Modeling of Delignification Process of Activated Wood and Equipment for its Implementation

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Abstract. The article is the analyses of the physical picture of the process of steam explosion treatment of pre-impregnated lignocellulosic material, on the basis of which the mathematical modeling is represented in the form of differential equations with boundary conditions. The obtained mathematical description allows to determine the degree of influence of various factors on the kinetics of the process.

1. Introduction
Delignification of activated wood is a two-stage combined pulping. Preliminary steam hydrolysis allows to remove most of the hemicelluloses from the wood and weaken the bonds between cellulose and pentosans, and the steam explosion due to the sharp decompression is intended to loosen the structure of the cell walls and partially separate the fibers from each other. These two interrelated phenomena make it possible to increase the reactivity of the resulting cellulose, which is intended for further chemical processing. The material after steam explosion treatment is a combination of cellulose, various lignin structures (native, low molecular weight, condensed), and hemicellulose residues in the form of mono- and oligosaccharides [1-4], and the products of degradation during steam explosion treatment are mono- and oligosaccharides, low-molecular and condensed lignin. Part of the native (original, natural) lignin remains unchanged.

2. Physicochemical picture of processes and phenomena occurring during delignification of activated wood
Before delignification, the purpose of which is to produce cellulose for further chemical processing, the blasted material is subjected to washing to extract destructured hemicelluloses (in the form of sugars) and low molecular weight lignin fragments (hereinafter, by-products of degradation). Lignocellulosic pulp after steam explosion treatment contains from 10 to 40% of by-products from the raw material, depending on processing conditions. From the total amount of products, a small part (approximately 5-7% of the total mass) is concentrated in the capillaries of the cell walls. 15-20% of the products of the total mass are enclosed in the channels and cavities of the fibers. 75-80% of the total mass, i.e. the remaining degradation products, constitute a free solution of the products in the water surrounding the individual fibers or bundles of fibers. After washing, the high-moisture fiber with a specified content of lignin and cellulose is loaded into the cooker, where the previously prepared delignifying agent is supplied. The material after the steam explosion treatment has an even
greater porosity due to the removal of easily hydrolyzable polysaccharides from it, as well as the highly developed specific surface formed as a result of the deflation due to the release of pressure. These properties contribute to a multiple acceleration of the penetration of the reagent into the cell wall of the wood material. The high humidity of the blasted fiber also helps to accelerate the diffusion of active substances.

The process of delignification of activated wood is greatly simplified compared to delignification of wood chips. The general mechanism of the delignification of activated wood and the sequence of the individual stages from which the transformation of lignocellulosic material into cellulose are as follows:

1) penetration of delignifying agents into the cell wall of the activated material, i.e. diffusion of the reagents (fig. 1) [5];

![Figure 1. Mechanism of penetration of delignifying agents into the material obtained after steam explosion treatment of wood chips with subsequent washing](image)

2) adsorption of active reagents in micelles on the high reaction surface of the activated material, accompanied by swelling of the cell walls [6];

3) stage of chemical reactions in the solid phase: interaction of the structures of phenylpropane units of lignin with the reagent, followed by a competing condensation reaction [7-9];

4) the final stage of chemical reactions: partial destruction of delignification products [10-11];

5) incomplete depolymerization and hydrolysis of hemicelluloses and cellulose [12-14];

6) further condensation or depolymerization of delignification products [15-16].

In the delignification process, a multicomponent mixture of vapors is formed, which consists predominantly of methyl alcohol, hydrogen sulfide, dimethyl sulphide and methyl mercaptan, turpentine, a small amount of acetone, methyl sulfur compounds, ammonia and ammonium sulphide. Therefore, taking into account the complexity of the phenomena of heat and mass transfer, in order to obtain a constructive mathematical description of a multistage process, we make the following assumptions:

1. We assume that the particle after the steam explosion treatment has the shape of a cylinder, that is, a one-dimensional problem is considered [17].

2. Since the water is in excess during the delignification, the change in its concentration during the reaction is neglected, and the delignification reaction is considered as a monomolecular, or first-order reaction [18].

3. The material after steam explosion treatment, subjected to delignification, consists of cellulose, low molecular weight lignin and part of natural lignin that has not undergone any changes during steam explosion treatment; hemicelluloses are absent [19-22].

4. The gas and solid phases are in a state of thermodynamic equilibrium, so the temperature of the particle is determined by the temperature of the resulting vapor-gas mixture.

3. Mathematical modeling of the delignification process of activated wood
After the process of steam explosion activation of wood, the raw material is a fibrous intermediate product with a component composition directly depending on the conditions of steam explosion treatment:
- alpha cellulose:
  \[ C_1 = 88.53 \exp(-0.0016t) - 0.08t^{1.56} \exp(-0.01t) \];

- lignin
  \[ C_2 = 10.89 \exp(0.01t) - 6.43 \cdot 10^{-6} t^{3.1} \];

- hemicellulose
  \[ C_3 = 7.65 \exp(0.012t) - 4.68 \cdot 10^{-9} t^{4.7} \exp(-0.008t) \];

- extractives
  \[ C_4 = 120.92 \exp(-0.014t) - 0.25t^{1.5} \exp(-0.025t) \];

- total solid products from spruce
  \[ C = 78.59 \exp(0.0026t) - 2.7 \cdot 10^{-16} t^{8.7} \exp(-0.03t) \].

The resulting fibrous product is subjected to washing from the degradation products of hemicelluloses and a portion of the low molecular weight lignin in a drum vacuum filter. The rate of filtration of the washing liquid (1/s) is determined from the Poiseuille equation [22]:

\[
q = \frac{\Delta p}{RL},
\]

where \( \Delta p \) - pressure drop on the sides of the layer of lignocellulosic material, Pa; \( l \) - layer thickness, m; \( R \) - the coefficient of filter resistance, equal to [27]

\[
R = \frac{32 \mu}{\varphi \rho d^2},
\]

where \( \mu \) - is the dynamic viscosity of the liquid, Pa\cdot s; \( \varphi \) - free area ratio of the filter; \( d \) - is the average diameter of the capillaries in the layer, m.

The degree of selection, or washing efficiency, is the ratio of the amount of dissolved substances in the obtained solution \( G \) to their quantity in the initial solution after the steam explosion treatment \( G_0 \) [23]:

\[
\eta = \frac{G}{G_0}.
\]

\( G_0 \) is the mass of substances formed as a result of steam explosion treatment (sugars and low molecular weight lignin) and subject to extraction during washing [24]:

\[
G_0 = m_{a.d.w.} \cdot (C_{3_b} + C_{2_a} - C_1 - C_2),
\]

where \( m_{a.d.w.} \) is the mass of absolutely dry wood exposed to steam explosion treatment, \( C_{3_b}, C_{2_a} \) are the mass fractions (% of the a.d.w.) of hemicelluloses and lignin in the original wood before the steam explosion treatment, \( C_1, C_2 \) - mass fractions (% of the a.d.w.) of hemicelluloses and lignin after steam explosion treatment in a material subjected to washing.

The washed fiber is loaded into the cooker, where the cooking liquor is circulated by the pump and the system heats up. Diffusive impregnation is described according to the Fick law, in which the concentration gradient (g/s) is defined as:

\[
\frac{dG}{d\tau} = -D A_{m} m_{lc} \frac{dC}{dl},
\]

where \( G \) is the amount of diffusible cooking liquor, g; \( \tau \) - duration of the diffusion process, s; \( m_{lc} \) - the mass of absolutely dry lignocellulosic fiber, which is supplied for delignification; \( C \) - concentration of solute, g/cm\(^3\); \( l \) is the distance at which diffusion takes place (mean particle diameter), cm; \( D \) - diffusion coefficient, depending on the parameters of the solvent, penetrating particles and temperature, cm\(^2\)/s.
\[ m_{ic} = m_{a.d.w.} \cdot (C_1 + C_2 + C_3 + C_4), \]  
where \( C_1, C_2, C_3, C_4 \) - the concentration of cellulose, lignin, hemicelluloses, extractives respectively after washing, determined by the expressions (1 – 4).

The specific surface area \( A_{sa} \) of the fibrous lignocellulosic material formed after steam explosion treatment (m²/kg) is determined from the data of:

\[ A_{sa} = \frac{0.01 - 0.004 \cdot p_{set} - 0.0003 \cdot p_{set}^2 + 0.0003 \cdot p_{set}^3 + 0.0008 \ln \tau_{dec} + 0.0015(\ln \tau_{dec})^2}{1 - 0.66 \cdot p_{set} + 0.12 \cdot p_{set}^2 + 0.144 \ln \tau_{dec} + 0.087(\ln \tau_{dec})^2} \]  
at the set temperature \( t_{set} \), the pressure \( p_{set} \) of steam explosion treatment and the decompression time of the reactor \( \tau_{dec} \), where \( p_{set} \) is also determined by the empirical expression [25-26]

\[ p_{set} = 2.04e^{2.74r_{set}^{0.3}}. \]  
The rate of direct reaction (change in concentration in time) at any time is directly proportional to the production of the volume concentrations of substances participating in the reaction [28-29]:

\[ \frac{dC_i}{d\tau} = k_m \prod_{i=1}^{n} C_i^{\frac{\mu_i}{\mu}}, \]

where \( k_m \) is the mass transfer coefficient complicated by chemical transformation, which can be determined from the expressions obtained as a result of modeling in [30]

\[ k_m = 5736.4 \exp(-0.0016r_{0.2}) - 5978.8r_{0.01} \exp(-0.056r_{0.1}). \]  
The weight and volume concentrations are connected by the relation [31]

\[ \frac{dC_i}{d\tau} = \frac{\rho_{mix} \frac{dV_i}{d\tau}}{\mu_i} + \frac{\rho_{mix}}{\mu_i} \frac{dp_{mix}}{d\tau}. \]  

During the passage of the cooking liquor through the layer of activated wood, due to heat-mass transfer and chemical reactions, the content of delignification products in the cooking liquor changes with time and the temperature over the cross section of the particle is determined from the heat and material balances recorded in differential form. The solid phase is represented by lignin and cellulose [32-33], the liquid phase is water contained in the fiber after washing, the reagent solution, the gas phase is air in the cooker, the gases formed during the interaction of lignin with the reagent (methyl mercaptan, dimethyl sulfide, hydrogen sulphide, turpentine, etc.), water and organic acids vapors. Since the process is formalized, the steam explosive activated material after washing is considered as lignocellulose - a mixture consisting of two main constituents: cellulose and lignin with known mass fractions.

The change cellulose weight is insignificant, and it is not taken into account in the description, that is \( \Delta m_c = 0 \).

The change in lignin mass will be presented as (cellulose does not participate in the delignification process):

\[ \frac{dm_l}{d\tau} = -k_l \cdot m_{a.d.w.} \cdot C_2, \]

where \( m_l \) - is lignin mass, \( \tau \) - is delignification time, \( k_l \) - is rate constant of delignification.

The reaction rate constant for lignin \( k_l \) (1/h) is calculated by the formula [34-35]:

\[ k_l = \frac{1}{\tau} \ln \frac{m_{ic}}{m_{ic} - x}, \]

where \( m_{ic} \) - the amount of initial lignocellulose or lignin; \( (m_{ic} - x) \) - the amount of residue (yield of cellulose) or lignin after \( \tau \) delignification hours. The weight of technical pulp after delignification is determined by the formula:

\[ m_{tc} = m_{a.d.w.} \cdot (C_2 + C_1). \]
Steam and gas formation during delignification is accompanied by absorption and release of heat, which in turn has a significant effect on the temperature change of both the individual particle and the layer as a whole. The temperature of the gas stream will determine the temperature of the solid particle, and the heat balance equation will be written as:

\[
\frac{\partial T}{\partial t} = \frac{\partial T}{\partial t} \left( \lambda_p \cdot \frac{\partial T}{\partial t} \right) - c_g \cdot m_g \cdot w_g \cdot \frac{\partial T}{\partial t} + q_{ch.r},
\]

where \( \lambda_p \) is the coefficient of thermal conductivity of a lignocellulosic particle, \( q_{ch.r} \) is the heat energy released (absorbed) by a chemical reaction; \( m \) is the mass of matter per unit volume of the cooker.

The heat balance [36-37] equation for the liquid phase in the differential form is written as:

\[
c_{mix}m_{mix}dT + c_{mix}dm_{mix} + dc_{mix}m_{mix}T = \sum_{i=1}^{n} Q_{load}c_i T_{i0} d\tau - \sum_{i=1}^{n} j_i c_i T F d\tau - \sum_{i=1}^{n} j_i c_i T F d\tau + \sum_{i=1}^{n} q_{ch.r} \sigma T \rho \bar{V} d\tau.
\]

The change in the heat content of a mixture of liquid components in the cooker is determined from the left side of equation (21). The first term on the right side determines the amount of heat that came with the components at boot time; the second term characterizes the loss of heat carried away by the components of the vapor mixture; the third term determines the heat consumption for the formation of vapors; the fourth is the heat of the chemical reaction. The material balance in the differential form will be written in the form:

\[
dm_{mix} = \sum_{i=1}^{n} Q_{load}c_i T_{i0} d\tau - \sum_{i=1}^{n} j_i c_i T F d\tau - \sum_{i=1}^{n} q_{ch.r} \sigma T \rho \bar{V} d\tau.
\]

The change in mass of the mixture in the cooker is determined from the left side of equation (22). The first term on the right side allows one to estimate the mass of the loaded components, the second allows for evaporation of the components, the third determines the change in mass due to chemical reactions.

The change in the heat capacity of a liquid mixture is defined as the sum of the products of the heat capacity of the i-th component of the mixture at its concentration:

\[
dc_{mix} = \sum_{i=1}^{n} c_i d\bar{X}_i.
\]

The concentration of the i-th component changes as a result of evaporation [38], the course of the chemical reaction and due to the loading:

\[
d\bar{X}_i = d\bar{X}_{i,\text{evap}} + d\bar{X}_{i,\text{ch.r}} + d\bar{X}_{i,\text{load}}.
\]

The change in the concentration of components in real cooking liquids can be determined as:

\[
d\bar{X}_{i,\text{evap}} = \frac{d\bar{P}}{\gamma_i \exp(A_i - B_i)} \frac{d\tau}{T^2} - \frac{\bar{X}_i B_i}{\gamma_i} d\tau.
\]

The change in the concentration of the mixture component per unit time determines the rate of the chemical reaction:

\[
d\bar{X}_{i,\text{ch.r}} = \frac{\mu_i}{\rho_{mix}} \left[ k \prod_{j=1}^{n} \left( \frac{\rho_{mix} \bar{X}_j}{\mu_j} \right) \bar{X}_i \right] d\tau - \frac{\bar{X}_i}{\rho_{mix}} d\rho_{mix}.
\]

The change in the concentration of the component due to the loading into the cooker is determined by the relation

\[
d\bar{X}_{i,\text{load}} = \frac{Q_i \rho_i}{m_{mix}} d\tau.
\]
Assuming that the components of the gas-vapor mixture are perfectly mixed, we will write the equation of the material balance of the gas-air mixture in a differential form for the stage of unloading the cooker due to a pressure drop:

$$\frac{dm_{\text{mix}}}{d\tau} = \frac{dm_{\text{vap}}}{d\tau} + \frac{dm_{\text{g-air}}}{d\tau} = \frac{dp_{\text{g-air}}}{d\tau} V_{\text{free}} = \frac{dp_{\text{g-air}}}{d\tau} V_{\text{free}} + \frac{dp_{\text{vap}}}{d\tau} V_{\text{free}}. \quad (28)$$

The temperature of the vapor-gas-air mixture is determined from the heat balance equation for the vapor-gas-air mixture:

$$\frac{dT}{d\tau} = \alpha(T_\text{v}-T_\text{a})F_{\text{inlet}} + \sum_{j=1}^n \frac{dp_j}{d\tau} \frac{\mu_j \gamma_j}{RT} + \sum_{j=1}^n \frac{dp_j}{d\tau} \frac{\mu_j \gamma_j}{RT^2} + \frac{\sum_{i=1}^m dy_i}{d\tau} \frac{\mu_i p_i}{RT} + \frac{\sum_{i=1}^m dy_i}{d\tau} \frac{\mu_i p_i}{RT^2} + \frac{\sum_{i=1}^m dy_i}{d\tau} \rho_{\text{free}}. \quad (29)$$

The density of the components is determined by the equation

$$c_{\text{air}} \rho_{\text{air}} + \sum_{j=1}^n c_j P_j + \sum_{j=1}^n c_j P_j = c_{\text{vap-air}} \rho_{\text{vap-air}}. \quad (30)$$

The heat capacity of the above mixtures can be determined according to the additivity rule [39-40].

$$c_{\text{air}} \rho_{\text{air}} + \sum_{j=1}^n c_j P_j + \sum_{j=1}^n c_j P_j = c_{\text{vap-air}} \rho_{\text{vap-air}}. \quad (31)$$

### 4. Method of experimental research

In the course of the work we used wood sorted from the species of coniferous species sorted to the middle size 5x5x0.5 mm. Samples of sawdust were subjected to chemical analysis for the quantitative content of extractives, holocellulose, alpha-cellulose, lignin, easily hydrolyzable and hardly hydrolyzable polysaccharides by known methods. The mass fractions of the components (in % of the a.d.) of pine were: 51 cellulose; lignin - 24.1; pentosans - 10.2; hexosans-7.6; extractive substances – 6.7. For a given wood species, a number of experiments on steam explosion treatment were carried out. The temperature of steam explosion treatment was: 130, 160, 190, 220 ºС, the processing time was 5, 10, 15, 20 minutes. In all the samples of the blasted and washed lignocellulosic material, the specific surface area was determined by the BET method. The analysis data were used to calculate the equations of the mathematical model.

To carry out experimental studies of the influence of temperature on the rate constant of delignification of coniferous wood preliminarily activated by steam explosion treatment, the samples were subjected to continuous delignification with sulphate and sulphite liquor at the plant, the scheme of which is shown in Fig. 2.

The plant for delignification of activated wood works as follows. The raw material in the form of wood chips is loaded into the feed hopper 1, where it is saturated with water, and then enters the steam explosion reactor 2, where saturated water vapor is fed. After the raw material has been left in the reactor, a relief valve 3 opens from the drive 7 and the activated lignocellulosic material is expelled into the cooler 4. The discharge valve closes again, the pump 10 is turned on, the liquor is pumped into the cooler, which circulates through the heat exchanger 5 and is heated through the wall by steam coming from superheater of the steam generator. At the end of the cooking process, the steam mixture is blown off, the valve 9 opens, and the pulp is blown into the blowing tank 8, from where it enters the receiver 11. The unit is equipped with an automation system. So, in there are temperature sensors T1 and pressure P1 in the reactor for steam explosion treatment, there are two temperature sensors T3 and T4, as well as a pressure sensor P2 in the cooler. To control the temperature and flow rate of the circulating cooking liquor, the sensors T5 and G2 are installed at the pump outlet.
Figure 2. Scheme of installation for wood delignification, previously activated by steam explosion treatment: 1 - bunker for loading wood material, 2 - reactor for steam-explosive activation, 3 - discharge unit, 4 - cooker, 5 - heat exchanger, 6 - thermocouples, 7 - liquid pump, 8 - blowing tank, 9 - blowing valve, 10 - circulating pump, 11 - product receiver

To regulate the temperature of the steam in the heat exchanger, a thermocouple T2 is installed. The pressure in the discharge line of the discharge unit is controlled by the pressure sensor P3. The gas flow rate at the primary blowing is controlled by the flowmeter G1 of regulation of the temperature of pressure and flow. All the sensor readings are collected in the controller and converted into an analog-digital converter (PC). The temperature in the cooker is controlled by the temperature of the steam in the heat exchanger, which is formed in the steam generator. The cooking temperature was 165-170°C, the duration - up to 5 hours. For comparison, similar experiments were conducted on cooking chips, used in traditional processes for the production of cellulose.

5. Results of experiments and discussion

To assess the efficiency of the steam explosion treatment, a number of sulphate pulpings were carried out on the experimental setup of both activated lignocellulosic material and conventional pine chips before delignification. The continuously circulating liquor was heated in a heat exchanger to a cooking temperature of 165°C, the concentration of the active alkali was 49 g/l, the cooking modulus was 4. The primary lignin content of the chips was 18% of the a. d. for activated lignocellulosic material (ALM) – 14.1% of a. c. (processed by steam explosion treatment at a temperature of 220°C for 5 minutes, $A_{sa} = 6.03$ m$^2$/g). The comparative results of the two pulpings are shown in Fig. 3.

A comparative analysis of the results of two pulpings showed that when cooking activated lignocellulosic material, the temperature increase occurs faster than in the case of chips, which is primarily due to the high moisture state after steam explosion treatment, which facilitates accelerated impregnation of liquor into the interior of the particles, hence the lignin destruction reaction begins earlier, than in the case of chips. This is proved by the data of curves 4 and 5, from which it can be seen that the transition of lignin to alkali from the activated material occurs much faster than in the case of chips, and the delignification process is about 1.5 - 2 times faster. This is also facilitated by a lower initial content of lignin at the beginning of delignification, in view of its partial degradation in steam explosion treatment. The yield of cellulose remains the same in both cases, however, when delignification of activated wood occurs earlier at the same time of cooking the chips and ALM, an increase in the yield of cellulose is likely.
Figure 3. Change in the composition of solid residues and liquors during sulphate pulping: 1 - temperature (ALM), 2 - temperature (chips), 3 - calculated temperature curve (for ALM), 4 - lignin in alkali (chips), 5 - lignin in alkali (ALM), 6 - yield of cellulose (chips) 7 - yield of cellulose (ALM), 8 - calculated cellulose yield curve (for ALM), 9 - consumption of active alkali (chips), 10 - consumption of active alkali (ALM).

Curves 9, 10 clearly illustrate that the consumption of active alkali with an equal initial concentration in both cases is quite different. For the same period of cooking, alkali is consumed in the case of activated lignocellulose by 15-17% less than for cooking chips. All these data prove the high efficiency of the application of steam-explosive activation of wood raw materials before delignification. A key role in improving the efficiency of the delignification process is undoubtedly played by the process of explosive separation into fibers, defibrillation at high temperatures of steam-explosive activation. Steam treatment (steam prehydrolysis) allows only to reduce the amount of lignin and hemicelluloses in the original wood, which is also important, and to create conditions for explosive boiling up of superheated liquid inside the material. The calculated curves 3 and 8 make it possible to confirm the correctness of the conclusions in the simulation, since the discrepancy with the experimental data is 6.4% and 13.1%, respectively. An increased percentage of the discrepancy with the experiments to determine the yield of cellulose is acceptable, since the very definition of the mass fraction of cellulose in a solid residue implies a series of experiments, when summing up the errors of which, such a high error percentage is formed.

The increase in the efficiency of delignification is caused by the highly developed specific surface of the material after steam-explosive activation and the increase in the size of the pores and capillaries, the change in the structure of the cell wall of the wood fiber, the high moisture content of the material after washing, the low initial content of lignin at the beginning of delignification, in view of its partial degradation during steam explosion treatment and almost complete absence of hemicelluloses. The use of explosive separation of the activated material on the particles doesn't only give a high specific surface, but also mechanically affects the condensed lignin fractions formed in the process of high-temperature steam hydrolysis. These insoluble lignin fractions are destabilized and undergo degradation, which subsequently facilitates both washing and diffusion impregnation and delignification itself.

The optimal parameters for steam explosion treatment are: type of wood - spruce, pine; fractional composition of raw materials - flake, chips; the temperature of the steam is from 210 to 230 °C; soaking time at the set temperature - 10 minutes; pressure - from 2.2 to 2.9 MPa; decompression time - 0.2 s; extractant of reducing substances (sugars) - ethanol-water solution with a temperature of 90 °C;
extractant of low molecular weight lignin - sodium hydroxide from 0.4 to 2% with a temperature of 20 °C.

The positive effect of the preliminary steam-explosive activation of wood before delignification consists in increasing the productivity of the cooker, reducing the consumption of reagents for cooking, the possibility of varying the reagents, and also in obtaining dissolved hemicelluloses during the steam explosion treatment. The shown efficiency of the process is fully confirmed by experiments and is in good agreement with the calculated data with an average error of 7.5%, which indicates the correctness of acceptance of the assumptions about the process, the adequacy of the developed mathematical model to the actual process of wood delignification, previously activated by steam explosion treatment, and the correctness of the assumptions. Mathematical modeling, as well as experimental research, is a source of data on the process of delignification of wood, previously activated by steam explosion treatment, and allows to determine the influence of various parameters on the efficiency of the delignification process. The constructed mathematical model was tested for adequacy by known methods of mathematical statistics. Under identical conditions, the results of experimental studies were compared with theoretical calculations.

6. Conclusion
Perfection of the mechanism of wood delignification process, previously activated by steam explosion treatment, consists in the development of new calculation methods aimed at increasing the efficiency of the process, and the improvement of technology consists in the use of new methods of processing wood raw materials, on the basis of which the problem of increasing the stability of positioning of domestic technologies in the world market of wood chemical Industry, particularly in the pulp and paper sector, is solved.

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References
[1] Gujjala, L. K., Bandyopadhyay, T. K., & Banerjee, R. 2016 Kinetic modelling of laccase mediated delignification of Lantana camara. Bioresource technology, 212: 47-54.
[2] Dagnino, E. P., Felissia, F. E., Chamorro, E., & Area, M. C. 2017 Optimization of the soda-ethanol delignification stage for a rice husk biorefinery. Industrial Crops and Products, 97: 156-165.
[3] Dutta, S. K., Halder, G., & Mandal, M. K. 2014 Modeling and optimization of bi-directional delignification of rice straw for production of bio-fuel feedstock using central composite design approach. Energy, 71: 579-587.
[4] Subhedar, P. B., Ray, P., & Gogate, P. R. 2017 Intensification of delignification and subsequent hydrolysis for the fermentable sugar production from lignocellulosic biomass using ultrasonic irradiation. Ultrasonics sonochemistry.
[5] Qing, Q., Zhou, L., Guo, Q., Huang, M., He, Y., Wang, L., & Zhang, Y. 2016 A combined sodium phosphate and sodium sulfide pretreatment for enhanced enzymatic digestibility and delignification of corn stover. Bioresource Technology, 218: 209-216.
[6] Karimi, M., Esfandiar, R., & Biria, D. 2017 Simultaneous delignification and saccharification of rice straw as a lignocellulosic biomass by immobilized Thrichoderma viride sp. to enhance enzymatic sugar production. Renewable Energy, 104: 88-95.
[7] Prathyusha, N., Kamesh, R., Rani, K. Y., Sumana, C., Sridhar, S., Prakasham, R. S., & Kumar, M. P. 2016 Modelling of pretreatment and saccharification with different feedstocks and kinetic modeling of sorghum saccharification. Bioresource technology, 221: 550-559.
[8] Susilo, J., & Bennington, C. P. J. 2007. Modelling kappa number and pulp viscosity in industrial oxygen delignification systems. Chemical Engineering Research and Design, 85(6): 872-881.

[9] Salmi, T., Wärn, J., Mikkola, J. P., & Rönnholm, M. 2005. Modelling and simulation of porous, reactive particles in liquids: delignification of wood. Computer Aided Chemical Engineering, 20: 325-330.

[10] Vega, A., Bao, M., & Lamas, J. 1997. Application of factorial design to the modelling of organosolv delignification of Miscanthus sinensis (elephant grass) with phenol and dilute acid solutions. Bioresource technology, 61(1): 1-7.

[11] Kumar, R., Hu, F., Hubbell, C. A., Ragauskas, A. J., & Wyman, C. E. 2013 Comparison of laboratory delignification methods, their selectivity, and impacts on physiochemical characteristics of cellulosic biomass. Bioresource technology, 130: 372-381.

[12] Rocha, G. J. M., Gonçalves, A. R., Oliveira, B. R., Olivares, E. G., & Rossell, C. E. V. 2012 Steam explosion pretreatment reproduction and alkaline delignification reactions performed on a pilot scale with sugarcane bagasse for bioethanol production. Industrial Crops and Products, 35(1): 274-279.

[13] Marton, G., Kovacs, M., Oreopoulou, V., & Koukios, E. G. 1988 Modelling of biomass fractionation by prehydrolysis-delignification. Chemical engineering science, 43(8): 1807-1812.

[14] Huron, M., Hudebine, D., Ferreira, N. L., & Lachenal, D. 2016 Impact of delignification on the morphology and the reactivity of steam exploded wheat straw. Industrial Crops and Products, 79: 104-109.

[15] Hubbell, C. A., & Ragauskas, A. J. 2010 Effect of acid-chlorite delignification on cellulose degree of polymerization. Bioresource Technology, 101(19): 7410-7415.

[16] Pinto, P. C., Oliveira, C., Costa, C. A., Gaspar, A., Faria, T., Ataide, J., & Rodrigues, A. E. 2015 Kraft delignification of energy crops in view of pulp production and lignin valorization. Industrial Crops and Products, 71: 153-162.

[17] Ratti, R. P., Delforno, T. P., Sakamoto, I. K., & Varesche, M. B. A. 2015 Thermophilic hydrogen production from sugarcane bagasse pretreated by steam explosion and alkaline delignification. International Journal of Hydrogen Energy, 40(19): 6296-6306.

[18] Timilsena, Y. P., Abeywickrama, C. J., Rakshit, S. K., & Brosse, N. 2013 Effect of different pretreatments on delignification pattern and enzymatic hydrolysability of miscanthus, oil palm biomass and typha grass. Bioresource technology, 135: 82-88.

[19] Marton, G., Kovacs, M., Oreopoulou, V., & Koukios, E. G. 1988 Modelling of biomass fractionation by prehydrolysis-delignification. Chemical engineering science, 43(8): 1807-1812.

[20] Mafuleka, S., & Kana, E. G. 2015 Modelling and optimization of xylose and glucose production from napier grass using hybrid pre-treatment techniques. Biomass and Bioenergy, 77: 200-208.

[21] Jabbari, M., et al. 2016 Drying of a tape-cast layer: Numerical modelling of the evaporation process in a graded/layered material. International Journal of Heat and Mass Transfer, 103: 1144-1154. DOI:10.1016/j.ijheatmasstransfer.2016.08.073

[22] Fomin A.A., Gusev V.G., Yudin R.V., Timerbaev N.F. and Retyunskiy O.Yu. 2016 Mechanical treatment of raw waste lumber an effective way to preserve the ecology and resources. IOP Conference Series: Materials Science and Engineering 142(1): 012091.

[23] Timerbaev N.F., Safin R.G., Ziatdinova D.F., Fomin A.A. and Mokhovikov A.A. 2016 The development of experimental setups and experimental studies of the process of energy-technological processing of wood. IOP Conference Series: Materials Science and Engineering 142(1): 012096. DOI:10.1088/1757-899X/142/1/012096

[24] Prosvirnikov D.B., Ziatdinova D.F., Timerbaev N.F., Saldaev V.A. and Gilfanov K.H. 2016 Mathematical modelling of the steam explosion treatment process for pre-impregnated lignocellulosic material. IOP Conference Series: Materials Science and Engineering 124(1): 012087. DOI:10.1088/1757-899X/124/1/012087

[25] Safin R., Barcik Š., Shaikhutdinova A., Safina A., Kaynov P. and Razumov E. 2015 Development of the energy-saving technology of thermal modification of wood in saturated
steam. Acta Facultatis Xylologiae 57(2): 39-47. DOI:10.17423/afx.2015.57.2.04

[26] Lashkov V.A., Levashko E.I. and Safin R.G. 2001 Heating of production wood chips in a saturated-steam medium. Inzhenerno-Fizicheskii Zhurnal, 74(1): 80-83.

[27] Ivanov, E. V., M. V. Shvyrev, and M. A. Artemova. 2004 Filtration of the extracting agent in porous particles with entrapped gas at low-frequency pressure oscillations in the extractor. Russian journal of applied chemistry, 77(10): 1662-1666.

[28] Bouzid, Majda, et al. 2011 In-pore tensile stress by drying-induced capillary bridges inside porous materials. Journal of colloid and interface science, 355(2): 494-502.

[29] Defraeye, Thijs, Bert Blocken, and Jan Carmeliet. 2013 Influence of uncertainty in heat–moisture transport properties on convective drying of porous materials by numerical modelling. Chemical Engineering Research and Design, 91(1): 36-42.

[30] Prosvirnikov D.B., Safin R.G., Ziatdinova D.F., Timerbaev N.F., and Lashkov V.A. 2016 Multifactorial modelling of high-temperature treatment of timber in the saturated water steam medium. IOP Conference Series: Materials Science and Engineering, 124(1): 012088. DOI:10.1088/1757-899X/124/1/012088

[31] Van Belleghem, Marnix, et al. 2014 Validation of a coupled heat, vapour and liquid moisture transport model for porous materials implemented in CFD." Building and Environment, 81: 340-353. DOI:10.1016/j.buildenv.2014.06.024

[32] Sadrtdinov A.R., Sattarova Z.G., Prosvirnikov D.B. and Tuntsev D.V. Modeling of thermal treatment of wood waste in the gasifiers. Proceedings of 2015 International Conference on Mechanical Engineering, Automation and Control Systems, MEACS 2015. art. no. 7414914. DOI:10.1109/MEACS.2015.

[33] Timerbaev N.F., Safin R.R., Safin R.G. and Ziatdinova D.F. 2014 Modeling of the process of energy-technological treatment of wood waste by method of direct-flow gasification. Journal of Engineering and Applied Sciences (EAAS) 9(5): 141-146

[34] Zhang, Hu, et al. 2014 Experimental study on the kinetics of water vapor sorption on the inner surface of silica nano-porous materials. International Journal of Heat and Mass Transfer, 78: 947-959. DOI:10.1016/j.ijheatmasstransfer.2014.07.047

[35] Choudhary, Anupama, Devendra Kumar, and Jagdev Singh. 2015 A fractional model of fluid flow through porous media with mean capillary pressure. Journal of the Association of Arab Universities for Basic and Applied Sciences, 21: 59-63. DOI:10.1016/j.jaubs.2015.01.002

[36] Sadrtdinov A.R., Safin R.G., Gerasimov M.K., Petrlov V.I., and Gilfanov K.K. 2016 The mathematical description of the gasification process of woody biomass in installations with a plasma heat source for producing synthesis gas. IOP Conference Series: Materials Science and Engineering, 124(1): 012092. DOI:10.1088/1757-899X/124/1/012092

[37] Sychevskii, V.A. 2015 Drying of colloidal capillary-porous materials. International Journal of Heat and Mass Transfer, 85: 740-749.

[38] Lashkov V.A., Sattarova Z.G., Taymarov M.A., Gerasimov M.K. and Halitov R.A. 2016 Modeling of a reduction zone of the gasifier installation. IOP Conference Series: Materials Science and Engineering, 124(1): 012111. DOI:10.1088/1757-899X/124/1/012111

[39] Sadrtdinov A.R., Esmagilova L.M., Saldaev V.A., Sattarova Z.G. and Mokhovikov A.A. 2016 Mathematical modeling for the development of equipment for thermochemical processing of wood waste in to dimethyl ether. IOP Conference Series: Materials Science and Engineering, 142(1): 012094. DOI:10.1088/1757-899X/142/1/012094

[40] Yang, Lianfa, Haisong Rong, and Yulin He. 2014 Deformation behavior of a thin-walled tube in hydroforming with radial crushing under pulsating hydraulic pressure. Journal of materials engineering and performance 23(2): 429-438. DOI:10.1007/s11665-013-0783-9