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Temperature and Humidity Model of the Wood Dryer

B. Hryniewicki* and M. Bartyś

Faculty of Mechatronics, Institute of Automatic Control and Robotics, Warsaw University of Technology, św. A. Boboli 8, 02-525 Warsaw, Poland

Doi: 10.12693/APhysPolA.146.374 *e-mail: bartlomiej.hryniewicki.dokt@pw.edu.pl

This paper presents an analytical model of temperature and humidity intended for automated controlling of the process of drying structural wood. The temperature and humidity model was presented in the form of a sequence of local sub-models including: heat flow from heating water to air, heat flow from air to wood, heat flow through the dryer walls, and air exchange between the dryer and the environment. The development of the model made it possible to develop a control strategy for the drying process using predictive control algorithms, ensuring the desired quality of the dried wood on the one hand and the economics of the drying process itself in terms of its energy consumption on the other.

topics: wood drying process, water and heat flow modeling, experimental verification of the models

1. Introduction

With the increase in requirements for high-quality dried structural wood, interest in automated control systems for the drying process has increased. The solutions commonly used in this regard [1–6] should be evaluated as not being in line with modern achievements in both the theory and practice of automatic control. A particularly important, in the era of energy savings, is to conduct the drying process in such a way as to optimize it, taking into account the constraints and conditions arising from the specifics of the process. Of particular importance in this case are the possibility of using model predictive control approaches. This is because they allow, among others, optimization of the drying process using a multi-criteria cost function. In the case of drying process, optimization takes into account energy consumption while ensuring control of the required wood quality parameters.

Among the main physical quantities affecting the wood drying process are: process temperature, relative dryer humidity, pressure, and air movement velocity, as well as the physicochemical parameters of the wood itself. The space of possible solutions to the optimization problem is limited by the ranges of permissible changes in the values of these quantities and specific requirements related to the drying process concerning, for example, phytosanitary treatment.

The end result of the drying process is the temperature and moisture content, as well as the internal stresses of the wood. However, due to the scope of the subject of this paper, we will limit ourselves here to the temperature and humidity model in the wood drying process. This is because in a typical wood dryer, the control system has can affect two quantities, namely temperature and humidity of the air in the dryer.

The influence on the temperature of the air in the environment of the dried wood is carried out by controlling the inflow to the dryer heating water mass flow, while the control of the level of relative humidity in the dryer is carried out by controlling the airflow exchanged with the ambient atmosphere. It should be noted that both of these quantities are mutually coupled. However, from the point of view of automatic control, changes in the air flow exchanged with the environment can be treated as so-called process disturbances. Technically, the control process is relatively complex.

The subject of this paper is the presentation and validation of an analytical model of the drying process, the block diagram of which in the form of a black box is shown in Fig. 1.

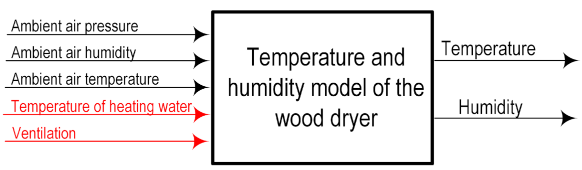

Fig. 1. Block diagram of the temperature and humidity model of the wood dryer.

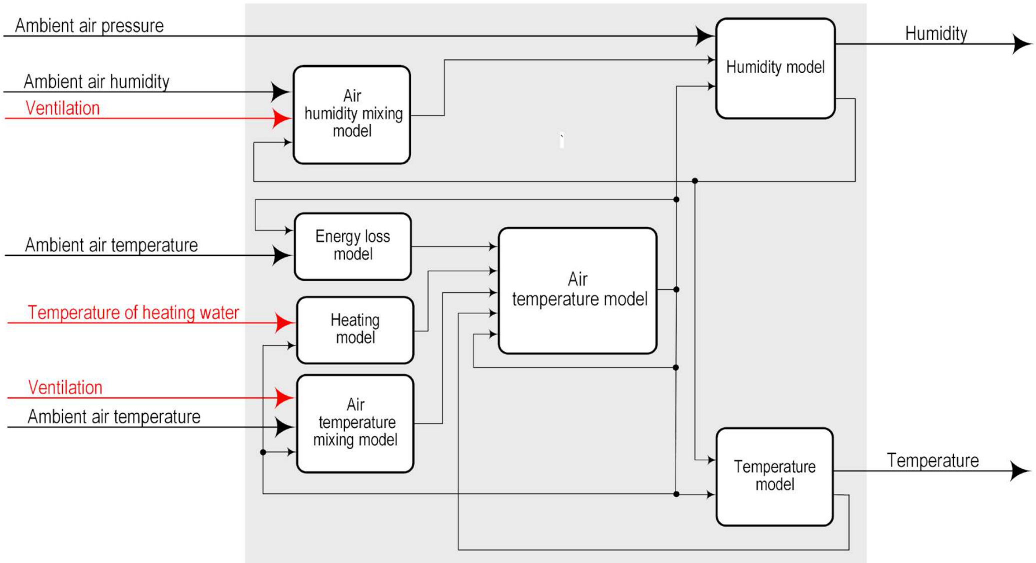

Fig. 2. Structure of the temperature and humidity model of the wood dryer.

In fact, the proposed model consists of seven interrelated submodels:

- air humidity mixing submodel,
- air temperature mixing submodel,
- air temperature submodel,
- heating submodel,
- energy loss submodel,
- temperature submodel,
- humidity submodel.

The structure of the model, along with the interconnections between its elements, is shown in Fig. 2.

The motivation to work on the building of the model of the temperature and humidity model came from purely practical needs. The drying process is an energy-intensive process. As a result of rising energy costs, the problem of energy savings becomes more and more important, and in particular, this also applies to the process of wood drying. The utilitarian goal of the work is to look for a solution that would make it possible to achieve savings by optimizing energy consumption. To this end, it is possible to develop a model-based predictive control strategy. However, the control strategy itself is beyond the scope of this paper.

The novelty of the paper is the proposal of an original model of air exchange between the dryer and the atmospheric environment. This model, unlike others found in the literature, additionally takes into account the exchange of air between the dryer and the atmosphere. This exchange has a significant impact on the energy consumption and the course of the drying process. In addition, the model includes also the flow of water evaporated from the dried wood in the balance of water mass flows. According to a review of the literature [7–14], such a model has not been the subject of research reports so far.

The structure of the paper is as follows: The introduction presents the motivation for the work and indicates its originality. Section 2 is devoted to the presentation of the partial models of the drying process. Section 3 is devoted to the description of the experimental work carried out and the discussion of the achieved results. Section 4 summarizes the results of the work.

2. Models of the process

The drying process is carried out in order to obtain the appropriate parameters of structural timber used mainly in the construction and furniture industries. As a result of this process, the wood is expected to have high dimensional stability, the required mechanical strength, and resistance to biological agents. Correctly carried out drying process of structural timber ensures the achievement of 16% moisture content, under the conditions of control of limit compressive and tension stresses and with properly carried out phytosanitary treatment [1, 15–24].

Modeling the course of the wood drying process is a complex task due to the scattering of wood parameters, depending, among others, on such factors as the species of wood, the season of harvesting, the period and method of seasoning, or even the history of changes in its moisture content. The process of drying wood is carried out in specially constructed dryers. During the drying process, thermodynamic processes related to thermal energy exchange, water transfer, and air mixing take place. As a result of drying, thermal energy is transferred from the heat exchanger supplied with heating water from the heating installation to the dried wood and the environment. The following main processes of thermal energy flow can be distinguished:

- flow of thermal energy from the heating water to the air of the dryer chamber,
- flow of thermal energy from the air of the dryer chamber to the wood,
- flow of thermal energy through the dryer walls to the environment,
- flow of thermal energy to the ambient environment through the vents.

2.1. Heat energy flow from heating water to air in the dryer chamber

In most heating systems used in dryers, the carrier of supplied thermal energy is heating water. However, it has a relatively low boiling point. Liquid water under low-pressure conditions is used only for heating low-temperature and conventional dryers, where the maximum temperature does not exceed 70°C.

Heat transfer from heating water to air is carried out using heat exchangers. They significantly increase the heat exchange surface area with the air. The process of heat exchange between a solid and air is called heat penetration or heat transfer and is described by the formula [25–33]

$$q_g = \alpha_g \, (T_g - T_a) \; A_g, \tag{1}$$

where q_g is heat energy flow from the exchangers to the air [W], α_g — coefficient of heat penetration from the heat exchangers to the air [W/(m^2 K)], T_g — temperature of heat exchanger [K, °C], T_a — air temperature [K, °C], A_g — area of exchanger [m^2].

As can be seen, in (1) it is necessary to know the temperature T_g of the exchanger. Technically, it is determined, as the mean of the inlet and outlet water temperature to and from the exchanger

$$T_g = \frac{T_{win} - T_{wout}}{2}, \tag{2}$$

where T_{win} is temperature of water entering the exchanger [K, °C], T_{wout} — temperature of water leaving the exchanger [K, °C].

2.2. Flow of thermal energy from air to wood

In the presented model, we assume that the process of heat energy flow from air to wood occurs mainly by convection. In the case of vacuum dryers, the heat flow can only occur by radiation or direct contact with heating elements.

The convective flow of heat energy from the air inside the drying chamber to the wood will be modeled analogously as in (1), namely

$$q_w = \alpha_w \, (T_a - T_w) \; A_w, \tag{3}$$

where q_w is heat flow transferred from air to wood [W], α_g — heat penetration coefficient [W/(m^2 K)], T_w — wood temperature [K, °C], A_w — wood surface area [m^2].

For simulation studies, a wood drying model takes into account not only the heat penetration but also the heat flow inside the wood and the heat required to release water bound to the wood.

2.3. Heat energy flow through the dryer walls to the environment

The flow of thermal energy through the dryer walls to the surroundings is an important source of energy loss that is significant from the point of view of potential energy savings. The energy transfer results from the temperature difference between the interior of the drying chamber and the environment. The flux of thermal energy flowing through the dryer walls will be modeled by the standard wall heat transfer equation

$$q_{\text{wall}} = \frac{\lambda_{\text{wall}} \, A_{\text{wall}}}{d_{\text{wall}}} \, (T_a - T_{aout}), \tag{4}$$

where λ_{wall} is heat penetration coefficient [W/(m K)], A_{wall} — dryer wall area [m^2], d_{wall} — thickness of the dryer walls [m], T_{aout} — temperature outside the dryer [K °C].

It should be noted that (4) models the heat loss through the dryer walls in a very simplified way.

2.4. Flow of thermal energy to the environment through the vents

To ensure that the drying process runs properly, it is necessary to control the relative humidity of the air in the drying chamber. The control of humidity is carried out by changing the degree of opening of the specially provided vents (air vents). Thanks to this, there is an exchange of air between the interior of the drying chamber and the environment. However, air exchange involves removing a certain mass of warm and moist air from the chamber and replacing it with cold and relatively dry air from the external environment. Assuming that the pressure inside the drying chamber does not change when the vents are opened, we can assume that the enthalpy change will be a measure of the energy lost due to air exchange.

Let us assume that the volume of air in the drying chamber is constant and the pressure is equal to atmospheric pressure. The density of dry air in the dryer will be expressed by the formula

$$\rho_{\text{dry}} = \frac{p}{r_{\text{dry}} \, T_a}, \tag{5}$$

where p is atmospheric pressure [Pa], r_{dry} — the individual gas constant for dry air = 287.05 J/(kg K).

Hence, the mass of dry air m_{adry} inside the chamber is equal to

$$m_{\text{adry}} = V_{\text{air}}\,\rho_{\text{dry}}, \tag{6}$$

where V_{air} is the volume of air in the drying chamber [m^3].

Total moisture is defined as the ratio of the mass of water to the mass of dry gas, i.e.,

$$X = \frac{m_w}{m_{\text{adry}}}. \tag{7}$$

The mixing ratio can also be determined from the formula [7–14]

$$X = 0.622\,\frac{\varphi\,p_n}{p - \varphi\,p_n}, \tag{8}$$

where φ is relative humidity, p_n — saturation pressure of water steam.

From (8), when substituting it into the transformed formula (7), it is possible to determine the water content in the air

$$m_w = 0.622\,m_{\text{adry}}\,\frac{\varphi\,p_n}{p - \varphi\,p_n}. \tag{9}$$

Assuming that the volume of air and pressure do not change, it can be assumed that the changes in the mass of water are due to the exchange of water with the environment and the inflow of water from the dried wood. We will apply a simplified moisture mixing scheme to the model. The change in the mass of water in the drying chamber is

$$\Delta m_w = m_{fw} + Y\,(X_{\text{outside}} - X_{\text{inside}})\,m_{\text{adry}}, \tag{10}$$

where m_{fw} is mass of water evaporated from the wood and mixed with the air, X_{outside} — total moisture of the outside environment of the drying chamber, X_{inside} — total moisture of the interior of the drying chamber, Y — coefficient of air exchange with the surroundings depending on the degree of opening of the vents.

Knowing the mass of water in the air allows one to determine the relative humidity in the dryer chamber

$$\varphi = \frac{X\,p}{p_n\,(0.622 + X)}. \tag{11}$$

The mass of moist air in the chamber is the sum of the mass of dry air and the water vapors. Assuming that the pressure in the chamber does not change, assume that the mass of dry air will not change as a result of opening the vents, i.e.,

$$m_{aw} = m_{\text{adry}} + m_w. \tag{12}$$

If there is no evaporation of water as a result of air mixing, it can be assumed that the specific heat of moist air can be described by the formula

$$c_{aw} = c_{\text{adry}} + X\,c_w, \tag{13}$$

where c_{adry} is specific heat of dry air [J/(kg K)], c_w — specific heat of water vapor [J/(kg K)].

Hence, the thermal energy transferred from the drying chamber to the surroundings through the vents can be expressed as the difference in the energy contained in the ejected and the aspirated air. The energy transferred to the surroundings is determined from the formula

$$E_{\text{out}} = Y\,c_{aw} m_{\text{adry}}\,T_a. \tag{14}$$

In turn, the energy transferred inside the drying chamber can be determined from

$$E_{\text{in}} = Y\,c_{awout}\,m_{\text{adry}}\,T_{aout}. \tag{15}$$

Thus, the change in energy in the drying chamber resulting from the exchange of air with the environment through the vents is equal to

$$\Delta E = Y\,m_{\text{adry}}\,\big(c_{awout}\,T_{aout} - c_{aw}\,T_a\big). \tag{16}$$

Finally, taking into account the effect on the temperature in the drying chamber of the flow of thermal energy from the heating water to the air, the flow of thermal energy from the air to the wood, the flow of thermal energy through the walls of the drying chamber to the surroundings, and the flow of thermal energy to the surroundings through the vents, we obtain

$$\Delta E = \alpha_g\,(T_g - T_a)\,A_g - \alpha_w\,(T_a - T_w)\,A_w - \frac{\lambda_{\text{wall}}\,A_{\text{wall}}}{d_{\text{wall}}}\,(T_a - T_{aout}) + Y\,m_{\text{adry}}(c_{awout}\,T_{aout} - c_{aw}\,T_a) \tag{17}$$

Thus, the temperature change inside the drying chamber can be determined from the formula

$$\Delta T = \frac{\Delta E}{c_{aw}}. \tag{18}$$

Using the above-given formulas, it is possible to model the temperature and humidity during the wood drying process.

3. Research experiment

Due to a number of simplifying assumptions, it should be assumed that the relations (1)–(18) describe in an approximate way the thermodynamic processes taking place in the dryer. However, the question arises whether and to what extent these equations can be useful in a technical sense, i.e., can they be used in the process of optimizing the drying process control strategy with a specific optimization criterion?

In order to rationalize the answer to this question, a classical approach to the verification of the analytical model was adopted based on the results of experimental studies and simulation studies. The main objectives set for the experimental studies were:

- experimental identification of unknown coefficients of analytical models,
- recording the time series of temperature and relative humidity changes in the dryer chamber,
- validation of the analytical model.

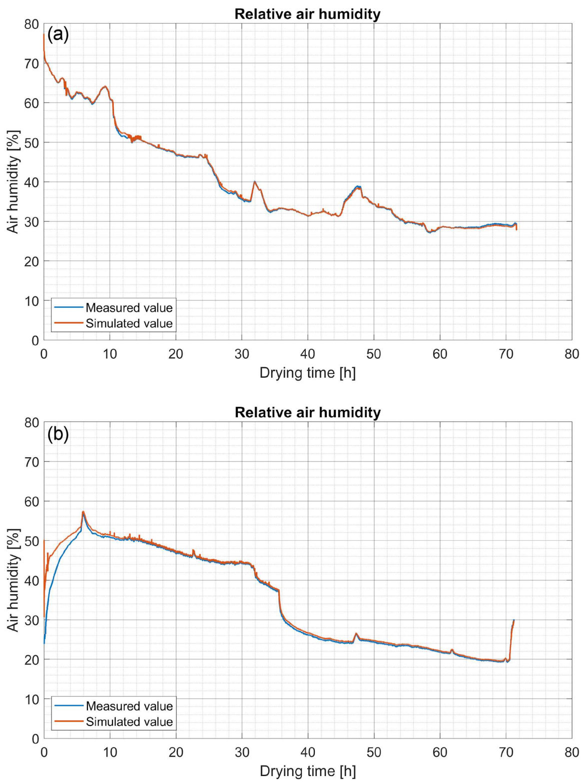

Fig. 3. Measured and simulation-derived change in relative humidity in the drying chamber during drying of batches 1 and 2. The waveforms for batch 1 are shown in panel (a), and for batch 2 in (b).

The research experiment was conducted in a conventional batch-type dryer. The chamber of this dryer is heated by thermal energy supplied through a heat exchanger. The primary circuit of the exchanger is supplied with heating water heated by a sawdust-fired water boiler. During the experiment, it was not possible to influence the temperature of the heating water, as it was regulated independently by the autonomous control system. This introduced some limitations to the conducted experimental research.

Experiments were carried out using a set of instruments to measure basic physical quantities such as temperature, relative humidity, moisture content, and air pressure. This allowed the parameters of the wood drying process to be identified and the developed model to be verified. The specification of the measured quantities along with the basic metrological parameters of the used measurement instruments are presented in Table I in Appendix.

For research purposes, as well as for comparison, the experiment was conducted a hundred times. For research reasons, each test was conducted for a different charge in the drying chamber, under unique atmospheric conditions. Therefore, for obvious reasons, the repeatability of recorded changes in temperature and relative humidity in the drying chamber was not to be expected. Their variation was due to many factors, the most important of which were indicated in Sect. 1.

Based on the experiments, the parameters of equations (1)–(18) were identified. These parameters are presented in Table II in Appendix of this paper.

The batches will be denoted hereafter by the numbers "1" and "2". In both cases, spruce wood in the form of boards with a cross-section of 6×30 cm and a length of more than 460 cm was subjected to drying. One difference between the two batches was that the wood of batch no. 1 was dried in February, while that of batch no. 2 was dried in April. Thus, they differed in the parameters of the wood itself (e.g., initial moisture content) as well as in the environmental conditions outside the dryer. Observation of the results of the experimental work shows that the drying process of batch no. 1 is quite typical, while that of batch two is quite unusual.

The simulation experiment was carried out using custom software prepared and executed for this purpose. Visualisations of the simulation and actual test results were prepared in the MATLAB environment. Section 4 presents selected results from both the simulation experiment and those obtained from tests in the dryer.

4. Experimental results

Experimental testing of batch no. 1 was conducted at an ambient temperature significantly lower than that of batch no. 2. Conducting tests at varying outdoor temperatures allowed at least a rough qualitative assessment of the effect of outdoor temperature on temperature and humidity inside the drying chamber. Figure 3 shows the measured and simulated relative humidity values for both batches.

From the waveforms shown in Fig. 3, there is an acceptable, and in places surprising, agreement between the relative humidity values measured in the drying chamber and those determined from the model. Some discrepancy between the measurements and the model output is noted only during the first hours of drying. Interpretation of this discrepancy is not straightforward and requires further research and analysis. Figure 4 shows the measured and simulated changes in air temperature in the drying chamber.

Again, a good agreement can be observed between the actual and simulated temperatures occurring in the drying chamber. The maximum difference between the measured and simulated temperature values from the 10th hour of the drying process does not exceed 2°C. The differences can be slightly larger in the first phase of drying, as can be seen especially in Fig. 4 for batch no. 2. The quality of the model should be considered

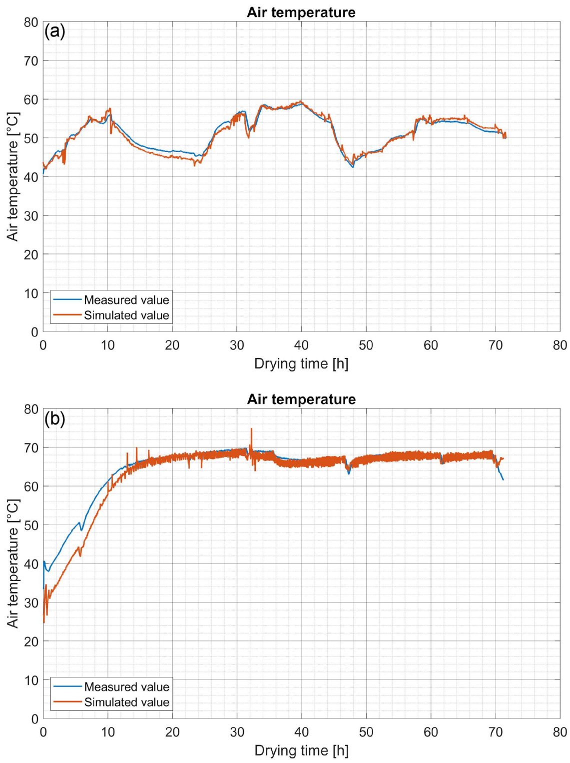

Fig. 4. Measured and simulation-derived temperature change in the drying chamber during drying of batches 1 and 2. The waveforms for batch 1 are shown in (a), and for batch 2 in (b).

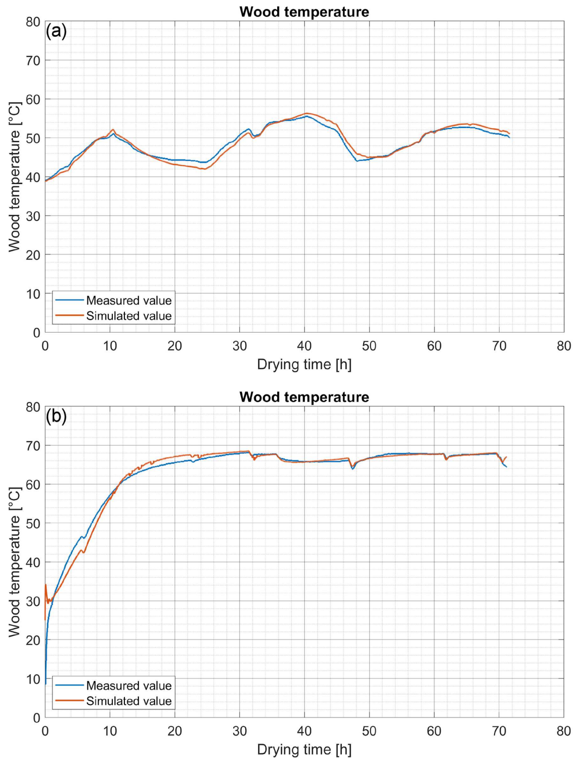

Fig. 5. Measured and simulation-derived change in wood temperature during drying of batches 1 and 2. The waveforms for batch 1 are shown in (a), and for batch 2 in (b).

acceptable when considering using it to construct a predictive control algorithm for the temperature control of the dryer. Figure 5 shows the measured and simulated temperature values on the surface of the dried wood.

In this case, the agreement between measured and simulated temperatures is very good. Based on the experimental data obtained, the value of the maximum average absolute modelling error was determined. This error is 0.7% for relative humidity, 1.65°C for air temperature in the chamber, and 0.85°C for wood surface temperature.

5. Conclusions

By considering the heat flow model of the dryer, it became possible to model both wood temperature and air humidity inside the dryer chamber. An original achievement of the work, which allowed us to improve the quality of the model, was the inclusion of heat flow through the walls of the dryer.

The obtained experimental and simulation results confirmed the practical usefulness of the analytical model of physical phenomena related to the transfer and accumulation of thermal energy proposed in this paper. In particular, the developed model is useful for adaptive control of the optimal drying process.

The experimental work carried out showed some imperfections of the proposed model, which become visible especially in the initial period of the drying process. Improvement of the model can be a subject and a challenge for further works.

Appendix

Table I lists the quantities to be measured together with the basic metrological parameters of the measuring instruments used. Table II lists the model parameters together with their determined values.

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TABLE I

Parameters of measuring equipment.

Measured value	Measuring device	Range	Uncertainty
air temperature	LG36-Box RH/T	−40–120°C	0.1°C
relative air humidity	LG36-Box RH/T	0–100%	0.1%
wood temperature	LG36 MoistureMouse	−20–120°C	0.2°C
wood moisture content on the wood surface	LG36 MoistureMouse	6–90% at 25°C	0.2°C
wood moisture content inside	LG36 MoistureMouse	6–90% at 25°C	0.2°C
outdoor air temperature	BME 280	−40–85°C	1°C
relative outdoor air humidity	BME 280	10–100%	3%
outdoor air pressure	BME 280	300–1100 hPa	1 hPa

TABLE II

List of model parameters.

Symbol	Name	Value	Unit
A_g	radiator surface	150	m^2
A_{wall}	dryer wall area	68.5	m^2
c_{dry}	specific heat of dry air	1005	J/(kg K)
c_w	specific heat of steam	1890	J/(kg K)
d_{wall}	dryer wall thickness	0.1	m
r_{dry}	individual gas constant for dry air	287.05	J/(kg K)
V_{air}	volume of air in the dryer chamber	51	m^3
Y	coefficient of air exchange with the surroundings	0–0.04	–
α_g	heat penetration coefficient from exchangers to air	16	$\mathrm{W/(m^2\ K)}$
α_w	heat penetration coefficient from air to wood	16	$\mathrm{W/(m^2\ K)}$
λ_{wall}	coefficient of heat conduction through the dryer walls	0.05	W/(m K)

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