optimization of the regime on the required category of quality are of the greatest interest (table 3).

Table 2: Results of optimization of the regime of drying on private criteria

№	operating factor	Values of operating factors for criteria of optimality				
		τ1 (hour)	τ2 (hour)	S_T	S_w	B_{min}
1	$u_{\text{рн}}$	0,1	0,1	0,18	0,18	0,18
2	$u_{\text{рк}}$	0,02	0,02	0,04	0,04	0,02
3	$u_{\text{п}1}$	0,2	0,174	0,1	0,1	0,1
4	$t_{\text{н}}$, ^{0}C	80	80	60	60,5	80
5	$t_{\text{к}}$, ^{0}C	92	100	100	99,5	100
Value of criterion of optimality		90,8	120	0,011	0,088	2,039

Table 3: Results of optimization of drying regimes on categories of quality

№	operating factor / criterion of quality	Values of operating factors criteria of optimality		
		I	II	III
1	$u_{\text{рн}}$	0,168	0,11	0,1
2	$u_{\text{рк}}$	0,036	0,033	0,038
3	$u_{\text{п}1}$	0,1	0,1	0,2
4	$t_{\text{н}}$, ^{0}C	66,25	74,7	80
5	$t_{\text{к}}$, ^{0}C	100	100	100
6	τ2 (hour)	247	179	143
7	B_{min}	1,703	1,299	1,263
8	S_T	0,019	0,03	0,035
9	S_w	0,01	0,015	0,02

Formulation of the problem was the following:

Ist category of quality:

$$\left.\begin{array}{l} \tau 2 \rightarrow \min \\ -1 \leq X \leq 1 \\ B_{\min} \geq 1{,}3 \\ S_w \leq 0{,}01 \\ S_T \leq 0{,}02 \end{array}\right\} \qquad (16)$$

II nd category of quality:

$$\left.\begin{array}{l} \tau 2 \rightarrow \min \\ -1 \leq X \leq 1 \\ B_{\min} \geq 1{,}2 \\ S_w \leq 0{,}015 \\ S_T \leq 0{,}025 \end{array}\right\} \qquad (17)$$

III rd category of quality:

$$\left.\begin{array}{l} \tau 2 \rightarrow \min \\ -1 \leq X \leq 1 \\ B_{\min} \geq 1{,}2 \\ S_w \leq 0{,}02 \\ S_T \leq 0{,}035 \end{array}\right\}$$

At the third stage, optimization of regimes in energy efficiency parameters was carried out. Two problems of optimization of these indicators are formulated on the basis of the data obtained at the previous stages of optimization for drying on the second (II) category of quality:

$$\left.\begin{array}{l} Q_т \rightarrow \min \\ -1 \leq x \leq 1 \\ B_{\min} \geq 1{,}2 \\ S_w \leq 0{,}015 \\ S_т \leq 0{,}025 \end{array}\right\} \qquad (19)$$

$$\left.\begin{array}{l} C_э \rightarrow \min \\ -1 \leq x \leq 1 \\ B_{\min} \geq 1{,}2 \\ S_w \leq 0{,}015 \\ S_т \leq 0{,}025 \end{array}\right\} \qquad (20)$$

Results of optimization are shown in Table 4

Table 4 : Results of optimization of drying regimes in terms of energy efficiency parameters

№	operating factor / criterion of quality	Values of operating factors in terms of optimization on parameters	
		$Q_т$	$C_э$
1	$u_{рн}$	0,11	0,1
2	$u_{рк}$	0,038	0,0385
3	$u_{п1}$	0,11	0,1
4	$t_н$, ^{0}C	62,4	71,6
5	$t_к$, ^{0}C	81	98,6
6	τ_1, hour	133,3	122,6
7	$Q_т$, GJ/m^3	1,867	1,882
8	$Q_э$, GJ/m^3	0,581	0,533
9	$Q_т + Q_э$, GJ/m^3	2,448	2,415

10	$C_э$, rubles	860	823

Note – $Q_э$ – amount of electricity

The values of parameters of the regime received as a result of optimization by solving a compromise task by the method of conditional centre of masses rather closely coincide with the regime parameters for the second (II) category of quality received by analytical optimization (table 5).

Table 5: Results of analytical and experimental optimization of drying regimes for conditional sawn timber

№	parameters of the regime /values of output parameter	Values			
		analytical optimization			experimental optimization
		On the second (II) category of quality	on $Q_т$	on $C_э$	
1	$u_{рн}$	0,11	0,11	0,1	0,114
2	$u_{рк}$	0,033	0,038	0,0385	0,033
3	$t_н$, ^{0}C	74,7	62,4	71,6	73,4
4	$t_к$, ^{0}C	100	81	98,6	95
5	T_{drying} ($W_к$ = 12 %), hour	125	133,3	122,6	1,38
6	S_w, % (category of quality)	1,5 (II)	-	-	0,835 (I)
7	inside tensions, (category of quality)	1,376 (II)	-	-	I – II
8	Consumption of energy on drying, GJ/m^3	-	2,448	2,415	2,769

Also the drying time is quite close: in the experiment, it is 9.4% higher that can be attributed primarily to idealization of conditions of drying in a computing experiment. It should be noted that experimentally received valued of an average quadratic deviation of wood humidity is significant, it is nearly 1.8 times less than those, obtained analytically. At the same time, according to the experiment this indicator of quality of drying completely corresponds to the first (I) category of quality. Obtained discrepancies in our opinion should be attributed to the error of method of analytical determination of Sw.

The fact is that this technique is calculated on final quantity of stages of the regime of drying and for the steeples regimes we considered that, hypothetically, the quantity of steps was 10. Obviously, that for increase in accuracy, it is necessary to increase quantity of these hypothetical steps to 20 -25. Besides, it should be noted that results of theory and the experiment rather closely coincide during drying by standard 3-staged regimes. Thus, drying time in the experiment differs from theoretical only by 5.5%. As in the previous case, there are discrepancies between theory and the experiment concerning Sw. It is true, to be fair, it should be noted that in this case these discrepancies are much less and their amount is about 16%. It also can be explained by the fact that in theory and experiment the number of steps (stages) of regime was still the same -3. It should also be noted that the application of standard regimes, both in theory and in practice, allowed obtaining quality of drying corresponding only to the third (III) category of quality. As for energy consumption, in experimental optimization they are more than in analytical one by 10-12% that confirms a rather reliability of carried out computing experiment.

Acknowledgement

The work is carried out based on the task on fulfilment of government contractual work in the field of scientific activities as a part of base portion of the state task of the Ministry of Education and Science of the Russian Federation to Ural State Forest Engineering University (the # 26.8660.2017/8.9 "The Research Methodology of Forms of Economic and Technological Reality in the Aspect of Sustainable Forest Management").

Conclusions

Optimization of drying regimes in parameters of energy efficiency has shown a rather close coincidence of parameters of the regime by optimization on the consumption of thermal energy and the total cost of energy. However the minimum cost of energy is achieved at the minimum time of drying that is explained by an essential difference in the cost of thermal and electric energy. The regimes of steeples structure received by computer modeling allow receiving sawn timber that fully meets the requirements of the consumer without application of moisture treatment and the conditioning processing. The developed technique of formation of the steeples regimes of drying of sawn timber allows determining structure and sizes of parameters of the regime depending on the required quality of drying and energy costs on its carrying out. Calculations of technical and economic efficiency have shown that the total annual economic effect at the volume of drying of 3000 m^3 can reach 1 million rubles, including on a power component – more than 750 thousand rubles, which is equivalent to more than 17 dollars per 1 m3 and it can be extended by including on power component.

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