Bulgarian Journal of Agricultural Science, 25 (Suppl. 2) 2019
Agricultural Academy

Process unit for drying sawn timber rotating in the ultra high frequency field with a discrete arrangement of magnetrons

Rustam S. Aipov, Ildar I. Gabitov, Midhat I. Tuhvatullin*, Andrey V. Linenko, Marat F. Tuktarov, Artur T. Akhmetshin

Federal State Budgetary Educational Establishment of Higher Education "Bashkir State Agrarian University", Ufa 450001, Bashkortostan, Russia
**Corresponding author:* midhat.tuhvatullin@mail.ru

Abstract

Aipov, R. S., Gabitov, I. I., Tuhvatullin, M. I., Linenko, A. V., Tuktarov, M. F. & Akhmetshin, A. T. (2019). Process unit for drying sawn timber rotating in the ultra high frequency field with a discrete arrangement of magnetrons. *Bulgarian Journal of Agricultural Science, 25* (Suppl. 2), 3–11

Wood is a natural and environmentally friendly construction material widely used in various fields of industrial and civil engineering. Timber drying process has an effect on the consumer properties of the final product and is basic in wood processing technology. Ultra high frequency range is the most effective in drying sawn timber with the use of electromagnetic energy. A process unit comprising discretely arranged magnetrons and a mechanism for rotation of sawn timber along the axis in the chamber is presented in the study. Magnetrons discretely and uniformly arranged ensure better distribution of heat on the sawn timber during rotation and reduces drying time. The engineering solution reduces drying time by 38.75% and increases the volume of dried timber by 27.3%. Variable drying mode control improves efficiency of the process by 8-10% depending on the timber species and initial moisture. Experimental dependences characterizing operational modes of the process unit are obtained. A mathematical model of sawn timber drying in the chamber with discretely arranged magnetrons and a mechanism to ensure rotation of sawn timber along the axis is developed. The mathematical model is made in the object-visual modelling MatLab package (Simulink). The model adequacy is confirmed experimentally, discrepancy between the experimental data and the data obtained from the mathematical modelling is no more than 3%.

Keywords: process unit; ultra high; frequency drying; magnetron; sawn timber; moisture; mathematical model

Introduction

Drying is the longest and most expensive operation in the technological process of a woodworking enterprise (Khamaletdinov et al., 2018). High-quality drying is the basis for excellent quality of timber products (Arkhangel'skiy, 2011).

The main advantage of ultra high frequency drying is even distribution of heat on the entire volume of the material. Ultra high frequency heating implies that sources of heat are inside the material body. This fact results in temperature gradients opposite in sign to the values observed in traditional methods of heating materials, which ensures multiple acceleration of various heat stimulated processes (Sergovskiy & Rasev, 1987).

Gorokhovskiy (2018), Gareev (2010), Sergovskiy (1987), Tarmian (2012), Dashti (2012), Tiaya et al. (2017) studied patterns of temperature and moisture changes and moisture transfer in capillary-porous bodies; use of electrical energy for drying timber – Arkhangelskiy (2011), Didenko (2003), Lykov (1968), Boldyrev (2010), Bartholme (2009), Brodie (2009), Harris (2008), Yongfeng (2014), Zhou (2009); theory of electromagnetic field – Dautov (1993), Pimenov

(2000), Li (2009), Alami (2017), Karampatea (2018), Masalimov et al. (2018).

The existing designs of ultra high frequency units for drying sawn timber are based on ultra high frequency generators (915 and 416 MHz). The process units are of high cost, sophisticated design, expensive to service and maintain. The high cost of an ultra high frequency process unit means a long payback period. Failures of the ultra high frequency generator and its replacement result in high material losses (Brodie, 2009).

Even heat distribution is difficult to obtain in ultra high frequency drying since timber located closer to the ultra high frequency source is overheated and timber deep in the stack cannot dry to the required degree of moisture (Lykov, 1968).

The existing methods of ultra high frequency drying of sawn timber report the following significant shortcomings (Li et al., 2008; Vongpradubchai & Rattanadecho, 2009): two zones are distinguished around the source of the electromagnetic field: the induction zone (short range) and the wave zone or radiation zone (long range). There is no definite dependence between the electric and magnetic components in the induction zone. As the distance from the radiation source increases the electric value of the field falls proportionally with the distance value cubed and the magnetic value falls proportionally with the distance value squared. So it is extremely difficult to obtain even heat distribution for the material located in the induction zone;

High intensity of internal water transfer observed in ultra high frequency drying is restrained by exchange with the external environment. If moisture-yielding capacity of the material is not increased when the timber is exposed to sufficient electromagnetic power the moisture of the upper layers is higher than that of the lower layers. This results in lower moisture yield and local overheating of the sawn timber.

The aim of the study: Improving efficiency of sawn timber drying through the use of discretely arranged magnetrons and a mechanism for rotation of sawn timber along the axis in the chamber.

Objectives of the study:

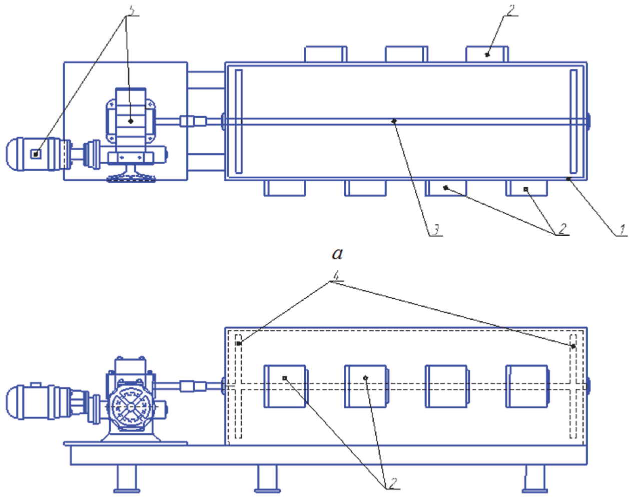
– To develop a design of the process unit comprising discretely arranged magnetrons and a mechanism to ensure rotation of sawn timber along the axis.

– To develop a mathematical model of the process unit with discretely arranged magnetrons and a mechanism to ensure rotation of sawn timber along the axis.

– To assess experimentally the dependence of moisture and temperature variances of sawn timber on time, to check the adequacy of the developed mathematical model.

Methods

A process unit comprising discretely arranged magnetrons and a mechanism to ensure rotation of the sawn timber along the axis in the chamber was developed based on the research results (Figure 1) (Aipov & Tukhvatullin, 2011). The process unit is a process chamber of $2.42 \times 0.6 \times 0.6$ м^3 with magnetrons of 1.2 kW each discretely arranged on the side surfaces of the chamber.



a

b

Fig. 1. A process unit incorporating discretely arranged magnetrons and a mechanism to ensure rotational movement of sawn timber along the axis in the chamber. *a* – top view, *b* – side view, *1* – process chamber, *2* – magnetrons, *3* – rotating shaft, *4* – frames with bindings for sawn timber stacks, *5* – gear motor to transfer rotation to the sawn timber stack

To ensure more efficient drying rotating shaft 3 is installed in process chamber 1, frames and bindings for the sawn timber stack 4 are mounted on the two sides of the shaft. The shaft can be driven by hand and automatically by using gear motor 6. To provide electric insulation of the unit a cover with clamps is put on top of the process chamber. To remove the evaporated moisture different ducts and vents of the forced air system are found in the process unit. To protect workers from the electromagnetic field a wire screen is installed around the ultra high frequency process unit.

Figure 2 shows a general view of the process unit with discretely arranged magnetrons and a mechanism to ensure rotation of sawn timber along the axis in the chamber. The main design components of the process unit can be seen in Figure 3.

Fig. 2. General view of the process unit: *1* – shaft for rotation of the sawn timber along the axis in the chamber, *2* – magnetrons, *3* – the unit housing, *4* – steel wire cover

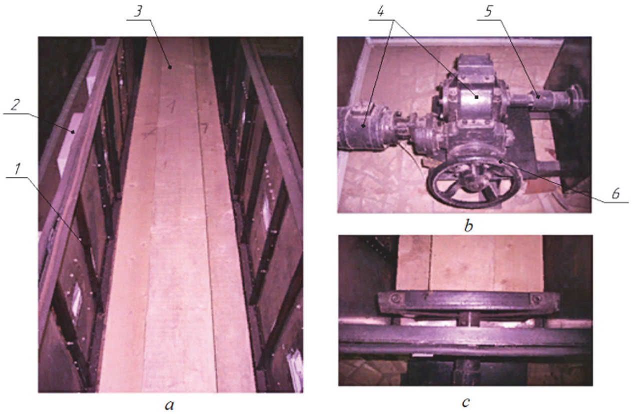


Fig. 3. The main design components of the process unit: *a* – the interior of the unit, *b* – gear motor to provide rotational movement of the sawn timber stack; *c* – frame with bindings for the timber stack, *1* – process chamber, *2* – magnetron, *3* – sawn timber stack, *4* – gear motor, *5* – shaft, *6* – mechanism to ensure hand-held rotation of the timber stack

Even heat distribution inside the process chamber is achieved through radiating the material with counter-directed electromagnetic flows from ultra high frequency electromagnetic sources and rotation of the sawn timber stack. The sources of 1.2 kW capacities each are arranged in a staggered pattern at 27.5 cm distance from one another, the rotational speed is 5...6 rpm (Aipov & Tukhvatullin, 2012).

Deep drying is provided if the moisture is transferred from the inner layers to the outer layers at low moisture gradients (Tukhvatullin, 2018). In ultra high frequency heating of the sawn timber stack an internal energy source should be provided by changing the direction of the transfer. The inner zone temperature can thus be controlled by monitoring water evaporation and moisture gradient through the timber. The equation for the moisture transfer in the sawn timber q, kJ is as follows (Didenko, 2003).

$$q = -\alpha\rho_0\left(\frac{dU}{dt} - \alpha\delta^T\left(\frac{dT}{dt}\right)\right) - \alpha p\left(\frac{dp}{dt}\right), \qquad (1)$$

where α – is the coefficient of potential diffusivity for molecular and capillary water transfer;

αp – the coefficient of convection diffusion (Vongpradubchai & Rattanadecho, 2009);

δ^T – thermogradient coefficient;

ρ_0 – density of absolutely dry timber, kg/m^3 (Vongpradubchai & Rattanadecho, 2009);

$\frac{dU}{dt}$ – change of moisture over time, %;

$\frac{dT}{dt}$ – change of temperature over time, °C;

$\frac{dp}{dt}$ – change of density over time, kg/m ^{3}.

Intensity of internal water transfer is restrained by the exchange with the external environment in ultra high frequency heating. If moisture yield is not increased when the material is exposed to sufficient electromagnetic power the moisture of the upper timber layers is higher than that of the inner layers (Dautov, 1993). Partial differential equations describe the patterns of heat and mass transfer in the timber stack exposed to ultra high frequency electromagnetic radiation from the discretely arranged sources (Tukhvatullin, 2018):

$$\begin{aligned}
&\frac{dT}{dt} = \alpha\nabla^2 T + \frac{\varepsilon^P r_0}{c_в}\frac{dU}{dt} + \frac{Q_v}{c_в\rho_0};\\
&\frac{dU}{dt} = \alpha_m\nabla^2 u + \alpha_m\delta^T\nabla^2 T + \varepsilon^p\frac{dU}{dt}; \qquad (2)\\
&\frac{dp}{dt} = \alpha_p\nabla^2\rho + \frac{\varepsilon^p}{c_в}\frac{dU}{dt},
\end{aligned}$$

where T – is timber temperature, °C;

U – timber moisture, °C;

ρ – timber density, kg/m^3;

α – thermal diffusivity (Li et al., 2013);

ε^p – phase transition criterion;

r_0 – latent heat of vaporization, kJ/ kg (Donghua et al., 2010);

$c_в$ – specific heat of water, kJ/ (kg·K) (Tukhvatullin, 2018);

Q_v – heat absorbed by a material, kJ/ kg.

Two main parameters determine operational modes of the drying unit: rotational speed of the sawn timber stack and number of actuated magnetrons.

The following parameters affect moisture in ultra high frequency electromagnetic drying of the sawn timber:

$$\dot{U} = f\{U_0, T_0, m_0, E, \omega, t\} \tag{3}$$

where U_0 – initial moisture is values, %;

T_0 – initial temperature values, °C;

m_0 – initial mass values of the sawn timber, kg;

E – magnetron power, kW;

ω – rotational speed of the sawn timber stack, rpm.

From the formula (2), it follows that moisture is changed under the effect of temperature field. The temperature field value depends on ultra high frequency radiation and rotational speed of the sawn timber stack (Boldyrev, 2010).

The general form of the dependence of temperature and moisture variances in the sawn timber stack dried in the process unit subject to initial conditions U_0, T_0, m_0 can be written as follows

$$\begin{aligned} \frac{dT}{dt} &= f\{E(t), \omega\}; \\ \frac{dU}{dt} &= f\{E(t), \omega\}, \end{aligned} \tag{4}$$

where $E(t)$ – is the electricity consumption for high-frequency drying, kWh.

To solve the system of equations (2), it is necessary to choose the coordinate system best suited for achieve the objective.

This coordinate system must meet the requirements of the lowest dimension and retaining the basic patterns of drying timber in ultra high frequency electromagnetic field.

Since the process unit is often used to dry long sawn timber built in round-shaped stacks a cylindrical coordinate system is preferred. Assuming the length of the timber is larger than its width and the timber is cylindrical in shape it is preferable to use a polar coordinate system.

With this in view we obtain the following formula equations (2)

$$\begin{aligned} \frac{dT}{dt} &= \alpha\left(\frac{1}{x}\cdot\frac{dT}{dx} + \frac{d^2T}{dx^2}\right) + \frac{\varepsilon^p r_0}{c_в}\cdot\frac{du}{dt} + \frac{\varepsilon 2\pi f\cdot \mathrm{tg}(\delta)E^2}{c_в\rho_0}\cdot\frac{1}{V}; \\ \frac{dU}{dt} &= \alpha_m\left(\frac{1}{x}\cdot\frac{du}{dx} + \frac{d^2u}{dx^2}\right) + \alpha_m\delta^T\left(\frac{1}{x}\cdot\frac{dT}{dx} + \frac{d^2T}{dx^2}\right) + \varepsilon^p\frac{du}{dx}; \\ \frac{dp}{dt} &= \alpha_p\left(\frac{1}{x}\cdot\frac{dp}{dx} + \frac{d^2p}{dx^2}\right) + \frac{\varepsilon^p}{c_в}\cdot\frac{du}{dt}, \end{aligned} \tag{5}$$

where V – is the volume of the sawn timber stack exposed to the electromagnetic field.

Results and Discussions

Figure 4 shows the mathematical model of the developed process unit incorporating discretely arranged magnetrons and a mechanism to ensure rotation of the sawn timber stack along the axis.

The following conditions are accepted as initial: 10 pine boards with dimensions 2.2×0.15×0.05 m^3; initial moisture of the timber is 84.5%; initial temperature of the timber is 22.4°C; initial density of the timber is 940 kg/m^3; thermal diffusivity is 0.15; criterion of phase transition is 1.1; thermogradient coefficient is 0.05. Rotational speed of the sawn timber stack is 5 rpm.

Figure 5 shows modelling results of drying the sawn timber stack in the process unit: *a* – moisture-time variance; *b* – temperature-time variance; *c* – moisture-temperature variance.

Moisture of the timber dropped from 8% to 9%, temperature of the timber rose from 22.5°C to 78°C within 14 hours of drying in the process unit (Figure 5a, b).

Figure 5 c demonstrates the moisture-temperature variance. The variance is difficult to trace.

So for a more detailed analysis we shall divide the whole drying process in the process unit into 4 sections:

– Section 1 – heating of wood (heating the loaded volume of the sawn timber up to 50...65°C in the chamber);

– Section 2 – drying of wood (removing intensively released moisture from the wood during further heating, the temperature is in the 60...70°C range);

– Section 3 – drying of wood (intensive removal of cellular moisture, the temperature is in the 65...75°C);

– Section 4 – drying of wood to the lowest moisture values (intensive removal of cellular moisture, the temperature is in the 70...80°C).

Thus we obtain the following mathematical model of the drying process:

$$\frac{dT}{dt} = \begin{cases} \sum_{i_1=0}^{n_1} a^1_{i_1} E^1(t)^{i_1} \text{ provided } T_0 \le T < T_1; \\ \sum_{i_2=0}^{n_2} a^2_{i_2} E^2(t)^{i_2} \text{ provided } T_1 \le T < T_2; \\ \sum_{i_3=0}^{n_3} a^3_{i_3} E^3(t)^{i_3} \text{ provided } T_2 \le T < T_3; \\ \sum_{i_4=0}^{n_4} a^4_{i_4} E^4(t)^{i_4} \text{ provided } T_3 \le T < T_4; \end{cases} \tag{7}$$

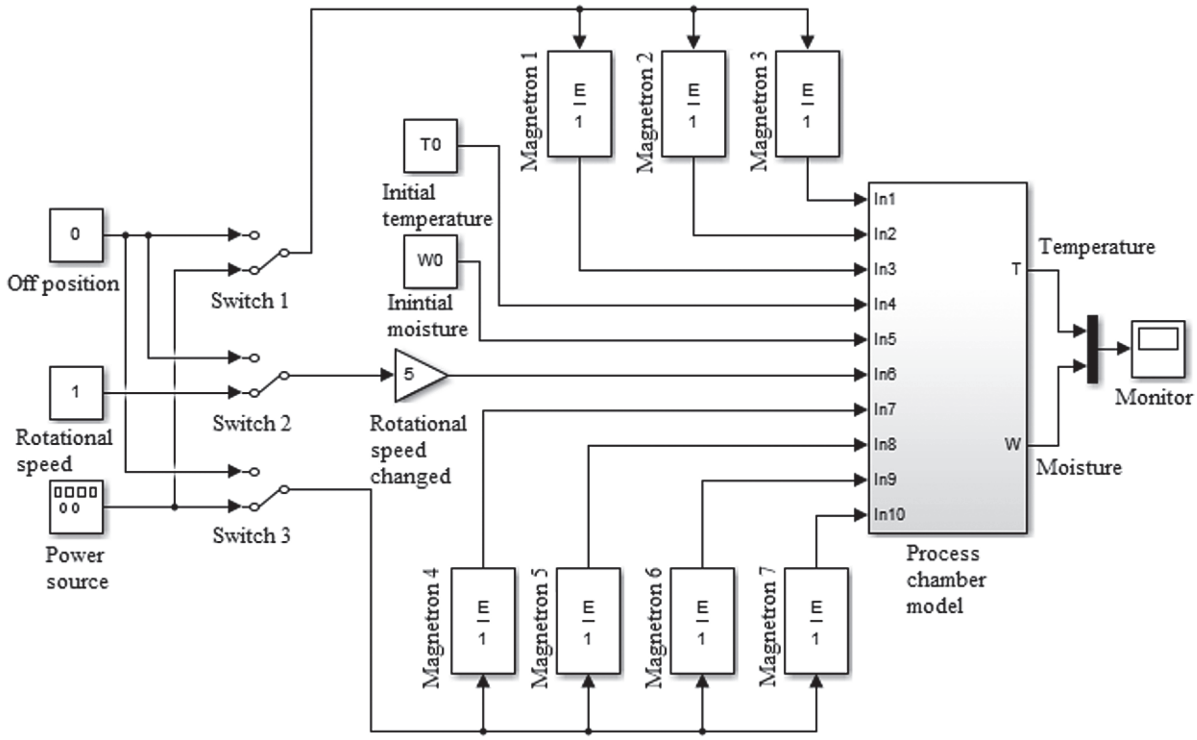


Fig. 4. Mathematical model of the process unit with discretely arranged magnetrons and a mechanism to ensure rotation of the sawn timber along the axis

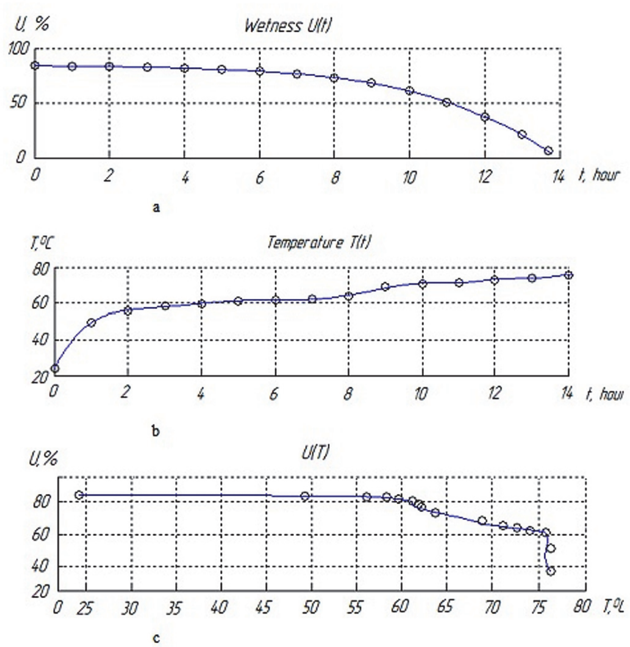


Fig. 5. Model results of drying the sawn timber stack in the process unit: *a* – moisture-time variance; *b*- temperature-time variance; *c* – moisture-temperature variance

$$\frac{dU}{dt} = \begin{cases} \sum_{j_1=0}^{m_1} a_{j_1}^1 E^1(t)^{j_1} \text{ provided } U_0 \le U < U_1; \\ \sum_{j_2=0}^{m_2} a_{j_2}^2 E^2(t)^{j_2} \text{ provided } U_1 \le U < U_2; \\ \sum_{i_3=0}^{m_3} a_{j_3}^3 E^3(t)^{j_3} \text{ provided } U_2 \le U < U_3; \\ \sum_{j_4=0}^{m_4} a_{j_4}^4 E^4(t)^{j_4} \text{ provided } U_3 \le U < U_4; \end{cases} \tag{8}$$

where values $U_1 ... U_4$ are taken based on the simplest form of the sections.

We obtain the following analytic expressions for each of the 4 sections

$$\begin{aligned} \frac{dT_1}{dt} &= 0.055E^4 - 1.164E^3 + 8.88E^2 - 28.915E + 34.72; \\ \frac{dT_2}{dt} &= 1.542E^4 - 7.807E^3 + 13.203E^2 - 9.428E + 3.288; \\ \frac{dT_3}{dt} &= 5.389E^4 - 17.276E^3 + 15.909E^2 + 0.0296E - 0.929; \\ \frac{dT_4}{dt} &= -0.241E^4 + 1.306E^3 - 1.691E^2 - 0.7788E + 4.314; \end{aligned} \tag{9}$$

$$\frac{dU_1}{dt} = -0.00001E^4 + 0.00023E^3 - 0.00139E^2 + 0.00175E - 0.0045;$$
$$\frac{dU_2}{dt} = 0.00296E^4 - 0.01343E^3 + 0.01212E^2 - 0.02692E - 0.06324; \quad (10)$$
$$\frac{dU_3}{dt} = 0.0499E^4 - 0.01600E^3 + 0.01702E^2 - 0.04179E - 0.25324;$$
$$\frac{dU_4}{dt} = -0.00235E^4 + 0.01276E^3 - 0.02309E^2 - 0.05547E - 0.1781.$$

Figure 6 shows graphs of moisture and temperature variances, a moisture-temperature variance for each of the four sections (Figure 6).

The models of the four sections were integrated into a single model of drying the sawn timber stack in the process unit and the following approximation results were obtained (Figure 7).

Division of the drying process into 4 sections result in a detailed analysis of wood moisture and temperature variances. The analysis results ensure quality modes of sawn timber drying.

Based on results of the mathematical modelling the drying time for the sawn timber stack was 14 hours. The final moisture of the sawn timber was no more than 7%.

Let us consider experimental dependences of moisture and temperature variances for the sawn timber stack in the process unit in one of the 4 operational modes. In this mode seven magnetrons were actuated and the mechanism to ensure rotation of the sawn timber stack in the chamber was operated.

A sawn timber stack was loaded into the chamber. The stack had the following dimensions: board length was 2200 mm, board width was 150 mm, and board thickness was 50 mm. The rotational speed of the sawn timber stack was ω = 5 rpm since based on the experiments this value ensured even distribution of heat in the chamber with discretely arranged magnetrons. The following equipment was used in experiments: a device for measuring the material moisture test 606-1 with an error of no more than 0.2%, surface thermometer test 905-T2, infrared pyrometer test 830-T1. Moisture and temperature were measured on the surface of the sawn tim-

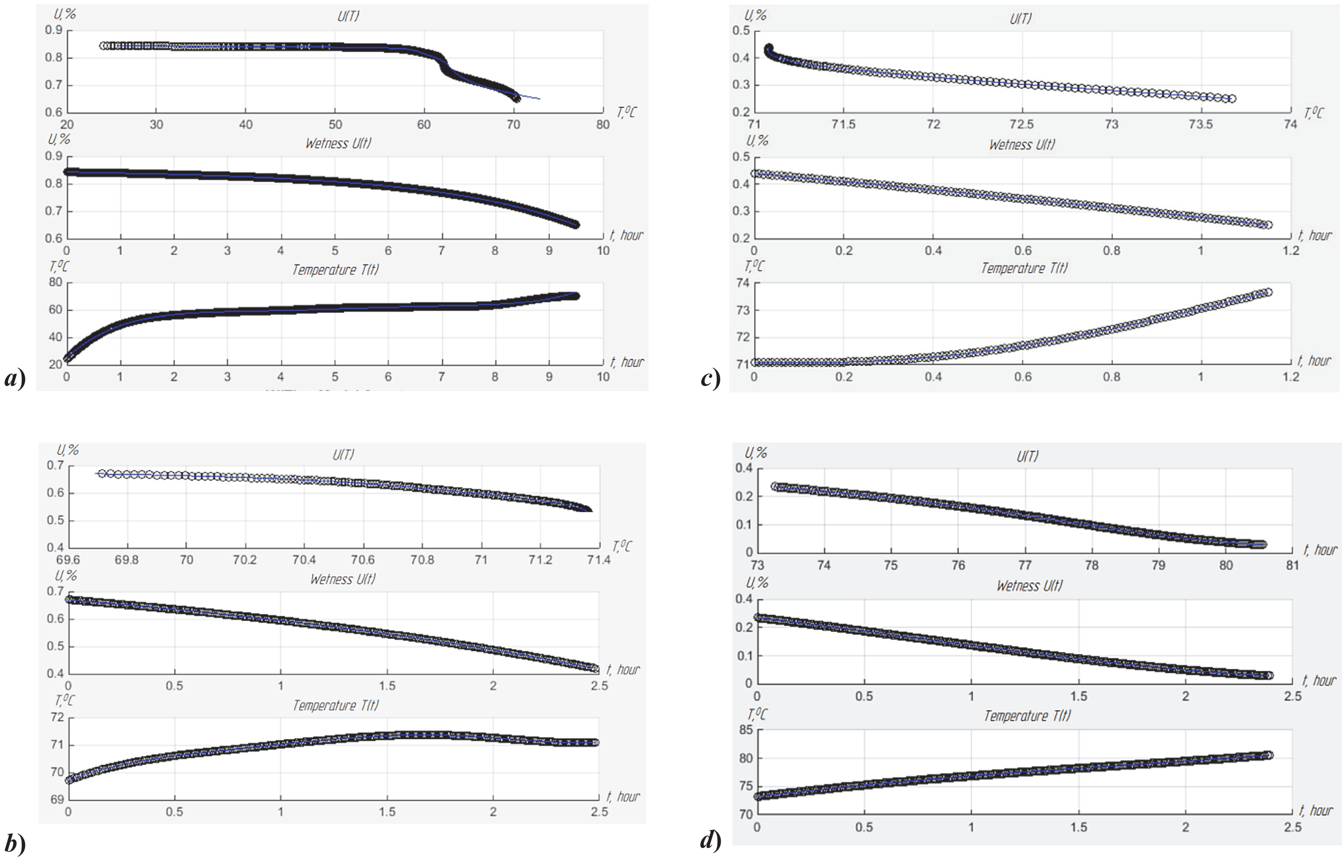


Fig. 6. Graphs of moisture and temperature variances, a moisture-temperature history for each of the four sections:
***a* – section 1; *b* – section 2; *c* – section 3; *d* – section 4**

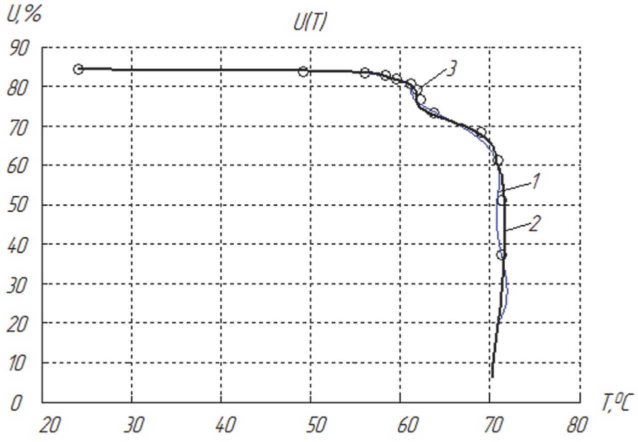


Fig. 7. Results of mathematical modelling of drying the sawn timber stack in the process unit: *1* – modelling results of ultra high frequency drying before division into 4 sections; *2* – Approximation modelling results of the 4 sections integrated into a single model of ultra high frequency drying, n3 – Experimental data

ber; at half the timber piece thickness and at a quarter of the timber piece thickness, the measuring interval was 100 mm along the length.

Figure 8 shows a sample timber piece used for measuring the temperature and moisture of the sawn timber sample (Figure 8).

Figure 9 shows experimental dependences of moisture variance based on measurement of ten samples of the sawn timber stack. Figure 10 shows experimental temperature variance based on measurement of ten samples of the sawn timber stack (Figure 9 and Figure 10).

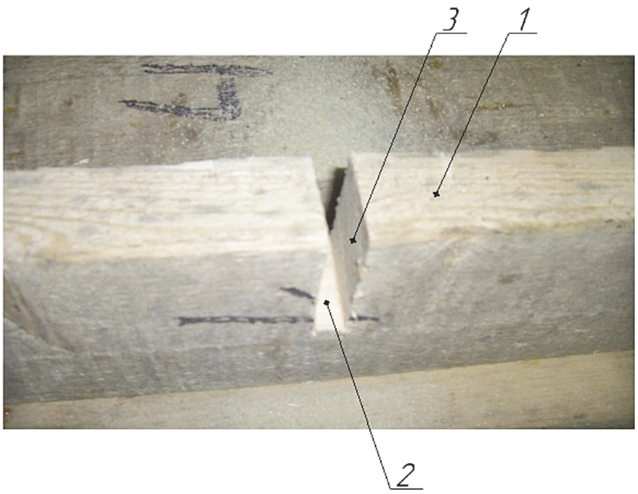


Fig. 8. Sample timber piece for measuring moisture and temperature: *1* – on the surface; *2* – at half the piece thickness; *3* – at a quarter of the piece thickness

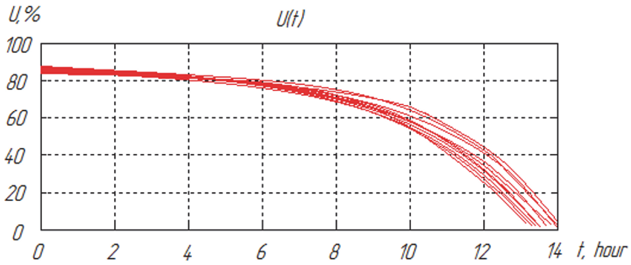


Fig. 9. Experimental dependences of moisture variance based on measurement of each timber sample

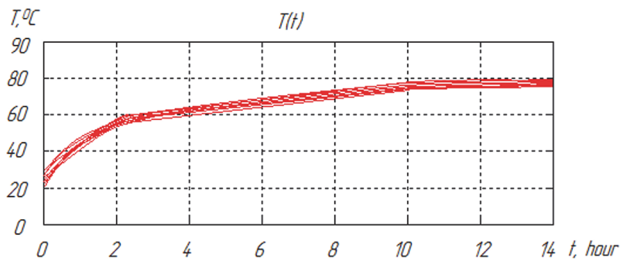


Fig. 10. Experimental dependences of moisture variance based on measurement of each timber sample

The time for drying the sawn timber stack in the process chamber did not exceed 14 hours. The moisture of the sawn timber stack decreased from 85.4% to 8.5%. The temperature range was from 22°C to 80°C. The process volume of the unit chamber equipped with discretely arranged magnetrons and a mechanism to ensure rotation of the sawn timber stack along the axis was 0.48 m^3. The consumption of electric energy for drying the sawn timber stack in the process unit was 117.6 kW per hour, the electricity consumption to dry 1 m^3 of the sawn timber was 245 kW per hour.

Conclusion

A process unit equipped with discretely arranged magnetrons and a mechanism to ensure rotation of sawn timber along the axis was developed. Theoretic dependences of the sawn timber moisture and temperature variances were obtained. The efficiency of the process unit was determined. Theoretic and experimental dependences were compared; the maximum discrepancy between the dependences did not exceed 3%. Therefore we believe the mathematical model adequately reflects physical processes and can be used in practical design calculations. It is recommended the process unit equipped with discretely arranged sources of ultra high frequency electromagnetic energy and a mechanism to ensure rotation of sawn timber along the axis be used at small innovative enterprises engaged in drying wood. The advantage of the proposed design over present-day ultra high frequency process units is higher quality of the dried sawn timber, higher drying speed at lower energy costs.

The process unit equipped with discretely arranged magnetrons and a mechanism to ensure rotation of the sawn timber along the axis ensures even heat distribution in the process chamber. So, powerful and expensive generators of ultra high frequency electromagnetic energy can be withdrawn from the process. Compared to other designs the process unit can lower operating costs by 40%, reduce dimensional indices and provides variable mode control. The process unit equipped with discretely arranged magnetrons and a mechanism to ensure rotation of sawn timber along the axis results in higher energy efficiency of 38.75% (energy consumption declined from 400 kWt to 245 kWt per hour). The energy efficiency is achieved due to shorter drying time of 36.4% (drying time decreased from 22 hours to 14 hours).

References

Aipov, R. S. & Tukhvatullin, **M. I.** (2011). UHF plant for drying lumber. Scientific and Production Journal *Farm Mechanic, Moscow: Sel'skiy mekhanizator Publ*., *8*, 8–9.

Aipov, R. S. & Tukhvatullin, M. I. (2012). Improving the Efficiency of Rotary Sawn wood Crashes by Discrete Sources of Microwave Magnetrons. *Current issues of the energy sector of the agro-industrial complex: proceedings of the International Scientific and Practical Conference*. Saratov, 7-9.

Arkhangel'skiy, Yu. S. (2011). Reference Book on the UHF Electrothermia. Saratov, OOO *"Nauch. kn.",* 559.

Bartholme, M., Avramidis, G., Viöl, W. & Kharazipour, A. (2009). Microwave drying of wet processed wood fibre insulating boards. *European Journal of Wood and Wood Products*, *67(3),* 357–360.

Boldyrev, P. V. (2010). Wood Drying: Practice Guide. *4th edition.* Sankt Peterburg, Profi Publ., 165.

Brodie, G. I. (2008). Innovative Wood Drying: Applying Microwave and Solar Technologies to Wood Drying. *VDM Publishing.*

Dashti, H., Tarmian, A., Faezipour, M., Hedjazi, S. & Shahverdi, **M.** (2012). Effect of pre-steaming on mass transfer properties of fir wood (*Abies alba* L.), A gymnosperm species with torus margo pit membrane. *BioResources*, *7(2),* 1907–1918.

Dautov, O. Sh. (1993). Engineering-Functional Equation for Stationary Problems in Actuation of Magnetic-Dielectric Bodies, Thesis of a doctor of technical sciences. Kazan', 240.

Didenko, A. N. (2003). UHF Energy: Theory and Practice. Russian Academy of Sciences, Department of Power Supply, Mechanical Engineering and Management Processes, Department of Electric Power Engineering Issues. Moscow, *Nauka Publ.,* 444.

Donghua, J., Muhammad, T., Afzal, M. G. & Alemayehu, **H. B**. (2010). Modeling of moisture diffusion and heat transfer during softening in wood densification. *International Journal of Engineering*, *42(4),* 191–200.

Gareev, F. Kh. (2010). Ultra high frequency plus vacuum: from the complex to the simple. *Lesprom Publ.,* 102–104.

Gorokhovskiy, A. G., Shishkina, E. E., Starova, E. V. &Mikov, **A. A.** (2018). Analysis of wood drying processes in absolutely non-isothermal modes. *IVUZ*, *2,* 88–96.

Harris, G. A., Torgovnikov, G., Vinden, P., Brodie, G. I. & Shaginov, A. (2008). Microwave pretreatment of backsawn messmate boards to improve drying quality: Part 1. *Drying Technology*, *26 (5),* 579–584.

Karampatea, A. & Siakavara, K. (2018). Analysis and synthesis of double negative dielectric media rectenna systems for ambient microwave energy harvesting. *International Journal of Antennas and Propagation*.

Khamaletdinov, R.R., Gabitov, I.I., Mudarisov, S.G., Farkhutdinov, I.M. & Shirokov, D.Y. (2018). Improvement in engineering design of machines for biological crop treatment with microbial products, *Journal of Engineering and Applied Sciences*, 13, 6500–6504.

Li, X. J. (2009). Mechanism of Heat Transfer and Characteristics of Microwave Vacuum Drying in Wood. *Environmental Science Press*. Beijing, China.

Li, X. J., Zhang, B. G. & Li, **W. J. (**2008). Microwave-vacuum drying of wood: Model formulation and verification. *Drying Technology*, *26(11),* 1382–1387.

Li, X., Luo, Y., Chen, H., He, X., Lv, J. & Wu, Y. (2013). Mathematical simulation of temperature profiles within microwave heated wood made for wood-based nanocomposites. *Journal of Nanomaterials*, *4.*

Luo, Y., Li, X. & Zhang, **J.** (2014). Theoretical study of wood microwave pretreatment in rectangular cavity for fabricating wood-based nanocomposites. *Journal of Nanomaterials*, *102.*

Lykov, A. V. (1968). Theory of Drying Process*:* textbook. Moscow, *Energiya Publ*., 471.

Masalimov, I. Kh., Faizrakhmanov, S. F., Gabitov, I. I., Martynov, V. M., Permyakov, V. N., Aipov, R. S., Yarullin, R. B., Davydova, A. A., Rakipov, I. R. & Ramazanov, A. S. (2018). Optimal operating modes reasoning of sunflower seeds microwave drying in a conveyor type unit. *Journal of Engineering and Applied Sciences*, *13,* 6570–6575.

Mbou, E. T., Njeugna, A., Kemajou, E., Sikame, N. R. & Ndapeu, **D.** (2017). Modelling of the Water Absorption Kinetics and Determination of the Water Diffusion Coefficient in the

Pith of Raffia vinifera of Bandjoun, Cameroon. *Advances in Materials Science and Engineering.*

Pimenov, Yu.V., Vol'man, V. I. & Muravtsov, **A. D.** (2000). Technical Electrodynamics*: Textbook for University Students*. Moscow, Radio i svyaz' Publ., 536.

Sergovskiy, P. S. & Rasev, **A. I**. (1987). Hydrothermal Processing and Wood Canning. Moscow, *Lesn. prom. Publ*., 360.

Slimani, A., Bennani, S. D., El Alami, A. & Terhzaz, J. (2017). Ultra wideband planar microstrip array antennas for C-band aircraft weather radar applications. *International Journal of Antennas and Propagation.*

Tarmian, A., Remond, R., Dashti, H. &Perre, P. (2012). Moisture diffusion coefficient of reaction woods: compression wood *of Picea bies* L. and tension wood of *Fagus sylvatica* L. *Wood Science Technology*, *46(1/3),* 405–417.

Tukhvatullin, M. I. (2018). Modelling Results of Lumber UHF Drying. *Proceedings of the International Scientific and Practical Conference 'Research in the Field of Natural Science, Engineering and Technology as a Factor of Scientific and Technological Progress'*, Belgorod, 137–141.

Vongpradubchai, S. & Rattanadecho, **P.** (2009). The microwave processing of wood using a continuous microwave belt drier. *Chemical Engineering and Processing*, *48(5),* 997–1003.

Zhou, Y. D., Fu, F., Li, X. J., Jiang, X. M. & Chen, Z. L. (2009). Effects of microwave treatment on residue growth stress and microstructure of *Eucalyptus urophylla*. *Journal of Beijing Forestry University, 31(2),* 2146–2150.